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Heuristic Job Rotation Procedures for Reducing Daily Exposure to Occupational Hazards

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This paper discusses 2 heuristic job rotation procedures for preventing industrial workers from being excessively exposed to ergonomics and safety hazards in their workplaces. The objective of the procedures is 2-fold: (a) to find a minimum number of workers required for the given set of jobs, and (b) to determine a set of safe worker–job–period assignments such that all workers' exposure to hazard does not exceed the permissible limit. Here, occupational hazards are divided into 2 categories: single- and variable-limit hazards. In the first category, workers are considered to have equal capability to withstand the hazard; in the second category, the limit of hazard exposure varies for different individuals. Numerical examples are presented to demonstrate the procedures.

job rotation ergonomics occupational hazards work assignments

1. INTRODUCTION

Industrial workers are frequently exposed to occupational hazards in their workplace. Such hazards can affect workers' physical and mental health, safety, and productivity. Excessive hazard exposure (above the permissible level) can lead to occupational injuries and illnesses which will, consequently, result in unnecessary compensation payments, indemnity, and medical services. Moreover, the total cost to society is believed to be substantially higher due to various indirect costs (e.g., lost productivity, costs of hiring and training replacement workers, overtime, administrative costs, and miscellaneous transfer payments).

Frequent safety and health problems in industrial facilities are musculoskeletal disorders (MSDs), cumulative trauma disorders (CTDs), hearing loss, heat stress, chemical or radiation burns, etc. These problems are the results of excessive exposure to occupational hazards such as industrial noise, heat, physical workload, and toxic chemicals and substances. The U.S. Occupational Safety and Health Administration (OSHA) has recommended a hierarchical approach to workplace hazard control: engineering approach, administrative approach, and the use of personal protection equipment [1]. Among them, the administrative approach provides a good compromise between implementation cost and effectiveness. Job rotation is one of the most frequently recommended administrative methods in the literature [1, 2, 3]. In brief, workers are required to change their jobs during the day. In this way, the physiological effect from hazardous jobs can be shared by many workers, instead of being accumulated by one worker. It is a helpful approach in reducing daily occupational hazard exposure of individual workers.

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An effective job rotation program is usually difficult to design and implement. It is necessary to find a number of workers for job rotation and safe work assignments for them. It is recommended the number of workers exposed to occupational hazard be kept at a minimum [4]. At the same time, their daily exposure to hazard must not exceed a permissible limit, which depends on the type of hazard. For example, to avoid over-exhaustion, NIOSH [5] recommended the daily energy expenditure limit to be 33% of the maximum oxygen uptake of an individual worker. This daily energy expenditure limit is also used in the job severity index (JSI) for evaluating the hazard of lifting tasks. Note that the daily limit of energy expenditure differs among workers. Exposure to loud noise is another example. For noise exposure, OSHA [1] suggests the permissible noise exposure limit for any worker to be an 8-hr time-weighted average (8-hr TWA) sound level of 90 dB*A*. This noise exposure limit, however, is the same for every individual.

In this paper, we propose two heuristic job rotation procedures to find the minimum number of workers for job rotation and to determine a set of safe daily worker–job–period assignments for them. The paper is organized as follows. Firstly, we categorize occupational hazards as single- and variable-limit ones. Next, we describe the heuristic job rotation procedures for both hazard categories. Then, we demonstrate the applications of the heuristic procedures by solving two job rotation problems. After discussing the advantages and limitations of the heuristic job rotation procedures, we finally give the conclusions.

2. CATEGORIES OF OCCUPATIONAL HAZARDS

Occupational hazards can be divided into two categories: single- and variable-limit hazards.

2.1. Single-Limit Hazards

An occupational hazard is considered to be a single-limit hazard if its permissible exposure limit is the same for every person. In other words, there is only one permissible limit that is defined for the hazard exposure and this permissible limit applies to every worker. When applying job rotation to single-limit hazards, all workers are considered identical. It is unnecessary to consider whether the worker is male or female, tall or short, heavy or skinny, physically strong or weak, etc.

Noise, heat, cold, radiation, and toxic chemicals or substances are examples of single-limit hazards. It is important to note that even a single-limit hazard may be withstood unequally by workers. Since inter-individual differences with respect to exposure are still not quite clear, it is thus inadvisable to consider otherwise.

2.2. Variable-Limit Hazards

An occupational hazard is considered to be a variable-limit hazard if workers have different capabilities to withstand it. It becomes necessary, especially when job rotation is to be implemented, to consider workers as different individuals. Workers' admissible exposure to hazard must be measured or estimated. Hazard sustainability may depend on gender, body weight, physical strength, race, training, etc.

Lifting, physical workload (or energy expenditure), and mental workload are examples of variable-limit hazards.

3. HEURISTIC JOB ROTATION PROCEDURES

Heuristic job rotation procedures are based on the following assumptions.

1. A workday is divided into work periods of equal duration.
2. Each job requires only one worker to perform within one work period.
3. Each worker can perform at most one job within one work period.
4. Job rotation is allowed only at the end of a work period.
5. There are more workers than jobs. As a result, some workers may be idle in some work

periods. However, all jobs will be performed throughout the workday.

6. All workers know the list of jobs they are able to perform.

Initially, it is necessary to define whether the occupational hazard under consideration is a single- or variable-limit one. The amount of hazard any worker is exposed to (and perceives) per work period must be measured or estimated. This amount can be expressed in its original unit or transformed into a weighted value. If the hazard is variable-limit, the permissible exposure limits for all involved workers must be known. For simple jobs, it is possible to assign any worker to them. However, job rotation might involve skilled jobs and not every worker possesses the right skills to perform those jobs. It is essential to know to which jobs each worker can be assigned.

3.1. Notation

a_{ij} worker–job assignability index; $a_{ij} = 1$ if worker i can be assigned to job j; $a_{ij} = 0$ otherwise

h_j quantity of hazard exposure of job j per period

l_i permissible daily exposure limit for a variable-limit hazard for worker i

L permissible daily exposure limit for a single-limit hazard

M number of workers available for job rotation (not all M workers have to be assigned)

n number of jobs to be performed

p number of equal-duration work periods per workday

3.2. Procedure

Heuristic job rotation consists of three phases: (a) finding a sufficient number of workers, (b) determining a set of safe worker–job–period assignments, and (c) improving existing worker–job–period assignments.

3.2.1. Finding a sufficient number of workers for job rotation (Phase 1)

When $a_{ij} = 1$ for all is and js, at least n workers will be necessary to rotate among n jobs so that all jobs will be performed throughout the entire workday. When jobs are severely hazardous, it is likely that the number of required workers M will be larger than n. When some $a_{ij} = 0$, it is anticipated that many more workers will be required. That is, $M \gg n$. A trial-and-error process is utilized to find this sufficient number of workers M. This procedure is the same for both single- and variable-limit occupational hazards. If workers are considered to be non-identical (for variable-limit hazards), select the M workers randomly.

- Step 1: Select M where $M \geq n$.
- Step 2: Construct an assignment table with M rows (for M workers) and p columns (for p work periods).
- Step 3: Re-list all n jobs in non-increasing order of h_j ($j = 1, \ldots, n$), and consider the n jobs accordingly.
- Step 4: For each job j, construct p copies of job j to be assigned to the p work periods.
- Step 5: Let s_i be the sum of h_js of all jobs currently assigned to worker i in all periods. Initially, set $s_i = 0$ for all is.
- Step 6: Start assigning each copy of job j. Firstly, set $m = 0$.

  6.1. Set $m = m + 1$. If $m > M$, stop. A new (larger) value of M must be assumed.

  6.2. If $s_m + h_j \leq L$ (for a single-limit hazard) or $s_m + h_j \leq l_i$ (for a variable-limit hazard), and $a_{mj} = 1$, proceed to step 6.3. Otherwise, go to step 6.1.

  6.3. Find any period k where (a) worker m has not yet been assigned, and (b) no other copy of job j has been assigned to any worker in period k. If there is a tie, break the tie arbitrarily.

  6.4. Assign this copy of job j to row m and column k of the assignment table.

  6.5. Return to step 6.1.

- Step 7: Keep on assigning the copies of each job in this way until all jobs have been assigned.

The final assignment table will show a set of feasible assignments for m workers where $m \leq M$.

3.2.2. Determining a set of safe worker–job–period assignments (Phase 2)

3.2.2.1. Single-limit occupational hazards. In this phase, the heuristic procedure tries to generate a set of safe worker–job–period assignments for m workers, n jobs, and p periods. In these assignments, if there is no worker whose sum of hazard exposure from all periods exceeds the permissible limit L, these assignments are feasible. The procedure then tries to generate the assignments for $m - 1$ workers. Again, if the feasible assignments for $m - 1$ workers are found, the procedure continues to generate the assignments for $m - 2$ workers, and so forth. The procedure stops when it fails to generate the feasible assignments for the decreasing number of workers. The procedure can be divided into three large steps.

Step 1. Generating worker–job–period assignments

Suppose that m workers are being considered. Construct an assignment table with m rows (for m workers) and p columns (for p periods). Re-list all n jobs in non-increasing order of h_j, and consider the n jobs accordingly. Let s_i be the sum of h_js from all jobs currently assigned to worker i in all work periods. When considering job j, the p copies of job j (representing job j for period 1, job j for period 2, and so on) must be assigned. To assign each copy of job j, (a) find any worker i whose s_i is currently the smallest and $a_{ij} = 1$, (b) find any period k that (a) worker i has not yet been assigned, and (b) no other copy of job j has been assigned to any worker in period k. If there is a tie, break the tie arbitrarily.

Then, assign this copy of job j to row i and column k of the assignment table. Keep on assigning the copies of each job until all jobs have been assigned. If the resulting work assignments for m workers are feasible (i.e., no s_is exceed L), the procedure then tries to generate a new set of assignments for $m - 1$ workers. If the resulting assignments for m workers are not feasible, go to the next step.

Step 2. Exchanging jobs to make the assignments feasible

The procedure tries to make any currently infeasible assignments feasible by exchanging jobs among workers in any work period. It starts with any worker, say worker a, whose $s_a > L$. Then, it tries to exchange jobs currently assigned to worker a and another worker's jobs, say worker d, so that $s_a \leq L$ and $s_d \leq L$. Note that any exchange here must correspond to the worker–job assignability index a_{ij}. The procedure searches for any exchange in all possible pairs among workers. If the procedure can make the assignments feasible, decrease the number of workers by one worker and return to step 1. If not, proceed to the next step.

Step 3. Randomly exchanging jobs to generate new assignments

This step tries to create a new set of assignments from an existing set. It randomly exchanges the jobs between any two workers in each period. Then, return to step 2 to try to adjust the work assignments to make them feasible. Again, note that any exchange here must correspond to the worker–job–assignability index a_{ij}. If the procedure needs to implement step 3, it will repeat step 3 for at most 500 times. While the procedure keeps repeating itself, if feasible assignments are found, it will then decrease the number of workers by one worker and return to step 1. If step 3 has been repeated 500 times and no feasible assignments have been found, the overall procedure then terminates.

3.2.2.2. Variable-limit occupational hazards. Instead of having a single value for the permissible exposure limit, the hazard has up to m values for m workers. Let l_i be the permissible limit for worker i and l_i must be known. Arrange a list of workers in non-increasing order of the permissible limits l_is such that $l_i \geq l_{i+1}$ for $i = 1, \ldots, m - 1$. The procedure will always assign the workers who have the largest l_is to perform all jobs first so that the number of workers is smallest. Note that this biasness is the difference between the procedures for single- and variable-limit hazards. The procedure can be divided into three large steps.

Step 1. Generating worker–job–period assignments

The procedure tries to generate the assignments for the m workers who are being considered. Construct an assignment table with m rows (for m workers) and p columns (for p periods). Re-list all n jobs in non-increasing order of h_j, and consider the n jobs accordingly. When considering job j, the p copies of job j (representing job j for period 1, job j for period 2, and so on) must be assigned. To assign each copy of job j,

- find any worker i whose $l_i - s_i$ is currently the largest and $a_{ij} = 1$;
- find any period k that (a) worker i has not yet been assigned, and (b) no other copy of job j has been assigned to any worker in period k. If there is a tie, break the tie arbitrarily.

Then, assign this copy of job j to row i and column k of the assignment table. Keep on assigning the copies of each job in this way until all jobs have been considered. If the resulting assignments for m workers are feasible (i.e., all m workers have $s_i \le l_i$, $i = 1, \dots, m$), the procedure then tries to generate a new set of assignments for $m - 1$ workers. If the resulting assignments for m workers are not feasible, go to step 2.

Step 2. Exchanging jobs to make the assignments feasible

The procedure tries to adjust any currently infeasible assignment to be feasible by exchanging jobs among workers in any period. It starts with any worker, say worker a, whose $s_a > l_a$. Then, it tries to exchange those jobs currently assigned to worker a and another worker's jobs, say worker d, so that $s_a \le l_a$ and $s_d \le l_d$. Note that any exchange here must correspond to the worker–job assignability index a_{ij}. The procedure searches for any exchange in all possible pairs among workers. If the procedure can make the assignments feasible, it will then decrease the number of workers by one worker and return to step 1. Otherwise, proceed to step 3.

Step 3. Randomly exchanging jobs to generate new assignments

The procedure in this step is similar to that in step 3 for single-limit hazards.

3.2.3. Improving worker–job–period assignments

The job rotation procedures for both hazard categories described earlier can generate feasible worker–job–period assignments for a minimum number of workers. However, some workers may be assigned unfairly. For example, there are g workers in the assignments. The current assignments are feasible because $l_i - s_i \ge 0$ for all g workers. However, workers have different capability to withstand the hazard. Suppose that $l_1 - s_1 = l_g - s_g$, but l_g is much less than l_1. Thus, worker g is unfairly assigned when compared to worker 1. The following procedure will help to improve existing feasible assignments so that the variance of the normalized residual capacity $(l_i - s_i)/l_i$ for all workers is minimized. It is applicable to both single- and variable-limit occupational hazards. For the former, set $l_i = L$ for all workers. Initially, let $r_i = (l_i - s_i)/l_i$.

The procedure tries to exchange jobs among g workers in any period. It starts with any worker, say worker a, whose r_a is currently the smallest. Set $r_{\min} = r_a$. Then, the procedure tries to exchange jobs currently assigned to worker a and another worker's jobs, say worker d, so that the new r_a is larger than $r_{\min}$ and the new r_d is also larger than $r_{\min}$. Note that any exchange here must correspond to the worker–job assignability index a_{ij}. The procedure searches for any exchange in all possible pairs among workers. It tries to decrease the variance of the normalized residual capacity until no further improvement can be made.

4. EXAMPLES

In this section, two numerical examples are given. The first example is job rotation for reducing noise hazard exposure, which shows the application of the heuristic job rotation procedure for single-limit occupational hazards. The second example is job rotation for reducing energy expenditure hazard. It shows how exposure to variable-limit occupational hazards can be reduced.

An MS-Excel program, Job Rotation Solver, is written according to the procedures described in section 3. It requires the following inputs: number of jobs n; number of workers m; hazard exposure per period of each job h_j; permissible exposure limit(s) of the hazard (L or l_i, for $i = 1, \dots, m$); and worker–job assignability index a_{ij} for all is and js. By default, Job Rotation Solver assumes that a workday is divided into four work periods $p = 4$.

4.1. Noise Hazard Example

The applicability of job rotation to reducing daily noise exposure can be illustrated as follows. Suppose that a facility consists of three workstations with noise levels of 93, 91, and 85 dB*A*, respectively. Three workers (A, B, and C) are assigned to attend the three workstations during an 8-hr day which is divided into four equal work periods. Nanthavanij and Yenradee [6] developed a *minimax* work assignment model to determine a set of work assignments such that a maximum daily noise exposure (i.e., 8-hr TWA) is minimized. By applying the minimax model to this problem, the maximum daily noise exposure is reduced to 90.54 dB*A*. However, the three workers are still exposed to noise hazard since their daily noise exposure exceeds 90 dB*A*. When an additional worker (*D*) is added to the workforce, the maximum daily noise exposure is now reduced to 89.65 dB*A*. With worker *D* joining the workforce, none of the four workers is exposed to noise hazard. If two additional workers are added to the original workforce (of three workers), it is obvious that the maximum daily noise exposure will be even lower than when only one additional worker is added. However, the number of idle work periods will also increase, resulting in decreased work productivity.

The optimization problem of how to find safe work assignments with a minimum number of workers (1DMAP-N) was first proposed by Nanthavanij and Yenradee [7]. Given a set of noisy workstations with known noise levels, 1DMAP-N is intended to identify *safe* daily work assignments (a) which require a minimum number of workers, and (b) in which none of the workers is exposed daily to noise exceeding 90 dB*A*. Their computational results indicated that 1DMAP-N is very difficult to solve to optimality. Using an optimization tool called LINGO, to our experience, the largest problem that could be solved consists of only five jobs ($n = 5$). This computational difficulty is obvious since 1DMAP-N can be viewed as a variant of the classical one-dimensional bin packing problem (1BPP), which is an *NP*-hard problem [8].

For readers who are not familiar with 1BPP, its objective is to find a minimum number of equal-sized (i.e., fixed-height) bins that is sufficient for being packed by a set of one-dimensional items with various sizes. When comparing 1BPP and 1DMAP-N, one can see that an item in 1BPP is analogous to noise per period that a worker is exposed to when performing a job in 1DMAP-N, where a bin is analogous to a worker. In 1BPP, all bins are identical. Similarly, all workers in 1DMAP-N can be considered as identical workers since the permissible daily noise exposure is the same for every worker.

1BPP is a dual problem of the minimum-makespan multiprocessor scheduling problem, or $P_m||C_{\max}$ [9]. Both problems share similar concepts in the development of solution algorithms. Based on a given number of identical machines m, number of jobs n, and processing time of job j (w_j), a maximum completion time (of all n jobs on these m machines) or a maximum makespan of all machines $C_{\max}$ must be minimized. This scheduling problem is a classical combinatorial optimization problem and is also an *NP*-hard problem.

With the same relationship between $P_m||C_{\max}$ and 1BPP, a dual problem of 1DMAP-N, the so-called minimax work assignment problem (minimax WAP), is also a variant of $P_m||C_{\max}$. The minimax WAP is intended to find a work assignment solution that minimizes the maximum daily noise exposure (also called $C_{\max}$) of all given m workers [6]. Nanthavanij and Kullpattaranirun [10] developed a specialized genetic algorithm (GA) approach that efficiently solves large-sized minimax WAP. Yaoyuenyong and Nanthavanij [11] also developed a heuristic method called the M-LPT swap heuristic to solve the minimax WAP. The method is modified from the longest processing time (LPT) first heuristic which is a well-known heuristic for $P_m||C_{\max}$.

Suppose that a production section of an automobile assembly factory has four pressing machines (MC1, MC2, MC3, and MC4). The noise levels of the four machines are 85, 95, 89, and 92 dB*A*, respectively. Each machine needs one worker to operate it on a full-time basis. It is seen that if four workers are assigned to operate the four machines constantly all day, two of them will be exposed daily to noise that exceeds 90 dB*A*; thus, they will be exposed to noise hazard.

A safety engineer plans to implement job rotation to alleviate this hazard exposure problem. Seven workers are available for job rotation. All of them are capable of operating any of the four pressing machines with equal work efficiency (i.e., a_{ij} = 1 for all *i*s and *j*s). A workday (8 hrs) is divided into four equal work periods. Although the noise level at each machine is known, it cannot be used in the procedure in its present form. This is because noise level (in *A*-weighted decibels) is measured and expressed using the logarithmic scale which cannot be added linearly. However, the daily hazard exposure in the procedure is a linear sum of hazard amounts from all work periods. The following formula is used to transform noise level $\overline{L}_j$(in *A*-weighted decibels) into noise exposure per period or h_j:

$$h_j = \frac{1}{p} 2^{\frac{\overline{L}_j - 90}{5}}.$$

Thus, we have h_1 = 0.1250, h_2 = 0.5000, h_3 = 0.2176, and h_4 = 0.3299.

For a permissible exposure limit, an 8-hr TWA of 90 dB*A* can be transformed into L = 1.0000 [1].

In step 1, five workers are initially selected for job rotation. Table 1 shows the assignment table which assigns the four copies of h_j in the following order: 0.5000, 0.3299, 0.2176, and 0.1250. The superscript shown in the table represents the sequence of assignment.

It is seen that the assignments for the five workers in Table 1 are feasible since there is no worker i whose $s_i > L$. Thus, steps 2 and 3 are not necessary. The procedure then needs to determine if the assignments for four workers exist. However, it is found that for four workers (m = 4), the assignments are infeasible, even when steps 2 and 3 are implemented. Thus, the procedure terminates.

Table 2 shows the safe worker–job–period assignments for the five workers who will rotate among the machines. None of the workers are exposed to noise beyond the permissible limit. When using Job Rotation Solver to solve this noise hazard problem, the minimum number of workers for job rotation is still five workers. However, another set of safe work assignments

TABLE 1. Assignment Table (m = 5): Noise Hazard Problem

	Work Period				
Worker *i*	**1**	**2**	**3**	**4**	s_i
Worker 1	0.5000^{1}	0.1250^{14}		0.3299^{7}	0.9549
Worker 2		0.5000^{2}	0.3299^{8}	0.1250^{15}	0.9549
Worker 3	0.2176^{9}		0.5000^{3}	0.2176^{12}	0.9352
Worker 4	0.1250^{13}	0.2176^{10}	0.1250^{16}	0.5000^{14}	0.9676
Worker 5	0.3299^{5}	0.3299^{6}	0.2176^{11}		0.8774

Notes. Superscripts represent the sequence of assignment; m—number of workers; s_i—the sum of h_js from all jobs currently assigned to worker i in all work periods, where h_j—quantity of hazard exposure of job j per period.

TABLE 2. Safe Work Assignments for Five Workers

Worker *i*	Work Period 1	2	3	4	8-hr TWA (dB*A*)
Worker 1	MC2	MC1	—	MC4	89.70
Worker 2	—	MC2	MC3	MC1	89.70
Worker 3	MC3	—	MC2	MC3	89.50
Worker 4	MC1	MC3	MC1	MC2	89.80
Worker 5	MC4	MC4	MC3	—	89.10

Notes. TWA—time-weighted average, MC—pressing machine.

TABLE 3. Improved Safe Work Assignments for Five Workers (From Job Rotation Solver, an MS-Excel Program)

Worker *i*	Work Period 1	2	3	4	8-hr TWA (dB*A*)
Worker 1	MC2	MC3	MC3	—	89.50
Worker 2	—	MC2	MC1	MC4	89.70
Worker 3	MC3	—	MC2	MC3	89.50
Worker 4	MC1	MC4	—	MC2	89.70
Worker 5	MC4	MC1	MC4	MC1	89.32

Notes. TWA—time-weighted average, MC—pressing machine.

is found as shown in Table 3. These new work assignments are better than the ones shown in Table 2 since Job Rotation Solver uses an improvement procedure described in section 3.2.3. to improve the work assignments. The variance of the normalized residual capacity of the work assignments in Table 3 is 0.00035 while that of the work assignments in Table 2 is 0.00128.

4.2. Energy Expenditure Hazard Example

Similar to the noise hazard problem, job rotation is a low-cost, yet effective, approach to prevent workers from over-exhaustion as a result of excessively expending their physical energy. The energy-based workforce scheduling problem (WSP-E) is intended to determine the work assignments for m workers (where $m \le M$) and n tasks such that the number of workers is minimized and, for each worker, the total energy cost does not exceed the daily working energy capacity. It is essential to determine the workers' work schedules for an 8-hr workday to correspond to the ergonomically recommended daily working energy capacity.

To present a mathematical model of WSP-E, additional variables must be defined [12]: x_{ijk}—1 if worker i is assigned to job j during work period k, 0 otherwise; y_i—1 if worker i is chosen from the workforce to perform any job, 0 otherwise. WSP-E can be mathematically expressed as follows.

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

$$\sum_{j=1}^{n}\sum_{k=1}^{p} h_j x_{ijk} \le l_i y_i \quad \text{for } i = 1, \dots, M;$$

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

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

$$x_{ijk} = \{0, 1\} \quad \text{for } i = 1, \dots, M; j = 1, \dots, n; k = 1, \dots, p;$$

$$y_i = \{0, 1\} \quad \text{for } i = 1, \dots, M.$$

In this model, h_j represents the amount of energy expenditure required to perform job j per period (kcal/period) and l_i is the recommended daily energy expenditure for worker i (i.e., 33% of his/her maximum oxygen uptake) (kcal/day). From the objective function, the problem objective is to determine the minimum number of workers m (where $m \leq M$) to rotate among n energy-demanding jobs. The first constraint implies that for each worker, the total daily energy expenditure must not exceed one's energy capacity. The second constraint stipulates that in each work period, a worker can be assigned to at most one job. However, the third constraint emphasizes the requirement that in each work period, each job must be performed and only one worker is required for each job. The fourth and fifth constraints are the binary integer constraints for the decision variables that represent worker–job–period assignments and for the decision variables that identify the chosen workers.

Suppose that a workplace has three physical jobs (J1, J2, and J3) to be performed in one 8-hr day. The amounts of energy required to perform these three jobs are 4 404, 3 200, and 2 200 kcal per day, respectively. A safety engineer is assigned to design and implement job rotation so that the workers will not be too exhausted at the end of the workday.

Four workers are available to be assigned to these three jobs and they can perform any job with equal efficiency. The maximum oxygen uptake (which indicates a person's energy capacity) of these workers is 3.54, 3.42, 3.16, and 2.78 L/min, respectively. Since it is recommended that individuals spend no more than 33% of their maximum oxygen uptake, the daily energy expenditure limits for the four workers can be estimated as follows: worker 1—2 804 kcal/day, worker 2—2 709 kcal/day, worker 3—2 503 kcal/day, and worker 4—2 202 kcal/day. Note that 1 L/min of oxygen uptake is equivalent to the energy expenditure of 5 kcal/min.

A workday is divided into four equal periods. Therefore, the amounts of energy expenditure per period of jobs J1, J2, and J3 are 1 101, 800, and 550 kcal/period, respectively. These jobs are relisted in this order: J1, J2, and J3. As for the workers, they shall be assigned in this order: worker 1, worker 2, worker 3, and worker 4. Table 4 shows the initial work assignments generated by the heuristic job rotation procedure (step 1).

It is obvious that the assignments in Table 4 are still infeasible since $s_4 > l_4$. Therefore, the procedure goes to step 2 to search for any exchange that makes the assignments feasible. It is found that by exchanging jobs between worker 2 and worker 4 in period 3

TABLE 4. Assignment Table (m = 4): Energy Expenditure Hazard Problem

	Work Period						
Worker i	**1**	**2**	**3**	**4**	l_i	s_i	$l_i - s_i$
Worker 1	$1\,101^{1}$	800^{5}	—	550^{9}	2 804	2 451	353
Worker 2	800^{6}	$1\,101^{2}$	550^{10}	—	2 709	2 451	258
Worker 3	—	550^{11}	$1\,101^{3}$	800^{7}	2 503	2 451	52
Worker 4	550^{12}	—	800^{8}	$1\,101^{4}$	2 202	2 451	–249

Notes. Superscripts represent the sequence of assignment; m—number of workers; l_i—permissible daily exposure limit for a variable-limit hazard for worker i; s_i—the sum of h_js from all jobs currently assigned to worker i in all work periods, where h_j—quantity of hazard exposure of job j per period.

TABLE 5. Revised Assignment Table

	Work Period						
Worker i	**1**	**2**	**3**	**4**	l_i	s_i	$l_i - s_i$
Worker 1	$1\,101^{1}$	800^{5}	—	550^{9}	2 804	2 451	353
Worker 2	800^{6}	$1\,101^{2}$	[800^{8}]	—	2 709	2 701	8
Worker 3	—	550^{11}	$1\,101^{3}$	800^{7}	2 503	2 451	52
Worker 4	550^{12}	—	[550^{10}]	$1\,101^{4}$	2 202	2 201	1

Notes. Superscripts represent the sequence of assignment; numbers shown in square brackets are the exchanged pair; l_i—permissible daily exposure limit for a variable-limit hazard for worker i; s_i—the sum of h_js from all jobs currently assigned to worker i in all work periods, where h_j—quantity of hazard exposure of job j per period.

TABLE 6. Safe Work Assignments for Four Workers

Worker i	Work Period 1	2	3	4	l_i	s_i	$(l_i - s_i)/s_i$
Worker 1	J1	J2	—	J3	2804	2451	0.1259
Worker 2	J2	J1	J2	—	2709	2701	0.0030
Worker 3	—	J3	J1	J2	2503	2451	0.0208
Worker 4	J3	—	J3	J1	2202	2201	0.0005

Notes. Numbers shown in the square brackets are the exchanged pair; J—job; l_i—permissible daily exposure limit for a variable-limit hazard for worker i; s_i—the sum of h_js from all jobs currently assigned to worker i in all work periods, where h_j—quantity of hazard exposure of job j per period.

(i.e., exchanging 550^{10} and 800^{8}), the resulting assignments for the four workers then become feasible as shown in Table 5. Next, the overall procedure tries to find any feasible assignments for three workers, but to no avail even after implementing step 2 and step 3. As a result, the procedure terminates. Table 6 shows safe work assignments for the four workers.

5. DISCUSSION

The heuristic job rotation procedures presented in this paper provides a practical means for safety practitioners who wish to implement job rotation in their work system as an approach to keep the workers' daily exposure to occupational hazards within the permissible limit. The procedures have both advantages and limitations. To implement job rotation to achieve its maximum effectiveness, it is imperative that one must be fully aware of the strengths and weaknesses of the heuristic job rotation procedures and must understand their requirements prior.

The advantages of the heuristic job rotation procedures can be listed as follows.

- The procedures are very applicable for large-sized job rotation problems because they utilize a heuristic algorithm to construct an initial solution and another heuristic algorithm to improve the initial solution to yield the best worker–job–period assignments.
- Based on their step-by-step computations, the procedures can be computerized; thus, allowing any novice to use the program to find the worker–job–period assignments conveniently. The computation time is also short owing to efficient heuristic algorithms.
- The procedures are applicable for both single- and variable-limit occupational hazards in industrial workplaces.
- The procedures can be implemented in batch manufacturing factories (e.g., assembly, metal cutting, garment, electronics) and chemical process industries (e.g., pharmaceutical, glass, steel, food processing), where workers are typically exposed to occupational hazards in which the daily exposure limit must not be exceeded.

However, the procedures have limitations which can hinder their implementation and effectiveness.

- The procedures only work for occupational hazards that are quantitative. It is also essential that the exposure amounts per work period be accurately measured or estimated. Furthermore, the total daily hazard exposure must be equal to a linear sum of amounts of hazard from all work periods.
- When the hazard exposure tends to fluctuate with time, it is difficult to accurately define its amount per work period. Although maximum exposure can be used to represent its worst-case exposure, the resulting assignments will require more workers than when using the average exposure which will increase the labor cost.
- At present, the heuristic job rotation procedures are based on an assumption that if workers can be assigned to perform a set of jobs, they can perform those jobs with equal work efficiency. This assumption is undoubtedly unrealistic

which can cause the job rotation solution to be unusable.

- To avoid any decline in productivity or work efficiency as a possible result of frequent worker–job changeovers, it is necessary to maintain flexible workforce for the work system where job rotation is to be implemented. Such skill flexibility can be obtained through job or skill training.
- There are other issues that may affect the effectiveness of job rotation, such as job satisfaction, appropriate length of work period, effect of worker–job changeover, etc. These issues must be evaluated so as to avoid any negative impact on worker performance.
- For any industry in which job rotation cannot be implemented due to the opposition or resistance from the labor union, the heuristic job rotation procedures cannot be utilized. Safety practitioners must then rely on other administrative approaches.

While there seem to be quite a few limitations, the heuristic job rotation procedures have several benefits and are a practical tool for enhancing workplace safety. The procedures need to be made more realistic by considering unequal work efficiencies not only among workers but also within the same worker when being assigned to different jobs.

6. CONCLUSIONS

Job rotation is a management technique commonly recommended in most occupational safety and health literature to help to reduce workers' exposure to occupational hazards. For a given set of jobs, a group of workers will rotate to perform the required activities (and be exposed to hazard). Well-managed job rotation will reduce all workers' hazard exposure at little cost. If all jobs must be attended by workers on a full-time basis, the number of workers must be at least equal to the number of jobs. Depending on the hazard levels of the jobs, the number of workers could be much greater than the number of jobs. In addition to finding out how many workers should be involved in job rotation, it is necessary to determine their daily work schedules. For example, which job a given worker should perform first, which job should be next, and so forth. At the end of the workday, the total hazard that each worker is exposed to must not exceed the permissible limit. Suppose that all workers can be assigned to any job, the number of possible combinations of worker–job–period assignments can be as large as $(m!)^p$ where m is the number of workers and p is the number of work periods per day.

Occupational hazards can be divided into two categories, those in which the permissible limit is the same for all workers and those in which the permissible limit varies among workers. For single-limit hazards, all workers are considered to be identical (in terms of hazard withstanding) and it does not matter which person gets the assignment. However, for variable-limit hazards, it is necessary to know each worker's hazard withstanding capability.

Two heuristic job rotation procedures are described in this paper. The first procedure is intended for single-limit hazards such as noise, heat, and radiation hazard. The second procedure is intended for variable-limit hazards such as lifting and physical workload hazard. To apply the heuristic job rotation procedure, it is necessary to know the amount of hazard exposure that one would be exposed to per period when performing the job. This hazard exposure must be expressed in a form that would allow a linear sum to represent the total daily hazard exposure. The procedure consists of three phases: (a) finding a sufficient number of workers, (b) determining a set of safe worker–job–period assignments, and (c) improving existing worker–job–period assignments. The objectives of both procedures are to find the minimum number of workers required for job rotation and to determine their safe worker–job–period assignments. Firstly, the procedure uses the assignment table to find just a sufficient number of workers for the given set of jobs. Their work assignments are also determined. Next, the procedure tries to adjust the work assignments in case some assignments are infeasible. Additionally, it tries to find work assignments for a smaller number of workers.

When the number of workers and their work assignments are determined, the procedure generates a new job rotation solution and repeats the steps in each phase to find a better solution. An MS-Excel program called Job Rotation Solver is developed to perform all necessary computations and yield a job rotation solution (the number of workers and their safe work assignments).

From the two hazard exposure examples, noise hazard and energy expenditure hazard, it is seen that the heuristic job rotation procedures are able to find the minimum number of workers required for job rotation and their safe worker–job–period assignments. These procedures will be a useful and practical tool for safety practitioners who would like to implement job rotation in their workplace to alleviate the workers' exposure to occupational hazards.

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