ERGONOMIC WORKFORCE SCHEDULING WITH PRODUCTIVITY AND EMPLOYEE SATISFACTION CONSIDERATION

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Abstract

In this paper, the ergonomic workforce scheduling problem (WSP) is investigated with a combined consideration of productivity and employee satisfaction. The problem is formulated as a mixed integer linear programming problem in which daily hazard exposure is one of the model constraints. Maximizing the total system productivity and maximizing the employee satisfaction among concerned workers are modeled as the problem objectives. Workers are heterogeneous in reference to their work ability, skill levels, preferred tasks, and preferred work partners. An ILOG CPLEX optimization software tool is employed to solve the ergonomic workforce scheduling problem to optimality. The problem is solved as single objective and multi-objective optimization problems. The results show that the resulting work schedules depend largely on the objective of the problem and it is necessary to be specific when developing daily work schedules for the workers.

Keywords: Workforce scheduling, Job satisfaction, Productivity, Optimization

1. INTRODUCTION

Workforce scheduling is a process of constructing work time table for workers while considering different conditions of workers and organization. It is a serious problem encountered in many industries, such as manufacturing, transportation, healthcare, emergency services, and universities. Minimizing total cost and maximizing total productivity (i.e., minimum idle shifts and maximum number of assigned tasks) are among the problem objectives. The workforce scheduling problem (WSP) is bounded by several constraints and involves multi-objective consideration. Complex worker and task requirements make WSP a difficult problem interfaced in real world situations. As an *NP-hard* or *NP-complete* problem (Brucker and Knust, 2006), the number of steps to solve the problem grows exponentially when the problem size increases. Its optimal solution is difficult to find within a reasonable amount of time. Considerable effort has been devoted for more than five decades to develop various solution approaches (e.g., optimization, heuristic, and metaheuristic).

A number of extensions of workforce scheduling have been studied by researchers. Among them is the ergonomic workforce scheduling problem. In industrial workplaces, there are many tasks that expose workers to ergonomics hazards such as lifting heavy objects, doing repetitive work, and working in hazardous environments (e.g., loud noise, high temperature, radiation, and toxic chemicals). Hazard exposure beyond a permissible limit can cause injuries, illness, or even death. Job rotation, being a compromised hazard exposure reduction strategy between cost and effectiveness, is an administrative approach commonly suggested by the U.S. Occupational Safety and Health Administration (OSHA).

The ergonomic consideration in WSP is usually known as cyclic workforce scheduling. Workers are periodically rotated among different tasks in order to alleviate the hazard exposure among a group of workers in a workday or shift-change horizon (Musliu et al., 2002; Mora and Musliu, 2004). Some studies considered rotating workers among work periods within a workday by evaluating the hazard exposures of workers quantitatively (Nanthavanij and Yenradee, 1999; Yaoyuenyong and Nanthavanij, 2003; Yaoyuenyong and Nanthavanij, 2006).

In practice, workforce scheduling involves more than one objective. Multi-objective consideration can be seen in WSP; however, the objectives are usually a combination of some constraint violations (Topaloglu and Seyda, 2006; Valls et al., 2009) or a combination of cost and productivity (Castillo et al., 2009). Productivity and job satisfaction were often studied in the last decade. Jaturanonda and Nanthavanij (2005) investigated person-job fit in competency-based and preference-based employee-job assignment problems. A weighted average of the core, technical, and behavior competencies is used as a measurement index for the competency-based model while the number of satisfied employees and average preference rank are used as indices for the preference-based model. Peters and Zelewski (2007) developed a model for the assignment based on worker competencies and preferences. Both preemptive and non-preemptive goal programming techniques were utilized. The importance weights were derived from an analytic hierarchy process (AHP). Akbari et al., (2012) considered the mixed-skilled WSP. Its objective was to maximize workers' satisfaction with the consideration of workers' availability, productivity, priority preference, seniority level, and number of required workers. Furthermore, workers' fatigue was believed to influence their performance and production output. Unfortunately, the effect of hazard exposure was not studied in detail.

It is believed that workers who are assigned to their preferred tasks and/or work with preferred partners tend to do good work. Happiness in the workplace helps to reduce a turnover rate, resulting in a decrease in human resource management cost. Satisfying employee preferences are found to provide many benefits to both workers and organization. Stolletz (2010) studied hierarchical workforce staffing for check-in systems at the airport. Individual employee preferences were included in their extended model. The preferences were provided in terms of preferred days-off, period of earliest shift-start, and period of latest shift-end. Maenhout and Vanhoucke (2010) presented a hybrid scatter search algorithm for the airline crew rostering problem. The objective was to assign a personalized roster to each crew member to minimize the overall operational costs, ensure impartiality and fairness of crew members, and satisfy crews' preferences for certain roster attributes.

In this research, the ergonomic WSP is investigated with a combined consideration of productivity and employee satisfaction. The problem is formulated with the concerned daily hazard exposure being one of the model constraints. The problem objectives are to maximize the total system productivity and employee satisfaction.

2. MATHEMATICAL MODEL

A mathematical model representing the multi-objective WSP has two objectives. They are:

1. Maximizing total system productivity (P)
2. Maximizing the employee satisfaction (S)

2.1 Assumptions

1. A workday is divided into equal work periods and the worker-task changeovers are allowed only at the end of the work period.
2. In any given work period, a worker can be assigned to perform at most one task.
3. The numbers of workers required to perform different tasks do not have to be equal.
4. The numbers of tasks that the individual workers can perform do not have to be equal.
5. For any given worker, the skill levels when performing different tasks do not have to be equal.
6. For any given worker, task and partner preferences can be identified.
7. The daily permissible limit of hazard exposure is known and is the same for all workers.

2.2 Notation

Parameters:

I, N number of available workers (or size of workforce) for job rotation

J number of tasks to be performed

K number of equal work periods per workday

L daily permissible limit of hazard exposure

h_j amount of hazard exposure per work period of task j

s_{ij} work scores of worker i when performing task j

w_j number of required workers to perform task j

a_{ij} = 1 if worker i can perform task j

= 0 otherwise

pt_{ij} = 1 if worker i chooses task j as his/her preferred task

= 0 otherwise

pp_{in} = 1 if worker *i* chooses worker *n* as his/her preferred partner to perform a task
= 0 otherwise

Decision variables:

x_{ijk} = 1 if worker *i* is assigned to perform task *j* in work period *k*
= 0 otherwise

y_i = 1 if worker *i* is chosen from the group of available workers
= 0 otherwise

UST_k = total number of worker-task pairs with task dissatisfaction in work period *k*

USP_{injk} = 1 if worker *i* is unsatisfied when being assigned to task *j* in work period *k* with worker *n*
= 0 otherwise

$$\text{Maximize} \quad Z_1 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} s_{ij} x_{ijk} \tag{1}$$

$$\text{Minimize} \quad Z_2 = \sum_{k=1}^{K} UST_k + \sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{j=1}^{J}\sum_{k=1}^{K} USP_{injk} \tag{2}$$

subject to

$$\sum_{j=1}^{J}\sum_{k=1}^{K} h_j x_{ijk} \le L \qquad \text{for } \forall\, i \tag{3}$$

$$\sum_{j=1}^{J} x_{ijk} \le 1 \qquad \text{for } \forall\, i, k \tag{4}$$

$$\sum_{i=1}^{I} x_{ijk} = w_j \qquad \text{for } \forall\, j, k \tag{5}$$

$$x_{ijk} \le a_{ij} \qquad \text{for } \forall\, i, j, k \tag{6}$$

$$x_{ijk} \le y_i \qquad \text{for } \forall\, i, j, k \tag{7}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\left(x_{ijk}\right) - \sum_{i=1}^{I}\sum_{j=1}^{J}\left(x_{ijk} \cdot pt_{ij}\right) = UST_k \qquad \text{for } \forall\, k \tag{8}$$

$$\left[\left(x_{ijk} + x_{njk}\right) - 1\right] - pp_{in} \le USP_{injk} \qquad \text{for } \forall\, i, j, k, n \ne i \tag{9}$$

$$x_{ijk}, y_i \in \{0, 1\} \qquad \text{for } \forall\, i, j, k \tag{10}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} s_{ij} x_{ijk} \ge Z_1^* \tag{11}$$

$$\sum_{k=1}^{K} UST_k + \sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{j=1}^{J}\sum_{k=1}^{K} USP_{injk} \le Z_2^* \tag{12}$$

From the above multi-objective model, the ergonomic WSP can be divided into four sub-problems. In the first two sub-problems, the two objectives are solved separately. That is, they are formulated as two single-objective WSPs. The last two sub-problems include both objectives in the problem formulation. However, the two objectives take turn to be solved as a primary goal. Specifically, the four sub-models are formulated as follows:

1. Sub-model P - Objective function (1) and constraints (3) – (10)
2. Sub-model S - Objective function (2) and constraints (3) – (10)
3. Sub-model PTS - Objective function (2) and constraints (3) – (11)
4. Sub-model STP - Objective function (1) and constraints (3) – (10), (12)

Additionally, Z_1^* and Z_2^* are optimal objective values obtained from solving sub-models P and S, respectively.

3. NUMERICAL EXAMPLE

Let us consider a workplace where there are 3 tasks to be performed. A workday is divided into 4 equal work periods (i.e., 2 hours/period). The permissible limit of hazard exposure is assumed to be 1 and is constant for every worker. Table 1 shows the amounts of hazard exposure per work period and numbers of required workers of these tasks.

Table 1: Hazard exposure per work period and number of required workers/task

Task	T1	T2	T3
Hazard exposure per period	0.3957	0.1493	0.3212
Number of required workers	1	3	2

Suppose that there are 10 workers (W1 – W10) who are available for job rotation. Workers are flexible and can perform more than one type of task. However, their skill levels are different. The skill level ranges from a score of 1 to 5. Score 1 represents the lowest skill level and score 5 the highest skill level. The total work score of each worker is the sum of scores from all tasks assigned to him/her within one workday. Logically, the higher the grand total work score, the greater the work system productivity is. Table 2 presents a list of tasks that the workers can perform and the corresponding work scores. A work score of 0 implies that the worker is incapable of performing that task.

Table 2: Work scores of worker-task pairs

Task	Worker									
	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
T1	1	0	2	1	1	0	2	1	2	2
T2	0	1	1	0	2	3	1	3	5	1
T3	3	3	1	3	3	1	4	2	1	3

Lists of preferred tasks and partners are presented in Tables 3 and 4, respectively. Workers can select 2 out of 3 tasks and 6 out of 10 persons for their preferred tasks and partners. The order of the tasks or partners on the list is irrelevant in this example. The employee satisfaction is achieved if a worker is assigned to a task from his preferred task list. If the task is performed by several workers, the partner satisfaction is achieved is the worker is assigned to team up with another worker from his/her preferred partner list.

Table 3: Preferred tasks **Table 4:** Preferred partners

Worker	Tasks			Workers									
	T1	T2	T3	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
W1	✓	-	✓	-	✓	✓	-	✓	-	✓	✓	-	✓
W2	-	✓	✓	✓	-	-	✓	-	✓	✓	-	✓	✓
W3	-	✓	✓	✓	-	-	✓	✓	✓	-	✓	✓	-
W4	✓	-	✓	✓	✓	✓	-	✓	-	-	✓	-	✓
W5	✓	-	✓	-	-	✓	✓	-	✓	✓	✓	-	✓
W6	-	✓	✓	✓	-	✓	✓	-	-	✓	-	✓	✓
W7	✓	-	✓	✓	✓	-	-	✓	✓	-	✓	-	✓
W8	-	✓	✓	✓	-	✓	✓	-	✓	✓	-	✓	-
W9	✓	✓	-	-	✓	✓	✓	-	✓	✓	-	-	✓
W10	✓	-	✓	-	✓	-	✓	✓	-	✓	✓	✓	-

The IBM ILOG CPLEX optimization software program version v.12.1.0 is utilized to solve the multi-objective WSP. An example of optimal daily rotating work schedules (from sub-model PTS) is presented in Table 5.

Readers can see that none of the 10 workers receives daily hazard exposure beyond the daily permissible limit (of 1). The minimum and maximum hazard exposure amounts are 0.3212 (for W2, W4, and W5) and 0.9636 (for W7), respectively. There are several workers who have been assigned to the tasks that they can perform best, resulting in the total work score of 79. For example, W1 is assigned to T3 (work score of 3) instead of being assigned to T1 (work score of 1). The work schedule solution meets all worker and task requirements. All utilized workers are only assigned to the tasks that they can perform. For the tasks that require more than one worker, the correct numbers of workers have also been assigned. For example, task T2 which requires 3 workers is assigned to workers W6, W7, and W9 in every work period. Moreover, the model attempts to match workers according to the preferred partner list. As can be seen, workers W6 and W9 are happy workers since they are assigned to their preferred partners (e.g., worker W6 would like to work with workers W7 and W9, and worker W9 would like to work with workers W6 and W7). Unfortunately, worker W7 would like to work with worker W6 but not with worker W9.

Table 5: *Optimal* work schedule solution of the sub-model PTS

Worker	Work period				Daily hazard exposure amount
	P1	P2	P3	P4	
W1	T3	-	T3	-	0.6424
W2	-	T3	-	-	0.3212
W3	-	T1	T1	-	0.7914
W4	-	T3	-	-	0.3212
W5	-	-	-	T3	0.3212
W6	T2	T2	T2	T2	0.5972
W7	T3		T3	T3	0.9636
W8	T2	T2	T2	T2	0.5972
W9	T2	T2	T2	T2	0.5972
W10	T1	-	-	T1	0.7914

Note: Total work score = 79; Total number of work-task dissatisfaction pairs = 10; Total number of utilized workers = 10 persons

The summary of selected results of four sub-models is presented in Table 6. The result of sub-model P shows that a maximum total work score is 79. The number of worker-task pairs with dissatisfaction is 12 (consisting of 2 task dissatisfactions and 10 partner dissatisfactions). Sub-model S aims to achieve the maximum employee satisfaction. In other words, the minimum number of worker-task pairs with dissatisfaction is expected. This number turns out to be zero. However, the total work score is reduced from 79 to 66. The number of utilized workers is increased from 8 to 9 persons.

Table 6: Summary of selected results from four sub-models

Index	Model			
	P	S	PTS	STP
Total work score	79	66	79	69
Total number of worker-task pairs with dissatisfaction	12	0	10	0
− Task dissatisfaction	2	0	2	0
− Partner dissatisfaction	10	0	8	0
Total number of utilized workers	8	9	10	9
Maximum hazard exposure of a worker	0.9636	0.9636	0.9636	0.9636
Minimum hazard exposure of a worker	0.5972	0.3212	0.3212	0.3212
Calculation time (second)	0.02	0.03	0.05	0.03

Next, let us consider the results from multi-objective optimization. Sub-model PTS adds the optimal objective value from Sub-model P as an extra constraint. Then, it is resolved for the maximum employee satisfaction (or minimum employee dissatisfaction). The results show that while the total work score achieves its maximum, the number of worker-task pairs with dissatisfaction can be further reduced from 12 to 10. From sub-model STP (satisfaction then productivity), the total work score can be increased from 66 to 69 while the number of worker-task pairs with dissatisfaction is kept at minimum (i.e., zero, from sub-model S). None of the workers is exposed to the concerned hazard beyond the daily permissible limit. The maximum daily hazard exposure is 0.9636 from all sub-models. The calculation time is relatively small ranging between 0.02 and 0.05 seconds.

4. CONCLUSION

This research extends a study in workforce scheduling by including a consideration of occupational hazard. It can be called "ergonomic workforce scheduling." Daily hazard exposures of workers are quantitatively determined and kept below a permissible limit while generating daily rotating work schedules. Unlike any previous works, productivity and job satisfaction considerations are concurrently considered. The problem is formulated as a multi-objective workforce scheduling problem with two objectives. Four sub-models can be formed and solved to optimality. They include: (1) maximizing total system productivity (P), (2) maximizing total employee satisfaction (S), (3) maximizing total system productivity then maximizing total employee satisfaction (PTS), and (4) maximizing total employee satisfaction then maximizing total system productivity (STP). The employee satisfaction is measured in terms of worker-task satisfaction and worker-partner satisfaction. Complex worker and task requirements, namely, workers' abilities, work skill levels, preferred tasks, preferred partners, and multiple-worker operation, are considered. The sub-models are formulated as mixed integer linear programing models. The results from a numerical example show that the resulting work schedules depend largely on the objective of the problem and it is necessary to be specific when developing daily rotating work schedules for the workers.

ACKNOWLEDGMENTS

The research study was sponsored by Office of Thailand Research Fund (RGJ-PHD Grant No. PHD/0329/2551) and Sirindhorn International Institute of Technology (SIIT), Thammasat University, Thailand (Faculty Research Budget).

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