CHAPTER 3

OPTIMIZATION APPROACH TO NOISE HAZARD PREVENTION

This chapter discusses an optimization procedure for noise hazard prevention. Three noise control approaches including: (1) engineering approach, (2) administrative approach, and (3) the use of hearing protective devices are presented. Six mathematical models are developed for determining the optimal noise control strategy. Then, three solution procedures that are engineering-based procedure, HPD-based procedure, and mixed procedure are proposed as well. The engineering-based and HPD-based procedure can be called the upper bound and the lower bound of total noise control cost, respectively. The mixed procedure utilizes all mathematical models to yield the optimal noise control strategy. Last section presents numerical examples to demonstrate the solutions of the mixed procedures.

3.1 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.

3.1.1 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, and
9. Reduction of noise by reducing its transmission through air.

3.1.2 Administrative Controls

Administrative controls are procedures to reduce the exposure of workers to noise rather than reducing the noise level. Examples of 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 breaks 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.

3.1.3 The Use of Hearing Protective Devices

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

3.1.4 The OSHA's Hierarchy of Noise Control

According to the U.S. Occupational Safety and Health Administration (OSHA), a noise conservation program is required in situations where the noise level exceeds 90 dB*A* (OSHA, 1983). The OSHA's hierarchy of noise controls is shown as the following order of priority:

(1) Engineering controls
(2) Administrative controls
(3) Using hearing protective device.

To reduce the workplace noise level, engineering controls are to be considered first. If they are not feasible, administrative controls such as job rotation should be considered next. The use of HPDs is specified as the last resort of noise reduction. It should be applied only when engineering and administrative controls fail to prevent the daily noise exposure from exceeding a permissible level.

3.2 Problem Description

In situations where the noise level exceeds 90 dB*A*, a noise conservation program is required (OSHA, 1983). The order of priority of implementing the noise hazard prevention is recommended by OSHA (1983). In the noisy workplace, the use of HPDs is considered as the complementary approach. 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 chapter, 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.

3.3 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.

3.3.1 Notation

b_t number of engineering control methods to reduce noise at machine t
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)
l_j daily noise load at worker location j
$\overline{L}_j$ combined noise level (dBA) at worker location j
$l_{\max}$ maximum daily noise load at any worker location
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)
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 load per work period at worker location j
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

$$W_i \quad = \quad 16.61\left[\log_{10}\left\{\sum_{j=1}^{n}\frac{C_j}{8}\left(2^{\frac{\bar{L}_j-90}{5}}\right)\right\}\right]+90. \tag{3.1}$$

If a worker is to be assigned to worker location j throughout an entire workday, his/her daily noise exposure (or 8-hour time-weighted average noise level, 8-hr TWA) will be equal to $\bar{L}_j$. In several countries, the permissible daily noise exposure is set at 90 dB*A*. For the sake of mathematical modeling, we define a unitless variable called daily noise load l to represent the daily noise exposure. The daily noise load l at worker location j can be computed from

$$l_j \quad = \quad 2^{\left(\frac{\bar{L}_j-90}{5}\right)}. \tag{3.2}$$

Note that a permissible daily noise load l_p is equal to one.

When job rotation is applied, the noise load per work period is used instead of daily noise load. At worker location j, its noise load per work period can be determined from the combined noise level $\bar{L}_j$ as follows.

$$w_j \quad = \quad \frac{1}{p}\times 2^{\left(\frac{\bar{L}_j-90}{5}\right)} \quad = \quad \frac{1}{p}\times l_j\ . \tag{3.3}$$

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

3.3.2 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 dB*A*. The second model (E2) is a safety-based model that intends to *minimize the maximum daily noise load* 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

The objective of the cost-based ENCP is to minimize the total noise control cost.

A total noise control cost consists of cost of controlling noise at the source and cost of blocking the noise transmission by a barrier. Both cost components can be written as the following equations.

$$\text{Cost of controlling noise at the source} = \sum_{t=1}^{q}\sum_{u=1}^{b_t}\left(cs_{tu} \times ys_{tu}\right) \tag{3.4}$$

$$\text{Cost of blocking the noise transmission path} = \sum_{v=1}^{s}\left(cb_v \times yb_v\right) \tag{3.5}$$

Thus, the objective function is to minimize the sum of Eqs. (3.4) and (3.5)

$$\text{Minimize}\left[\sum_{t=1}^{q}\sum_{u=1}^{b_t}\left(cs_{tu} \times ys_{tu}\right) + \sum_{v=1}^{s}\left(cb_v \times yb_v\right)\right]. \tag{3.6}$$

The cost-based ENCP requires two sets of constraints: (1) noise load constraint; and (2) binary variable constraint.

After applying the selected noise control at the source, the reduced noise level at noise source t, L_t', can be computed from

$$L_t' = L_t - \sum_{u=1}^{b_t}\left(NRs_{tu} \times ys_{tu}\right) \qquad t = 1,\ldots, q. \tag{3.7}$$

As a result of noise control, the combined noise levels at all (if controlling at the noise source has been applied) or some (if blocking the noise transmission path has been applied) worker locations will be reduced. Letting NRb_{jv} be the amount of noise reduction (dBA) at worker location j after installing barrier v, the combined noise level at that location then becomes

$$\bar{L}_j = 10\log\left[10^{\left(\frac{L_{ab}-120}{10}\right)} + \sum_{t=1}^{q}\frac{10^{\left(\frac{L_t'-120}{10}\right)}}{d_{jt}^2}\right] + 120 - \sum_{v=1}^{s}\left(NRb_{jv} \times yb_v\right) \qquad j = 1,\ldots, n. \tag{3.8}$$

The daily noise load constraint can be written as

$$l_j \leq 1. \tag{3.9}$$

Finally, the binary variable constraint is defined for ys_{tu} and yb_v.

$$ys_{tu}, yb_v = (0, 1) \qquad t = 1,\ldots, q;\ u = 1,\ldots, r_t;\ v = 1,\ldots, s \tag{3.10}$$

Thus, the cost-based ENCP model will have the objective function (Eq. (3.6)) and constraints (Eqs. and inequality (3.7) – (3.10)) as summarized below:

$$\text{Minimize} \quad \left[\sum_{t=1}^{q}\sum_{u=1}^{b_t}\left(cs_{tu} \times ys_{tu}\right) + \sum_{v=1}^{s}\left(cb_v \times yb_v\right)\right] \tag{3.11}$$

subject to

$$l_j \;\le\; 1 \qquad j = 1,\ldots, n; \tag{3.12}$$

$$\bar{L}_j \;=\; 10\log\left[10^{\left(\frac{L_{ab}-120}{10}\right)} + \sum_{t=1}^{q}\frac{10^{\left(\frac{L'_t-120}{10}\right)}}{d_{jt}^2}\right] + 120 - \sum_{v=1}^{s} NRb_{jv} \times yb_v \qquad j = 1,\ldots, n; \tag{3.13}$$

$$L'_t \;=\; L_t - \sum_{u=1}^{b_t}\left(NRs_{tu} \times ys_{tu}\right) \qquad t = 1,\ldots, q; \tag{3.14}$$

$$ys_{tu}, yb_v \;=\; \{0, 1\} \qquad \forall t,u,v \;. \tag{3.15}$$

Model E2 – Minimizing the Maximum Daily Noise Load

The objective of the safety-based ENCP is to minimize the maximum daily noise load at any worker location, $l_{\max}$.

$$\text{Minimize} \qquad l_{\max} \tag{3.16}$$

The safety-based ENCP requires three sets of constraints: (1) budget constraint; (2) noise load constraint; and (3) binary variable constraint.

Since the sum of both costs must not exceed the given noise control budget EB, the budget constraint can be formulated as

$$\left[\sum_{t=1}^{q}\sum_{u=1}^{b_t}\left(cs_{tu} \times ys_{tu}\right) + \sum_{v=1}^{s}\left(cb_v \times yb_v\right)\right] \;\le\; EB. \tag{3.17}$$

The combined noise levels at all worker locations are shown in Eq. (3.8). From Eq. (3.8), the daily noise load constraint can be expressed as

$$2^{\left(\frac{\bar{L}_j-90}{5}\right)} \;\le\; l_{\max}. \tag{3.18}$$

The binary variable constraint has already been defined in Eq. (3.10). Therefore, the safety-based ENCP model will have the objective function (Eq. (3.16)) and constraints (Eqs. (3.7) - (3.8) and (3.10), and inequalities (3.17) - (3.18)) as summarized below:

$$\text{Minimize} \quad l_{\max} \tag{3.19}$$

subject to

$$2^{\left(\frac{\bar{L}_j-90}{5}\right)} \leq l_{\max} \qquad j = 1,\ldots, n; \tag{3.20}$$

$$\left[\sum_{t=1}^{q}\sum_{u=1}^{b_t}\left(cs_{tu} \times ys_{tu}\right)+\sum_{v=1}^{s}\left(cb_v \times yb_v\right)\right] \leq EB; \tag{3.21}$$

$$\bar{L}_j = 10\log\left[10^{\left(\frac{L_{ab}-120}{10}\right)}+\sum_{t=1}^{q}\frac{10^{\left(\frac{L'_t-120}{10}\right)}}{d_{jt}^{2}}\right]+120-\sum_{v=1}^{s} NRb_{jv} \times yb_v \qquad j = 1,\ldots, n; \tag{3.22}$$

$$L'_t = L_t - \sum_{u=1}^{b_t}\left(NRs_{tu} \times ys_{tu}\right) \qquad t = 1,\ldots, q; \tag{3.23}$$

$$ys_{tu}, yb_v = \{0, 1\} \qquad \forall t,u,v \ . \tag{3.24}$$

3.3.3 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 research. 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

$$f_j = \sum_{k=1}^{p-1}\left[1-\sum_{i=1}^{m}\left(x_{ijk}\times x_{i,j,k+1}\right)\right] \qquad j = 1,\ldots, n. \tag{3.25}$$

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

$$F = \sum_{j=1}^{n}\sum_{k=1}^{p-1}\left[1-\sum_{i=1}^{m}\left(x_{ijk}\times x_{i,j,k+1}\right)\right]. \tag{3.26}$$

The objective of this work assignment model (model A1) is to minimize the total worker-location changeover, F.

There are five constraints including:

(1) The first constraint guarantees that the TWA of all workers cannot exceed 90 dB*A* (Eq. (3.28))

(2) The second constraint represents assumption 4 (Inequality (3.29))

(3) The third constraint represents assumption 3 and also makes sure that all machines are operated in every period and throughout the 8-hour day (Inequality (3.30))

(4) The fourth constraint states that all workers cannot work more than p periods (Eq. (3.31)) and

(5) The fifth constraint states the binary constrain for the work assignment problem (Inequality (3.32)).

Thus, model A1 can be expressed as follows.

$$\text{Minimize} \quad \sum_{j=1}^{n}\sum_{k=1}^{p-1}\left[1-\sum_{i=1}^{m}\left(x_{ijk}\times x_{i,j,k+1}\right)\right] \tag{3.27}$$

subject to

$$\sum_{j=1}^{n}\sum_{k=1}^{p} w_j x_{ijk} \le 1 \qquad i = 1,\ldots, m; \tag{3.28}$$

$$\sum_{j=1}^{n} x_{ijk} \le 1 \qquad i = 1,\ldots, m;\ k = 1,\ldots, p; \tag{3.29}$$

$$\sum_{i=1}^{m} x_{ijk} = 1 \qquad j = 1,\ldots, n;\ k = 1,\ldots, p; \tag{3.30}$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \le p \qquad i = 1,\ldots, m; \tag{3.31}$$

$$x_{ijk} = \{0, 1\} \qquad \forall i, j, k. \tag{3.32}$$

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

The objective of model A2 is to minimize the number of workers in feasible workforce so that all workers do not receive noise exceeding the permissible level.

Five constraints are required for this work assignment model including:

(1) The first constraint guarantees that the TWA of assigned workers cannot exceed 90 dB*A* (Eq. (3.34))

(2) The second constraint represents assumption 4 (Inequality (3.35))

(3) The third constraint represents assumption 3 and also makes sure that all machines are operated in every period and throughout the 8-hour day (Eq. (3.36))

(4) The fourth constraint states that all workers cannot work more than p periods for the 8-hour day (Inequality (3.37)) and

(5) The fifth constraint states the binary constraint for the work assignment problem (Eq. (3.38)).

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

$$\text{Minimize} \quad \sum_{i=1}^{M} y_i \tag{3.33}$$

subject to

$$\sum_{j=1}^{n}\sum_{k=1}^{p} w_j x_{ijk} \le y_i \qquad i = 1,\ldots, M; \tag{3.34}$$

$$\sum_{j=1}^{n} x_{ijk} \le 1 \qquad i = 1,\ldots, M;\ k = 1,\ldots, p; \tag{3.35}$$

$$\sum_{i=1}^{m} x_{ijk} = 1 \qquad j = 1,\ldots, n;\ k = 1,\ldots, p; \tag{3.36}$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \le p \cdot y_i \qquad i = 1,\ldots, M; \tag{3.37}$$

$$x_{ijk}, y_i = \{0, 1\} \qquad \forall i, j, k. \tag{3.38}$$

3.3.4 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 only at the worker locations that are very noisy. 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. Some or all workers available workers may be selected to perform the job rotation.

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

The objective of the model of the selection of HPDs is to minimize the number of HPDs used in workplace.

The constraints for the model H1 are shown as follows:

(1) Eq. (3.40) is the budget constraint. The HPD cost, $\sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \cdot ch_l$, must not exceed the HPD budget

(2) Inequality (3.41) represents that any worker location must not have more than one HPD

(3) Inequality (3.42) ensures that the noise loads of all workers are less than 1 after applying job rotation and/or ware the HPD

(4) Eq. (3.43) represents assumption 4 and makes sure all workers are not idle in every work period

(5) Eq. (3.44) represents assumption 3 and also makes sure that all worker locations are operated in every period throughout the 8-hour day, and

(6) Eq. (3.45) is the binary variable constraint.

$$\text{Minimize} \quad \sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \tag{3.39}$$

subject to

$$\sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \cdot ch_l \;\leq\; HB; \tag{3.40}$$

$$\sum_{l=1}^{z} yh_{jl} \;\leq\; 1 \qquad j = 1,\ldots, n; \tag{3.41}$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} \frac{1}{p} \cdot 2^{\left(\frac{\bar{L}_j - 90 - \sum_{l=1}^{z} NRh_l \cdot yh_{jl}}{5}\right)} \cdot x_{ijk} \;\leq\; 1 \qquad i = 1,\ldots, m; \tag{3.42}$$

$$\sum_{j=1}^{n} x_{ijk} \;=\; 1 \qquad i = 1,\ldots, m;\ k = 1,\ldots, p; \tag{3.43}$$

$$\sum_{i=1}^{m} x_{ijk} \;=\; 1 \qquad j = 1,\ldots, n;\ k = 1,\ldots, p; \tag{3.44}$$

$$x_{ijk}, yh_{jl} \;=\; \{0, 1\} \qquad \forall i, j, k, l\,. \tag{3.45}$$

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

The objective and constraints of model H2 are identical to those of model H1 except for two constraints, which are:

(1) Eq. (3.50) states that some workers in some periods can be idle.

(2) Inequality (3.52) states that workers who are selected to work in this workplace can be idle in some periods.

$$\text{Minimize} \quad \sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \tag{3.46}$$

subject to

$$\sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \cdot ch_l \quad \leq \quad HB; \tag{3.47}$$

$$\sum_{l=1}^{z} yh_{jl} \quad \leq \quad 1 \qquad j = 1,\ldots, n; \tag{3.48}$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} \frac{1}{p} \cdot 2^{\left(\frac{\bar{L}_j - 90 - \sum_{l=1}^{z} NRh_l \cdot yh_{jl}}{5}\right)} \cdot x_{ijk} \quad \leq \quad 1 \quad i = 1,\ldots, M; \tag{3.49}$$

$$\sum_{j=1}^{n} x_{ijk} \quad \leq \quad 1 \qquad i = 1,\ldots, M;\ k = 1,\ldots, p; \tag{3.50}$$

$$\sum_{i=1}^{m} x_{ijk} \quad = \quad 1 \qquad j = 1,\ldots, n;\ k = 1,\ldots, p; \tag{3.51}$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \quad \leq \quad p \cdot y_i \qquad i = 1,\ldots, M; \tag{3.52}$$

$$x_{ijk}, y_i, yh_{jl} \quad = \quad \{0, 1\} \qquad \forall i, j, k, l. \tag{3.53}$$

3.4 Solution Procedures

Initially, it is necessary to obtain the following input 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

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.

3.4.1 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 dB*A* 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.

3.4.2 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 the locations having the noise levels above 90 dB*A* 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.

3.4.3 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 dB*A*.

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 dB*A*) and find a minimum total cost EC^*. If $EC^* \le TB$, 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.

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 F^* 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 $n \le m \le M$. 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 F^* 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 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 dB*A*. Safety, cost, and productivity concerns have also been considered in the mixed procedure.

Fig. 3.1 shows a flow chart that summarizes the mixed procedure.

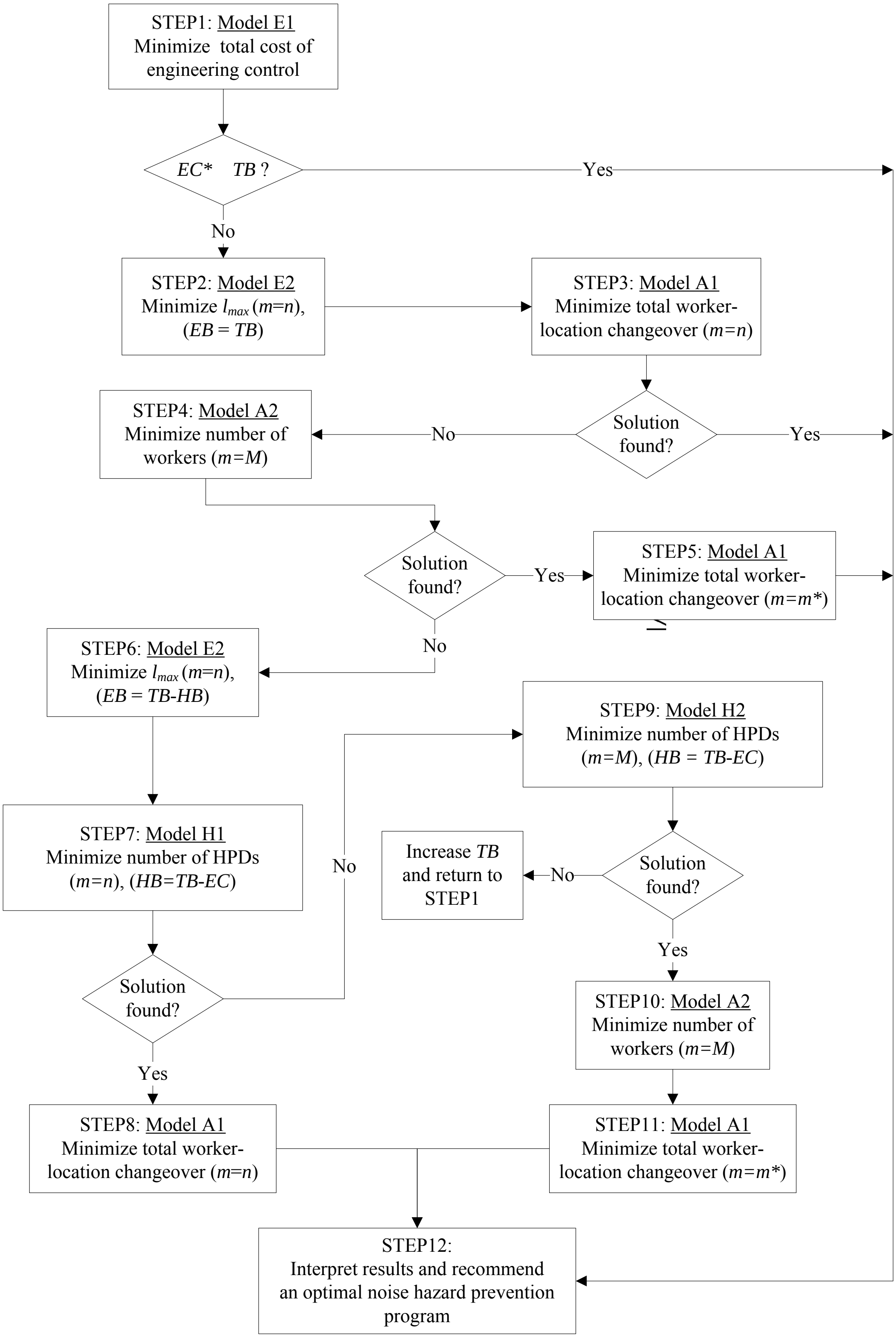

Fig. 3.1 A flow chart depicting the mixed procedure

3.5 Numerical Examples and Results

Consider the industrial facility that houses five machines (q = 5). At present, there are four workers (m = 4) being assigned to four different worker locations (n = 4). If necessary, an additional worker can be assigned to work in this facility (M = 5). An 8-hour workday is divided into four equal work periods (p = 4). Ambient noise level is assumed to be 70 dB*A*. Table 3.1 shows location coordinates of the five machines (M1, M2, M3, M4, and M5), their noise levels, and location coordinates of the four worker locations (WL1, WL2, WL3, and WL4).

Table 3.1 Location coordinates of machines, machine noise levels, and location coordinates of worker locations

Machine	Location Coordinate (m)		Machine Noise (dB*A*)	Worker Location	Location Coordinate (m)	
	x-coordinate	*y*-coordinate			*x*-coordinate	*y*-coordinate
M1	2	2	94	WL1	2	3.5
M2	5	2	95	WL2	5	3.5
M3	7	4.5	98	WL3	5	5.5
M4	5	7	88	WL4	2	5.5
M5	2	7	96			

From the given data and using Eq. (3.1), the combined noise levels at the four worker locations are found to be 93.02, 94.97, 93.59, and 93.86 dB*A*, respectively. Supposing that job rotation is not implemented, it is seen that all four workers (W1, W2, W3, and W4) are exposed to noise hazard. As such, an effective noise hazard control strategy is required to reduce their daily noise exposures.

Engineering controls for reducing machine noise at individual machines, costs, and noise reduction levels are presented in Table 3.2. Additionally, there are two types of barrier for blocking the noise transmission path. Type-1 barrier costs 9,000 baht and it reduces noise levels at worker locations WL1 and WL4 by 10 and 4 dB*A*, respectively. Type-2 barrier costs 10,000 baht. When installing this barrier, noise levels at worker locations WL2 and WL3 will be reduced by 4 and 9 dB*A*, respectively. There are two types of HPD, type-A and type-B, which can be worn at any of the four worker locations. Type-A HPD costs 100 baht and its effective NRR is 8 dB*A*. Type-B HPD costs 500 baht, with an effective NRR of 12 dB*A*. Readers should note that cost data in this research is based on the estimated cost in Thailand. To convert the Thai currency (baht) into the U.S. currency ($), we use the following currency exchange rate: 40 baht = $1.00.

Table 3.2 Methods for reducing machine noise, costs, and noise reduction

Machine	Method 1		Method 2	
	Cost (baht)	Noise Reduction (dB*A*)	Cost (baht)	Noise Reduction (dB*A*)
M1	6,000	9	12,000	14
M2	9,500	11	10,500	13
M3	9,000	10	10,500	15
M4	7,000	9	10,000	15
M5	8,500	12	11,500	16

Three levels of noise hazard control budget are evaluated. They are:

Case I: Total budget = 12,000 baht

Case II: Total budget = 16,000 baht

Case III: Total budget = 20,000 baht

In all three cases, the budget for HPDs *HB* is 1,000 baht. The 12-step design procedure is applied to determine the optimal noise hazard control strategy for this facility under each budget level.

3.5.1 Case I: Total budget = 12,000 baht

After solving Model E1 in Step 2, the following engineering controls are recommended.

- Reducing noise at machine M2 using engineering control method 1
- Reducing noise at machine M3 using engineering control method 1
- Using type-1 barrier to block the noise transmission path

As a result, the *reduced* daily noise loads at all four worker locations are 0.32264, 0.81364, 0.94432, and 0.89176, respectively. Since each daily noise load is less than 1.00, it indicates that workers' daily noise exposures do not exceed 90 dB*A*. However, the total cost of engineering controls *EC** is 27,500 baht which is beyond the total budget of 12,000 baht. Thus, the solution is infeasible.

Next, Model E2 is used to determine feasible engineering controls that will minimize the maximum noise load per period under the given budget. The new solution recommends that noise level at machine M3 be reduced using engineering control method 2, incurring the total cost *EC* of 10,500 baht. Also, the four daily noise loads at the four worker locations are 1.41016, 1.47988, 1.03604, and 1.60620, respectively. Since all daily noise loads exceed 1.00, noise hazard still exists. With $p = 4$, the noise loads per work period will be 0.35254, 0.36997, 0.25901, and 0.40155, respectively.

Assuming that the recommended noise control (reducing noise at machine M3) has been implemented, job rotation is next considered using Model A1 with the number of workers $m = 4$ (the current workforce). However, each noise load per period is still greater than 0.25. Thus, job rotation using only four workers ($m = 4$) is insufficient. Model A2 is then utilized with all available workers considered in job rotation. The solution shows that there is no feasible work assignment solution for $m = 5$.

Since engineering controls and job rotation fail to prevent noise hazard exposure (under the given budget), the use of HPDs is now considered. Using the original noise data and setting the HPD budget HB = 1,000 baht, Model E2 is applied with the new engineering controls budget EB = 12,000 – 1,000 = 11,000 baht. The solution is found to be identical to the previous one (when Model E2 was used with EB = 12,000).

Once again, assume that the recommended noise control has been implemented. Next, Model H1 is applied (using the number of workers $m = 4$). The solution recommends that two sets of type-B HPD be worn at worker locations WL2 and WL4 and the total HPD cost *HC* is equal to the HPD budget *HB*. Therefore, the total noise control budget is $EC + HC$ = 10,500 + 1,000 = 11,500 baht (< *TB*). With the use of HPDs at both worker locations, the new noise loads per work period at the four worker locations are 0.35254, 0.07010, 0.25901, and 0.07608, respectively. Table 3.3 shows the resulting work assignment solution when job rotation is also implemented. The total worker-location changeover *F* is 7 times. All daily noise exposures (8-hour TWAs) are below 90 dB*A*.

Table 3.3 Work assignments for four workers, $F = 7$ (Case I)

Worker	Work Period				8-hour TWA
	1	2	3	4	(dB*A*)
W1	WL1	WL4*	WL1	WL2	88.84
W2	WL3	WL3	WL4*	WL4*	87.11
W3	WL4*	WL1	WL3	WL3	89.60
W4	WL2	WL2*	WL2*	WL1	85.85

*Worker locations where the use of HPDs is enforced.

To further enhance work system productivity, Model A1 is used to determine the work assignment solution with the minimum total worker-location changeover F^*. The *improved* solution with $F^* = 4$ is shown in Table 3.4. Note that all 8-hour TWAs are still below 90 dB*A*.

Table 3.4 *Improved* work assignments for four workers, $F^* = 4$ (Case I)

Worker	Work Period				8-hour TWA
	1	2	3	4	(dB*A*)
W1	WL3	WL3	WL2*	WL2*	86.98
W2	WL1	WL1	WL4*	WL4*	88.89
W3	WL4*	WL4*	WL1	WL1	88.89
W4	WL2*	WL2*	WL3	WL3	86.98

*Worker locations where the use of HPDs is enforced.

In summary, the optimal noise hazard control strategy for the given facility with *TB* = 12,000 baht can be described as follows.

1. Reduce noise level at machine M3 using engineering control method 2.
2. Implement job rotation using the current workforce, with the work assignments for the four workers as shown in Table 3.4.
3. Enforce the use of type-B HPD at worker locations WL2 and WL4.

The above described noise hazard control strategy will require the total budget of 11,500 baht. As seen in Table 3.4, none of the four workers receives daily noise exposure exceeding 90 dB*A*.

3.5.2 Case II: Total budget = 16,000 baht

In Case II, the total budget is increased to 16,000 baht, with the budget for HPDs still being 1,000 baht. Using the 12-step design procedure, the required noise hazard control cost is 15,000 baht. The resulting optimal noise control strategy is as follows.

1. Reduce noise level at machines M1 and M3 using engineering control method 1.
2. Use all five workers in job rotation, with their work assignments as shown in Table 3.5.
3. HPDs are not required at all four worker locations.

Table 3.5 Work assignments for five workers (Case II)

Worker	Work Period				8-hour TWA (dB*A*)
	1	2	3	4	
W1	WL4	WL4	WL1	-	89.91
W2	-	WL1	WL2	WL2	89.51
W3	WL1	-	WL4	WL4	89.91
W4	WL3	WL3	WL3	WL1	89.93
W5	WL2	WL2	-	WL3	89.79

3.5.3 Case III: Total budget = 20,000 baht

In Case III, the total budget is increased to 20,000 baht, with the budget for HPDs still being 1,000 baht. Using the 12-step design procedure, the new optimal noise hazard control strategy in which only engineering controls and job rotation are required is recommended. The total noise control cost is 19,000 baht. The resulting noise hazard control strategy can be described as follows.

1. Install type-1 and type-2 barriers.
2. Implement job rotation using the current workforce (m = 4), with the work assignments for the four workers as shown in Table 3.6.
3. HPDs are not required at all four worker locations.

Table 3.6 Work assignments for four workers (Case III)

Worker	Work Period				8-hour TWA (dB*A*)
	1	2	3	4	
W1	WL1	WL1	WL2	WL2	88.04
W2	WL2	WL2	WL1	WL1	88.04
W3	WL4	WL4	WL4	WL4	89.86
W4	WL3	WL3	WL3	WL3	84.58

As seen in the three cases, the 12-step design procedure is able to determine the optimal noise hazard control strategy that can prevent workers' daily noise exposures from exceeding 90 dB*A* based on the given budget. The strategy is also sensitive to the total budget and its allocated portion to engineering controls. If the engineering controls budget is sufficient, HPDs will not be required. In case of job rotation, the rotation using the current workforce (where the numbers of workers and worker locations are equal) will be considered first. If noise exposures still exceed 90 dB*A*, additional workers will then be considered in job rotation.

It should be remembered that the optimal strategy is likely to vary if a different noise control budget is set. As a result, there is no single best noise hazard control strategy that will be suitable for all noise situations. When the budget is sufficiently large, there might be several noise hazard control strategies that are feasible. These strategies may differ based on the total noise control cost and/or the combination of noise controls to be implemented.

When the problem size is large, the optimization approach fails to determine the optimal solution or sometimes cannot find the solution. Thus, the next two chapters will discuss the development of genetic algorithms and heuristics to deal with the large-sized problem of the noise hazard prevention problem.