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Applying Mathematical Modeling to Create Job Rotation Schedules for Minimizing Occupational Noise Exposure

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This research developed worker schedules by using administrative controls and a computer programming model to reduce the likelihood of worker hearing loss. By rotating the workers through different jobs during the day it was possible to reduce their exposure to hazardous noise levels. Computer simulations were made based on data collected in a real setting. Worker schedules currently used at the site are compared with proposed worker schedules from the computer simulations. For the worker assignment plans found by the computer model, the authors calculate a significant decrease in time-weighted average (TWA) sound level exposure. The maximum daily dose that any worker is exposed to is reduced by 58.8%, and the maximum TWA value for the workers is reduced by 3.8 dB from the current schedule.
Keywords: hearing loss, job rotation, mathematical modeling, noise exposure

Noise induced hearing loss exacts both an economic and personal toll in U.S. industries. Based on their review of job-related illness data from the Bureau of Labor Statistics, Leigh and Miller[1] found that hearing loss (along with carpal tunnel syndrome) accounted for more lost days than any other occupational illness and was associated with more than 300 occupations. In their review of worker's compensation claims in Washington State, Daniell et al.[2] discovered that annual disability settlements for hearing related problems approach $22.8 million dollars. From a human cost perspective, occupational noise exposure has been associated with social and psychological difficulties for its victims. Based on interviews conducted with 40 metalworkers suffering hearing loss, Hetu et al.[3] identified such difficulties as (1) anxiety and stress due to listening and communication problems, (2) perceived isolation in groups, and (3) negative self-image. These social/psychological changes can also negatively affect a victim's interaction with family members.[4] Hallberg[4] interviewed wives whose husbands suffered noise induced hearing loss. A summary of the wives' responses indicated that the husband's hearing loss was often the cause of misunderstandings and irritation within the family. These negative psychological and social consequences can also discourage worker reports of symptoms associated with occupational hearing loss. Based on focus group interviews of industrial workers conducted by Hetu et al.,[5] the fear of being socially stigmatized was a powerful incentive not to report symptoms of noise induced hearing loss. This reluctance to report symptoms can increase the severity of hearing loss over time and impair the effectiveness of company-sponsored hearing conservation programs. In addition, occupational noise exposure can increase worker fatigue experienced during shift work.[6] According to Neibel and Freivalds[7] intermittent broadband noise can also lead to decreases in productivity and increases in employee fatigue due to annoyance and distraction.

Noise induced hearing loss is prevalent in the wood processing industry. However, the majority of research in this area has focused on the occupational risk factors associated with forestry workers and logging operations.[8–11] These studies, in turn, concentrated primarily on occupational vibration exposure/white finger diseases, giving very little attention to noise induced hearing loss. This oversight is an important one, given that the National Institute for Occupational Safety and Health (NIOSH)[12] has estimated

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that approximately 41.3% of workers involved in lumber and wood product production are exposed to noise levels at or above 85 dBA on a daily basis. A NIOSH Health Hazard Evaluation[13] of two sawmill facilities provides support for this conclusion. The results of this investigation indicated that 73% of the surveyed sawmill operations had noise levels exceeding the NIOSH recommended noise exposure limit. In addition, 72.5% of sawmill employees demonstrated varying degrees of hearing loss, based on audiometric testing.

NIOSH[12] has identified engineering and administrative controls of noise exposure to be necessary components of a comprehensive hearing loss prevention program. Although engineering controls (i.e., physical changes to the workplace) are considered to be the primary means of safety intervention, administrative controls (changes in policy or procedure) can be used to supplement the physical changes. In terms of hearing loss, NIOSH[14] has suggested that job rotation scheduling (i.e., having workers perform different jobs throughout the workday) can be used as an administrative control to reduce daily noise exposure. In other research Paul et al.[15] demonstrated that job rotation could reduce the physical workload placed on refuse collectors. It should be noted, however, that this study was limited because changes in the workers' exposure to occupational noise was not taken into consideration. The details concerning how job rotation schedules should be developed to limit noise occupational exposure remain relatively unexplored by current safety research.

Thus, reducing occupational noise exposure for various sawmill activities is of major importance to public health. The methodologies presented in this research develop job rotation schedules that limit the daily noise exposure by sawmill workers. These methodologies could also be used in other settings where noise exposure is a significant concern.

The Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor[16] and NIOSH[12] have determined threshold limit values for noise pressure levels that represent conditions that workers may be legally exposed to repeatedly. These standard are used to evaluate the time-weighted average (TWA) of the job rotation schedules that are investigated.

PROBLEM SETTING

The specific results presented in this study are based on noise and ergonomic evaluations of a sawmill operation at a cabinet manufacturer located in the southeastern United States. The noise evaluation consisted of area monitoring of 11 workstations within the sawmill. The sawmill itself was only a part of the total cabinetmaking operation at this plant. Raw timber from the yard outside the sawmill was debarked and sent into the mill. The sawmill operation involved the production of lumber from these trees, and the finished boards were sent to a storage building and eventually used as raw material for the cabinet-production portion of the facility. Specifically, the sawmill itself was responsible for the sawing, edging, trimming, and grading of these boards. Nine operations comprised the sawmill; these are presented in Figure 1. Note that there were 11 workstations because two of the operations require two workers.

The first task, the head saw, involves cutting the debarked trees into small boards and large, square canes. The head saw tailor then sorts these boards and canes (and any scrap pieces of wood), sending the boards and scrap to the edger and chipper, respectively, and sending the canes to the gang saw. The gang saw cuts the canes into smaller boards and sends them to the descrambler and

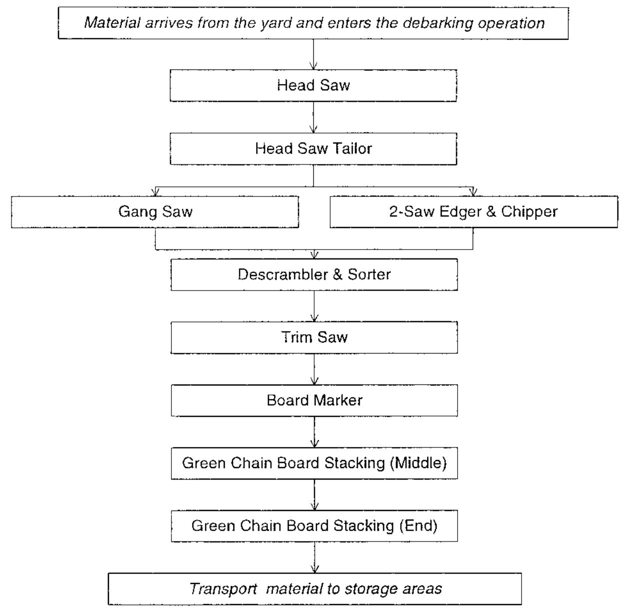

FIGURE 1. Sawmill flow chart

sorter while the edger trims the edges of its boards, also sending them to the descrambler and sorter. The descrambler and sorter arranges the boards onto a conveyor that takes them to the trim saw. The trim saw trims the ends of the boards and releases them to the green chain. There, the boards are graded and marked by the board marker, and the board stackers at the end of the green chain load the boards onto carts to be taken out of the sawmill. Operators generally work four 10-hour days (Monday–Thursday), and occasionally an 8-hour day on Friday.

METHODOLOGY

Data Collection

The first step in the occupational noise evaluation was to perform area noise surveys to measure noise levels in terms of the A-weighted sound level. The testing device for the noise survey was a high quality Bruel & Kjaer (Naerum, Denmark) 2230 Level 1 SLM. The sound level meter was calibrated at the start of the sampling days and rechecked again at the end of each day. Noise samples were taken in the morning and afternoon at each job position, with roughly 30 min of data collection per job location. Data collection at each job position appeared to represent a typical work load situation.

The sound pressure level (SPL) readings per job position are listed in Table I. The values are in units of decibels and are morning and afternoon logarithmic averages of two 2-min SPL values. The third column shows the log average SPL over the course of the day, which represents the sound exposure of each operation. The A-weighted sound level recorded was for the two-saw edger and chipper (for both the morning and afternoon samples). All of the jobs except the head saw operation and gang saw operation had average SPL values greater than the 80 dBA recommended by NIOSH as the maximum noise level without hearing protectors. The gang saw and head saw operators were both located in booths, and it should be noted that the morning SPL for the gang saw operator was greater than the 80 decibel recommended limit.

TABLE I. Mean Sound Pressure Levels Recorded Across Sawmill Operations

Job	Time Period 8:00–11:00	11:30–15:30	8:00–15:30
Head saw booth (Job 1)	77.9	77.0	77.5
Head saw tailor (Job 2)	98.2	99.5	98.9
Gang saw booth (Job 3)	81.6	77.9	80.1
Two-saw edger & chipper (Job 4)	100.5	100.2	100.4
Descrambler & sorter (Job 5)	96.0	95.9	96.0
Trim saw (Job 6)	94.2	93.0	93.6
Board marker (Job 7)	91.8	92.5	92.2
Green chain middle (Jobs 8 & 9)	89.9	88.3	89.2
Green chain end (Jobs 10 & 11)	87.6	86.3	87.0

Each operation required one worker except the green chain middle and the green chain end, which each required two workers. To simplify the problem, the green chain middle (end) was split into two subjobs, green chain middle (end) I and II, each of which was performed by one worker. Therefore, a total of 11 workstations and 11 workers were included in the problem.

Job Rotation

The rotation plan was formulated to minimize the noise exposure for the sawmill workers. To develop a rotation schedule that could be practically applied, the 10-hour workday was partitioned into four 2.5-hour time periods that were used for the rotating scheme.

An example job rotation schedule for five workers and five jobs is provided in Table II. Based on this solution the job rotation schedule for a given worker can be determined by moving down a single column. For example, the rotation schedule for worker A would be

$$\text{Job 1} \rightarrow \text{Job 4} \rightarrow \text{Job 2} \rightarrow \text{Job 2}$$

There was an existing job rotation plan within the sawmill based on three jobs in which workers could be rotated every 2.5 hours. These jobs were the descrambler and sorter, the trim saw, and the two-saw edger and chipper. The effectiveness of this three-job rotation plan was tested using a mathematical model. The mathematical model was then used to find the best rotation schedule for these three jobs. However, if other jobs with SPLs lower than the current three in the rotation plan were added, the noise exposure might be reduced. Therefore, an 11-job rotation plan that covered all 11 jobs in the facility was also studied.

The Mathematical Model

For n jobs and n workers, n! different worker assignment scenarios can be performed during a single s-hour time period. Assuming that the worker assignments are independent of time period, there would be $(n!)^s$ possible job rotation schedules. This specific problem consists of 11 workers allowed to rotate every 2.5 hours.

TABLE II. An Example of a Job Rotation Schedule

Time Period	Worker A	Worker B	Worker C	Worker D	Worker E
Period 1	Job 1	Job 5	Job 3	Job 2	Job 4
Period 2	Job 4	Job 5	Job 2	Job 3	Job 1
Period 3	Job 2	Job 3	Job 1	Job 4	Job 5
Period 4	Job 2	Job 1	Job 4	Job 3	Job 5

Therefore, n in the problem equals 11, and s equals 4. All possible ways to assign the workers is $(11!)^4$. Because this is a large number, efficient methods for evaluating these different alternatives were used.

The mathematical model was developed and applied to minimize the maximum daily noise exposure encountered among the workers. The average noise exposure level for each job was based on the noise sampling data collected within the mill. NIOSH noise regulations concerning safe duration of noise exposure were used to find the solution. The mathematical programming model and variable definitions are shown here.

Variable Definitions

I set of workers $i = 1, 2, \ldots, n$
J set of jobs $j = 1, 2, \ldots, n$
T set of working periods $t = 1, 2, \ldots, s$
x_{ijt} = 1 if worker i does job j at time t, 0 otherwise
D_{max} = the maximum daily noise dose among all workers
T_j = the maximum allowable exposure duration for job j given its average SPL

Mathematical Programming Formulation

$$\text{Min } D_{max} \qquad (1)$$

Subject to

$$D_{max} \geq \sum_{j=1}^{n} \sum_{t=1}^{s} \frac{2.5 \cdot x_{ijt}}{T_j} \quad \forall\, i \qquad (2)$$

$$\sum_{i=1}^{n} x_{ijt} = 1 \quad \forall\, j, t \qquad (3)$$

$$\sum_{j=1}^{n} x_{ijt} = 1 \quad \forall\, i, t \qquad (4)$$

$$x_{ijt} \in (0, 1) \quad \forall\, i, j, t \qquad (5)$$

The objective function (1) is to minimize the maximum daily noise dose among all workers. Workers can be rotated at the end of each 2.5-hour time period. For this specific setting, working hours are 10 hours per day; therefore, there are 4 rotated periods (s). The number of workers depends on the number of jobs that the workers can rotate through. In the computer simulations both 3-job and 11-job rotations were performed. Therefore, n equals 3 in the first computer simulation, and n equals 11 in the second computer simulation. The maximum allowable exposure duration for task j, (T_j) is calculated using the NIOSH criterion.

Two constraint sets are included in this formulation. The first set (constraint 2) guarantees that D_{max} is the maximum daily noise dose among all workers. The coefficient in this constraint depends on the length of the rotation interval. For example, if the rotation interval is 2.5 hours, the coefficient will be 2.5 (as shown in [2]). The second set (constraints 3 and 4) includes assignment constraints. Constraint 3 ensures that each task is done by only one worker during each time period, whereas constraint 4 ensures that each worker only performs one task during each time period.

COMPUTER SIMULATION RESULTS

The mathematical model was solved using CPLEX (ILOG, Mountain View, Calif.), which is a commercial optimization

TABLE III. Current Three-Job Rotation Schedule

Current	Worker 1	Worker 2	Worker 3
Period 1	descrambler and sorter	trim saw	two-saw edger and chipper
Period 2	two-saw edger and chipper	descrambler and sorter	trim saw
Period 3	trim saw	two-saw edger and chipper	descrambler and sorter
Period 4	descrambler and sorter	trim saw	two-saw edger and chipper
Dose	21.2	19.5	28.2
8-Hour TWA	98.3	97.9	99.5

package. A computer simulation was first conducted for a three-job rotation to compare the current rotation schedule with the optimal rotation schedule found by the mathematical model. Then all 11 jobs were considered, to improve the rotation schedule.

Three-Job Rotation

The current rotation schedule used at the sawmill is rotating three jobs including the two-saw edger and chipper (job1), descrambler and sorter (job 2), and trim saw (job 3) at the end of each 2.5-hour period. Table III shows the current rotation schedule, the daily noise doses, and the TWAs. All doses and TWAs were calculated using the NIOSH criterion. A mathematical model was used to generate the optimal rotation schedule to compare with the current rotation schedule. The optimal rotation schedule is shown in Table IV. The maximum daily noise dose was reduced by 6.0%, and the maximum TWA was reduced by 0.3 dB.

All three jobs in the current rotation plan were in high SPL areas, so the optimal three-job rotation schedule based on only these three jobs cannot reduce the daily noise exposure very much. If other jobs with lower SPLs are considered in the rotation plan, the daily noise exposure level should be reduced. Therefore, in the next computer simulation all 11 jobs were introduced into the rotation plan.

Eleven-Job Rotation

In the second computer simulation all 11 jobs were introduced into the rotation plan. Applying the mathematical model, the maximum daily exposure dose is 11.6, which equates to a TWA of 95.6 dB. This reduces the maximum daily noise dose by 58.8% and the maximum TWA by 3.8 dB from the current three-job rotation schedule. Moreover, the maximum TWA is reduced by 4.8 dB from the nonrotation schedule. The rotation schedule for 11 jobs is shown in Table V.

DISCUSSION AND CONCLUSION

A mathematical model has been developed and solved to provide a rotation schedule to minimize daily noise exposure encountered among workers in a sawmill. In this specific problem a mathematical model provides a schedule that reduces the highest noise exposure level by 0.3 dB relative to the current schedule for a three-job rotation. The optimal solutions based on a three-job rotation formulation marginally reduce noise exposure to workers because these three jobs were at high SPLs. By introducing additional jobs with lower SPLs into the rotation plan, it was possible to reduce the TWA by as much as 3.8 dB.

The results of this study suggest that a mathematical modeling approach to the scheduling of work may have benefits in terms of reducing worker exposure to occupational noise; however, a listing of the current model's assumptions and limitations would be prudent. First, the model assumes that the hours worked per day and the days worked per week are constant. Given this assumption, the current model may be inadequate when these parameters vary between workers or vary over weeks. Second, the model assumes that the workers are paid the same rate regardless of which task is performed. If this assumption is not true, the model may develop schedules that result in a marked pay imbalance between workers. The model further assumes that all worker participants have been adequately cross-trained in each job involved in the schedule. This assumption requires the employer to implement worker job enlargement prior to rotation schedule implementation to maintain stable levels of productivity and product quality. A final assumption of the model is that the jobs involved in the rotation are within a close physical proximity to one another (so close that travel time between jobs could be disregarded in the calculations). Although this assumption held true for the sawmill example (none of the involved jobs were more than 45 m from one another), great variation in travel distances between jobs (i.e., hundreds of meters) would prove problematic for the model in its current form. In summary, the model works best when (1) the work schedule is stable in terms of hours per day and days per week, (2) the pay rate for jobs involved in rotation is equal, (3) workers can be adequately cross-trained in those jobs that comprise the rotation schedule, and (4) the jobs involved in rotation are in close physical proximity to one another so that travel time between jobs is not a factor in noise exposure.

A primary limitation to the model is its focus on minimizing exposure to a single workplace hazard, occupational noise (using the NIOSH criterion for exposure). The model does not take into account the OSHA criterion for noise exposure or other potential hazards such as thermal environments, occupational vibration,

TABLE IV. Optimal Rotation Schedule for Three Jobs Based on 2.5-Hour Time Periods

IP Solution	Worker 1	Worker 2	Worker 3
Period 1	two-saw edger and chipper	trim saw	descrambler and sorter
Period 2	trim saw	two-saw edger and chipper	descrambler and sorter
Period 3	two-saw edger and chipper	descrambler and sorter	trim saw
Period 4	trim saw	descrambler and sorter	two-saw edger and chipper
Dose	26.5	21.2	21.2
8-Hour TWA	99.2	98.3	98.3

TABLE V. Optimal Rotation Plan for 11 Jobs Using the NIOSH Criterion

NIOSH	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11
Period 1	6	4	5	11	8	1	2	9	3	6	10
Period 2	8	11	10	7	2	4	9	6	1	5	3
Period 3	5	3	7	2	9	11	6	10	4	8	1
Period 4	8	1	6	7	9	3	10	2	11	5	4
Dose	7.9	11.6	8.4	11.6	10.2	11.6	11.4	11.4	11.6	10.4	11.6
8-Hr TWA	94.0	95.6	94.2	95.6	95.1	95.6	95.5	95.5	95.6	95.2	95.6

toxic substance exposure, and work-related musculoskeletal disorders. A secondary limitation lies in the fact that the time required for the model to find the optimal solutions increases as the number of jobs and workers or the frequency of rotation increases. Finally, it should also be noted that job rotation scheduling is only an administrative solution to reducing occupational noise exposure. Systematic scheduling must be used in conjunction with noise-reducing engineering controls, personal hearing protection, and hearing testing as part of an overall hearing conservation program. Given these assumptions and limitations, future research in this area should focus on the further development of the job rotation problem as well as mathematical modeling approaches to finding scheduling solutions that help protect worker safety and health.

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