Designing Safe Job Rotation Schedules with Minimum Productivity Loss

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Repetitive exposure to industrial noise is the common cause of hearing loss and several other persistent and unnoticeable harmful health effects. In certain situation, 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 develops an optimization model of a job-rotation scheduling problem with a productivity loss minimization objective. The design of safe workforce schedules are made based on a numerical example. The analysis results show that the proposed model can be used to control and limit the daily noise exposure levels of workers to a safe level of 90 dBA, while maintaining the overall productivity loss due to setup time required by job rotation at the lowest possible level.

Keywords: Noise exposure, job rotation, productivity, occupational safety, optimization

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I. 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), 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 (Ologe et al, 2008). In addition to the effects just described, the health consequence from noise exposure is cumulative and sometimes unnoticeable (Anjorin et al., 2015).

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. 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. Hearing protection can be seen as another simple option for noise exposure control. However, 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).

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 (NIOSH, 1996). 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 (Rissén, 2002) and motivation (Kaymaz, 2010) 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 (Horton et al., 2015) and muscle disorders (Comper and Padula, 2014) 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 (Diego-Mas et al., 2009; Asensio-Cuesta, 2012; Otto and Scholl, 2013; Mossa et al., 2016).

To date, there are few studies that aim to design job rotation schedules for industrial noise exposure control. Tharmmaphornphilas et al. (2003) used a mathematical modeling approach to design job rotation schedules that minimize the maximum daily noise exposure among workers. Tharmmaphornphilas and Norman (2004) 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) 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) 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. Yaoyuenyong and Nanthavanij (2008) 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). 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) extended the previous model by Aryanezhad et al. (2009) 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), 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. 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.

II. 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. Then, the minimum number of workers, required to create safe job-rotation schedules determined by Model I, is introduced as the initial workforce size of the second model (Model II). The problem objective of Model II 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) There are multiple workstations in a manufacturing plant, each of which requires a specific number of workers to operate throughout the shift.
(2) Workers can be assigned to perform a task at any workstation, but must remain at that workstation until the 4-hour shift is over.
(3) There are two 4-hour shifts in one day. Workers can work up to two shifts per day
(4) Whenever a worker is assigned to perform a task at a new workstation, setup time is required.
(5) The time for workers to move from one workstation to another is neglected.
(6) Only setup time incurred when workers are rotate from one task to another at the end of the first 4-hour shift is considered as the source of unnecessary productivity loss.

2.2. Mathematical Model

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,…,n)
j	Number of workstations (j = 1,…,m)
t	Number of shifts in a day (t = 1 or 2)

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 at workstation j during shift t 0 otherwise

Parameters

D_{jt}	Noise dose of workstation j during shift t
L_{jt}	Sound pressure level of workstation j during shift t
M_{jt}	Number of workers required at workstation j during shift t
N_i	Number of shifts worked by worker i
S_{ij}	Setup time of worker i for task at workstation j

The objective function of Model I can be expressed as,

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

Subject to

$$\sum_{j=1}^{m}\sum_{t=1}^{2} X_{ijt} D_{jt} \le 1 \qquad \forall\ i \qquad (1)$$

$$\sum_{j=1}^{m} X_{ijt} \le 1 \qquad \forall\, i\,, t \qquad (2)$$

$$\sum_{i=1}^{n} X_{ijt} = M_{jt} \qquad \forall\, i \qquad (3)$$

$$\sum_{J=1}^{m}\sum_{t=1}^{p} X_{ijt} \le 2 \qquad \forall\, i \qquad (4)$$

$$N_i - Y_i \times BigM \le 0 \qquad \forall\, i \qquad (5)$$

The objective function is to minimize the number of workers involved in a production process, while keeping the accumulated noise dose lower than 1 (1). Constraint (2) indicates that a worker can perform one job at a time. Constraint (3) ensures that each workstation is operated by the required number of workers. Constraint (4) states that any worker can perform at most 2 shifts in a day. Finally, constraint (5) ensures that worker i is included in the job-rotation workforce (Y_i = 1) when the worker is assigned to any shift ($N_i > 0$).

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 workstation j 0 otherwise

Parameters

Z_{ij}	$= X_{ij2} - X_{ij1}$ 1 when a workstation is operated by different workers during two shifts 0 otherwise

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

$$Z_{ij} \le B_{ij} \times \quad BigM \qquad \forall\, i\,, j \qquad (6)$$

The objective function is to minimize the total setup time caused by job rotation. In addition to constraints (1-5), constraint (6) 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.

III. CASE STUDY

The proposed model is applied to a small-sized metal container manufacturing plant, which is located in Samutprakarn, Thailand. As shown in Fig. 1, the manufacturing process of metal containers comprises 8 workstations, which are operated in sequence. Each workstation, except storage and warehouse, contains multiple numbers of machines. Each machine requires a worker to operate during each shift, as shown in Fig. 1.

The tasks performed by workers are limited to operate and monitor machines. They do not require repetitive or considerable physical effort from workers. At the current stage, without job rotation, all workers remain at their workstations throughout the day. Workers, with the same task assignment, stay at the same workstations and are exposed to the same noise levels. The average values of noise levels at all workstations are collected, using the digital sound level meter Datalogger model DT-8852 (IEC-61672-1 Class II, ANSI S1.4 type 2), and summarized in Table 1.

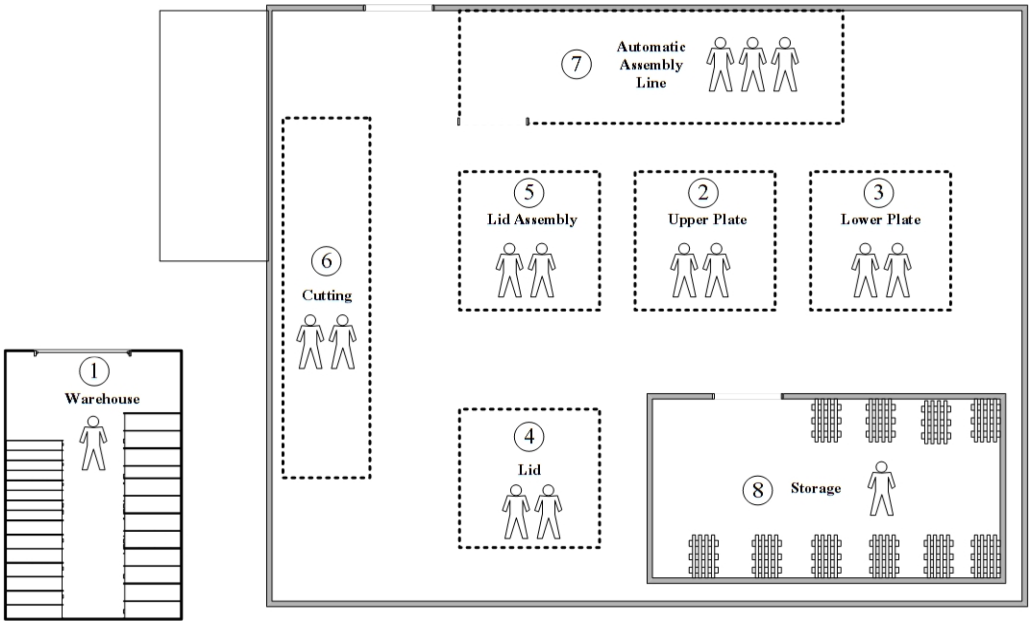

FIGURE 1. METAL BUCKET MANUFACTURING PLANT LAYOUT.

TABLE 1. AVERAGE NOISE LEVEL OF EACH WORKSTATION.

dBA / Time	Ware-house	Upper Plate	Lower Plate	Lid	Lid Assembly	Cutting	Automatic Assembly Line	Storage
8.00-12.00	60	92	92	89	93	86	89	70
13.00-17.00	65	95	91	88	92	84	88	71

TABLE 2. NOISE EXPOSURE LEVEL OF WORKERS UNDER A WORKFORCE SCHEDULE WITHOUT JOB ROTATION.

Worker i	Work-station j	Noise dose	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

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.

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

where C_i is the actual exposure time under a certain SPL, T_i is the allowable exposure time for worker i under a certain sound pressure level, and n is the total number of shifts of exposure during the total exposure time. T_i can be calculated using the following formula.

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

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

$$TWA\ SPL = 16.61 \log(D) + 90$$

The noise doses of 15 workers are shown in Table 2. At present, all workers remain at the same workstation, repeatedly performing the same task throughout two shifts. This results in a noise dose of above 1.00 and TWA SPL of above 90 dBA over an 8-hour period for some workers. According to OSHA, the permissible average noise exposure over an 8-hour period is 90 dBA (OSHA).

To account for the setup time and productivity loss incurred by rotating workers, the amount of setup times required for workers to resume the operation of a machine at new workstations is collected, as shown in Table 3. It must be noted that there is no setup time required for the operation of warehouse and storage.

IV. 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 1 is used to determine the safe job-rotation schedule with minimum number of workers. 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 4.

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 set up. To estimate the loss in terms of productivity.

The total setup time of our first safe job-rotation schedule due to 14 times of rotation is about 61.24 minutes and 3.602 minutes in average.In order to come up with alternate safe job-rotation schedules with less setup time, the next step of the iteration is to reevaluate the existing 17-worker job-rotation schedule using Model 2. 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 2 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 total setup time is 17.76 minutes and cannot be reduced further. The details of job-rotation schedules determined by Model 2 are shown in Table 5.

To explore further setup-time reduction opportunity, an additional worker is repeatedly added to the workforce. The productivity loss in terms of setup time is evaluated at each increment of workforce size. When the number of workers reaches

19, the setup time is 17.76 minutes and cannot be reduced further by employing more workers. When the information on labor and productivity loss costs are available, decision makers can select the most appropriate safe job-rotation schedule.

TABLE 3. THE SETUP TIME REQUIRED FOR EACH GROUP OF WORKERS.

Worker i	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

TABLE 4. NOISE EXPOSURE LEVEL OF WORKERS UNDER A WORKFORCE SCHEDULE WITH JOB ROTATION.

Worker i	Work-station j Shift 1	Work-station j Shift 2	Noise Dose	TWA SPL (dBA)
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

TABLE 5. SAFE JOB-ROTATION SCHEDULES FROM MODEL 2.

Worker i	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		

V. 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, more than one third of the original workforce of 15 workers is exposed to noise levels above the current threshold limit of 90 dBA. When job rotation is implemented, 2 more workers are needed to share and control the noise burden on every worker to be below 90 dBA over an 8-hour exposure period. The use of job rotation also requires total 61.24 minutes of setup time or 3.602 minutes on average per person. Each minute of the setup period is considered as the source of productivity loss, as the workers do not produce any throughput. By using Model II, the total setup time is significantly reduced to 17.76 minutes, and can be reduced further by adding more workers to the workforce. 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 setup time 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.

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. The effects of job rotation on the quality of the manufactured product can be considered as well.

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