MULTI-WORKDAY ERGONOMIC WORKFORCE SCHEDULING WITH DAYS OFF

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Abstract

Most ergonomic workforce scheduling problems (WSPs) are concerned with developing daily work schedules for industrial workers so as to prevent their daily hazard exposures from exceeding a permissible limit. In this paper, we consider the WSP with a planning period that covers several workdays. Additionally, allowable days off are included in the work schedules. It is assumed that all workers working at the same workstation (or in the same work area) are exposed to the same hazard level. Daily operation schedules of workstation and worker limitations are also considered. An integer linear programming model is developed to represent the multi-workday ergonomic workforce scheduling problem. Its objective is to determine a minimum number of utilized workers for the given planning period such that all workers' daily hazard exposures do not exceed the permissible daily limit. An optimization software tool called ILOG CPLEX is employed to obtain the optimal solution.

Keywords: Multi-workday workforce scheduling, Ergonomics, Hazard exposure, Optimization

1. INTRODUCTION

Nowadays, workforce scheduling is an important and challenging problem for many organizations both in manufacturing and service industries. It has impact on labor cost, employee morale, and safety. The workforce scheduling problem (WSP) is a combinatorial optimization problem that is intended to assign a group of workers or employees to work in a set of shifts (e.g. morning, afternoon, night) or to perform a set of tasks over a given time period. Several problem constraints and restrictions are considered when a feasible work schedule solution is developed. The objective of WSP varies depending upon the application, work environment, and work policy of the workplace. Its emphasis might be on the minimization of either the total number of workers (Alfares, 2002) or total cost (Elshafei and Alfares, 2008). WSP has been studied in various service systems, for example, the crew scheduling of the Hong Kong Light Rail Transit (Chu and Chan, 1998), the scheduling of staff at the United States Postal Service (Bard et al. 2003), and the staff scheduling in the healthcare system (Brunner and Edenharter, 2011).

Typically, WSP has two different planning horizons. They are: (1) multi-period planning within one workday, and (2) multi-workday planning. The multi-period WSP focuses on assigning workers to tasks or shifts to different work periods in one workday.

This problem is also known as the job rotation problem in the occupational safety and health field. Sarbar et al. (2008) studied the multi-period scheduling of workers for a large assembly line work system. They developed a mathematical model with the consideration of competencies and preference of workers. A work period was set equal to the line's preset task time between two product units. The objective was to satisfy personnel requirements at each station in each period during the planning horizon while minimizing the cost and dissatisfaction.

The multi-workday WSP (MW-WSP) is applicable for various work environments. The problem focuses on assigning employees to work shifts or tasks in several workdays during a pre-defined planning period (e.g., 1 week, 1 month). For example, Pan et al. (2010) studied the manpower scheduling in a manufacturing environment. The objective was to develop multi-workday work schedules that minimize the total payment on employees. A mixed integer mathematical model was developed to represent the problem. A two-stage heuristic algorithm was proposed to solve this problem.

Many industrial workers are frequently exposed to ergonomics hazards in their workplaces. Examples of common ergonomics hazards are industrial noise, thermal, mental stress, and physical workload. Excessive hazard exposure can lead to occupational injuries and illnesses, job dissatisfaction, and decreased work efficiency and productivity. To avoid excessive exposure to ergonomics hazard, workers might be rotated among different tasks, workstations, or work areas within the same workday. It is necessary to determine the effective work schedules that help to prevent workers from being exposed to any concerned ergonomics hazard beyond a daily permissible limit. Carnahan et al. (2000) introduced the scheduling problem by aiming at smoothing a Job Severity Index (JSI) that was used to assess the potential for back injury. The daily rotating work schedules were obtained using integer programming and genetic algorithm. Tharmmaphornphilas and Norman (2003) developed a mathematical model to minimize the maximum daily noise exposure among workers. Yaoyuenyong and Nanthavanij (2006) proposed a hybrid procedure to determine an optimal number of workers for job rotation without being exposed to excessive noise hazard in the manufacturing environment.

Job rotation is an administrative approach for hazard exposure reduction. In fact, there are other benefits of job rotation, for examples, preventing injuries, reducing employee boredom, and balancing workloads. Seçkiner and Kurt (2008) used job rotation scheduling in multi-working day planning where each worker will receive constant number of days-off each week. Their objective was to minimize the workload cost among workers. A job rotation considering employees' boredom was studied in Ayough et al. (2012). They tried to rotate jobs among operators during the workday so that the total cost including assignment and boredom costs was minimized. Moreover, a job rotation in an assembly line employing disabled workers can be found in Costa and Miralles (2009).

As seen above, the multi-workday workforce scheduling problem with a consideration of safety or ergonomics hazard is still not explored. In this paper, we intend to determine a minimum workforce size for job rotation during a multi-workday planning period so that each day the ergonomics hazard exposure of any worker does not exceed a daily permissible limit. Additionally, days off are allowed when generating the daily rotating work schedules.

2. MULTI-WORKDAY ERGONOMIC WORKFORCE SCHEDULING

The multi-workday ergonomic workforce scheduling problem (MW-WSP) focuses on developing multi-workday daily rotating work schedules for industrial or service workers. According to most safety laws, workers must not be exposed to a given occupational hazard beyond a daily permissible limit. MW-WSP also considers worker limitation and workstation operation schedule. Specifically, workers are heterogeneous. The worker can be assigned to specific jobs or tasks according to his/her qualifications. The workstations also have specific operation schedules. Their shutdown periods are predetermined for all workdays within the planning horizon. The number of workdays for workers are known, including the required number of days off for individual during the planning period. Each workday can be divided into multiple work periods. Workers are rotated among different tasks or workstations during the workday to reduce their hazard exposures. At any workstation, the hazard exposure is uniform. That is, all workers performing individual tasks at the same workstation are exposed to the same hazard level.

Generally, the larger the number of workers utilized in job rotation, the lesser the hazard exposure amount each worker will receive. Nevertheless, increasing the number of workers results in increased total labor cost. As such, it is important to determine the optimal workforce size for job rotation. In summary, the objective of MW-WSP is to determine the minimum number of utilized workers and their safe daily rotating work schedules with days off for a multi-workday planning period.

3. MATHEMATICAL MODEL

MW-WSP can be formulated as a mixed integer linear programming problem (MILP). Its objective is to determine a minimum set of workers for multi-workday job rotation and their daily rotating work schedules that satisfy ergonomics, worker limitation, workstation operation schedules, and workstation requirement constraints. The problem must satisfy the following conditions:

1. Each worker must not be exposed to a given hazard exposure beyond a daily permissible limit.
2. In each work period, each worker can be assigned to only one task.
3. When the workstation is occupied (i.e., tasks are being performed), the number of required workers for the workstation must be satisfied.

4. Each worker must be assigned to work for a given number of workdays during the planning period.

5. Worker limitation and workstation operation constraints must be satisfied.

The formulation of mathematical model is based on the following assumptions:

1. A workday is divided into equal work periods. Job rotation occurs only at the end of the work period.

2. In any given work period of the workday, a workstation may or may not be occupied depending upon its operation schedule.

3. The numbers of workers required at different workstations do not have to be equal.

4. If a workstation is scheduled to be occupied, all tasks at that workstation must be performed. Similarly, if the workstation is shut down, all tasks at that workstation will not be performed.

5. The numbers of tasks that the workers can perform are known and do not have to be equal.

6. All workers at the same workstation receive the same amount of hazard irrespective of the tasks being performed.

7. The hazard exposure per period at each workstation and the daily permissible limit of hazard exposure are known.

Parameters:

T number of workdays in a planning period; $t \in \{1,\dots, T\}$

K number of work periods per workday; $k \in \{1,\dots, K\}$

J number of workstations; $j \in \{1,\dots, J\}$

I number of available workers for job rotation; $i \in \{1,\dots, I\}$

L daily permissible limit of hazard exposure

m_i number of workdays per planning period for worker i

p_{jk}^{t} 1 if workstation j is occupied in work period k on workday t; 0 otherwise

w_j number of workers required for workstation j

h_j hazard exposure level per work period at workstation j

a_{ij} 1 if worker i can be assigned to a task at workstation j; 0 otherwise

Variables:

n number of utilized workers for job rotation

Decision variables:

$$X_{ijk}^{t} = \begin{cases} 1 & \text{if worker } i \text{ is assigned to workstation } j \text{ in work period } k \text{ in workday } t \\ 0 & \text{otherwise} \end{cases}$$

$$Y_i^t = \begin{cases} 1 & \text{if worker } i \text{ is assigned to work in workday } t \\ 0 & \text{otherwise} \end{cases}$$

$$e_i = \begin{cases} 1 & \text{if worker } i \text{ is selected for job rotation} \\ 0 & \text{otherwise} \end{cases}$$

The mathematical model can be expressed as follows.

$$\text{Minimize} \quad n = \sum_{i=1}^{I} e_i \tag{1}$$

subject to

$$\sum_{j=1}^{J}\sum_{k=1}^{K} X_{ijk}^{t} h_j \le L \qquad \forall i,t \tag{2}$$

$$\sum_{j=1}^{J} X_{ijk}^{t} \le 1 \qquad \forall i,k,t \tag{3}$$

$$\sum_{i=1}^{I} X_{ijk}^{t} = w_j p_{jk}^{t} \qquad \forall j,k,t \tag{4}$$

$$\sum_{t=1}^{T} Y_i^{t} = m_i e_i \qquad \forall i \tag{5}$$

$$X_{ijk}^{t} \le p_{jk}^{t} \qquad \forall i,j,k,t \tag{6}$$

$$X_{ijk}^{t} \le a_{ij} \qquad \forall i,j,k,t \tag{7}$$

$$X_{ijk}^{t} \le Y_i^{t} \qquad \forall i,j,k,t \tag{8}$$

$$Y_i^{t} \le e_i \qquad \forall i,t \tag{9}$$

$$X_{ijk}^{t} \in \{0,1\},\ Y_i^{t} \in \{0,1\},\ e_i \in \{0,1\} \qquad \forall i,j,k,t \tag{10}$$

4. NUMERICAL EXAMPLE

A hypothetical job shop facility is being considered. The facility has three workstations (T1, T2, and T3) and ten available workers (W1 – W10). At each workstation, the ergonomics hazard is uniform. The planning period is six workdays (D1 – D6). All workers must work five workdays during the planning period, with one day off. A workday is divided into four equal work periods (P1 – P4). For simplicity, it is assumed that the daily permissible hazard exposure limit *L* is 1. Table 1 shows the hazard exposure amount per work period and number of required workers at each workstation. The workstation operation schedule is shown in Table 2. Table 3 shows the data of available workers.

Table 1: Workstation data.

Workstation	Hazard Exposure Amount per Work Period	Number of Required Workers
T1	0.4418	1
T2	0.3236	2
T3	0.1858	2

Table 2: Workstation operation schedule.

	D1				D2				D3			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
T1	-	Y	Y	Y	Y	Y	Y	-	Y	Y	Y	-
T2	Y	-	Y	Y	-	Y	-	Y	Y	Y	Y	-
T3	-	Y	Y	Y	Y	Y	-	Y	Y	Y	Y	Y
	D4				D5				D6			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
T1	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	Y	Y
T2	Y	Y	Y	Y	Y	Y	Y	-	Y	-	Y	Y
T3	Y	Y	Y	-	Y	-	Y	Y	Y	Y	-	Y

Note: Y = occupied; - = shut down

Table 3: Worker data.

	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
T1	Y	Y	Y	Y	Y	Y	N	Y	Y	N
T2	Y	Y	Y	Y	Y	N	Y	Y	N	Y
T3	Y	Y	Y	Y	Y	Y	Y	N	Y	Y

Note: Y = the worker can be assigned to the workstation; N = the worker cannot be assigned to the workstation

An optimization software program called ILOG CPLEX is employed to solve the problem to optimality. The optimal solution requires seven workers (from the ten available workers) to prevent any workers' daily hazard exposure from exceeding 1. Daily hazard exposures of the seven workers are shown in Table 4. The minimum and maximum daily hazard exposure among workers during the planning period are 0.4418 and 0.9992, respectively. Table 5 shows the daily rotating work schedules for the six-day period.

Table 4: Daily hazard exposures of the seven workers.

	D1	D2	D3	D4	D5	D6
W1	0.9512	0.4418	0.8134		0.9512	0.6276
W3	0.9512	0.5094	0.7654	0.9992		0.9512
W4	0.8134		0.833	0.9512	0.833	0.6472
W5		0.6472	0.8134	0.7654	0.6276	0.6952
W8	0.9708	0.4418	0.9708	0.9708	0.7654	
W9		0.9992	0.5574	0.8134	0.8134	0.6276
W10	0.6952	0.6952		0.9708	0.833	0.833

Table 5: The six-day daily rotating work schedules.

Utilized Worker	D1				D2				D3			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
W1	T2	-	T3	T1	-	T1	-	-	T1	-	T3	T3
W3	-	T1	T2	T3	-	T3	-	T2	T2	T1	-	-
W4	-	T3	T1	T3					-	T2	T2	T3
W5					-	T2	-	T2	T3	T3	T1	-
W8	T2	-	T2	T2	T1	-	-	-	T2	T2	T2	-
W9					T3	T3	T1	T3	T3	T3	T3	-
W10	-	T3	T3	T2	T3	T2	-	T3				
Utilized Worker	**D4**				**D5**				**D6**			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
W1					T1	-	T2	T3	T3	T1	-	-
W3	T3	T3	T3	T1					T3	-	T2	T1
W4	T3	T2	T1	-	T3	T2	T2	-	T2	-	-	T2
W5	-	T1	T2	-	-	T1	-	T3	T2	T3	-	T3
W8	T2	T2	-	T2	T2	-	T1	-				
W9	T1	T3	T3	-	T3	-	T3	T1	-	-	T1	T3
W10	T2	-	T2	T2	T2	T2	T3	-	-	T3	T2	T2

Note: blank cell = day off; - = idle period

5. CONCLUSION

This paper introduces the multi-workday ergonomic workforce scheduling (MW-WSP) with days off. Its objective is to develop a mathematical model to determine the minimum number of workers for job rotation and to generate safe daily rotating work schedules for workers during a given planning period for preventing them from receiving concerned ergonomics hazard beyond a daily permissible limit. Both the worker limitation and workstation operation schedule are considered in this problem. Workers have limited task skill and can be assigned to some tasks. Some workstations do not have to be occupied on a full-day basis. Additionally, some workstations have several tasks to be performed (by several workers). During the given planning period, the workers are required to work for several workdays with some days off. A mixed integer linear programming model is developed to represent MW-WSP. From the given numerical example, daily rotating work schedules are generated for each workday during the planning period for the selected workers. The result also shows that the daily hazard exposure of each worker does not exceed the daily permissible limit.

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