Asia-Pacific Journal of Science and Technology

https://www.tci-thaijo.org/index.php/APST/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Safe job rotation scheduling with minimum setup time

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Abstract

Workforce scheduling can be a challenging task especially for heavy industries, where workers are regularly exposed to the excessive indoor noise levels of a harsh working environment. Repetitive exposure to loud noise can lead to hearing loss. In some situations, job rotation is a necessary measure for reducing the daily noise exposure among workers. However, excessive rotation of workers can result in an unnecessary loss of productivity and work flow continuity, due to the time required for machine setup and transferring workers between workstations. This study uses mathematical modeling techniques to design job rotation schedules. The goal is to control and limit the daily noise exposure levels of workers to a safe level of 90 dBA, while minimizing the total setup time caused by job rotation. A case study of a metal container manufacturing plant in Thailand is presented to illustrate the application of the proposed model in a realistic situation. At first, this study determines the optimal workforce schedule with a minimum number of workers required to process tasks. Then, an additional worker is added to the workforce to reduce the need to rotate workers, resulting in less setup time and productivity loss. This repeats until the productivity loss due to setup cannot be reduced further. When labor and productivity loss costs are known, planners are able to select the most desirable job rotation schedule.

Keywords: Noise exposure, Job rotation, Productivity, Occupational safety, Optimization

1. Introduction

Heavy industrial manufacturing processes usually generate high levels of noise from operations such as cutting, punching, blanking, piercing, etc. Long-term exposure to the high levels of noise can affect worker health both psychologically and physiologically. According to Al-Dosky (2014) [1], exposure to a high noise level is the cause of headache, nervousness, stressful, and speech interference among workers. Repetitive exposure to industrial noise can also affect workers in terms of hearing loss and communication disorders [2]. In addition to the effects just described, the health consequence from noise exposure is cumulative and sometimes unnoticeable [3].

There is a hierarchy of measures that can be followed to reduce and control the noise exposure level. The first step is to evaluate the possibility of eliminating the source of hazardous noise. At this step, success in noise control comes from the ability to locate the sources of noise, understand the noise-producing mechanism, and transform them to be quiet. Whenever complete elimination of hazardous noise is impossible, engineering control practices, such as lubrication, calibration, and alignment of machines can be performed to reduce noise to safer levels. Sometimes, machine parts are needed to be redesigned or covered with sound absorption materials. In most cases, it is impossible to eliminate noise in a heavy industry manufacturing process, or even reduce it to safer levels by the use of only engineering controls. In this situation, administrative controls can be considered as an additional measure to further reduce noise exposure. Instead of controlling the sources of noise, administrative controls focus on the allocation of workers to tasks. In general, the effects of noise on workers can be controlled by limiting the duration of time a worker is exposed to loud noises, or limiting the number of exposed workers. Additional training can be provided to promote noise hazard awareness and good practices in preventing hearing loss among workers. Hearing protection can be seen as another simple option for noise exposure control. However, it is the employer's responsibility to provide a safe working environment for workers, and not to put a burden on workers to protect themselves. Besides, the use of personal protective equipment is inefficient in practice due to various reasons. A high percentage of workers in manufacturing still neglect the importance of wearing adequate protective equipment, as surveyed by Bedi (2006) [4].

Job rotation is an administrative control suggested by NIOSH, to be used alongside with engineering controls to bring the daily noise exposure of employees down to a more manageable level [5]. Job rotation is an inexpensive and flexible occupational risk control strategy. The rotation of employees between quiet and noisy operations at certain time intervals helps reduce the accumulated noise exposure load on one particular group of workers. A properly designed job rotation schedule can even promote job satisfaction [6] and motivation [7] among workers. The use of job rotation for industrial noise exposure control does not appear to have received much research attention, recently. Job rotation has been more commonly explored in the context of ergonomic risk control, lately. For instance, the effects of job rotation schedule on muscle fatigue [8] and muscle disorders [9] have been recently investigated. A designing approach for job rotation schedules that balance and reduce ergonomic risk has been developed in a number of previous studies [10-13].

To date, there are few studies that aim to design job rotation schedules for industrial noise exposure control. Tharmmaphornphilas et al. (2003) [14] used a mathematical modeling approach to design job rotation schedules that minimize the maximum daily noise exposure among workers. Tharmmaphornphilas and Norman (2004) [15] extended their previous model to investigate the proper length of the rotation interval that can help to reduce worker stress and the potential for worker injuries. Kullpattaranirun and Nanthavanij (2005) [16] introduced the problem of noise hazard prevention in a more complex scenario, with the consideration of job assignment restrictions. They used both conventional and heuristic genetic algorithm for problem solving. Yaoyuenyong and Nanthavanij (2006) [17] pointed out the importance of keeping the number of workers exposed to noise to a minimum. They proposed a hybrid procedure to determine the rotation schedule that uses the lowest number of workers. The job rotation models developed by Nanthavanij and his research team also appeared in their subsequent works, which involve the development of a budget-based noise control decision support system [18] and budget-based hazard prevention solution [19]. The cost aspect is taken into accounted in these two-previous works. Yaoyuenyong and Nanthavanij (2008) [20] also resumed their study in noise exposure reduction using job rotation, but this time, in the context of both single-limit and variable-limit occupational hazards. The consideration of both types of occupational hazards in job rotation schedule design is also addressed in the previous study by Aryanezhad et al. (2009) [21]. They proposed a multi-objective linear programming model that aims to reduce both noise exposure and low back injuries. Thereafter, researchers began to explore and understand the impact that job rotation has on productivity. Deljoo et al. (2009) [22] extended the previous model by Aryanezhad et al. (2009) [21] to be a skill-based job rotation scheduling model. Relationships between job tasks and skill utilization, as well as the idleness among workers, are considered. Another attempt to incorporate the productivity aspect into job rotation scheduling for noise exposure control was made by Nanthavanij et al. (2010) [23], where the productivity is measured in terms of worker-task competency scores. In their work, a heuristic procedure is used to schedule the minimum number of workers to perform a set of tasks, such that the noise exposure of workers does not exceed the daily permissible limit, and the productivity is maximized. The consideration of noise exposure impact together with labor skill factors and productivity in these previous studies makes a job rotation approach more practical for implementation. To this end, future research for safe job-rotation schedules will include issues of productivity.

While the impact of job rotation on productivity has been being studied by researchers, the investigation of the impact of job rotation on productivity loss cannot be found in the literature. Despite the ability of job rotation to control noise exposure, excessive rotation frequency can result in an unnecessary loss of productivity and continuity in work flow. This is because rotating workers between jobs requires additional setup time, as well as the time for workers to relocate and adjust into new working conditions. A loss of production time, therefore, results in productivity loss. The lack of setup time consideration makes job rotation less practical when dealing with systems with significant process setup time. The main contribution of this research is the development of safe job-rotation scheduling models that consider setup time and the corresponding productivity loss. This research proposes job rotation scheduling models to keep the daily noise exposure of all workers below the limit value of 90 dBA, while maintaining the productivity loss due to setup to a minimum. Throughout this paper, the proposed models are called the safe job-rotation scheduling model. The details of the model are given in the next section of the paper. A case study of metal container manufacturing process is presented.

2. Model formulation

In this section, two models are formulated as a shift-scheduling problem. The first model (Model I) is used to determine the optimal workforce schedule with minimum number of workers required to process tasks, under a constraint that limited the maximum daily noise exposure level of each worker. According to OSHA, the permissible average noise exposure over an 8-hour period is 90 dBA [24].

Based on the locations and noise level of workstations, the noise exposure level normalized to an 8-hour worker day (noise dose, *D*) and the time weighted average sound pressure level (*TWA-SPL*) for an 8-hr working period can be calculated using the following equations.

$$D = \sum_{i=1}^{n} \frac{C_i}{T_i} \tag{1}$$

where C_i is the actual exposure time under a certain SPL, T_i is the allowable exposure time under a certain SPL, and *n* is the total number of shifts of exposure during the total exposure time.

$$T = \frac{8}{2^{(L-90)/5}} \tag{2}$$

where *L* is the reference exposure duration under a certain level of SPL

$$TWA\ SPL = 16.61\log(D) + 90 \tag{3}$$

Then, the minimum number of workers, required to create safe job-rotation schedules determined by the first model, is introduced as the initial workforce size of the second model (Model II). The problem objective of the second model is to minimize the productivity loss due to setup. An additional worker is assigned to the workforce to reduce the need to rotate workers and productivity loss. An additional worker is added until the overall setup time cannot be reduced further.

2.1 Assumptions

The main assumptions used in developing the models are the following:
(1) Each worker can perform all tasks, but can be assigned to perform only one task during each shift.
(2) Each task requires a specific number of workers during each shift.
(3) Workers can relocate to perform a new task only at the end of each 4-hour shift.
(4) There are two shifts in one day. Workers can work up to two shifts per day
(5) Whenever a worker is assigned to perform a task at a new workstation, setup time is required.
(6) The time for workers to move from one workstation to another is neglected.

2.2 Mathematical model

2.2.1 Model I: Safe scheduling model with minimum number of workers

The notation used to formulate the model is defined here.

Indices
i Number of workers ($i = 1, \ldots, n$)
j Number of work stations ($j = 1, \ldots, m$)
t Number of periods ($t = 1, \ldots, p$)

Decision Variables
Y_i 1 when worker *i* is assigned to perform any task
0 otherwise
X_{ijt} 1 when worker *i* is assigned to perform task *j* during shift *k*
0 otherwise

Parameters
D_{jt} Noise dose of station *j* at period *t*
L_{jt} Sound pressure level of station *j* at period *t*
M_{jt} Number of workers required for station *j* at period *t*
S_{ij} Setup time of worker *i* at station *j*
T_{jt} Maximum allowable exposure duration given average SPL (L_{jt}) of station *j* at period *t*

The objective function of Model I can be expressed as,

$$\text{Minimize } \sum_{i=1}^{n} Y_i$$

Subject to

$$\sum_{j=1}^{m} \sum_{t=1}^{p} X_{ijt} D_{jt} \le 1 \qquad \forall\, i \tag{4}$$

$$\sum_{j=1}^{m} X_{ijt} \leq 1 \qquad \forall\, i\,, t \tag{5}$$

$$\sum_{i=1}^{n} X_{ijt} = M_{jt} \qquad \forall\, i \tag{6}$$

$$\sum_{j=1}^{m} \sum_{t=1}^{p} X_{ijt} \leq 2 \qquad \forall\, i \tag{7}$$

$$\sum_{j=1}^{m} \sum_{t=1}^{p} X_{ijt} - Y_i \times BigM \leq 0 \ \ \forall\, i \tag{8}$$

The objective function is to minimize the number of workers involved in a production process, while keeping the accumulated noise dose lower than 1 (equation (4)). Equation (5) indicates that a worker can perform one job at a time. Equation (6) expresses that the number of workers assigned to each station must meet the task requirements. Equation (7) states that any worker can perform at most 2 shifts in a day. Finally, equation (8) ensures that worker *i* is included in the job-rotation workforce (Y_i = 1) when the worker is assigned to any shift ($\sum_{j=1}^{m} \sum_{t=1}^{p} X_{ijt}$> 0).

2.2.2 Model II: Safe scheduling model with minimum setup time

Additional notation used to formulate the model is defined here.

Decision Variables

B_{ij} 1 when worker *i* is assigned to rotate to process *j*
0 otherwise

Parameters

Z_{ij} Changes in a working process during the day = X_{ij2}-X_{ij1}

The objective function of Model II can be expressed as,

$$\text{Minimize } \sum_{i=1}^{n} \sum_{j=1}^{m} B_{ij} S_{ij}$$

Subject to constraints (1-5) and

$$Z_{ij} \leq B_{ij} \times BigM \qquad \forall\, i\,, j \tag{9}$$

The objective function is to minimize the total setup time caused by job rotation. In addition to equations (4-8), equation (9) is used to determine the value of B_{ij} required to create a safe job-rotation schedule. If a workstation is operated by different workers during two shifts (Z_{ij} = 1), the value of B_{ij} is set to 1.

In this study, Model I and II are used in tandem to determine the appropriate number of workers. First, Model I am applied to achieve a safe job-rotation schedule, with minimum number of workers. The minimum required number of workers is calculated by the summation of Y_i. The safe job rotation plans obtained via Model I is rescheduled using Model II, to minimize the incurred setup time. At the point, with the use of Model II, an additional worker is repeatedly added to the workforce to reduce the need to rotate workers. The problem is resolved until it reaches the point where the setup time cannot be reduced any further.

3. Case Study

A case study of a metal bucket manufacturing plant in Samutprakarn, Thailand, is presented here in order to gain an intuitive grasp of how to design job rotation schedules using our proposed model. The manufacturing plant case study serves as an example of small manufacturing enterprises, the sector that employs the largest proportion of production workers in Thailand.

As shown in Figure 1, the production line, composed of a series of metal manufacturing processes including cutting, rolling, welding, and punching, is located within the manufacturing plant. During 2 shifts of 4 hours each per day, the processes transform metal sheet into 15-liter rectangular and circular buckets. Each process comprises a single or multiple workstations. During each shift, each workstation needs exactly one worker to operate. The level of noise in each process area inside the plant is measured using a Datalogger model DT-8852 (IEC-61672-1 Class II, ANSI S1.4 type 2) and shown in Figure 1.

The noise exposure levels of 15 workers are shown in Table 1. At present, all workers remain at the same workstation, repeatedly performing the same task throughout two shifts. This results in the exposure to noise levels above 90 dBA over an 8-hour period for some workers.

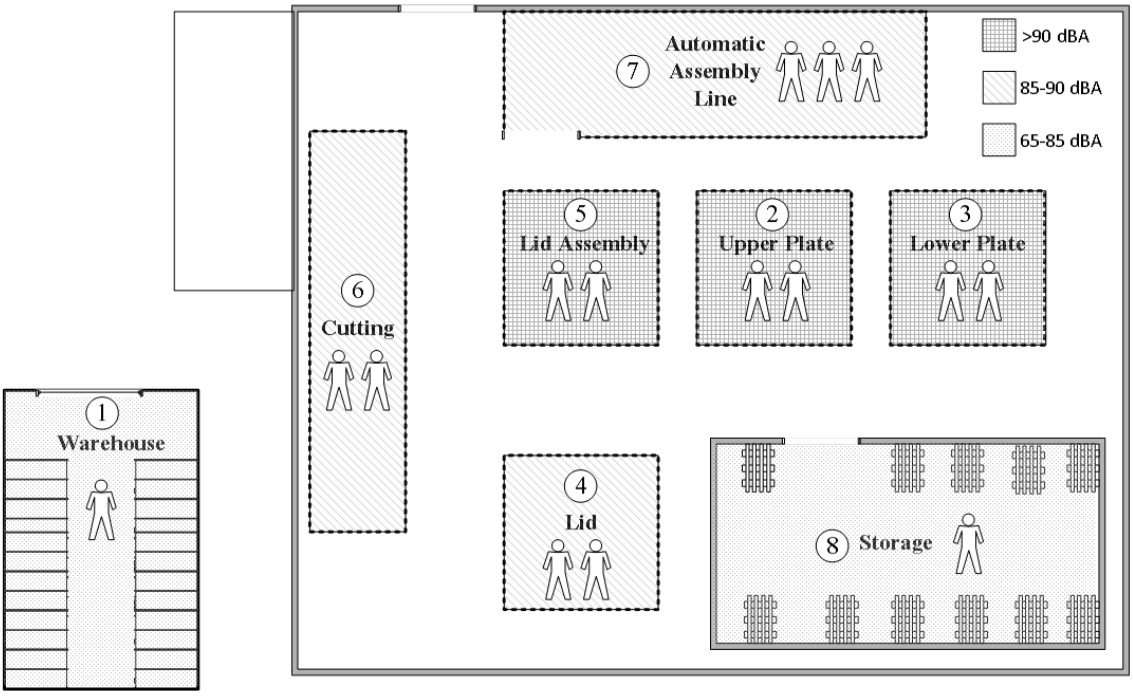

Figure 1 Metal bucket manufacturing plant layout

Table 1 Noise exposure level of workers under a workforce schedule without job rotation

Worker	Workstation	Noisedose	TWA SPL(dBA)
1	1	0.02	62.9
2	2	1.66	93.7
3	2	1.66	93.7
4	3	1.23	91.5
5	3	1.23	91.5
6	4	0.81	88.5
7	4	0.81	88.5
8	5	1.42	92.5
9	5	1.42	92.5
10	6	0.51	85.1
11	6	0.51	85.1
12	7	0.81	88.5
13	7	0.81	88.5
14	7	0.81	88.5
15	8	0.07	70.5

To estimate the loss in terms of productivity, the setup times required for a machine at each process, to switch from one worker to another, are collected and summarized in Table 2.

Table 2 The setup time required for workers

Worker	Set up time (minutes)					
	Upper Plate	*Lower Plate*	*Lid*	*Lid Assembly*	*Cutting*	*Automatic Assembly Line*
1	2.32	3.65	5.04	7.23	2.04	5.78
2	4.66	2.33	1.98	5.64	2.87	7.79
3	3.94	4.87	3.45	6.54	5.06	5.69
4	2.25	5.56	4.32	5.25	4.65	6.74
5	2.04	6.02	5.65	4.79	3.78	9.85
6	5.03	2.89	1.78	7.02	4.25	8.63
7	4.55	3.48	2.33	6.56	5.21	7.24
8	2.78	4.59	5.02	4.87	2.65	6.23
9	3.65	5.64	6.14	5.68	3.02	8.02
10	4.89	2.47	5.18	4.75	4.30	7.32
11	5.01	3.68	2.60	6.24	2.47	8.14
12	2.79	4.97	3.74	4.68	5.02	5.98
13	3.54	6.05	4.23	7.14	3.74	6.32
14	3.68	5.26	2.58	6.84	4.26	7.41
15	4.10	4.65	3.89	5.21	3.36	9.13
16	2.37	3.54	2.68	4.26	4.15	6.87
17	3.64	6.12	5.21	6.04	2.54	5.21
18	5.23	4.10	3.48	4.63	3.12	7.87
19	2.03	2.41	6.10	4.87	1.87	5.2
20	3.10	4.74	5.20	6.57	2.41	5.36
21	4.22	5.01	4.96	5.81	2.20	5.94
22	3.45	4.17	5.23	6.16	3.22	7.91
23	3.41	5.24	4.86	5.49	2.88	6.78

*No setup time required for warehouse and storage

Table 3 Noise exposure level of workers under a workforce schedule with job rotation

Worker	Workstation		Noise Dose	TWA SPL (dBA)
	Shift 1	*Shift 2*		
1	7	4	0.81	88.5
2	8	5	0.69	87.3
3	6	5	0.95	89.6
4	6	3	0.86	88.9
5	3	-	0.66	87.0
6	5	8	0.79	88.3
7	-	2	1.00	90.0
8	2	-	0.66	87.0
9	3	6	0.88	89.1
10	-	2	1.00	90.0
11	1	3	0.58	86.1
12	4	7	0.81	88.5
13	7	7	0.81	88.5
14	5	6	0.98	89.8
15	2	1	0.68	87.2
16	4	7	0.81	88.5
17	7	4	0.81	88.5

4. Result

In this case study, job rotation is intended to be a temporary method of limiting the daily noise exposure of all workers to below 90 dBA. The proposed models are used to design a safe job-rotation schedule. At first, Model I is used to determine a safe job-rotation schedule with minimum number of workers. Opensolver version 2.7.1 is used as the solver. The minimum number of workers required to create a safe job-rotation schedule is 17. The details of work schedule and the noise exposure levels of all workers are shown in Table 3.

According to the result, the 8-hr TWA SPL values of all workers are below 90 dBA. The number of times a worker is relocated to a new workstation is as much as 14 times. Only one worker remains at the same workstation throughout 2 shifts. Each time a workstation is operated by a new worker, there is productivity loss due to the time required for setup.

The total setup time of our first safe job-rotation schedule due to 14 times of rotation is about 61.24 minutes. Assuming that job rotation has no effect on the cycle time of each workstation. In order to develop alternate safe job-rotation schedules with less setup time and productivity loss, the next step of the iteration is to reevaluate the existing 17-worker job-rotation schedule using Model II. The number of workers is fixed at 17 while determining a safe job-rotation schedule under the setup time minimization objective. Under this scenario, the overall setup time reduces down to just 22.54 minutes. Then, an additional worker is added into the workforce to further reduce the setup time. Model II is used to determine a safe job-rotation schedule, again. This continues until the setup time cannot be reduced further. When the number of workers is 19, the setup time is 17.76 minutes and cannot be reduced further. The details of job-rotation schedules determined by Model II are shown in Table 4. When labor and productivity loss costs are known, planners are able to choose the most appropriate safe job-rotation schedule.

It is worth mentioning that Opensolver is able to reach each of the obtained optimal solutions in less than one minute, for our case study. The computation time is expected to be extended in relation to the increased number of shifts and workers. When the computation time is excessively large, heuristic approach can be used to shorten the computation time, as shown in the previous work by Asawarungsaengkul and Nanthavanij (2008) [25].

5. Conclusion and Discussion

Job rotation can be an effective short-term noise exposure control measure. An excessive noise exposure burden on a particular group of workers can be reduced to a safe level. However, as illustrated in this study, there are two main shortcomings of job rotation, including the need for more workers and setup time. The latter results in productivity loss, especially when the process under consideration tends to have long setup time. Neglecting such loss can lead to inadequate production capacity.

The mathematical scheduling algorithms proposed in this study consider two objective functions in sequence. The first objective function aims to minimize the number of workers. Once the minimum required number of workers is known, the second objective function is applied to reschedule this group of workers under setup time minimization objective. After that, an additional worker is repeatedly added to the workforce in order to reduce setup time. The noise exposure level of workers and total setup time are evaluated at each workforce size.

Based on the case study analysis results, the proposed models can be used to design safe job-rotation schedules, while taking setup times into consideration. Without job rotation, there are 6 out of 15 workers, whose noise exposure level exceeds an 8-hour TWA of 90 dBA. When using the safe job-rotation schedule determined by Model I, the required minimum number of workers is 17. The slight increase in the workforce is necessary to keep all the workers from being exposed to excessive noise levels. However, the rotation requires 61.24 minutes of setup time, which is equivalent to about 12.8% in production loss. By using Model II, the setup time can be significantly reduced to 22.54 minutes, given that the workforce size remains at 17 workers. The small amount of setup time can be reduced further by introducing additional workers, until the number of workers reaches 19. When the acceptable level of productivity loss due to job rotation is known, decision makers can choose the most appropriate scheduling plan based on the overall labor and productivity loss costs.

Table 4 Safe job-rotation schedules from Model II

Worker	17 Workers			18 Workers			19 Workers		
	Shift 1	*Shift 2*	*TWA SPL (dBA)*	*Shift 1*	*Shift 2*	*TWA SPL (dBA)*	*Shift 1*	*Shift 2*	*TWA SPL (dBA)*
1	5	6	89.8	2	6	89.1	5	-	88.0
2	6	3	88.9	6	3	88.9	1	3	86.1
3	4	4	88.5	3	-	87.0	5	-	88.0
4	-	2	90.0	-	2	90.0	3	-	87.0
5	-	2	90.0	-	2	90.0	-	2	90.0
6	7	7	88.5	5	-	88.0	2	-	87.0
7	4	4	88.5	5	1	88.1	3	1	87.2
8	5	1	88.1	4	4	88.5	6	6	851
9	3	8	87.4	3	8	87.4	7	7	88.5
10	1	3	86.1	1	3	86.1	-	3	86.0
11	3	6	89.1	6	6	85.1	2	8	87.4
12	6	5	89.6	7	7	88.5	6	6	85.1
13	2	-	87.0	7	7	88.5	7	7	88.5
14	2	-	87.0	4	4	88.5	4	4	88.5
15	7	7	88.5	2	-	87.0	4	4	88.5
16	8	5	87.3	8	5	87.3	8	5	87.3
17	7	7	88.5	7	7	88.5	7	7	88.5
18	-	-	-	5	-	87.0	-	5	87.0
19	-	-	-	-	-	-	-	2	90.0
Setup time (min)	22.54			20.02			17.76		

For future research, job rotation studies still need to move beyond just safety control to address the issue of productivity in all aspects. The proposed safe job-rotation scheduling models can be extended to include additional constraints related to shift availability and skill limitations of workers. Travel time between workstations can be considered as well.

6. Acknowledgement

The authors gratefully acknowledge the financial support provided by Thammasat University Research Fund under the TU Research Scholar, Contract No. 2/21/2560. The authors also would like to thank Suebsak Nanthavanij, PhD, for his valuable suggestion about good practices for noise exposure control.

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