DESIGNING MULTI-WORKDAY NOISE-SAFE JOB ROTATION SCHEDULES BASED ON SKILL AND DEMAND REQUIREMENTS

BY

PAVINEE RERKJIRATTIKAL

A THESIS SUBMITTED IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF ENGINEERING
(LOGISTICS AND SUPPLY CHAIN SYSTEMS ENGINEERING)
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
THAMMASAT UNIVERSITY
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A Thesis Presented

By

PAVINEE RERKJIRATTIKAL

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Abstract

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Job rotation is a timely and cost-effective management approach, widely used for noise exposure mitigation. This thesis aims to improve the practicality of job rotation methodology by considering the following important characteristics of manufacturing systems. First, the ability of job rotation to control noise exposure, while achieving key manufacturing requirements and objectives, is addressed. Second, the effects of job rotation on process continuity and productivity are considered. Third, this research demonstrates the capability of the proposed job rotation approach in maintaining the safety of worker over overtime and extended work hours. Integer programming is used to develop noise-safe job rotation models under cost minimization objective. Demand and skill required by tasks are formulated as constraints in the proposed model. The effectiveness of the models is evaluated under different overtime policies, levels of skilled worker availability, and levels of product demand. According to the model validation results, the proposed model is shown to remain effective in maintaining the safety of workers under scenarios where some workers are required to work overtime to fulfill the demand requirements.

Keywords: Job rotation, Noise exposure, Productivity, Workforce Scheduling, Overtime assignment, Workers Skill

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Chapter 1
Introduction

1.1 Job Rotation Scheduling

In the heavy engineering industry, noise is one of the most frequently reported occupational hazards. According to the National Institute for Occupational Safety and Health (OSHA), about 22 million workers in the U.S. are exposed to harmful noise levels each year. Long-term exposure to excessive noise levels is the most common cause for permanent hearing loss. Other adverse occupational effects of noise include communication and concentration interferences, psychological stress, and mental fatigue (Al-Dosky, 2014). To reduce noise exposure issues in a workplace, noise control goals must be developed, providing a basis for identifying appropriate noise control strategies. Then, a hierarchy of noise control suggested by National Institute for Occupational Safety and Health (NIOSH) shown in Figure 1.1 can be employed.

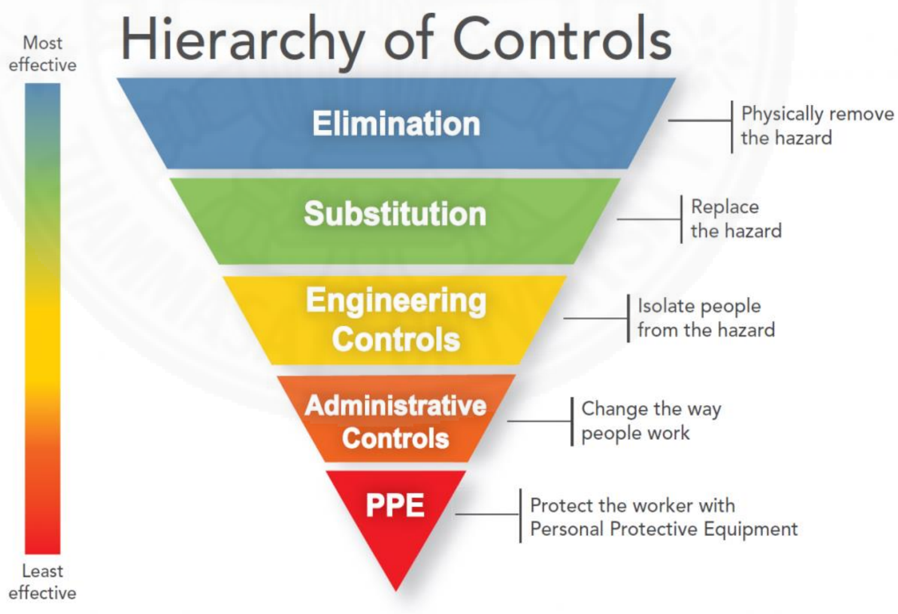


Figure 1.1 Hierarchy of controls suggested by NIOSH.

Source: National Institute of Occupational Safety and Health (NIOSH)

Among all the methods in the hierarchy, the most effective noise control method is to permanently eliminate noise sources or to replace noise generation equipment with less hazardous one. Engineering control method can be implemented to redesign and modify the workplace to reduce noise-induced discomfort. During this process, noise barriers and noise absorbers are normally used. Generally, these aforementioned methods are costly and time consuming, as they require major changes to the process. Also, in many cases, additional actions are needed to further reduce noise exposure to the point where workers are fully protected from noise hazard. In this regard, administrative controls can be used as a supplementary noise control method. The control method involves managing the working schedule of workers and the operating hours of noisy tasks, to limit the exposure duration of workers. Job rotation is one of the administrative control methods, widely used in manufacturing assembly lines, for mitigating worker exposure to occupational risks. When using job rotation, workers are rotated through tasks to reduce the period of exposure to excessive noise for individuals. The use of job rotation does not require large investment in the adjustment of machinery and working environment. However, job rotation may not be effective in circumstances where the noise levels of all tasks are similarly high. This is in accordance to the principle of safe job rotation shown in Figure 1.2. In order to realize an effective noise-safe job rotation, there must be tasks with different noise levels and adequate noise-safe working environment, allowing workers to even out the risk of excessive daily noise exposure.

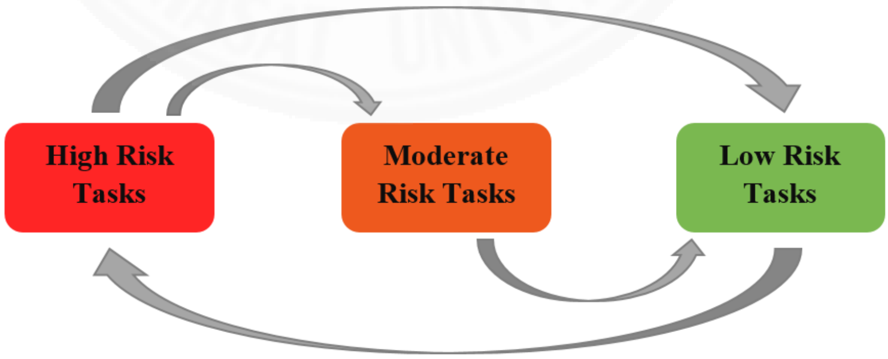


Figure 1.2 Principal of safe job rotation.

1.2 Research Objective

This thesis aims to improve the practicality of job rotation modeling by incorporating demand requirements, which is an essential component in workforce scheduling problems, commonly neglected in the previous job rotation research. The thesis also demonstrates the ability of job rotation to control noise exposure levels among workers, where a workforce with limited availability of skilled workers has to fulfill varying demand requirements over prolonged work hours.

1.3 Research Contribution

This thesis proposes a noise-safe job rotation model that enables workers to fulfill demand requirements, while keeping their daily noise exposure levels within a permissible limit. The proposed job rotation model is suitable for manufacturing systems where productivity is affected by process continuity, worker skills, and task skill requirements. The model is solved and validated using a numerical example representing situations faced by Small-to-Medium Enterprises (SMEs), where small-sized workforces and overtimes are used to maintain sufficient production capacity. The effects of overtime policies, proportions of skilled workers, and demand levels on total labor cost and average daily noise dose among workers are investigated. In conclusion, this thesis explores the effective use of job rotation in simultaneously controlling the noise exposure levels of workers and minimizing the total labor cost, under the scenarios with prolonged exposure duration, limited skilled workers, and increased demands.

Chapter 2
Literature Review

The use of job rotation to prevent industrial workers from being excessively exposed to occupational hazards is well documented in the literature. In general, optimization models are formulated, with an aim to reduce the burden of exposure to occupational hazards of workers to a more manageable level. In this section, the job rotation researches aimed for reducing noise hazard as well as the job rotation researches that combined safety and productivity aspects altogether are discussed.

2.1 Ergonomics Job Rotation Scheduling

Ergonomics risk such as musculoskeletal disorders or back injuries is majorly caused by repetitive awkward movements. Carnahan B. J. et al (2000) proposed the integer programming model to minimize the maximum job severity index (JSI), which is the commonly used measurement for the injuries from manual lifting loads. Later, Tharmmaphornpilas W. and Norman B. A. (2007) developed the optimization model that minimize both JSI and number of lost days from injuries. Alternatively, the ergonomics job rotation modeling can be formulated to limit time spent in repetitive movement, as proposed by Asensio-Cuesta S. et al (2012), or to maximize movement turnover (Botti L. et al ,2017). There are numbers of researches that incorporate productivity aspects into their ergonomics job rotation modeling. Mondal P. K. et al (2013) developed a skill-based ergonomics job rotation modeling to maximize workers competency score, the higher task competency score means that it is the task that the worker performs best. On the other hand, productivity-based ergonomics job rotation scheduling can be formulated to maximize overall production level (Mossa G. et al, 2016) or minimize production cycle time (Moussavi S. E. et al, 2016).

2.2 Noise-safe Job Rotation Scheduling

Tharmmaphornpilas et al. (2003) developed the optimization model minimize the maximum daily noise dose among workers. Alternatively, job rotation models can be equipped with a set of constraints that provide a mechanism for limiting the maximum daily noise exposure level of workers, while the optimization objectives can be formulated for specific process enhancements. As shown in previous work, Yaoyuenyong S. and Nanthavanij S. (2006) used a heuristic approach to determine a noise-safe job rotation plan, where the objective function minimizes the number of workers exposed to a noise hazard. For harsh industrial workplaces, especially those with heavy machinery and a high degree of manual work, there is a high potential for workers to be exposed to a broad range of occupational hazards. Previous job rotation studies highlighted the challenge of simultaneously managing noise and other occupational hazards under job rotation scheme. Tharmmaphornpilas W. and Norman B. A. (2004) demonstrate the use of their models in finding the proper job rotation frequency, and minimizing the noise exposure level and job severity index (JSI). The development of a noise-safe job rotation model in the multiple-hazard context considers factors affecting process performance.

2.3 Noise-safe Job Rotation Scheduling with Productivity

When using job rotation, there is a need to laterally transfer workers among a number of different tasks where each requires different skills and competency levels. When workers have insufficient skills for the tasks, tasks are normally performed at decreased productivity levels (Nanthavanij et al., 2010). To resolve skill mismatch and skill shortage issues, skill-based job rotation models have been further developed. Delijoo et al. (2009) propose a skill-based job rotation model encompassing four objective functions related to noise exposure injuries, low back injuries, job priority, and workers' idleness. Under the job priority objective, workers are assigned to tasks based on their ability to fulfill task skill requirements. Aryanezhad et al. (2009) develop a skill-based job rotation model that minimizes the maximum daily noise dose and the lost workdays due to lifting injuries among workers, simultaneously. Niakan et al. (2016) formulate a job rotation model that considers the three aspects of sustainability for a cellular manufacturing system, where noise exposure control is considered as a social criterion. In their work, the inclusion of realistic manufacturing conditions is made, by considering product demand, worker skill level, and skill-level requirements for machines. Aside from skill issues, the need to regularly rotate workers between tasks can adversely affect productivity, particularly for processes with long setup time. Asawarungsaengkul K. and Nanthavanij S. (2008) keep the number of worker-location changeovers and the number of workers exposed to noise hazards at a minimum, while maintaining the noise exposure levels of workers within the safe limit. The number of changeovers is translated into the amount of productivity loss in recent studies. Olapiriyakul et al. (2016) show that the rotation of workers between workstations has the effect of interrupting process continuity, potentially resulting in a significant productivity loss. Rerkjirattikarn et al. (2017) demonstrate that job rotation with an excessive rotation frequency can significantly reduce productivity, due to the need for workers to adjust to new working conditions. Their noise-safe job rotation model minimizes the number of workers and the total setup time. Based on these research findings, the development of skill-based job rotation models, with the consideration of productivity, is essential to realize a more effective and practical use of job rotation. The details of previous safe job rotation scheduling researches are summarized in Table 2.1.

Table 2.1 The summary of safe job rotation literature review

Author(s) (Year)	Objective(s)			Description(s)
	Ergonomics	Noise-safe	Productivity	
Carnahan B. J. et al (2000)	✓			- Min. maximum Job Severity Index (JSI) - Multi-workday job rotation scheduling.
Tharmmaphornpilas W. et al (2003)		✓		- Min. maximum noise dose.
Tharmmaphornpilas W. and Norman B. A. (2004)	✓	✓		- Determine proper rotation interval and frequency.
Yaoyuenyong S. and Nanthavanij S. (2006)		✓		- Min. number of workers.
Tharmmaphornpilas W. and Norman B. A. (2007)	✓			- Min. Job Severity Index (JSI) number of lost days.
Asawarungsaengkul K. and Nanthavanij S. (2008)		✓	✓	- Min. number of workers and worker-location changeover.
Delijoo V. et al (2009)	✓	✓	✓	- Skill-based assignment. - Min. idleness, lost days from back pain.

Aryanezhad M. B. et al (2009)	✓	✓	✓	- Skill-based assignment. - Min. lost days from lifting injuries.
Nanthavanij S. et al (2010)			✓	- Max. competency score. - Skill-based assignment.
Asensio-Cuesta S. et al (2012)	✓		✓	- Skill-based assignment. - Min. repeated movement time.
Mondal P. K. et al (2013)	✓		✓	- Consider workers competency score and physical skills.
Mossa G. et al (2016)	✓		✓	- Skill-based assignment. - Max. overall production level.
Moussavi S. E. et al (2016)	✓		✓	- Skill-based assignment. - Min. daily production cycle time.
Niakan F. et al (2016)		✓	✓	- Skill-based assignment. - Demand requirements.
Rerkjirattikarn P. et al (2016)		✓	✓	- Min. number of workers. - Min. total setup time.
Botti L et al (2017)	✓		✓	- Skill-based assignment. - Max. movement turnover.
Rerkjirattikarn P. et al (2017)		✓	✓	- Min. number of workers. - Min. total setup time.

2.4 Research Gap

Despite the continued development on different aspects of noise-safe job rotation modeling, numerous challenges still exist for the efficient implementation of the methodology in the manufacturing industry. First, the attempt to rotate workers to different tasks can be hampered by a lack of a sufficient number of workers, especially skilled workers. Research is still needed to help decision makers understand the efficacy of their job rotation schedules under limited labor resources. Second, during a period where demand requirements are high relative to the available production capacity, it is quite a challenge to adhere to a noise-safe job rotation schedule, and to maintain the required levels of productivity, at the same time. However, demand requirements are rarely considered in noise-safe job rotation problems. Third, when overtime is permitted, some workers may be assigned to work overtime, exposing them to excessive noise levels over an extended period of time, in order to fulfill the demand. These challenges are normally found in small-to-medium sized enterprises (SMEs) with small workforces and a limited number of skilled workers. Solving the job rotation problem under such a situation is still lacking in the literature. This study fills these research gaps by developing a noise-safe job rotation model that can be used under skill and demand requirements. A situation which requires some workers to work overtime to meet demand requirements is presented. As opposed to most of the previous job rotation studies that create job rotation plans for only one workday, our study designs job rotation plans over a 6-day period. In one workday, there are two 4-hour regular shifts and one 4-hour overtime (OT) shift. This study is the first to incorporate overtime assignment into the noise-safe job rotation problem. This helps investigate the ability of the proposed model in mitigating the noise exposure levels of workers over an extended working period. The relationship between worker skill and productivity levels is defined in this study, to develop optimal job rotation schedules capable of achieving both productivity and noise exposure criteria. Workers are classified into skilled and unskilled workers. It is assumed that unskilled workers can only perform a subset of tasks with lower productivity. This provides a realistic representation of the working conditions of SMEs, where unskilled workers are the primary source of labor. In the next section, a skill- and demand-based job rotation model is formulated, to minimize the total labor cost and limit the noise exposure levels of worker to 90 decibel A (dBA), over a 6-day period. After that, the model is verified and validated, using a numerical example. Finally, the cost performances and the required number of workers for three different overtime policies are evaluated. A selection of overtime assignment plans can be made based on a decision maker's preferences.

Chapter 3
Methods of Approach

3.1 Noise Level Calculation

In general, Sound Pressure Level (SPL) or noise level relative to workstations are assessed using Sound Level Meter (SLM) in the unit of decibel A (dBA), which is the relative loudness perceived by human ears. The following formula given by OSHA is used to transform the cumulative noise level of workers in a working day, when there are two or more work periods of different noise levels in a day into Daily Noise Dose (DND).

$$DND = \sum_{N=1}^{n} \frac{C_N}{T_N} \quad (1)$$

where C is the actual exposure duration in hours under a certain noise level, and N is the number of periods in a working day. T is the allowable noise exposure periods corresponding to a certain noise level, which can be calculated using

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

where L is the noise exposure level measured in dBA. As recommended by OSHA, the safe limit of Daily Noise Dose (DND) is 1, which is equivalent to 90 dBA.

3.2 Mathematical Model Formulation

In this section, the development of the job rotation model is presented, starting from the mathematical model proposed by Rerkjirattikarn P., et al (2017), until the recent mathematical model. Later, the difference of both models is discussed in section 3.2.2.4.

3.2.1 Mathematical Model I

The mathematical model for the noise-safe job rotation scheduling is divided into 2 phases. First, the model in Phase I aims for determining an optimal number of workers required in the job rotation plan under a constraint that controls daily noise levels of workers. Then, the optimal number of workers is set as the initial workforce size of the model in Phase II. The objective of the model in Phase II is to minimize the total setup time, which accounted as productivity loss in minutes from rotating workers. In both phases, the main assumptions are listed as follows.

(1) Each of the worker can perform only one task at a time.
(2) A specific number of workers is required to perform each task, during each shift.
(3) Workers can relocate to a new task at the end of each shift.
(4) There are 2 4-hr shifts in a workday.
(5) Setup time is required whenever a worker is assigned to rotate to the other tasks.
(6) The moving time from one workstation to another is neglected.

3.2.1.1 Phase I: Minimize Number of Workers

The important notations used in the model formulation are summarized below.

(1) Indices

i Number of workers (i = 1, …, n)

j Number of workstations (j = 1, …, m)

t Number of periods (t = 1,…, p),

(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 j during shift t; 0 otherwise

(3) 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*

(4) Mathematical Model

Minimize $\sum_{i=1}^{n} Y_i$ (3)

Subject to $\forall\ i$

$$\sum_{j=1}^{m}\sum_{t=1}^{p} X_{ijt}D_{jt} \leq 1 \qquad \forall\ i \qquad (4)$$

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

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

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

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

Equation (3) is the objective function that is to minimize total number of workers employed in the job rotation plan, while keeping the noise level of workers to be lower than 1 (Equation (4)). Equation (5) ensures that a worker is assigned to perform only one task in each shift. Equation (6) ensures that number of workers assigned to each task meet the task requirements. Equation (7) states that workers can perform up to 2 shifts in a workday. Lastly, Equation (8) ensures that worker *i* is included in the job rotation plan, when the worker is assigned to any shift, the value of Y_i becomes 1.

3.2.1.2 Phase II: Minimize Total Setup Time

Additional notations used to formulate the mathematical model in Phase II are defined below.

(1) Decision Variables

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

(2) Parameters

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

(3) Mathematical Model I: Phase II

$$\text{Minimize } \sum_{i=1}^{n}\sum_{j=1}^{m} B_{ij}S_{ij} \qquad (9)$$

Subject to constraints in Equation (4) – (8) and

$$Z_{ij} \leq B_{ij} \times BigM \qquad \forall\ i,j \qquad (10)$$

The objective function, Equation (9) is to minimize the total setup time caused by job rotation. Equation (10) is used to determine if the task rotation is required to maintain safe noise levels of workers throughout a workday. If a workstation is operated by a different worker during two working shifts (Z_{ij} = 1), then the value of B_{ij} becomes 1.First, the mathematical model in Phase I is used to determine an optimal number of workers employed in the job rotation schedule, under a constraint that restricts safe noise levels. Then, the optimal number of workers from Phase I is used as an initial workforce size in Phase II, to minimize the total setup time. In each iteration of Phase II, an additional worker is repeatedly included in the model to reduce the need to rotate workers. The problem reaches optimality, when an additional worker is included but the total setup time is no longer reduced.

3.2.2 Mathematical Model II

The noise-safe job rotation model is formulated with the consideration of product demand and task skill requirements, using an integer programming approach. The proposed model is solved to determine the optimal rotation schedules, under the cost minimization objective. Constraints are formulated to ensure that the demand and daily noise dose requirements are met over a 6-workday period. Each workday consists of two 4-hour regular shifts and a 4-hour overtime shift. Job rotation is used to reduce and control the noise exposure levels of workers to a safe level of 90 dBA. Important assumptions are summarized below.

(1) Workers are classified into skilled and unskilled workers.
(2) Tasks differ in their skill and competency requirements, where unskilled workers can only perform a subset of tasks at lower productivity level

(3) Workers are able to perform tasks at higher levels of productivity, when continuing to perform tasks at the same workstations for more than one consecutive shift.

(4) Workers can perform one task at a time during each shift, and can only be rotated to other workstations at the end of each shift.

(5) The number of workers assigned to each workstation varies, depending on the level of demand to be fulfilled.

(6) Labor costs are classified into direct and indirect costs. The direct cost includes daily wages and overtime wages, while the indirect cost includes the overhead costs of workers.

(7) The overtime wage is 1.5 times the regular shift wage.

The important notations used to formulate the mathematical model II are described as follows.

3.2.2.1 Indices

i Number of workstations (i = 1,..., I)

j Set of work shifts (j=1,…, J), represented as morning shift (MS), afternoon shift (AS), and overtime shift (OS)

s Skill levels of workers (s = 1,…, S)

n Number of workers (n = 1,..., N)

t Number of workdays (t = 1,..., T)

3.2.2.2 Parameters

D_i Noise level at workstation i

W_i Demand requirement of workstation i

$P_{i,s}$ Production rate of worker with skill level s, at workstation i

$SP_{i,s}$ Steady-state production rate achieved when worker with skill level s continues to perform task at workstation i over consecutive shifts.

LD_s	Daily wage of worker with skill level *s*
LO_s	Overtime wage of worker with skill level *s*
OH_s	Overhead cost of worker with skill level *s*
MD	Maximum allowable noise exposure level
MO	Maximum number of overtime shift.

3.2.2.3 Decision Variables

$X_{i,j,s,n,t}$ = 1 if worker *n*, with skill level *s*, works at workstation *i*, shift *j*, on day *t*; 0 otherwise.

$Y_{i,s,n,t}$ = 1 if worker *n*, with skill level *s*, works both morning and afternoon shifts at workstation *i*; 0 otherwise.

$Z_{i,s,n,t}$ = 1 if worker *n*, with skill level *s*, works both afternoon and overtime shifts at workstation *i*; 0 otherwise.

$A_{s,n,t}$ = 1 if worker *n*, with skill level *s*, is scheduled to work on day *t*; 0 otherwise.

$C_{s,n}$ = 1 if worker *n*, with skill level *s*, is selected under the job rotation plan; 0 otherwise.

3.2.2.4 Mathematical Model

Minimize

$$\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{s=1}^{S} LD_s \cdot A_{s,n,t} + \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{s=1}^{S}\sum_{i=1}^{I} LO_s \cdot X_{i,j=OS,s,n,t} + \sum_{n=1}^{N}\sum_{s=1}^{S} OH_s \cdot C_{s,n} \quad (11)$$

Subject to

$$\sum_{i=1}^{I} X_{i,j,s,n,t} \leq 1 \qquad \forall\, j,s,n,t \quad (12)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{i,j,s,n,t} \leq 3 \cdot A_{s,n,t} \qquad \forall\, s,n,t \quad (13)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} D_i \cdot X_{i,j,s,n,t} \leq MD \qquad \forall\, s,n,t \quad (14)$$

$$2 \cdot \sum_{i=1}^{I} X_{i,j=OS,s,n,t} - \sum_{i=1}^{I} X_{i,j=MS,s,n,t} + \sum_{i=1}^{I} X_{i,j=AS,s,n,t} \leq 0 \qquad \forall\, s,n,t \quad (15)$$

$$\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{s=1}^{S}\sum_{j=1}^{J} P_{i,s} \cdot X_{i,j,s,n,t} + \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{s=1}^{S} SP_{i,s} \cdot (Y_{i,s,n,t} + Z_{i,s,n,t}) \geq W_i \qquad \forall\, i \quad (16)$$

$$Y_{i,s,n,t} \leq \frac{X_{i,j=MS,s,n,t}+X_{i,j=AS,s,n,t}}{2} \qquad \forall i,s,n,t \quad (17)$$

$$Y_{i,s,n,t} + 1 \geq X_{i,j=MS,s,n,t} + X_{i,j=AS,s,n,t} \qquad \forall i,s,n,t \quad (18)$$

$$Z_{i,s,n,t} \leq \frac{X_{i,j=AS,s,n,t}+X_{i,j=OS,s,n,t}}{2} \qquad \forall i,s,n,t \quad (19)$$

$$Z_{i,s,n,t} + 1 \geq X_{i,j=AS,s,n,t} + X_{i,j=OS,s,n,t} \qquad \forall i,s,n,t \quad (20)$$

$$\sum_{t=1}^{T} A_{s,n,t} \leq M \cdot C_{s,n} \qquad \forall s,n \quad (21)$$

$$\sum_{t=1}^{T} \sum_{i=1}^{I} X_{i,j=OT,s,n,t} \leq MO \qquad \forall s,n \quad (22)$$

$$\sum_{i=1}^{I} X_{i,j=OT,s,n,t} + \sum_{i=1}^{I} X_{i,j=OS,s,n,t+1} \leq 1 \qquad \forall s,n,t-1 \quad (23)$$

The objective function (11) minimizes the total labor cost, which consists of the daily wages, overtime wages, and overhead. Equation (12) ensures that each worker is assigned to one task during each time period. Equation (13) keeps track of the assigned workdays of workers. Equation (14) keeps the daily noise dose of all workers within the permissible exposure limit. Equation (15) specifies that only workers, who perform both morning and afternoon shifts, are eligible to perform overtime work. Equation (16) ensures that all demand requirements are satisfied. Equations (17) and (18) assign $Y_{i,s,n,t}$ as 1, when worker n works at the same workstation, during morning and afternoon shifts, in workday t. Equations (19) and (20) assign $Z_{i,s,n,t}$ as 1, when worker n works at the same workstation, during afternoon and overtime shifts, in workday t. Equation (21) counts the number of workers to be employed under job rotation. Equation (22) ensures that the total number of overtime shifts assigned to workers, does not exceed the maximum allowable number of overtime shifts. Equation (23) ensures that workers are not assigned to work overtime over two consecutive days, under the non-consecutive overtime policy.

As oppose to the mathematical model I, this model considers productivity gained from process continuity, rather than productivity loss accounted as unnecessary setup required by job rotation. In the model II, it is assumed that workers are able work at a faster pace, when they are assigned to perform at the same workstation on consecutive shifts. That is, the lesser amount of job rotation frequency results in more productivity and outputs from uninterrupted process. Moreover, the mathematical model I plans only a one-workday job rotation schedule and does not consider workstations complexity and skill requirements, the ability to satisfy demand under job rotation scheme and overtime shift assignment, as there are only 2 working shifts per day in the model I.

3.2.2.5 Numerical Example

A manufacturing system with 5 independent workstations is considered. The initial workforce consists of 5 skilled workers and 5 unskilled workers. The planning horizon of 6 working days, the typical number of working days per week for SMEs in Thailand, is assumed. The demand requirements and noise levels of workstations are shown in Table 3.1.

Table 3.1 Demand requirements and noise levels of workstations

Workstations	**Demand Requirements (Units)**	**Noise Level (dBA)**	**Noise dose per shift**
W1	1,600	91	0.57
W2	900	93	0.76
W3	1,000	82	0.16
W4	1,300	87	0.33
W5	1,400	85	0.25

Normally, skilled and unskilled workers perform tasked at initial production rates, as shown in Table 3.2. When workers perform tasks at the same workstations for two or more consecutive shifts, workers learn their jobs and perform tasks at steady-state productivity rates. A more complex learning and forgetting model used by Azizi et al. (2010) can also be used to define the effect of the job rotation interval on worker productivity. The tasks at workstation W2 and W3 are complex, and can only be performed by skilled workers. The production rate of unskilled workers for these workstations is specified as zero. Workers are paid the full daily wages, when scheduled to work morning or afternoon shift or both. The daily wage, overtime wage, and overhead cost per worker per 6 working days of skilled and unskilled workers are shown in Table 3.3.

Table 3.2 Initial and steady-state production rates

Workstations	**Initial Production Rate (Units/shift)**		**Steady-state Production Rate (Units/shift)**	
	Skilled	**Unskilled**	**Skilled**	**Unskilled**
W1	100	80	140	100
W2	120	0	150	0
W3	90	0	122	0
W4	60	40	78	48
W5	80	60	100	72

Table 3.3 Direct and indirect labor costs

Labor Cost	**Skilled Workers**	**Unskilled Workers**
Daily Wage (THB per day)	450	300
Overtime (THB per OT shift)	340	225
Overhead (THB per worker)	1,500	1,500

The ability of the proposed job rotation model to formulate noise-safe job rotation plans is evaluated under three different scenarios that are based on three overtime policies: 1) no overtime allowed 2) unlimited overtime and 3) non-consecutive overtime. For each scenario, job rotation plans are created based on two different ratios of skilled and unskilled workers: 1) 5 skilled and 5 unskilled workers, denoted as 5:5 and 2) 2 skilled workers and 8 unskilled workers, denoted as 2:8. Prior to the result analysis, the schematic summary of the model framework is provided in Figure 3.1.

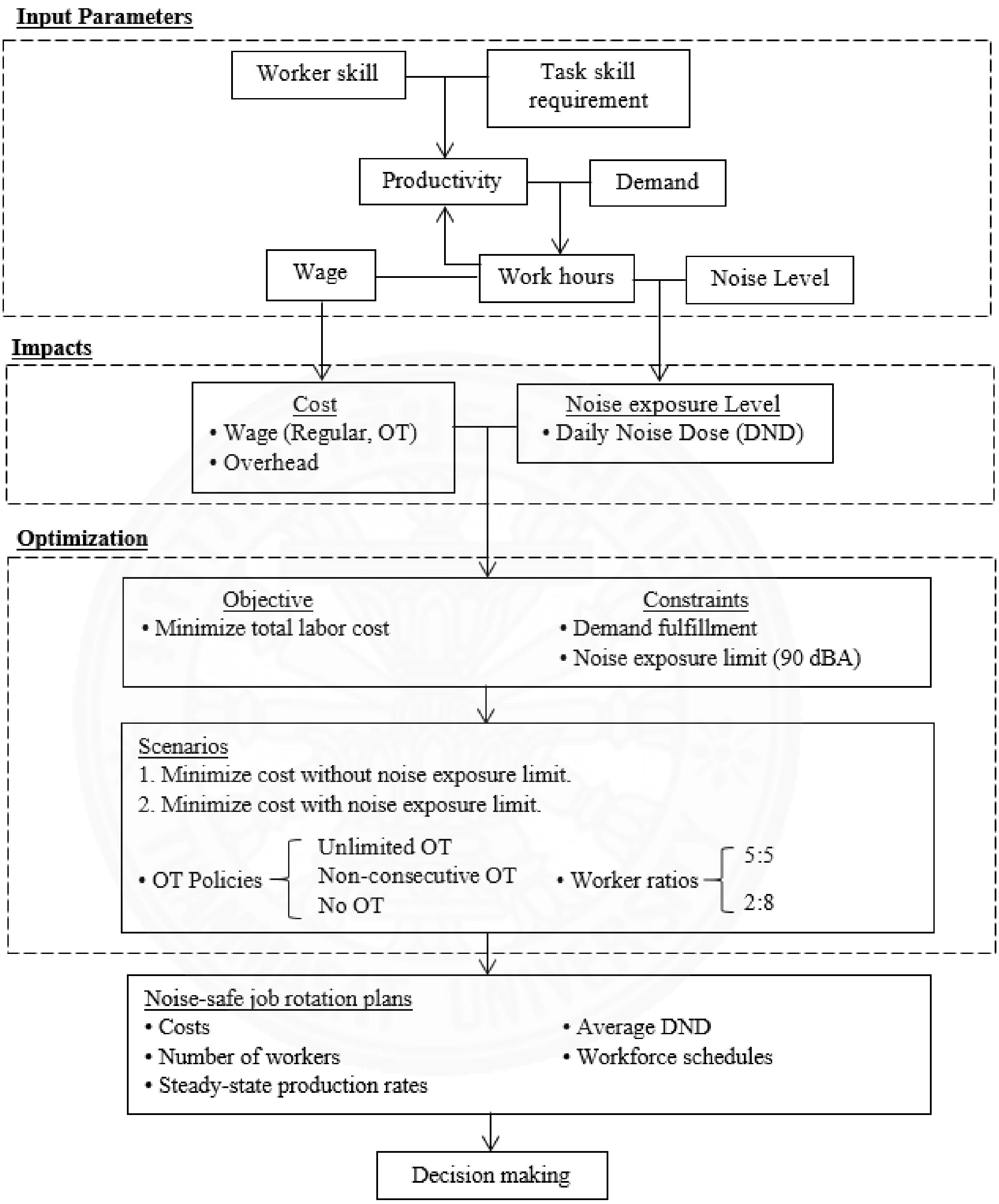


Figure 3.1 Summary of model framework

Chapter 4
Results and Discussion

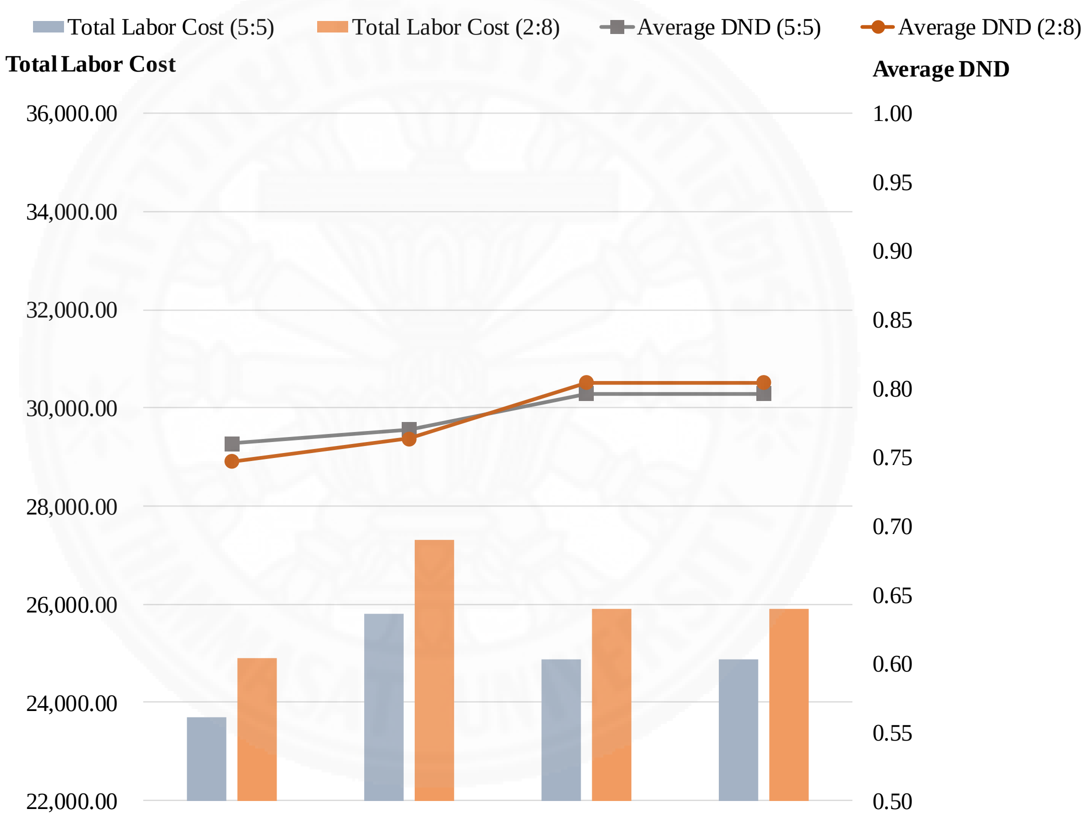
Gurobi optimizer in OpenSolver version 2.9.0 is used as the optimization tool. First, the problem is solved to obtain the optimal solutions where there is no overtime allowed. The solutions of the no-overtime scenario, with and without noise exposure control, are shown in Table 4.1. This is to validate the model's noise exposure control ability, and to observe its effects on process performance. Without a noise exposure limit, all workers are exposed to hazardous cumulative noise levels. When operated under a noise exposure limit of 90 dBA, workers are subjected to an increased number of job rotations, to ensure a noise-safe working schedule. As a result, there are a fewer number of shifts that workers can operate at their steady-state production rates. The noise exposure criterion is achieved at the expense of higher labor cost, due to the need to hire skilled workers to achieve sufficient production capacity.

Table 4.1 Performance comparison between job rotation plans without and with noise exposure limit

	without Noise Exposure Limit	**with Noise Exposure Limit**
Total Labor Cost (THB)	23,700	25,800
Maximum Daily Noise Dose	1.516	0.923
Number of workers*	6 (6)	7 (0)

*Total number of workers (number of workers with DND > 1.0)

Here, the effects of different overtime policies on the process performance are investigated. The case being considered reflects the situation where the cost of acquiring additional workers is more expensive than assigning existing workers to work overtime, to achieve sufficient production capacity. The ability of noise-safe job rotation plans, to react to higher levels of demand under limited availability of skilled workers, is also investigated. In Figure 4.1, the labor cost and average DND among workers associated with no-overtime and different overtime policies are shown. The average DND is used here, as opposed to the maximum DND previously used, to represent the overall noise exposure burden of the workforce. The use of overtime provides lower-cost alternatives, where workers are exposed to slightly higher DND levels, compared to the no-overtime scenario. With overtime shifts, it becomes possible to maintain sufficient levels of production capacity, using smaller workforce sizes. In all cases, when the number of skilled workers is limited to 2, more unskilled workers are needed to achieve the required production capacity, resulting in higher labor costs.

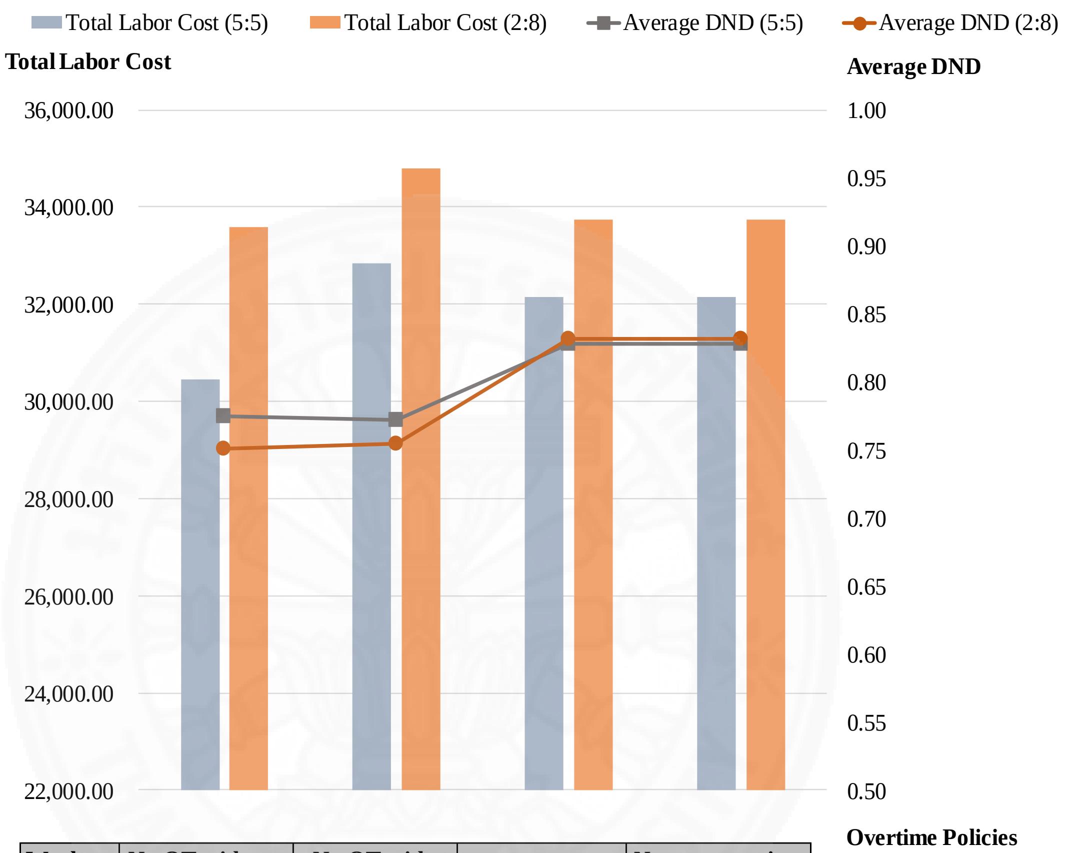


	Workers Ratio	No OT without Noise	No OT with Noise	Unlimited OT	Non-consecutive OT
No. of Workers	5:5	6(5)	7(4)	6(5)	6(5)
	2:8	7(2)	8(2)	7(2)	7(2)

* Total (Skilled)

Figure 4.1 Performance comparison between job rotation plans under different overtime policies and workers ratio

In this part of our result analysis, the job rotation scheduling problem is solved at a demand increase of 30%, the comparison of total cost and average DND in each overtime policy and worker ratio is shown in Figure 4.2.



	Workers Ratio	No OT without Noise	No OT with Noise	Unlimited OT	Non-consecutive OT
No. of Workers	5:5	8(5)	9(4)	8(4)	8(4)
	2:8	10(2)	10(2)	9(2)	9(2)

* Total (Skilled)

Figure 4.2 Performance comparison between job rotation plans under different overtime policies and workers ratio at 130% demand levels

The increase in demand requires the workforce to generate more outputs. For the no-overtime policy, more workers are hired, resulting in higher overhead cost. For the policies with overtime, workers are assigned with more overtime shifts, leading to more intense DNDs on workers. Here, our focus is on the unlimited and non-consecutive overtime policies, due to their lower costs, compared to the no-overtime policy. At a demand increase of 30%, the average DND among workers increases by about 4 %. The details of worker noise exposure, shift assignment, and costs, associated with the no overtime without noise restriction, the no overtime with noise restriction, the unlimited overtime and the non-consecutive overtime policies, are shown in Tables 4.2, 4.3, 4.4 and 4.5, respectively. From Table 4.4 and 4.5, the job rotation plans under unlimited and non-consecutive overtime policy keep the noise exposure level of all workers under the noise exposure limit, with the same amount of cost. Another interesting observation is that, under the non-consecutive overtime policy, overtime shifts are more evenly distributed among workers. For safety, the non-consecutive overtime job rotation plan offers safer working conditions for workers in the long term. The evenly distributed work hours help to prevent any worker from obtaining excessive cumulative effects of occupational exposure to noise and other hazards.

Table 4.2 Tasks and daily noise dose of job rotation schedule under no overtime policy without noise restriction, limited skilled workers and 130% demand levels

	Workforce	Tasks (MS,AS,OS) DND						Number of Shifts		Workday
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Regular	Overtime	
Skilled Worker	1	W2,W3,- 0.923	W2,W3,- 0.923	W2,W2,- 1.516	W2,W2,- 1.516	W3,W3,- 0.330	W3,W3,- 0.330	12	0	6
	2	W3,W3,- 0.330	W3,W2,- 0.923	W1,W1,- 1.149	W2,W2,- 1.516	W3,W3,- 0.330	W3,W3,- 0.330	12	0	6
Unskilled Worker	1	W4,W4,- 0.660	W4,W4,- 0.660	W4,W1,- 0.904	W4,W1,- 0.904	W5,W5,- 0.500	W4,W4,- 0.660	12	0	6
	2	W4,W4,- 0.660	W5,W5,- 0.500	W4,W4,- 0.660	W5,W5,- 0.500	- 0.000	W4,W4,- 0.660	10	0	5
	3	W5,W5,- 0.500	W5,W5,- 0.500	W5,W5,- 0.500	W4,W4,- 0.660	W4,W4,- 0.660	W1,W1,- 1.149	12	0	6
	4	W4,W4,- 0.660	W1,W1,- 1.149	W5,W5,- 0.500	W4,W4,- 0.660	W1,W5,- 0.824	W5,W5,- 0.500	12	0	6
	5	W1,W1,- 1.149	W5,W5,- 0.500	W1,W1,- 1.149	W1,W1,- 1.149	W4,W4,- 0.660	W4,W4,- 0.660	12	0	6
	6	W4,W4,- 0.660	W1,W5,- 0.824	W1,W1,- 1.149	W4,W4,- 0.660	- 0.000	W1,W1,- 1.149	10	0	5
	7	W5,W5,- 0.500	W5,W5,- 0.500	W4,W4,- 0.660	W4,W4,- 0.660	W1,W5,- 0.824	W5,W5,- 0.500	12	0	6
	8	W4,W4,- 0.660	- 0.000	W4,W4,- 0.660	- 0.000	W4,W5,- 0.580	W1,W1,- 1.149	8	0	4
								18,600	-	15,000*
				Average DND		0.751		**Total Cost**		33,600 THB

* Overhead cost

Table 4.3 Tasks and daily noise dose of job rotation schedule under no overtime policy with noise restriction, limited skilled workers and 130% demand levels

	Workforce	**Tasks (MS,AS,OS) DND**						**Number of Shifts**		**Workday**
		Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Regular**	**Overtime**	
Skilled Worker	1	W2,W3,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	12	0	6
	2	W3,W3,- 0.330	W2,W3,- 0.923	W2,W3,- 0.923	W3,W3,- 0.330	W3,W2,- 0.923	W2,W3,- 0.923	12	0	6
Unskilled Worker	1	W4,W4,- 0.660	W1,W5,- 0.824	W1,W4,- 0.904	W4,W4,- 0.660	W1,W5,- 0.824	W1,W5,- 0.824	12	0	6
	2	W1,W5,- 0.824	W1,W4,- 0.904	W4,W4,- 0.660	W1,W5,- 0.824	W5,W5,- 0.500	W5,W5,- 0.500	12	0	6
	3	W4,W5,- 0.580	W1,W5,- 0.824	W4,W4,- 0.660	W4,W4,- 0.660	W1,W5,- 0.824	W1,W4,- 0.904	12	0	6
	4	W1,W5,- 0.824	W1,W4,- 0.904	W1,W4,- 0.904	W1,W4,- 0.904	W4,W4,- 0.660	W1,W4,- 0.904	12	0	6
	5	W5,W5,- 0.500	W1,W5,- 0.824	W5,W5,- 0.500	W4,W4,- 0.660	W4,W1,- 0.904	W1,W4,- 0.904	12	0	6
	6	W4,W5,- 0.580	W4,W4,- 0.660	W5,W1,- 0.824	W1,W4,- 0.904	W4,W1,- 0.904	W5,W5,- 0.500	12	0	6
	7	W5,W5,- 0.500	W4,W4,- 0.660	W4,W4,- 0.660	W5,W5,- 0.500	W4,W1,- 0.904	W4,W4,- 0.660	12	0	6
	8	W5,W5,- 0.500	-,W1,- 0.574	W1,W4,- 0.904	W4,W1,- 0.904	W4,W4,- 0.660	W5,W1,- 0.824	11	0	6
								19,800	-	15,000*
				Average DND		0.754		**Total Cost**		34,800 THB

*Overhead cost

Table 4.4 Tasks and daily noise dose of job rotation schedule under unlimited overtime policy, limited skilled workers and 130% demand levels

	Workforce	Tasks (MS,AS,OS) DND						Number of Shifts		Workday
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Regular	Overtime	
Skilled Worker	1	W3,W2,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	W3,W2,- 0.923	W3,W2,- 0.923	12	0	6
	2	W3,W3,- 0.330	W2,W3,- 0.923	W3,W3,- 0.330	W2,W3,- 0.923	W3,W2,- 0.923	W3,W2,- 0.923	12	0	6
Unskilled Worker	1	W5,W1,- 0.824	W4,W1,- 0.904	W4,W1,- 0.904	W1,W5,- 0.824	W4,W1,- 0.904	W1,W5,- 0.824	12	0	6
	2	W1,W5,- 0.824	W4,W1,- 0.904	W5,W5,- 0.500	W5,W5,- 0.500	W5,W5,- 0.500	W5,W5,- 0.500	12	0	6
	3	W4,W1,- 0.904	W1,W5,- 0.824	W5,W1,- 0.824	W1,W5,- 0.824	W1,W5,- 0.824	W4,W1,- 0.904	12	0	6
	4	W4,W1,- 0.904	W4,W4,W4 0.990	W4,W1,- 0.904	W5,W1,- 0.824	W4,W4,W4 0.990	W4,W4,W4 0.990	12	3	6
	5	W1,W5,- 0.824	W4,W4,W4 0.990	W4,W4,W4 0.990	W4,W4,W4 0.990	W5,W5,W5 0.750	W4,W4,W4 0.990	12	5	6
	6	0.000	0.000	0.000	0.000	0.000	0.000	0	0	0
	7	W5,W5,- 0.500	W1,W4,- 0.904	W4,W1,- 0.904	W1,W5,- 0.824	W4,W1,- 0.904	W1,W4,- 0.904	12	0	6
	8	W4,W4,- 0.660	W1,W5,- 0.824	W4,W4,W4 0.990	W5,W1,- 0.824	W1,W4,- 0.904	W5,W5,W5 0.750	12	2	6
								18,000	2,250	13,500*
				Average DND		0.832		**Total Cost**		33,750 THB

*Overhead cost

Table 4.5 Tasks and daily noise dose of job rotation schedule under non-consecutive overtime policy, limited skilled workers and 130% demand levels

	Workforce	Tasks (MS,AS,OS) DND						Number of Shifts		Workday
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Regular	Overtime	
Skilled Worker	1	W2,W3,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	W3,W2,- 0.923	W3,W2,- 0.923	12	0	6
	2	W3,W2,- 0.923	W2,W3,- 0.923	W2,W3,- 0.923	W3,W3,- 0.330	W3,W3,- 0.330	W2,W3,- 0.923	12	0	6
Unskilled Worker	1	W1,W5,- 0.824	W1,W5,- 0.824	W1,W5,- 0.824	W4,W4,- 0.660	W1,W5,- 0.824	W1,W4,- 0.904	12	0	6
	2	W1,W5,- 0.824	W1,W5,- 0.824	W4,W1,- 0.904	W5,W5,- 0.500	W1,W5,- 0.824	W5,W1,- 0.824	12	0	6
	3	0.000	0.000	0.000	0.000	0.000	0.000	0	0	0
	4	W4,W4,- 0.660	W1,W4,- 0.904	W5,W5,W5 0.750	W1,W4,- 0.904	W4,W1,- 0.904	W4,W1,- 0.904	12	1	6
	5	W4,W4,W4 0.990	W1,W5,- 0.824	W5,W5,W5 0.750	W1,W5,- 0.824	W4,W4,- 0.660	W5,W5,- 0.500	12	2	6
	6	W4,W1,- 0.904	W4,W4,W4 0.990	W1,W4,- 0.904	W5,W5,- 0.500	W1,W5,- 0.824	W4,W4,W4 0.990	12	2	6
	7	W4,W4,W4 0.990	W5,W1,- 0.824	W1,W5,- 0.824	W1,W5,- 0.824	W4,W1,- 0.904	W4,W4,W4 0.990	12	2	6
	8	W4,W4,W4 0.990	W1,W5,- 0.824	W4,W4,W4 0.990	W1,W4,- 0.904	W1,W4,- 0.904	W5,W5,W4 0.830	12	3	6
								18,000	2,250	13,500*
				Average DND		0.832		**Total Cost**		33,750 THB

* Overhead cost

Chapter 5
Conclusions and Recommendations

5.1 Conclusions

This study develops a noise-safe job rotation model, which enables workers to fulfill demand requirements, while ensuring that their noise exposure levels are below the permissible limit. The proposed model is suitable for use when the productivity of tasks can be affected by working continuity, worker skill, and task skill requirements. When performing tasks at the same workstation for more than one consecutive shift, workers are assumed to perform tasks at steady-state rates. The inclusion of demand requirements and overtime shifts is made in our numerical example, to address the scenario where some workers are required to work overtime to obtain a sufficient production capacity, exposing them to industrial noise over an extended period of time. The limited availability of skilled labor is also considered. This gives a good representation of the occupational conditions of manufacturing SMEs. It is worth mentioning that the incorporation of demand requirements, which is usually neglected in the literature, helps improve the practicality of the noise-safe job rotation approach.

The proposed job rotation model is formulated with the objective of cost minimization, using the integer programming technique. This paper evaluates overtime policy alternatives in the context of noise-safe job rotation under the aforementioned conditions. First of all, the use of our job rotation model can reduce the noise exposure levels of workers to safe levels. The impact of noise on the total cost is foreseen. Then, the evaluation of overtime policy alternatives demonstrates to decision makers that, when overtime is used to increase production capacity, workers who work overtime are exposed to industrial noise over a prolonged period, resulting in a more intense average daily noise dose among workers. Despite its adverse effect on noise exposure, the use of overtime can offset the cost of hiring additional workers. According to the results, the adequacy of a skilled workforce is the most significant factor to be considered for cost-effective noise-safe job rotation. The selection of an overtime policy also affects the operating cost considerably. Unlimited and non-consecutive overtime policies offer promising levels of overhead cost saving and are attractive solutions, particularly because their average DND is still well below the permissible limit of 1.0. Finally, the ability of job rotation to simultaneously control noise exposure and meet demand is verified at a demand level of 130%. The increases in DND among workers and labor cost are observed. The performances of unlimited and non-consecutive overtime policies are compared. It is pointed out that decision makers can select the most appropriate overtime policy, based on how overtime shifts are distributed among workers over the planning horizon. Under non-consecutive overtime policy, the amount of overtime a worker is allowed to work in a given time period is restricted. Overtime shifts are more evenly distributed among workers.

5.2 Limitations

The main limitation of the current study is that the current optimization tool is only capable for solving job rotation problems with small- to medium-sized workforces under a short planning horizon. For large-scale problems, with increased numbers of workers, working shifts, and workdays, other optimization tools such as Cplex, or other problem solving methods such as heuristic approaches may be used for improved solving capacity. Alternatively, workers can be treated as groups instead of individuals. Each group may contain multiple numbers of workers with similar skills and preferences. Also, the demand requirements used in the model are assumed to be known and constant, while in reality, actual demand requirements are more likely to be stochastic. Lastly, this job rotation model may not be as effective when there are more than one occupational hazards, besides noise hazard. Rotating workers based on noise levels alone may potentially cause other occupational health-related issues.

5.3 Recommendations

The present state of the proposed model, with the inclusion of overtime shifts and a multiple-day planning period, serves as a platform for developing job rotation approaches capable of dealing with workers' job satisfaction. Future research can consider the preferences of workers on the amount of overtime shifts or work hours per week, to improve their job satisfaction. The ability of a job rotation plan to assign workers to work overtime during their preferred time slots can be realized as well. Other occupational hazards, associated with muscle loading, lifting task, and exposure to excessive heat or vibration, can be considered along with noise hazard. It is also worthwhile to consider the linkage between demand and noise exposure in more detail, as they are the main conflicting requirements. An examination of demand and noise level uncertainties can be made. Lastly, workers' learning ability can be considered over a longer planning period.

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