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Design of Optimal Noise Hazard Control Strategy With Budget Constraint

Krisada Asawarungsaengkul
Suebsak Nanthavanij

Sirindhorn International Institute of Technology, Thammasat University, Pathumthani, Thailand

An analytical design procedure to determine optimal noise hazard control strategies for industrial facilities is presented. Its objective is to determine a set of appropriate noise controls to eliminate or reduce noise levels so that workers' daily noise exposure does not exceed a permissible level. From a given noise control budget, engineering controls will be firstly implemented, followed by administrative controls, and then the use of hearing protection devices. Six optimization models are developed and sequentially applied to select appropriate noise controls without exceeding the budget. Numerical examples are presented to demonstrate the application of the proposed design procedure.

noise control strategy industrial noise hazard 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 [1]. Exposure to high noise levels is a leading cause of hearing loss and may also result in other harmful health effects. In the USA, it has been estimated that 30 million workers are currently exposed to noise hazard on the job and an additional 9 million workers risk getting hearing loss [1]. A major cause that contributes to this problem is a lack of effective noise hazard control program in the workplace.

Regarding noise hazard prevention, three preventive approaches are generally recommended: (a) engineering approach, (b) administrative approach, and (c) the use of hearing protection devices (HPDs). The engineering approach has been discussed at length in many textbooks. Details of engineering controls can be found in several publications [2, 3, 4, 5, 6, 7]. More specifically, topics such as development of quieter machines, noise reduction methods, noise absorption materials, and process change for noise reduction have also been discussed in the literature [8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. Sutton [18] has presented a procedure to identify possible methods of noise reduction and to select the best method using a cost–benefit analysis.

Discussion on the administrative approach is relatively scarce. Job rotation is usually recommended as a practical means of preventing noise hazard exposure. Nanthavanij and Yenradee [19] developed a minimax work assignment model to determine an optimal set of work assignments for workers so that the maximum daily noise exposure that any worker received was minimized. For large job rotation problems, a genetic algorithm was developed to determine near-optimal minimax work assignments [20]. Yaoyuenyong and Nanthavanij [21] also developed a simple heuristic for solving large minimax work assignment problems. For industrial facilities where noise levels were excessively high, Nanthavanij and Yenradee [22] recommended that

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Correspondence and requests for offprints should be sent to Suebsak Nanthavanij, Management Technology Program, Sirindhorn International Institute of Technology, Thammasat University, Pathumthani 12121, Thailand. E-mail: <suebsak@siit.tu.ac.th>.

the number of workers be greater than the number of machines/workstations. They also developed a mathematical model to determine a minimum number of workers and their work assignments for working at noisy worker locations so that their daily noise exposure did not exceed the permissible level.

Various types of HPDs and their properties have been extensively discussed [2, 3, 4, 5, 6]. In addition, there have been research studies on the development and testing of effective HPDs [23, 24, 25, 26]. Resistance to using HPDs by workers was also studied by Feeney [27].

According to the U.S. Occupational Safety and Health Administration (OSHA), a noise conservation program is required in situations where noise levels exceed 90 dB*A* [28]. To reduce noise levels, engineering controls are to be implemented first. If they are not feasible, administrative controls such as job rotation should be implemented next. The use of HPDs is specified as the last resort of noise reduction. They should be applied only when engineering and administrative controls fail to prevent daily noise exposure from exceeding the permissible level. HPDs should be used to assist, not to replace, engineering and administrative controls. Often, managements choose not to follow OSHA's hierarchy of noise control due to large capital investment that is normally required for engineering controls and difficulty in implementing engineering and administrative controls. As a result, only HPDs (earplugs, earmuffs, etc.) are often provided to workers for noise hazard control.

Sanders and McCormick [29] recommended that a combination of noise controls be used to achieve a desired level of abatement. However, finding the appropriate combination of noise controls is usually difficult especially when requirements such as the allocated budget and permissible exposure level need to be simultaneously considered.

In this paper, we introduce an analytical design procedure to determine an optimal strategy for industrial noise hazard control with respect to a given budget and noise levels in the facility. The order of priority of noise controls also follows OSHA's hierarchy of noise control. In section 2, we describe optimization models used in the proposed procedure. The analytical design procedure is explained in detail in section 3. Then, section 4 shows how different levels of budget will affect the noise hazard control strategy. Finally, we give conclusions in section 5.

2. MATHEMATICAL MODELS OF NOISE CONTROLS

Consider an industrial facility where workers are present at various locations during an 8-hr workday. Suppose that the only noise sources in this facility are machines. At any worker location, the noise level to which an assigned worker is exposed is a combined noise level at that location (transmitted from all noise sources). A formula to compute the combined noise level at location j, $\bar{L}_j$ (dB*A*), from multiple noise source ts (where $t = 1, \ldots, q$) is shown here.

Letting L_{ab} be ambient noise level (dB*A*), L_t be noise level (dB*A*) measured at 1 m from machine t, and d_{tj} be Euclidean distance (m) between machine t and location j, $\bar{L}_j$ is computed from

$$\bar{L}_j = 10\log\left[10^{\left(\frac{L_{\text{ab}}-120}{10}\right)} + \sum_{t=1}^{q}\frac{10^{\left(\frac{L_t-120}{10}\right)}}{d_{tj}^2}\right] + 120. \qquad (1)$$

For simplicity, we can refer to the combined noise level as noise load. By dividing a workday into p equal work periods, a formula for computing the noise load per work period at worker location j, w_j, is

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

Note that any worker assigned to worker location j will receive the noise load w_j. For a work system in which workers may not stay at one location throughout the workday, it is necessary to determine an 8-hr time-weighted average (8-hr TWA, dB*A*) sound level that each worker receives. Let **S** be a set of worker locations *j*s where worker *i* is alternately present; the 8-hr TWA that worker *i* receives, W_i, is

$$W_i = 16.61\left[\log_{10}\left\{\sum_{k\in \mathrm{S}} w_k\right\}\right] + 90. \qquad (3)$$

For example, consider worker W1 who works at two worker locations in an 8-hr workday which is divided into four equal work periods. Noise loads per work period at the two locations are assumed to be 0.28 and 0.15, respectively. Let us further assume that worker W1 works at the first location in the first two periods, and then rotates to the second location in the last two periods. Using Equation 3, the 8-hr TWA of worker W1 can be computed:

$$W_{\mathrm{W1}} = 16.61[\log_{10}\{0.28 + 0.28 + 0.15 + 0.15\}] + 90 = 88.91 \text{ dB}A.$$

Generally, the permissible daily noise exposure level is 90 dB*A*. To prevent noise hazard exposure, a total noise load that any worker receives in one workday must not exceed 1.

The development of the optimization models is based on the following notations.

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*
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_t'	noise level (dB*A*) measured at machine *t* (at 1-m distance) after noise reduction
m	number of workers in the current workforce
M	number of available (current + additional) workers
n	number of worker locations
NRb_{jv}	amount of noise (dB*A*) reduced at worker location *j* after installing barrier *v*
NRh_l	amount of noise (dB*A*) reduced after wearing HPD *l*
NRs_{tu}	amount of noise (dB*A*) reduced at machine *t* after applying engineering control method *u*
q	number of machines (noise sources)
r_t	number of engineering control methods to reduce machine noise at machine *t*
s	number of engineering control methods to block the noise transmission path
TB	total noise control budget ($TB = EB + HB$)
$w_{\max}$	maximum noise load 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

2.1. Models of Engineering Controls Selection

For engineering controls, we consider only controlling at the machine and controlling along the path (i.e., using the barrier to block the noise transmission path). The former implies that machine noise is reduced. Thus, all worker locations will benefit from such noise control. Note that for a given machine, there could be several engineering control methods for reducing machine noise. The latter, however, will reduce noise levels at some worker locations (only those locations where the barrier can block the noise transmission path).

The problem of selecting appropriate engineering controls is formulated as cost- and safety-based models. Two mathematical models are developed. The first model (E1) is the cost-based model which is intended to minimize the total cost for implementing feasible engineering controls (i.e., reducing machine noise and/or blocking the noise transmission path by barriers) such that the combined noise level at any worker location does not exceed 90 dB*A*. The second model (E2) is the safety-based model which is intended to minimize the maximum noise load per work period among all worker locations such that the resulting total cost does not exceed an allocated engineering control budget *EB*.

2.1.1. Model E1: minimizing total cost of engineering controls

Minimize

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

subject to

$$L'_t = L_t - \sum_{u=1}^{r_t}\left(NRs_{tu}\times ys_{tu}\right); t=1,\dots,q;$$

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

$$+120-\sum_{v=1}^{s}\left(NRb_{jv}\times yb_v\right); j=1,\dots,n;$$

$$2^{\left(\frac{\bar{L}_j-90}{5}\right)}\le 1; j=1,\dots,n; ys_{tu}, yb_v=\left(0,1\right); \forall t,u,v.$$

2.1.2. Model E2: minimizing maximum noise load per work period

Minimize $w_{\max}$ subject to

$$\frac{1}{p}\times 2^{\left(\frac{\bar{L}_j-90}{5}\right)}\le w_{\max;}\quad j=1,\dots,n;$$

$$L'_t = L_t - \sum_{u=1}^{r_t}\left(NRs_{tu}\times ys_{tu}\right); t=1,\dots,q;$$

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

$$+120-\sum_{v=1}^{s}\left(NRb_{jv}\times yb_v\right); j=1,\dots,n;$$

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

$$ys_{tu}, yb_v=\left(0,1\right); \forall t,u,v.$$

2.2. Job Rotation Models

The only administrative control considered in this paper is job rotation. This is mainly because job rotation has been widely recommended in the literature, and mathematical models of the job rotation problem have been well defined. Basically, workers are allowed to rotate among worker locations so that a maximum daily noise exposure that any worker receives does not exceed 90 dB*A*.

Two mathematical models are developed for job rotation. The first model (A1) is intended to determine a set of feasible work assignments for the current workforce such that a total worker–location changeover is minimized. At any worker location, a worker–location changeover occurs when the current worker moves out to another location and a new worker moves in. To some extent, productivity of a work system might be decreased due to possible needs for learning and adapting to a new task. Thus, it is logical to keep the number of worker–location changeovers as few as possible. The second model (A2) covers a situation in which additional workers need to be considered in job rotation due to excessive noise levels in the facility. The model's objective is to determine a minimum number of workers (in the increased workforce) such that none of them receives a daily noise exposure above 90 dB*A*.

It is worth noting that the two job rotation models do not consider costs since the implementation of job rotation does not require any equipment investment or workplace modification. It is assumed that any incurred costs due to decreased productivity will be absorbed by the production department. If additional workers are needed in job rotation, it is also assumed that they are existing workers (perhaps from other departments), not new workers. If skill training is required, the cost of training will be absorbed by the human resources department.

The following assumptions are required for the implementation of job rotation.

1. The maximum working duration (for workers and machines) per day is 8 hrs.
2. A workday can be divided into p equal periods. Job rotation occurs only 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. Workers' efficiency is independent of the task they are assigned to perform. Similarly, task output is independent of the workers.

2.2.1. Model A1: minimizing total worker–location changeover

For the work system in which job rotation is not implemented, workers are fixed at their assigned worker locations. Thus, the total worker–location changeover is zero. When job rotation is implemented, different workers may be alternately assigned to the same worker location. Each time a worker is replaced by another worker, the worker–location changeover occurs. A formula to determine the number of worker–location changeovers at worker location j, f_j, is

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

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

$$F = \sum_{j=1}^{n}\sum_{k=1}^{p-1}\left[1-\sum_{i=1}^{m}\left(x_{ijk}\times x_{i,j,k+1}\right)\right]. \quad (5)$$

Model A1 can be expressed as follows.
Minimize

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

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

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

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

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \le p; i=1,\dots,m; x_{ijk}=(0,1); \forall i,j,k.$$

2.2.2. Model A2: minimizing number of workers in the increased workforce

When workplace noise is excessive, it might be necessary to add additional workers to increase the workforce. Letting M be number of available workers in the increased workforce where $M > n$, model A2 can be expressed as follows.

$$\text{Minimize } \sum_{i=1}^{M} y_i \text{ subject to}$$

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

$$\sum_{j=1}^{n} x_{ijk} \le 1; i=1,\dots,M; k=1,\dots,p;$$

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

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \le p\times y_i; i=1,\dots,M; x_{ijk}, y_i=(0,1);$$
$$\forall i,j,k.$$

2.3. Models of the Use of HPDs

The use of HPDs should be considered as a supplementary noise hazard control approach. That is, it should be applied only when engineering controls and job rotation fail to prevent workers' daily noise exposure from exceeding 90 dB*A*. Additionally, the number of worker locations where the use of HPDs is enforced should be as few as possible. In practice, HPDs should be worn only at very noisy worker locations. There are many types of HPDs available, with different noise reduction ratings (NRR) and prices. At any given location, suitable types of HPDs to be used must be specified.

Two mathematical models for selecting appropriate HPDs are developed. Note that both models consider job rotation and the use of HPDs concurrently.

2.3.1. Model H1: minimizing number of HPDs (m = n)

Model H1 is intended to determine a minimum number of HPDs based on the given HPD budget *HB* and the number of workers *m* (the current workforce). The model also yields type(s) of HPDs and those worker locations where HPDs must be worn.

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

$$\sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \times ch_l \le HB;$$

$$\sum_{l=1}^{z} yh_{jl} \le 1; j = 1, \dots, n;$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} \frac{1}{p} \times 2^{\left(\frac{\bar{L}_j - 90 - \sum_{l=1}^{z} NRh_l \times yh_{jl}}{5}\right)} \times x_{ijk} \le 1;$$

$$i = 1, \dots, m;$$

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

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

$$x_{ijk}, yh_{jl} = (0,1); \forall i, j, k, l.$$

2.3.2. Model H2: minimizing number of HPDs (n ≤ m ≤ M)

Model H2 is used to determine the minimum number of *HPDs* when all available workers *M* are considered in job rotation. Nevertheless, not all of them need to be assigned to worker locations.

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

$$\sum_{j=1}^{n}\sum_{l=1}^{z} yh_{jl} \times ch_l \le HB;$$

$$\sum_{l=1}^{z} yh_{jl} \le 1; j = 1, \dots, n;$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} \frac{1}{p} \times 2^{\left(\frac{\bar{L}_j - 90 - \sum_{l=1}^{z} NRh_l \times yh_{jl}}{5}\right)} \times x_{ijk} \le 1;$$

$$i = 1, \dots, M;$$

$$\sum_{j=1}^{n} x_{ijk} \le 1; i = 1, \dots, M; k = 1, \dots, p;$$

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

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \le p \times y_i; i = 1, \dots, M;$$

$$x_{ijk}, y_i, yh_{jl} = (0,1); \forall i, j, k, l.$$

3. DESIGN PROCEDURE

The analytical design procedure to determine the optimal noise hazard control strategy requires the six optimization models described in section 2 to be applied in sequence by following the OSHA's hierarchy of noise control. The procedure consists of the following 13 steps.

Step 1: Obtain essential input data listed here:

- number of work periods per workday *p*;
- number of available workers *M*;
- combined noise level at each worker location $\bar{L}_j$ (*j* = 1, ... , *n*);
- ambient noise level L_{ab};
- noise level generated by each machine (at 1-m distance) L_t (*t* = 1, ... , *q*);
- feasible methods for reducing machine noise at each machine, costs, and amount of noise reduced;
- feasible methods for blocking the noise transmission path, costs, and amount of noise reduced at affected worker locations;
- types of HPDs, costs, and noise reduction ratings;
- total noise control budget *TB*;
- allocated budget portions for engineering controls and the use of HPDs (*EB* and *HB*, respectively).

Step 2: Using model E1, find feasible engineering controls for reducing machine noise at the source and/or for blocking the noise transmission path that will prevent daily noise exposure at each worker location from exceeding 90 dB*A*; find a minimum total cost *EC**. If *EC** ≤ *TB*, go to step 13. Otherwise, proceed to step 3.

Step 3: Using model E2 and setting *EB* = *TB*, determine feasible engineering controls that minimize the maximum daily noise exposure $w_{\max}$ among all *n* worker locations and a total cost *EC*. Assuming that such engineering controls are implemented, determine the new combined noise levels at all worker locations.

Step 4: Implement job rotation using the current workforce (*m* workers). Using model A1, find a set of work assignments with the minimum total worker–location changeover *F** such that all daily noise exposure does not exceed 90 dB*A*. If the optimal work assignment solution can be found, go to step 13. Otherwise, proceed to step 5.

Step 5: From the increased workforce (*M* workers), use model A2 to find the minimum number of workers *m** to attend all *n* worker locations on a rotational basis such that their daily noise exposure does not exceed 90 dB*A*. If *m** can be found, proceed to step 6. Otherwise, go to step 7.

Step 6: 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 *F**. Then, go to step 13.

Step 7: If engineering controls and job rotation are insufficient in preventing noise hazard exposure, the use of HPDs is considered next. Firstly, use the current workforce (*m* workers) and the original set of noise data (by discarding the recommended engineering controls in step 3). Model E2 is utilized once more with the budget for engineering controls *EB* = *TB* – *HB* to determine the maximum daily noise exposure that any worker receives and the total cost *EC*. Again, assuming that the recommended engineering controls are implemented, determine the new combined noise levels at all worker locations.

Step 8: Setting the revised HPD budget *HB* = *TB* – *EC* and using the new combined noise levels, model H1 is utilized next to determine the work assignment solution with the use of HPDs among *m* workers, the minimum number of HPDs for the worker locations with excessive noise levels, and a total cost *HC*. If a feasible solution can be found, proceed to step 9. Otherwise, go to step 10.

Step 9: With the use of HPDs at some worker locations, re-compute workers' noise exposure. 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 safety requirements but also enhances overall productivity of the work system. Next, go to step 13.

Step 10: The use of HPDs is re-considered using the number of workers *n* ≤ *m* ≤ *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) and their daily work assignments. If the solution (number of HPDs, total cost *HC*, number of workers, work assignments, and noise exposure levels at all worker locations) can be found, go to step 11. Otherwise, increase the noise control budget *TB* and, if necessary, revise *EB* and *HB*. Then, return to step 2.

Step 11: Re-compute noise exposure at the worker locations where HPDs are to be enforced (from step 10). 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).

Step 12: 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 11.

Step 13: The result will provide the optimal noise hazard control strategy based on the given total budget (and allocated portions for engineering controls and the use of HPDs). Depending on the given noise data and noise control methods, the solution will recommend a feasible combination of engineering controls, job rotation, and the use of HPDs that will prevent workers' daily noise exposure from exceeding 90 dB*A*. Safety, cost, and productivity concerns have also been considered in this design procedure.

4. NUMERICAL EXAMPLES

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-hr workday is divided into four equal work periods ($p = 4$). Ambient noise level is assumed to be 70 dB*A*. Table 1 shows location co-ordinates of the five machines (M1, M2, M3, M4, and M5), their noise levels, and location co-ordinates of the four worker locations (WL1, WL2, WL3, and WL4).

From the given data and using Equation 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 exposure.

TABLE 1. Location Co-Ordinates of Machines, Machine Noise Levels, and Location Co-Ordinates of Worker Locations

	Location Co-Ordinate (m)		
Machine	***x***	***y***	**Machine Noise (dB*A*)**
M1	2	2	94
M2	5	2	95
M3	7	4.5	98
M4	5	7	88
M5	2	7	96

	Location Co-Ordinate (m)	
Worker Location	***x***	***y***
WL1	2	3.5
WL2	5	3.5
WL3	5	5.5
WL4	2	5.5

Engineering controls for reducing machine noise at individual machines, costs, and noise reduction levels are presented in Table 2. Additionally, there are two types of barriers for blocking the noise transmission path. Type-1 barrier costs US $225 and it reduces noise levels at worker locations WL1 and WL4 by 10 and 4 dB*A*, respectively. Type-2 barrier costs US $250. When this barrier is installed, noise levels at worker locations WL2 and WL3 will be reduced by 4 and 9 dB*A*, respectively. There are two types of HPDs, type-A and type-B, which can be worn at any of the four worker locations. Type-A HPD costs US $2.50 and its effective NRR is 8 dB*A*. Type-B HPD costs US $12.50, with an effective NRR of 12 dB*A*. Readers should note that cost data in this paper is based on the estimated cost in Thailand. To convert the Thai currency (baht) into the U.S. currency (US $), we use the following currency exchange rate: 40 baht = US $1.

Three levels of noise hazard control budget are evaluated. They are case I: *TB* = US $300, case II: *TB* = US $400, case III: *TB* = US $500. In all three cases, the budget for HPDs *HB* is US $25. The 13-step design procedure is applied

TABLE 2. Methods for Reducing Machine Noise, Cost, and Noise Reduction

	Method 1		Method 2	
Machine	**Cost (US$)**	**Noise Reduction (dB*A*)**	**Cost (US$)**	**Noise Reduction (dB*A*)**
M1	150.00	9	300.00	14
M2	237.50	11	262.50	13
M3	225.00	10	262.50	15
M4	175.00	9	250.00	15
M5	212.50	12	287.50	16

to determine the optimal noise hazard control strategy for this facility under each budget level.

4.1. Case I: *TB* = US $300

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 noise loads per work period at all four worker locations are 0.08066, 0.20341, 0.23608, and 0.22294, respectively. Since each noise load per period is less than 0.25, it indicates that workers' daily noise exposure does not exceed 90 dB*A*. However, the total cost of engineering controls *EC** is US $687.50, which is beyond the total budget of US $300. 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 US $262.50. Also, the four noise loads per period at the four worker locations are 0.35254, 0.36997, 0.25901, and 0.40155, respectively. Since all noise loads per work period exceed 0.25, noise hazard still exists.

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* = US $25, model E2 is applied with the new engineering controls budget *EB* = US $300 – US $25 = US $275. The solution is found to be identical to the previous one (when model E2 was used with *EB* = US $300).

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* = US $262.50 + US $25 = US $287.50 (<*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 shows the resulting work assignment solution when job rotation is also implemented. The total worker–location changeover *F* is 7 times. All daily noise exposure (8-hr TWAs) is below 90 dB*A*.

TABLE 3. Work Assignments for 4 Workers, *F* = 7 (Case I)

Worker	Work Period 1	2	3	4	8-hr TWA (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

Notes. TWA—time-weighted average, WL—worker location, *—worker locations where the use of hearing protection devices 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 4. Note that all 8-hr TWAs are still below 90 dB*A*.

TABLE 4. Improved Work Assignments for 4 Workers, *F* = 4* (Case I)

Worker	Work Period 1	2	3	4	8-hr TWA (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

Notes. TWA—time-weighted average, WL—worker location, *—worker locations where the use of hearing protection devices is enforced.

In summary, the optimal noise hazard control strategy for the given facility with *TB* = US $300 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 4;
3. enforce the use of type-B HPD at worker locations WL2 and WL4.

The noise hazard control strategy described here will require the total budget of US $287.50. As seen in Table 4, none of the four workers receives daily noise exposure exceeding 90 dB*A*.

4.2. Case II: *TB* = US $400

In Case II, the total budget is increased to US $400, with the budget for HPDs still being US $25. Using the 13-step design procedure, the required noise hazard control cost is US $375. 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 5;
3. HPDs are not required at all four worker locations.

TABLE 5. Work Assignments for 5 Workers (Case II)

Worker	Work Period 1	2	3	4	8-hr TWA (dB*A*)
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

Notes. TWA—time-weighted average, WL—worker location.

4.3. Case III: *TB* = US $500

In Case III, the total budget is increased to US $500, with the budget for HPDs still being US $25. Using the 13-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 US $475. 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 6;
3. HPDs are not required at all four worker locations.

TABLE 6. Work Assignments for 4 Workers (Case III)

	Work Period				8-hr TWA
Worker	1	2	3	4	(dBA)
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

Notes. TWA—time-weighted average, WL—worker location.

As seen in the three cases, the 13-step design procedure is able to determine the optimal noise hazard control strategy that can prevent workers' daily noise exposure 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 the 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 exposure still exceeds 90 dB*A*, additional workers will then be considered in job rotation.

5. CONCLUSIONS

This paper discusses the analytical design procedure to determine the optimal noise hazard control strategy within the given budget. Depending on noise data, number of workers, feasible noise control methods, and allocated budget, the optimal strategy recommends a combination of engineering controls, job rotation, and/or the use of HPDs to prevent workers' daily noise exposure from exceeding 90 dB*A*. Six optimization models are developed, two for engineering controls, two for job rotation, and two for the use of HPDs. The order of application also follows OSHA's hierarchy of noise control. The design procedure consists of 13 steps. The six optimization models are sequentially utilized in these steps to determine the optimal noise hazard control strategy.

For engineering controls, model E1 is intended to find feasible engineering controls to reduce all workers' daily noise exposure to a safety level at a minimum cost. Model E2, on the other hand, is intended to determine engineering controls within the given budget that minimize the maximum daily noise exposure at any worker location. For job rotation, model A1 is firstly applied to find the optimal work assignment solution based on the current workforce such that all daily noise exposure does not exceed 90 dB*A* and the total worker–location changeover is minimized. If no solution exists, model A2 is then applied using the increased workforce to determine the minimum number of workers and their work assignments to achieve safety daily noise exposure. Models H1 and H2 consider both job rotation and the use of HPDs to find a safety work assignment solution with the minimum number of HPDs used in the facility. Two workforce sizes, $m = n$ and $n \le m \le M$, are assumed for the two models, respectively.

Readers should be reminded 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. In terms of their benefit, all feasible strategies will result in safe noise exposure in all workers. Based on the cost–benefit analysis, one might be tempted to choose the strategy that requires the lowest total cost, which normally is the strategy with job rotation and/or the use of HPDs. However, it has been long known that workers typically resist wearing HPDs unless the devices are strongly enforced and the workers are closely monitored. In practice, this behavior can make the implemented strategy ineffective. Thus, one needs to consider both total cost and effectiveness of the noise hazard control strategy before making a decision.

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