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Optimization Approach to Hazard Prevention Budgeting Problem

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An analytical approach to optimally allocate the hazard prevention budget so as to eliminate or reduce hazard exposures in the industrial workplace is presented. Two hazard control approaches are considered: engineering approach and administrative approach. For the engineering approach, we consider controlling at the source of hazard and blocking the hazard along the transmission path. For the administrative approach, only job rotation is considered. From the given hazard prevention budget, four optimization models are sequentially employed to select appropriate hazard controls without exceeding the allocated budget. A sensitivity analysis is performed to study how the hazard prevention solution is affected by the budget portion allocated to engineering controls.

Significance: Workers are commonly exposed to various occupational hazards such as chemical, radiation, noise, thermal, and physical loads. The proposed approach is able to determine the hazard prevention solution based on the given budget that prevents the workers' daily hazard exposures from exceeding the permissible level. The resulting solution follows the OSHA's hierarchy of hazard prevention by applying engineering controls first, followed by administrative controls.

Keywords: Capital budgeting problem, hazard prevention, engineering controls, administrative controls, job rotation, sensitivity analysis

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1. INTRODUCTION

Nowadays, most working conditions still do not meet the minimum standards and guideline issued by health and safety organizations (LaDou, 2003). The actual number of people dying each year could be well over two million, and more than a million occupational injuries have also resulted each year (Takala, 2002). Worker productivity, health, and safety issues are major concerns of industry, especially in developing countries (Shikdar and Sawaqed, 2003). It is clear that improper workstation design, mismatch between worker abilities and job demands, and poor working environment lead to the reduction in worker productivity and product quality. Ergonomics technology, if properly applied, can eliminate or reduce occupational health and safety problems in the workplace and enhance performance (Shikdar and Sawaqed, 2004). Riel and Imbeau (1995a; 1995b) presented the economic justification of investments for health and safety interventions. They classified health and safety costs into three categories: insurance costs, work related costs, and perturbation costs. The activity-based costing is also discussed in their research studies.

Frequently occurred injuries and health problems in the workplace are caused by excessive exposure to occupational hazards. For examples, low back injury is caused by overexertion; hearing loss is caused by excessive exposure to loud noise. To eliminate or reduce occupational hazards, three control approaches are generally recommended. They are: (1) engineering approach, (2) administrative approach, and (3) the use of personal protective equipments (PPEs). According to the OSHA's hierarchy of hazard control, engineering controls are to be implemented first since they are the most effective approach. For examples, improper lifting tasks can be redesigned with the aiding tools or handling equipments; noisy machine can be modified with the new machinery parts or provided with proper maintenance so that the noise level will be decreased. If such controls are not feasible or inadequate, administrative controls such as job rotation should be implemented next. Job rotation is one of the most frequently recommended administrative methods in literature (NIOSH, 1981; OSHA, 1983). Basically, workers are assigned to do various jobs and also rotate their jobs in different periods during the day. In this way, the effect from hazardous jobs can be split and shared by many workers, instead of concentrating on some particular workers. Job rotation offers a trade-off between safety and productivity of the work system (Olishifski and Standard, 1988). The use of personal protective equipments (PPEs) is to be used as the last resort of hazard controls. PPEs should be used to assist, not to replace, engineering and administrative controls. Sanders and McCormick (1993) recommends that the three approaches be used in combination. This is especially practical when the hazard prevention budget is limited.

In most industrial workplaces, the presence of occupational hazards is inevitable. To protect workers from such hazards, both the exposure duration and permissible exposure level are usually established. It is also common to set the permissible level as the quantity that must not be exceeded within an 8-hour workday. For examples, OSHA (1983) imposes an 8-hour time-weighted average (TWA) of 90 dB*A* as the daily permissible noise level. NIOSH (1997) recommends the daily energy expenditure limit to be 33 percent of maximum oxygen uptake of an individual worker. The permissible levels for other occupational hazards such as heat exposure, chemical exposure, and radiation can be found in literature.

To our knowledge, the capital budgeting problem to select a feasible set of engineering and administrative controls for effective hazard prevention has not received much attention from industrial engineering researchers. In this paper, we introduce an optimization approach to determine the effective hazard prevention strategy based on the given budget. The paper is organized as follows. Firstly, we formulate mathematical models for two engineering controls and for an administrative control, to be applied in sequence. Next, we propose a step-by-step solution procedure that is applicable to a wide range of workplace hazards. Then, we illustrate the effectiveness of the solution procedure using a simulated numerical example of industrial noise control. Lastly, the sensitivity of the hazard prevention solution on the engineering control budget is studied.

2. APPROACH TO HAZARD PREVENTION BUDGETING PROBLEM

The hazard controls considered in this paper include only engineering and administrative controls. Typically, engineering controls require large capital investment, but they yield very effective hazard prevention. Administrative controls are not as costly and not as effective as the engineering controls. The optimization approach to the hazard prevention budgeting problem can be described as follows.

Firstly, a set of engineering controls that result in a minimum-cost hazard prevention solution in which the daily exposures to hazard at all worker locations do not exceed the permissible level are determined. If the total hazard prevention cost is within a given budget, an optimal solution is obtained. If the total budget is insufficient, the engineering control budget is then set at the total budget. Using this revised budget, a feasible set of engineering controls that minimize the maximum hazard level (per work period) at any worker location is determined. At this stage, it should be noted that the hazard level at some worker location still exceeds the permissible level.

Next, job rotation which is a popular administrative control is considered. Assuming that the number of available workers is equal to the number of worker locations, a job rotation pattern that allows workers to rotate among worker locations in different work periods such that their hazard exposures do not exceed the permissible level is determined. If such rotation pattern can be found, the hazard prevention solution is obtained. However, job rotation causes the worker-location changeover and, to some extent, can result in decreased productivity. It is thus logical to search for a hazard prevention solution in which the number of worker-location changeovers is minimized.

In this section, four optimization models are formulated. The model development is based on the following notation.

cb_v	cost of installing physical barrier *v* (to block the transmission path of the hazard)
cs_{tu}	cost of controlling the hazard at hazard source *t* using engineering control method *u*
EB	engineering control budget
EC	total cost of engineering controls
F	total worker-location changeover
f_j	number of worker-location changeovers at worker location *j*
HRb_{jv}	amount of hazard reduced at worker location *j* after installing physical barrier *v*
HRs_{jtu}	amount of hazard reduced at worker location *j* after applying engineering control method *u* at hazard source *t*
m	number of workers in the *current* workforce
M	number of available workers in the *new* workforce
n	number of worker locations
p	number of work periods per workday
PEL	daily permissible exposure level to the hazard under consideration
q	number of hazard sources
r	number of valid engineering control methods for controlling at the hazard source
s	number of valid engineering control methods for blocking the hazard transmission path
w'_j	hazard level per work period at worker location *j* before applying engineering controls
w_j	hazard level per work period at worker location *j* after applying engineering controls
$w_{\max}$	maximum hazard level 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* (from the available workforce) is assigned; 0 otherwise

yb_v 1 if hazard reduction using physical barrier v is applied; 0 otherwise
ys_{tu} 1 if hazard reduction at hazard source t using engineering control method u is applied; 0 otherwise

2.1 Models of Engineering Controls

For engineering controls, we consider: (1) controlling at the hazard source, and (2) blocking the hazard along the transmission path. Controlling at the hazard source implies that the hazard is reduced, and all worker locations in that work area will benefit from such hazard control. Controlling the hazard along the path can reduce the hazard at only some worker locations. Note that for a given hazard source, there could be several engineering control methods for reducing the hazard under consideration.

The selection of appropriate engineering controls is formulated as *cost-based* and *safety-based* models. The first model (E1) is a *cost-based* model that is intended to *minimize the total cost* when applying feasible engineering controls such that the hazard level at any worker location does not exceed *PEL*. The second model (E2) is a *safety-based* model that is intended to *minimize the maximum hazard level per work period* among all worker location *j*'s such that the resulting total cost does not exceed the allocated engineering control budget *EB*. Models E1 and E2 are integer programming models. The difficulty in solving the two models depends on w'_j, whether it is linear or nonlinear.

2.1.1 Model E1 – Minimizing the Total Cost of Engineering Controls

Model E1 yields a minimum total hazard prevention cost *EC** when only engineering controls are implemented. It provides the solution in which the hazard levels at individual worker locations do not exceed *PEL*.

$$\text{Minimize} \quad EC \qquad \ldots \qquad (1)$$

subject to

$$EC = \left[\sum_{t=1}^{q}\sum_{u=1}^{r}\left(cs_{tu} \times ys_{tu}\right) + \sum_{v=1}^{s}\left(cb_v \times yb_v\right)\right] \qquad \ldots \qquad (2)$$

$$w_j = w'_j - \sum_{t=1}^{q}\sum_{u=1}^{r} HRs_{jtu} \times ys_{tu} - \sum_{v=1}^{s} HRb_{jv} \times yb_v \qquad j = 1,\ldots,n \qquad \ldots \qquad (3)$$

$$w_j \le \frac{PEL}{p} \qquad j = 1,\ldots,n \qquad \ldots \qquad (4)$$

$$ys_{tu}, yb_v = \{0, 1\} \qquad \forall t,u,v \qquad \ldots \qquad (5)$$

2.1.2 Model E2 – Minimizing the Maximum Hazard Level per Work Period

Model E2 determines a feasible set of engineering controls that minimize the maximum hazard level per work period $w_{\max}$ at any worker location without exceeding the given engineering control budget. Note that when $EB < EC^*$, $w_{\max}$ is greater than PEL/p.

$$\text{Minimize} \quad w_{\max} \qquad \ldots \qquad (6)$$

subject to

$$w_j = w'_j - \sum_{t=1}^{q}\sum_{u=1}^{r} HRs_{jtu} \times ys_{tu} - \sum_{v=1}^{s} HRb_{jv} \times yb_v \qquad j = 1,\ldots,n \qquad \ldots \qquad (7)$$

$$w_j \le w_{\max} \qquad j = 1,\ldots,n \qquad \ldots \qquad (8)$$

$$\left[\sum_{t=1}^{q}\sum_{u=1}^{r}\left(cs_{tu} \times ys_{tu}\right) + \sum_{v=1}^{s}\left(cb_v \times yb_v\right)\right] \le EB \qquad \ldots \qquad (9)$$

$$ys_{tu}, yb_v = \{0, 1\} \qquad \forall t,u,v \qquad \ldots \qquad (10)$$

2.2 Models of Administrative Controls

The only administrative control considered in this paper is job rotation. Job rotation is a management practice that rotates workers among worker locations so that the maximum hazard level that any worker receives in one workday does not exceed *PEL*. This is mainly because job rotation has been widely recommended in literature and the mathematical models of the job rotation problem are well defined. It is noted that an 8-hour workday is divided into equal work periods and workers are allowed to rotate to other worker locations only at the end of the work period.

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 the total worker-location changeover is minimized. The worker-location changeover occurs when a worker moves from one worker location to another. Job rotation might result in decreased productivity 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 small as possible. The second model (A2) considers the situation in which more workers are required for job rotation due to excessive hazard levels in the workplace. The model objective is to determine the minimum number of workers (in the workforce) to rotate among the given worker locations such that none of the workers receives the daily hazard exposure beyond *PEL*. Model A1 can be classified as a variant of the knapsack problem while Model A2 is a variant of the bin packing problem.

It is worth noting that both job rotation models do not include any cost component since job rotation does not need any equipment investment or workplace modification. It is also assumed that any incurred cost due to decreased productivity will be absorbed by the production department. In a case where more workers are needed for job rotation (Model A2), it is assumed that they are existing workers (perhaps from other departments), not new workers. If skill training is required, the training cost will be absorbed by the human resource department.

The following assumptions are required for both job rotation models.

1. The maximum working time (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 he/she is assigned to perform. Similarly, the task output is independent of the worker.

2.2.1 Model A1 – Minimizing the Total Worker-Location Changeover

For any worker location, the number of worker-location changeovers reflects the number of workers who are rotated to attend that worker location in all *p* work periods. If the same worker is assigned to attend in every work period, the number of worker-location changeovers is zero. In case of multiple workers, the number of changeovers increases every time the worker is changed.

For worker location *j*, the number of worker-location changeovers f_j is computed from

$$f_j = \sum_{k=1}^{p-1}\left[1-\sum_{i=1}^{m}\left(x_{ijk}\times x_{i,j,k+1}\right)\right] \qquad j=1,\ldots,n \qquad \ldots \qquad (11)$$

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

$$F = \sum_{j=1}^{n}\sum_{k=1}^{p-1}\left[1-\sum_{i=1}^{m}\left(x_{ijk}\times x_{i,j,k+1}\right)\right] \qquad \ldots \qquad (12)$$

Model A1 determines a minimum total worker-location changeover F^* when the number of workers is equal to the number of worker locations. Furthermore, all workers' hazard exposures do not exceed *PEL*. The model can be expressed as follows.

$$\text{Minimize} \quad \sum_{j=1}^{n}\sum_{k=1}^{p-1}\left[1-\sum_{i=1}^{m}\left(x_{ijk}\times x_{i,j,k+1}\right)\right] \qquad \ldots \qquad (13)$$

subject to

$$\sum_{j=1}^{n}\sum_{k=1}^{p} w_j x_{ijk} \le PEL \qquad i=1,\ldots,m \qquad \ldots \qquad (14)$$

$$\sum_{j=1}^{n} x_{ijk} \le 1 \qquad i=1,\ldots,m;\ k=1,\ldots,p \qquad \ldots \qquad (15)$$

$$\sum_{i=1}^{m} x_{ijk} = 1 \qquad j=1,\ldots,n;\ k=1,\ldots,p \qquad \ldots \qquad (16)$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \le p \qquad i=1,\ldots,m \qquad \ldots \qquad (17)$$

$$x_{ijk} = \{0, 1\} \qquad \forall i,j,k \qquad \ldots \qquad (18)$$

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

Model A2 yields a minimum number of workers m^* for job rotation so as to prevent the workers' hazard exposures from exceeding *PEL*. However, the total worker-location changeover may or may not be the minimum.

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

$$\text{Minimize} \quad \sum_{i=1}^{M} y_i \qquad \ldots \qquad (19)$$

subject to

$$\sum_{j=1}^{n}\sum_{k=1}^{p} w_j x_{ijk} \leq PEL \cdot y_i \qquad i = 1,\ldots, M \qquad \ldots \qquad (20)$$

$$\sum_{j=1}^{n} x_{ijk} \leq 1 \qquad i = 1,\ldots, M;\ k = 1,\ldots, p \qquad \ldots \qquad (21)$$

$$\sum_{i=1}^{m} x_{ijk} = 1 \qquad j = 1,\ldots, n;\ k = 1,\ldots, p \qquad \ldots \qquad (22)$$

$$\sum_{j=1}^{n}\sum_{k=1}^{p} x_{ijk} \leq p \cdot y_i \qquad i = 1,\ldots, M \qquad \ldots \qquad (23)$$

$$x_{ijk}, y_i = \{0, 1\} \qquad \forall i, j, k \qquad \ldots \qquad (24)$$

3. SOLUTION PROCEDURE

A solution procedure for the hazard prevention problem requires the four optimization models described in Section 2 to be used in sequence. Because of its analytical nature, it is necessary to develop a formula to compute the hazard level at any worker location. Knowing the number of work periods per day p, the hazard level per work period can be computed for all worker locations. Firstly, an optimal total hazard prevention cost EC^* will be determined. If this total cost exceeds the given budget, engineering control budget *EB* has to be determined. It is convenient to set the engineering control budget equal to the total budget. When implementing job rotation, it is recommended to firstly use Model A1 to determine a solution with a minimum total worker-location changeover F^*. The other model is used only when Model A1 is unable to provide an optimal solution.

The procedure comprises the following seven steps.

Step 1: Obtain essential input data listed below.

- number of work periods per workday
- number of available workers for job rotation
- hazard level at each worker location
- hazard level generated by each hazard source
- feasible methods for controlling hazard at the source for each hazard source, costs, and amounts of hazard reduced
- feasible methods for blocking the hazard transmission path, costs, and amounts of hazard reduced at affected worker locations

Step 2: Using Model E1, find feasible engineering controls for reducing hazard at the source and for blocking the hazard transmission path that will prevent the daily hazard exposure at each worker location from exceeding *PEL* and find the minimum total cost EC^*. If $EC^* \leq EB$, go to Step 7. Otherwise, proceed to Step 3.

Step 3: Using Model E2, determine feasible engineering controls that minimize the maximum hazard level per work period among all n worker locations and the total cost *EC*. Next, assume that such engineering controls are implemented. Determine the new hazard levels at all worker locations.

Step 4: Apply job rotation to the current workforce (m workers). Using Model A1, find a set of work assignments with the minimum total worker-location changeover such that all daily hazard exposures do not exceed *PEL*. If an optimal work assignment solution can be found, go to Step 7. Otherwise, proceed to Step 5.

Step 5: Using Model A2 to find the minimum number of workers (m^*) to attend all n worker locations on a rotational basis such that their daily hazard exposures do not exceed *PEL*. Then, proceed to Step 6.

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. Then, go to Step 7.

Step 7: The result will provide an optimal hazard prevention solution based on the given total budget.

4. NUMERICAL EXAMPLE

In this section, we demonstrate how the four optimization models (in Section 2) and the solution procedure (in Section 3) can be employed to find an optimal hazard prevention solution. We select industrial noise hazard as an occupational hazard to be prevented since it is a common hazard that can be found in most industrial workplaces. Moreover, noise-induced hearing loss is one of the most common occupational diseases and the second most self-reported occupational illness or injury. Exposure to high noise levels is a leading cause of hearing loss and may also result in other harmful health effects. In USA, it has been estimated that 30 million workers are currently exposed to loud noise on the job and an additional 9 million workers risk getting hearing loss (NIOSH, 1998). A major cause that contributes to this problem is a lack of effective noise control program in the workplace. 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).

Engineering controls of industrial noise have been widely discussed in literature. Sutton (1976) also presented a procedure to identify possible methods of noise reduction and to select the best method using a cost/benefit analysis. However, the discussion on administrative approach is relatively scarce. Job rotation is usually recommended to reduce the worker's exposure to loud noise. Nanthavanij and Yenradee (1999) 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 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). A heuristic genetic algorithm for the *minimax* work assignments is later introduced by Kullpattaranirun and Nanthavanij (2005). Yaoyuenyong and Nanthavanij (2003) also developed a simple heuristic for solving large *minimax* work assignment problems. For workplaces where noise levels are excessive, Nanthavanij and Yenradee (2000) recommended that the number of workers be greater than the number of worker locations. They also developed a mathematical model to determine the minimum number of workers for working in noisy work areas so that their daily noise exposures do not exceed the permissible level.

For a workplace with multiple noise sources, the combined noise level at worker location j, $\bar{L}_j$ (dB*A*), can be computed. Letting L_{ab} be ambient noise level (dB*A*), L_t be machine noise level measured at 1-m distance (dB*A*), and d_{jt} be Euclidean distance (m) between worker location j and noise source t, $\bar{L}_j$ is computed from

$$\bar{L}_j = 10\log\left[10^{\left(\frac{L_{ab}-120}{10}\right)} + \sum_{t=1}^{q} \frac{10^{\left(\frac{L_t-120}{10}\right)}}{d_{jt}^2}\right] + 120 \qquad \ldots \qquad (25)$$

Knowing $\bar{L}_j$ at worker location j, noise exposure per work period w'_j is computed from

$$w'_j = \frac{1}{p} \times 2^{\left(\frac{\bar{L}_j-90}{5}\right)} \qquad \ldots \qquad (26)$$

Using Equation (26), one can easily verify that *PEL* for industrial noise hazard is 1.00. When workers are present at various locations during an 8-hour workday, the 8-hour time-weighted average (8-hour TWA) sound level (dB*A*) that worker i receives (or W_i) can be computed from

$$W_i = 16.61\left[\log_{10}\left\{\sum_{j=1}^{n} \frac{C_j}{8}\left(2^{\frac{\bar{L}_j-90}{5}}\right)\right\}\right] + 90 \qquad \ldots \qquad (27)$$

where C_j is the length of time (hr) that the worker spends at worker location j.

Consider an industrial facility that has five noisy machines (q = 5). At present, there are five workers (m = 5) being assigned to five different worker locations (n = 5). If necessary, two additional workers can be assigned to work in this facility (M = 7). An 8-hour workday is divided into four equal work periods (p = 4). The ambient noise level in the workplace is assumed to be 70 dB*A*. Table 1 shows location coordinates of the five machines (M1, M2, M3, M4, and M5), their noise levels, and location coordinates of the five worker locations (WL1, WL2, WL3, WL4, and WL5).

From the data given in Table 1 and using Equations (25) and (27), the 8-hour TWAs at the five worker locations are 92.91, 94.18, 93.80, 92.99, and 94.90 dB*A*, respectively. If each worker is assigned to one worker location and job rotation is not allowed, it is clear that all five workers (W1, W2, W3, W4, and W5) receive the noise exposure that exceeds 90 dB*A*. An effective noise hazard prevention program is required to reduce their daily noise exposures.

Suppose that feasible engineering controls for reducing machine noise at individual machines, costs, and noise reduction levels are presented in Table 2. There are also two types of barrier for blocking the noise transmission path. Type-1 barrier costs 9,000 baht (where 40 baht is approximately 1 USD) and it reduces the noise levels at worker locations WL1 and WL3 by 4 and 9 dB*A*, respectively. Type-2 barrier costs 10,000 baht. With this barrier installed, the noise levels at worker locations WL2 and WL4 will be reduced by 9 and 4 dB*A*, respectively.

Table 1. Location coordinates of the machines, machine noise levels, and location coordinates of the 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	2	7	96	WL3	2	5.5
M4	5	7	88	WL4	5	5.5
M5	7	5	98	WL5	9	5.0

Table 2. Engineering controls 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	10,000	9	14,000	14
M2	9,500	11	10,500	13
M3	9,000	10	10,500	15
M4	7,000	9	12,000	14
M5	8,500	12	11,500	16

The 7-step procedure is applied to find an optimal hazard prevention solution for this facility. After solving Model E1 in Step 2, the solution recommends the following engineering controls:

- Reduce machine noise at machine M2 using engineering control method 1
- Reduce machine noise at machine M5 using engineering control method 1
- Use type-1 barrier to block the noise transmission path

As a result, the *reduced* noise exposures per period at all five worker locations are 0.18444, 0.18940, 0.11111, 0.22577, and 0.13218, respectively. Since each noise exposure per period is less than 0.25, the workers' daily noise exposures do not exceed 90 dB*A*. The minimum total cost *EC** is 27,000 baht.

Let us investigate two cases in which the total budget is less than *EC**.

Case I: Total budget = 21,600 baht
Case II:Total budget = 10,800 baht

Thus, *EB* is set at 21,600 baht and 10,800 baht in Case I and Case II, respectively.

Case I: *EB* = 21,600 baht

In Step 3, Model E2 is used to determine feasible engineering controls that will minimize the maximum noise exposure per period under the engineering control budget of 21,600 baht. The new solution recommends that noise levels at machines M3 and M5 be reduced using engineering control methods 1 and 2, respectively. The total hazard prevention cost *EC* is 20,500 baht. Also, the five noise exposures per period are 0.31585, 0.34745, 0.18420, 0.20626, and 0.11848, respectively. Since there are two noise exposure values that exceed 0.25, the workplace noise hazard has not yet been prevented.

In Step 4, assuming that both engineering controls have been implemented, job rotation is next considered using Model A1 with the number of workers $m = 5$ (current workforce). Table 3 shows the resulting work assignment solution after job rotation has been implemented. The minimum total worker-location changeover F^* is 7 times. All daily noise exposures (8-hour TWAs) are below 90 dB*A*. Since an optimal hazard prevention solution is obtained in Step 4, Model A2 will not be used in Case I.

Table 3. Work assignments for the five workers (Case I: *EB* = 21,600 baht)

Worker	Work Period				8-hour TWA (dB*A*)
	1	2	3	4	
W1	WL5	WL1	WL1	WL4	89.68
W2	WL2	WL2	WL5	WL5	89.49
W3	WL1	WL3	WL3	WL3	88.98
W4	WL3	WL5	WL2	WL2	89.98
W5	WL4	WL4	WL4	WL1	89.51

Since five workers are assigned to five worker locations, no idle workers are seen in any work period (see Table 3). Thus, the work assignment solution in which the numbers of workers and worker locations are equal and a total worker-location changeover is the minimum will result in the most economic job rotation solution.

Case II: *EB* = 10,800 baht

In this case, the allocated engineering control budget is 10,800 baht. Following the solution procedure to Step 5, an optimal solution is found and the total hazard prevention cost is 8,500 baht. The optimal hazard prevention solution can be described as follows.

1. Reduce the machine noise at machine M5 using engineering control method 1.
2. Use seven workers in job rotation with the work assignments as shown in Table 4.

Table 4. Work assignments for the seven workers (Case II: *EB* = 10,800 baht)

Worker	Work Period				8-hour TWA (dB*A*)
	1	2	3	4	
W1	WL5	WL2	WL3	-	89.48
W2	-	WL4	WL1	WL2	89.90
W3	WL3	-	-	WL3	88.43
W4	WL2	-	WL2	-	87.84
W5	-	WL1	WL5	WL1	88.94
W6	WL4	WL5	WL4	WL4	89.58
W7	WL1	WL3	-	WL5	89.34

The resulting work assignment solution requires 14 worker-location changeovers. None of the seven workers receives the daily noise exposure that exceeds 90 dB*A*. To further enhance productivity (in Step 6), Model A1 is used to determine the work assignment solution with a minimum total worker-location changeover for the seven workers. The *improved* work assignment solution is shown in Table 5, with the minimum total worker-location changeover $F^* = 7$. Also, all 8-hour TWAs are below 90 dB*A*.

Table 5. *Improved* work assignments for the seven workers

Worker	Work Period				8-hour TWA (dB*A*)
	1	2	3	4	
W1	-	-	WL3	WL3	88.43
W2	-	WL5	WL2	WL2	89.23
W3	WL2	WL2	-	-	87.84
W4	WL1	WL1	-	WL4	89.77
W5	WL4	WL4	WL4	WL5	89.58
W6	WL5	-	WL1	WL1	88.94
W7	WL3	WL3	WL5	-	89.72

When the number of workers is greater than the number of worker locations, idle workers are found in some work periods (as seen in Tables 4 and 5). Applying Model A1 to the work assignment solution in Table 4 may help to reduce the total worker-location changeover (from 14 to 7 times), but it does not help to reduce the number of idle workers. One may view this work system as not being quite productive since it needs seven workers to do what five workers can. Because of the safety concern, the work system that does not seem to be economical is however recommended. In practice, the idle workers may be assigned to work in other work areas that are less noisy. However, their daily hazard exposures including those from such work areas must not exceed *PEL*.

As seen in the above two cases, the optimization procedure is able to recommend an optimal hazard prevention strategy that can prevent the workers' daily hazard exposures from exceeding *PEL*. It is also seen that the two recommended solutions vary in terms of the implemented engineering controls and the numbers of workers. In fact, these differences can be contributed to the engineering control budget. In the next section, the sensitivity of the hazard prevention solution to the allocated engineering control budget is investigated.

5. SENSITIVITY ANALYSIS

It is seen in the noise hazard prevention example that when the allocated engineering control budget is changed, the recommended engineering controls and the number of workers involved in job rotation are both affected. Specifically, when the engineering control budget is reduced, fewer and less expensive (or less effective) engineering controls are selected for implementation; thus, increasing the need for job rotation and, in several cases, more workers as well. A work system with a large number of worker-location changeovers tends to result in decreased productivity.

When the minimum total hazard prevention cost EC^* (as determined by Model E1) exceeds the given budget, the engineering control budget EB is usually set as a portion of EC^*. Letting α be an index ranging between 0 and 1.00, inclusive, which defines the amount of engineering control budget, we obtain $EB = \alpha \cdot EC^*$. When $\alpha = 0$, it implies that no engineering controls are to be implemented. Only job rotation will be considered. When $\alpha = 1.00$, only the engineering controls will be implemented.

Let us once again analyze the noise hazard prevention example in Section 4, with the number of workers in the available workforce increased to 10 workers ($M = 10$). For the sensitivity analysis, α is varied between 0 and 1.00, with 0.10 increments. At each α, the total hazard prevention cost EC, the number of workers involved in job rotation m^*, and the total worker-location changeover F^* are computed. The results are shown in Table 6.

Table 6. Hazard prevention cost, number of workers, and total worker-location changeover

α	$EB = \alpha \cdot EC^*$	EC	m^*	F^*
1.00	27,000	27,000	5	0
0.90	24,300	22,000	5	4
0.80	21,600	20,500	5	7
0.70	18,900	17,500	5	8
0.60	16,200	15,500	7	6
0.50	13,500	11,500	7	5
0.40	10,800	8,500	7	7
0.30	8,100	7,000	10	5
0.20	5,400	0	10	5
0.10	2,700	0	10	5
0	0	0	10	5

Fig. 1 shows how EC, m^*, and F^* change when α changes. At $\alpha = 1.00$, the optimization procedure utilizes only Model E1 to determine the minimum-cost hazard prevention solution that considers only the engineering controls. Since job rotation is not implemented, $F^* = 0$. Although it results in the most expensive hazard prevention solution, it is also the most effective. When decreasing α, the allocated engineering control budget EB is subsequently reduced. Job rotation is then implemented to help to reduce the workers' hazard exposures. Models E1, E2, and A1 are sequentially utilized to find the hazard prevention solution. At $0.70 \leq \alpha \leq 1.00$, five workers ($m^* = 5$) are still sufficient for job rotation, resulting in an economic work system. It is seen that the lower α gets, the larger F^* is. This change indicates that workers need to rotate among worker locations more often as the hazard prevention program relies more on job rotation to reduce the hazard exposure. At $0.40 \leq \alpha \leq 0.60$, job rotation requires two additional workers ($m^* = 7$) to rotate among the five worker locations. With more workers, F^* is now decreased. However, as α gets lower, F^* is increased again. At $\alpha \leq 0.30$, three additional workers are required for job rotation ($m^* = 10$) and F^* is once again decreased. One can see that this pattern tends to repeat itself every time m^* is increased.

The analytic nature of the optimization procedure enables industrial engineers to evaluate different hazard prevention solutions based on the given budget, hazard control approach, and the impact on productivity. The sensitivity plot shown in Fig. 1 can help to select the hazard prevention strategy that offers a balance between the required budget and the acceptable decreased productivity. Readers should note that the sensitivity plot is likely to be problem-dependent. For each hazard prevention problem, it is necessary to perform the sensitivity analysis to study how EC, m^*, and F^* vary with α.

6. CONCLUSIONS

The development of an effective hazard prevention strategy is viewed as the capital budgeting problem. From the given budget, hazard data, feasible hazard control methods, and work system data, an optimal hazard prevention solution that recommends valid combination of feasible engineering controls and job rotation to prevent the workers' daily hazard exposures from exceeding the permissible level is determined.

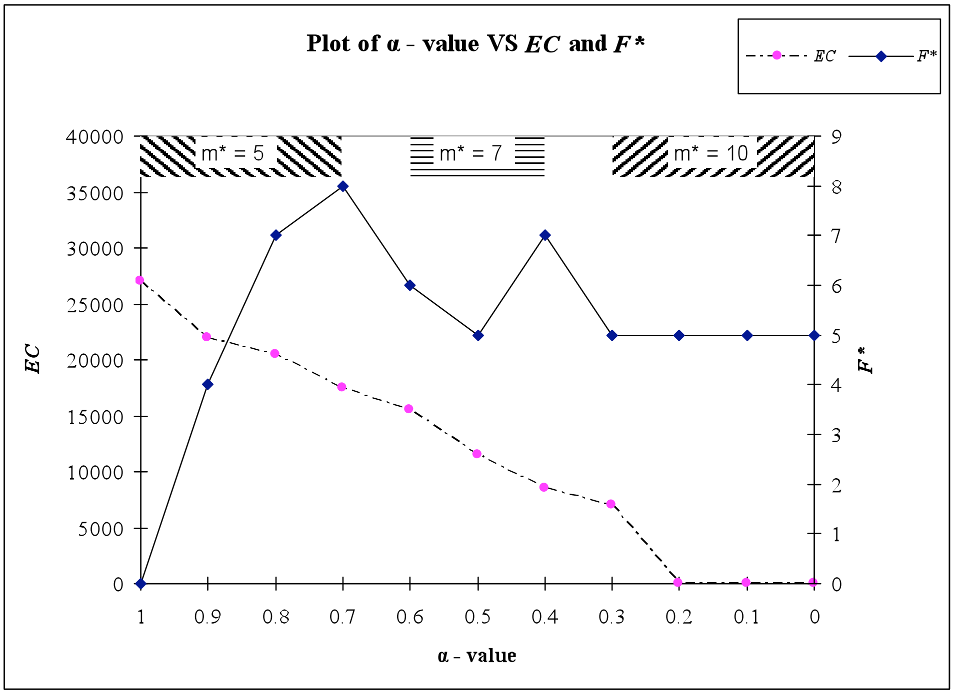

Figure 1: A sensitivity plot for the industrial noise hazard example

The solution procedure uses four optimization models, two models for engineering controls and the other two for job rotation, to find the effective hazard prevention strategy without exceeding the budget. Models E1 is a *cost-based* optimization model that is intended to find a set of feasible engineering controls to reduce all workers' daily hazard exposures to a safe level at a minimum total cost. Model E2, on the other hand, is used to determine the engineering controls (without exceeding a given budget) that minimize the maximum daily hazard exposure at any worker location. For the administrative approach, only job rotation is considered. Firstly, Model A1 is used to find the optimal work assignment solution based on the current workforce such that all daily hazard exposures do not exceed *PEL* and the total worker-location changeover is minimized. If no solution exists, Model A2 is used to determine the minimum number of workers for job rotation and their work assignments to achieve the *safe* daily hazard exposure.

The use of personal protective equipments (PPEs) is not considered in this solution procedure. Readers should note that although the use of PPEs is the least expensive approach of hazard control, it is generally not effective in practice since it relies heavily on the workers not only to wear them but also to wear them properly. Moreover, most workers tend to ignore wearing PPEs due to their uncomfortable design. Therefore, it has often been recommended that PPEs be used only as a supplementary protection.

Although only a noise hazard prevention example is illustrated in this paper, the optimization models described in the paper are general and can be applied to a wide range of occupational hazards. Initially, a measure of hazard level must be mathematically formulated. Then the hazard levels at all worker locations are computed. The four models are sequentially utilized in the seven steps to determine the optimal noise hazard prevention solution. It is observed that the size of the engineering control budget has some affect on the number of workers for job rotation and the total worker-location changeover. From the sensitivity analysis, changes in the total hazard prevention cost, number of workers, and total worker-location changeover are found to depend on the allocated engineering control budget. The sensitivity plot can be constructed to assist industrial engineers and/or safety practitioners in selecting a preferred hazard prevention strategy based on the given budget and acceptable decreased productivity. Readers should also be reminded that the optimal hazard prevention strategy is likely to vary if a different hazard control budget is set or a different feasible set of engineering and administrative controls are available. As a result, there is no single best strategy that will be suitable to all hazard prevention problems.

7. ACKNOWLEDGMENTS

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