



รายงานวิจัยฉบับสมบูรณ์

โครงการ การใช้ระบบสับเปลี่ยนหน้าที่ในการทำงานเพื่อลดอัตราการเจ็บที่หลังของคนงาน
(Apply Job Rotation to Minimize Worker Low Back Injuries)

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(Apply Job Rotation to Minimize Worker Low Back Injuries)

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สนับสนุนโดยทบวงมหาวิทยาลัย และสำนักงานกองทุนสนับสนุนการวิจัย

(ความเห็นในรายงานนี้เป็นของผู้วิจัย ทบวงฯ และสกว. ไม่จำเป็นต้องเห็นด้วยเสมอไป)

โครงการ การใช้ระบบสลับเปลี่ยนหน้าที่ในการทำงานเพื่อลดอัตราการเจ็บที่หลังของพนักงาน (Apply Job Rotation to Minimize Worker Low Back Injuries)

บทคัดย่อ

จากสถิติพบว่าพนักงานจำนวนมากได้รับบาดเจ็บจากการทำงานในระบบการขนถ่ายสินค้าด้วยกำลังคน และระดับการบาดเจ็บของพนักงานอยู่ในขั้นรุนแรง งานวิจัยชิ้นนี้เสนอวิธีการใช้หลักการสลับเปลี่ยนหน้าที่ในการทำงานเพื่อลดอัตราการเจ็บของพนักงาน งานวิจัยได้ถูกแบ่งออกเป็น 2 ส่วน กล่าวคือ ในส่วนที่ 1 เป็นการศึกษาเทคนิคริกอร์สเพื่อพัฒนาตารางการทำงานของพนักงานเพื่อลดอัตราการเจ็บที่หลังของพนักงาน และพิจารณาประโยชน์ที่ได้รับจากการรู้ข้อมูล ในระดับต่างๆ 3 ระดับเพื่อช่วยในการตัดสินใจ คือ 1) รู้ข้อมูลปริมาณงานในอดีตเท่านั้น 2) รู้ข้อมูลปริมาณงานที่เกิดขึ้นทันทีที่งานนั้นเกิดขึ้น 3) รู้ข้อมูลปริมาณงานที่จะเกิดขึ้นล่วงหน้า ผลการวิจัยพบว่าความรู้ข้อมูลปริมาณงานที่เกิดขึ้นทันทีและรู้ข้อมูลปริมาณงานที่จะเกิดขึ้นล่วงหน้า จะช่วยลดจำนวนวันที่พนักงานหยุดงานเนื่องจากการบาดเจ็บได้ และประโยชน์จากการรู้ข้อมูลจะเพิ่มขึ้นอย่างมากเมื่อปริมาณงานที่เกิดขึ้นในระหว่างวันมีความแตกต่างกันมากเมื่อเปรียบเทียบกับเมื่อปริมาณงานที่เกิดขึ้นในระหว่างวันมีความแตกต่างกันน้อย ในส่วนที่ 2 เป็นการพัฒนาตารางการทำงานของพนักงาน ที่ทำให้เกิดค่าแรงรวมและค่าความสูญเสียรวมจากการบาดเจ็บต่ำที่สุด โดยพิจารณากรณีที่จำนวนคนงานน้อยกว่าหรือเท่ากับจำนวนงาน ผู้วิจัยได้พัฒนาวิธีการสร้างรูปแบบทางคณิตศาสตร์ชนิดมิกซ์อินทีเจอร์ แบบ 2 ขั้นตอนขึ้น เพื่อสร้างตารางการทำงานของพนักงานด้วยวิธีการนี้ ตารางการทำงานของพนักงานที่ได้จะทำให้เกิดค่าแรงรวมต่ำที่สุด และความสูญเสียจากการบาดเจ็บของพนักงานน้อย

Abstract

In manual material-handling environments, a large number of workforce injuries are sustained each year and the injuries are often of a severe nature. This research investigates a job rotation methodology to reduce the potential for workforce injuries. Two aspects of the research have been done. The first aspect is to study a recourse technique and develop worker schedules using a heuristic method to minimize low back injuries and evaluate the value of information based upon 3 levels of information including 1) only historical task demand information is known, 2) task demand information is known in real-

time as the tasks are completed, and 3) where task demands are known in advance. The results show that real-time and advance task demand information can provide significant benefits with regard to reducing the maximum number of worker lost days due to low back injuries. When task demands have high variability, utilizing task demand information to generate worker schedules is more helpful as compared to the case where task demands do not vary significantly. The second aspect develops worker schedule to minimize the total labor cost and the total injury loss when the number of worker is less than or equals to the number of tasks. This research also considers worker skill requirement to perform tasks. A two-stage mixed integer programming is proposed as a solution methodology. With this two-stage MIP model, worker schedule with the lowest total cost and less total injury loss can be developed.

1. Executive Summary

1.1 ความสำคัญและที่มาของปัญหาที่ทำการวิจัย

In order to remain successful in a competitive market, a manufacturing company needs to develop an operations strategy that allows it to improve product quality and quantity, deliver products on time, and reduce inventory. Since the human element is a key factor in running a company, it should be included in the operations plan. Currently, workers are primarily assigned to tasks based on their experience and knowledge of how to run the required machines or perform the required operations. Workers are often either selected by management or volunteer for the jobs and are later approved by management.

Assigning workers based upon their experience and skills can be a way to improve productivity and product quality. On the other hand, it may lead to a schedule where workers always perform the same tasks. Performing the same tasks repetitively with the same posture for a long period of time may accrue stress, induce boredom, and create fatigue. Moreover, it may be a cause of occupational illness and injury, which results in a significant amount of lost time and money

Generally, the prevention of these occupational injuries can be done in many ways including 1) engineering solutions such as job redesign, workplace redesign, tool redesign, and automation, 2) administrative controls such as revision of work-rest schedules, rotating workers among jobs, training, exercises, and job/career changes, and 3) personal protective equipment. Job rotation, which is one of administrative control solutions, is a method of rotating workers across various tasks that have different physical and mental demands over time. It is a promising method to manage worker fatigue, reduce worker stress and injuries, reduce errors, and increase worker satisfaction. Job rotation has been implemented in many settings; for example, refuse-collecting, cashiering, and poultry processing, sawmill operation.

Although job rotation is a promising means to manage daily exposure due to physical stress, poorly designed job rotation plans can increase worker stress. Previous researches have been done to develop a heuristic methodology to generate a proper worker rotation schedule. However, those researches applied only historical data to generate worker rotation schedule and also relaxed some practical constraints such as skill requirement to operate tasks.

1.2 วัตถุประสงค์

1.2.1 Study a job rotation method to reduce the potential of worker low back injuries and reduce an amount of time and money spent in solving this problem.

1.2.2 Study a recourse technique and develop worker schedules to minimize low back injuries and evaluate the value of information based upon 3 levels of information.

1.2.3 Explore methodologies that are proper to generate worker rotation plans to minimize worker low back injury considering worker skill requirement constraints.

1.3 ระเบียบวิธีการวิจัย

This research can be organized into 2 phases:

1) study a recourse technique and develop worker schedules to minimize low back injuries and evaluate the value of information based upon 3 levels of information including 1) task demands that are known from history, 2) task demands that are collected right after they have occurred in real-time, and 3) task demands that are known in advance.

2) Explore methodologies that are proper to generate worker rotation plans to minimize worker low back injury considering worker skill requirement constraints in case of the number of workers is greater than or equals to the number of tasks.

1.3.1 Phase 1: Value of Information to develop worker rotation schedule

The problem considers assigning workers to tasks in a manual-lifting environment where the number of lifting tasks and the number of workers are equivalent. During each period, a worker can perform only one task and a task can be done by only one worker. This research presents a methodology to generate a job rotation schedule to reduce the potential for worker low back injury based upon levels of task demand information. Three levels of task demand information are explored including 1) task demands that are known from history, 2) task demands that are collected right after they have occurred in real-time and 3) task demands that are known in advance.

To assess worker stress due to lifting, the Job Severity Index (JSI) is applied. The JSI is a function of lifting weight to worker lifting capacity. From worker low back injury statistics and studies, tasks that have low JSI values imply low injury potential and tasks that have high JSI values imply high injury potential. However, economical loss due to low back injuries is not linearly dependent on JSI. For example, the injury expense for workers working at JSI levels above 1.5 is \$60,000 per 100 FTE (200,000 exposure hours) as compared with an injury expense of only \$1,000 per 100 FTE for workers working at JSI levels of 1.5 and below. Therefore, an objective function based upon the number of lost working days due to lifting is developed. The number of lost days can be represented as a piecewise linear function of JSI.

After developing a specific objective function, which is minimizing the maximum number of worker lost days for any of the workers, a greedy with diversification heuristic is developed to create job rotation schedules based upon three levels of task demand information. The greedy with diversification heuristic includes a greedy method and a diversification technique. The greedy method is used to find a local optimal solution while the diversification technique is used as a mechanism to escape from the local optimum by perturbing the local optimal solution. The greedy and diversification processes are repeated until a stopping criterion is met.

This heuristic method is adjusted for each level of task demand information. In the case where the current task demands are unknown, the heuristic method searches for a robust worker schedule based upon 1000 historical task demands from the simulation program. In the case that task demands are obtained once they have already occurred, a robust worker schedule generated from historical task demand data is used as an initial solution for the heuristic method. Once the actual task demands during the first time interval have already occurred, the heuristic method adjusts the workers' schedules for the remaining hours based upon the actual task demands during the previous hour. For the case where all task demands are known in advance, the problem characteristics change from stochastic to deterministic. The heuristic method is also applied to this deterministic case to generate worker schedules that minimize the maximum number of worker lost days for any of the workers.

1.3.2 Phase 2: Mathematical models to develop worker schedules considering worker skills.

This research proposes worker assignment models to develop worker rotation schedule considering worker skills to perform tasks when the number of workers is greater than or equals to the number of tasks. Two main objectives are considered in the proposed models including the total labor cost and the total injury loss. Lifting tasks and low back injury are utilized as example in the proposed models.

Detail of the models is now described. During each working period, all tasks must be performed but a worker may or may not be chosen to perform a task. A worker can be assigned to a task only if he/she has higher skill level than the skill level requirement of that task. If a worker is assigned to at least one task, he/she will be in the payment list. Otherwise that worker is out of the payment list. Each worker must work individually. No more than one worker performs the same task and no more than one task is assigned to a worker during the same time duration. However, workers can be rotated to perform different tasks at the end of each hour. Rotating workers could be a way to reduce the potential of worker injury.

This research proposes two stage mixed integer programming model to determine worker rotation schedule. When the number of workers is equivalent to the number of tasks, the first stage is used to develop worker schedule that minimizes the maximum JSI value. Then the second stage is applied to minimize the total number of worker lost day while keeping all JSI values below the maximum value of the first stage or 1.5, which is the threshold. In case of the maximum JSI value that is greater than 1.5, an additional number of workers should be considered. When the number of workers is greater than the number of tasks, the proper number of workers should be determined. Using a large number of workers increases the total labor cost while using a small number of workers increases the injury loss. The first stage model is proposed to minimize the total labor cost while maintain the JSI value of workers to be below the threshold of 1.5. After the total labor cost is determined, an improved worker assignment can be developed by the second stage model, which is minimizing the total number of worker lost day while keeping the maximum JSI value to be below the threshold and the total labor cost to be below the value from the first stage.

1.4 ผลการวิจัย

1.4.1 Experimental results for Phase I

- As more task demand information is made available for scheduling the average maximum number of worker lost days decreases. The average maximum number of worker lost days in the case that only the historical task demands are known is 7.2 days more than the average maximum number of worker lost days in the case that task demands are known in real time and the average maximum number of worker lost days in the case that task demands are known in real time is 5.7 days more than the average maximum number of worker lost days in the case that task demands are known in advance.
- When task demands have high variability, utilizing task demand information to generate worker schedules is more helpful as compared to the case when task demands do not vary significantly.

1.4.2 Experimental results for Phase II

- When the number of workers and tasks are equivalent, the maximum JSI value from the first stage model can be classified into 2 groups: the maximum JSI value that is less than or equals to 1.5 and the maximum JSI value that is greater than 1.5. In case that the maximum JSI value that is less than or equals to 1.5, the total number of lost days from the second stage model decreases on average 0.25 days. However, if the maximum JSI value is set to 1.5, the total number of lost days from the second stage model decreases, on average 1.18 days.
- When the number of workers is greater than the number of tasks, the first stage determines the proper group of workers that minimizes the total labor cost while keeping the maximum JSI value to be below 1.5. If the number of workers is allowed to increase, the total number of lost days decreases on average 182.65 days. While maintaining the total labor cost the same, the second stage decreases the number of lost days on average 5.26 days.

1.5 ผลงานที่ส่งเพื่อตีพิมพ์

1.5.1 Wipawee Tharmmaphornphilas, and Bryan A. Norman, "Job Rotation Plans for Reducing Low Back Injuries with Real-Time Information," Proceedings of the 13rd Industrial Engineering Research Conference, May 16-19, 2004, Houston, Texas, USA, CD Rom format.

1.5.2 Wipawee Tharmmaphornphilas, and Bryan A. Norman, "The Value of Information to Develop Job Rotation Plans to Reduce Worker Low Back Injuries," submitted to International Journal of Industrial Ergonomics.

1.5.3 Wipawee Tharmmaphornphilas, "A Multi-Objective Mixed Integer Programming to Develop Worker Schedules Considering Worker Injury," submitted to International Journal of Production Research

2. เนื้อหางานวิจัย

2.1. ความสำคัญและที่มาของปัญหาที่ทำการวิจัย

In order to remain successful in a competitive market, a manufacturing company needs to develop an operations strategy that allows it to improve product quality and quantity, deliver products on time, and reduce inventory. Since the human element is a key factor in running a company, it should be included in the operations plan. Currently, workers are primarily assigned to tasks based on their experience and knowledge of how to run the required machines or perform the required operations. Workers are often either selected by management or volunteer for the jobs and are later approved by management [5.1].

Assigning workers based upon their experience and skills can be a way to improve productivity and product quality. On the other hand, it may lead to a schedule where workers always perform the same tasks. Performing the same tasks repetitively with the same posture for a long period of time may accrue stress, induce boredom, and create fatigue. Moreover, it may be a cause of occupational illness and injury, which results in a significant amount of lost time and money [5.2, 5.3]. For example, in 1994, about 11.4 billion dollars was spent on worker's compensation cost for low back injuries. The Bureau of Labor

Statistics (BLS) conducted a survey to investigate workplace injuries. The survey consisted of a random sample of about 250,000 private sector establishments. The BLS reported that in 1994, approximately 705,800 injury cases (32%) were the result of overexertion or repetitive motion. Specifically, there were 367,424 injuries due to overexertion in lifting (65% affected the back); 93,325 injuries due to overexertion in pushing or pulling objects (52% affected the back); 68,992 injuries due to overexertion in holding, carrying, or turning objects (58% affected the back); 92,576 injuries or illnesses due to repetitive motion, including typing or key entry, repetitive use of tools, and repetitive placing, grasping, or moving of objects other than tools; and 83,483 injuries or illnesses due to other and unspecified overexertion events [5.4].

Since low back injury is one of the most serious occupational injuries and lifting tasks are the major cause of this injury, this research begins by selecting lifting tasks to be an example of a task requiring repetitive motions and considering low back pain to be an example of a corresponding occupational injury. Even though the direct research scope only considers lifting tasks and low back pain, the solution methodology can be applied to other kinds of repetitive motions and injuries. For example, it can be used to reduce the potential of hearing loss due to performing tasks for long periods of time in high noise pressure level environments.

Generally, the prevention of these occupational injuries can be done in many ways including 1) engineering solutions such as job redesign, workplace redesign, tool redesign, and automation, 2) administrative controls such as revision of work-rest schedules, rotating workers among jobs, training, exercises, and job/career changes, and 3) personal protective equipment [5.5]. A significant amount of money is needed to be spent when applying engineering solutions. Moreover, no perfect workplace can be achieved within reasonable financial constraints, or even if there are no financial limits [5.2]. For low back injuries, there are not many personal protective devices for preventing workers from

accruing stress. Therefore, administrative controls are often the most cost effective method for solving this problem.

Job rotation, which is one of administrative control solutions, is a method of rotating workers across various tasks that have different physical and mental demands over time. It is a promising method to manage worker fatigue, reduce worker stress and injuries, reduce errors, and increase worker satisfaction. Job rotation has been implemented in many settings; for example, refuse-collecting [5.6], cashiering [5.7], and poultry processing [5.8], sawmill operation [5.9].

Although job rotation is a promising means to manage daily exposure due to physical stress, poorly designed job rotation plans can increase worker stress. Moreover, when job rotation is applied in real settings, one factor that makes finding an effective job rotation plan difficult is worker task uncertainty. Uncertainty is unavoidable in the real world. A manufacturing company faces different aspects of uncertainty every day such as machine breakdowns, material delays, and worker absenteeism. Uncertainty in task demands is another major problem that increases difficulty in operating a firm. Task demands often cannot be known in advance or they may change over time. For example, there may be unexpected orders, orders may be changed, or orders with high priority may enter into the process. Problems with an uncertain nature are known as stochastic problems.

This research focuses on finding the ways to develop job rotation plans for workers who work in manual lifting industry to reduce the potential of low back injury. To simulate real settings, uncertain task demands and non-identical workers are assumed. Similar research has been done by Carnahan et al. [5.10] and Tharmmaphornphilas [5.11]. However, there are some other aspects that should be explored to provide more practical research results.

Carnahan et al. [5.10] implemented a genetic algorithm to provide multiple good job rotation schedules and then used a clustering method to determine a general set of rules governing

task exposure for each group of workers. Job Severity Index (JSI) [5.12, 5.13] was used as a measure of injury potential that workers receive from performing lifting tasks. Tharmmapornphilas [5.11] studied the same problem as Carnahan et al.; however, the number of worker lost days due to low back injuries was used as a system performance measure. A greedy with forced diversification approach, which is a fast heuristic search method, was applied to develop a robust job rotation schedule. This method performs well under uncertainty.

It was assumed in both Carnahan et al. [5.10] and Tharmmapornphilas [5.11] that workers are fully trained and workers have enough ability to perform any task. In the real world, some tasks may require specific skills. A worker may not be able to perform every task. Therefore, this research interests in introducing skill requirement constraints into the problem. These skill requirement constraints make the problem harder but more realistic.

Both Carnahan et al. [5.10] and Tharmmapornphilas [5.11] heuristic methods deal with uncertainty by generating the rotation plans based upon historical data. Using only historical data provides good robust rotation plans. However, when the real time information can be known, the better worker schedules may receive by applying a recourse technique. Scheduling with recourse generates rotation plans based upon realizations of the task demands. Instead of using only the approximated data, actual task demands that have occurred from the previous periods are used as part of the information to generate worker schedules for the next period. Therefore, when there is high variation among task demands, the recourse technique can provide more effective schedules.

This research can be organized into 2 phases:

- 1) Study a recourse technique and develop worker schedules to minimize low back injuries and measure the value of information based upon 3 levels of information. The detail of this study is available in section 2.2.

2) Explore methodologies that are proper to generate worker rotation plans to minimize worker low back injury considering worker skill requirement constraints. The detail of this study is available in section 2.3.

2.2 Phase 1: Value of Information to develop worker rotation schedule

2.2.1 Problem statement

The problem considers assigning workers to tasks in a manual-lifting environment where the number of lifting tasks and the number of workers are equivalent. During each period, a worker can perform only one task and a task can be done by only one worker. This research presents a methodology to generate a job rotation schedule to reduce the potential for worker low back injury based upon levels of task demand information. Three levels of task demand information are explored including 1) task demands that are known from history, 2) task demands that are collected right after they have occurred in real-time and 3) task demands that are known in advance.

To simulate real settings, the lifting task demands may change over time and workers' lifting profiles vary. The lifting task demands include the lifting weight, the lifting frequency, the lifting height, and the horizontal lifting distance. Task demands, except the lifting height, are uniformly distributed with different ranges during each period. Each lifting task may be comprised of small subtasks determined by the lifting height. The number and types of subtasks can be different. Six different types of subtasks are considered: subtask FK is the task of lifting from floor level to knuckle height, subtask FS is the task of lifting from floor level to shoulder height, subtask FR is the task of lifting from floor level to reach height, subtask KS is the task of lifting from knuckle height to shoulder height, subtask KR is the task of lifting from knuckle height to reach height, and subtask SR is the task of lifting from shoulder height to reach height.

Example lifting task demands are illustrated in Table 1. This task is composed of 2 subtasks determined by the lifting heights, FK and SR. The lifting weight, the lifting frequency, and

the horizontal lifting distance are uniformly distributed with different ranges during each period. For example, the lifting weights of subtask FK are uniformly distributed between 20-23 kg during 8 am to 12 pm and between 30-35 kg during 1 pm to 5 pm. The lifting frequencies are 5 to 8 lifts/minute during 8 am to 10 am, 7 to 9 lifts/minute during 10 am to 12 pm, etc. Working hours are 8 hours from 8 AM to 5 PM with a one hour lunch break. Other lifting tasks may be comprised of different numbers and types of subtasks but simulated similarly.

Another aspect of the problem that is considered to make it realistic is that there are different worker profiles. Non-identical workers are considered, i.e. they may have different genders, anthropometry, ages, strengths, etc. Workers are grouped into percentiles based upon their genders and lifting capacities. Lifting capacity is determined by the maximum acceptable weight that workers can lift repeatedly for long periods without undue stress or over-tiring [5.12].

Table 1 Example lifting task demand descriptions

Task descriptions	Duration	Subtasks (Lifting height)	
		FK	SR
Lifting Weight (kg)_	8:00-12:00	20-23	20-25
	1:00-5:00	30-35	27-31
Lifting Frequency (lifts/min)	8:00-10:00	5-8	10-15
	10:00-12:00	7-9	8-9
	1:00-5:00	4-5	4-7
Horizontal lifting distance (cm)	8:00-12:00	30-40	15-20
	1:00-5:00	18-20	17-22

2.2.2 Solution methodology

The objective of the job rotation is to reduce the potential for worker low back injury due to lifting. To assess worker stress due to lifting, the Job Severity Index (JSI) that has been

proposed by Ayoub et al. is applied [5.12]. The JSI is a function of lifting weight to worker lifting capacity. From worker low back injury statistics and studies, tasks that have low JSI values imply low injury potential and tasks that have high JSI values imply high injury potential. However, economical loss due to low back injuries is not linearly dependent on JSI. For example, the injury expense for workers working at JSI levels above 1.5 is \$60,000 per 100 FTE (200,000 exposure hours) as compared with an injury expense of only \$1,000 per 100 FTE for workers working at JSI levels of 1.5 and below [5.13]. Therefore, an objective function based upon the number of lost working days due to lifting is developed. The number of lost days can be represented as a piecewise linear function of JSI as in equation (1). The model is based upon the data from Liles et al. [5.13] and is fitted with an R-square of 0.98.

$$\begin{aligned}
 \text{Number of lost days} &= 0.89 + 8.63x && \text{if } 0 \leq x \leq 1.5 \\
 &= -547.54 + 374.25x && \text{if } 1.5 \leq x \leq 1.6 \\
 &= 20.05 + 19.51x && \text{if } x \geq 1.6
 \end{aligned} \tag{1}$$

The objective is then to minimize the maximum JSI, and subsequent number of lost days, for any of the workers.

After developing a specific objective function, which is minimizing the maximum number of worker lost days for any of the workers, a greedy with diversification heuristic is developed to create job rotation schedules based upon three levels of task demand information: 1) task demands that are known from history, 2) task demands that are collected right after they have occurred in real-time, and 3) task demands that are known in advance.

The greedy with diversification heuristic includes a greedy method and a diversification technique. The greedy method is used to find a local optimal solution while the diversification technique is used as a mechanism to escape from the local optimum by perturbing the local optimal solution. The method starts by randomly generating an initial

solution and then calculating the number of lost days of each worker. Neighboring solutions are explored by rotating the worker with the highest JSI value to perform other tasks one period at a time. The current solution is replaced if its neighbor provides a better objective function value. For n workers, n tasks, and m periods, there are $m(n-1)$ neighbor solutions. The best solution among these $m(n-1)$ neighbors, if it is better than the current solution, will replace the current solution. This process is continued until no further improvement is possible and a local optimum is found.

Once a local optimum is found, a diversification technique is applied. The diversification technique is a way to help the procedure escape from the locally optimal solution. The diversification technique used in this heuristic method is randomly swapping two workers with a probability of 0.4 during each period (the value of 0.4 was based on a preliminary study and is further justified in [5.11]). Diversification is used to drive the search to explore new areas of the search space. The solution from the diversification is assigned to be the current solution regardless of its results and then the improvement process or greedy procedure starts again from this solution. The greedy and diversification processes are repeated until a stopping criterion is met. In the experiments, 50 non-improving consecutive moves was used as a stopping criterion for small problems, which have 4 workers and 4 tasks and 150 non-improving consecutive moves was used as a stopping criterion for big problems, which have 8 workers and 8 tasks.

This heuristic method is adjusted for each level of task demand information. In the case where the current task demands are unknown but the historical task demands are known, a simulation program is used to generate task demands in advance based on historical task demand data. The lifting task demands are simulated to calculate the corresponding JSI values for each worker task and hour combination. A thousand JSI values of each worker task and hour combination are used to calculate their means and standard deviations. These means and standard deviations are used as representatives of different scenarios

that may occur. Then, the heuristic method searches for a robust worker schedule for this set of information.

In the case that task demands are obtained once they have already occurred, a robust worker schedule generated from historical task demand data is used as an initial solution for the heuristic method. Once the actual task demands during the first time interval have already occurred, the heuristic method adjusts the workers' schedules for the remaining hours based upon the actual task demands during the previous hour. This is done by treating the first interval's task demands as known and then using the simulated values for the remaining periods applying the heuristic to schedule the remaining periods. This process is repeated every hour when more actual task demand information is acquired.

For the case where all task demands are known in advance, the problem characteristics change from stochastic to deterministic. A mathematical programming model can be formulated to find the optimal solution [5.11]. However, its computational time grows exponentially with the problem size. Therefore, the heuristic method is also applied to this deterministic case to generate worker schedules that minimize the maximum number of worker lost days for any of the workers.

2.2.3 Experimental results

To determine the performance of worker schedules based upon the three levels of task demand information, 10 test problems are generated. The test problems differ in their sizes. Two problem sizes are used: 4 workers and 4 tasks and 8 workers and 8 tasks. Each problem size is composed of 5 problem sets differing in their worker profiles and task demands. Problems 1-5 in Table 2 have 4 workers and 4 tasks and problems 6-10 have 8 workers and 8 tasks. Since this paper considers uncertain task demands, 100 scenarios of each test problem are generated for evaluation purposes.

For all 1000 scenarios (100 scenarios for each problem), the maximum number of worker lost days in the case where task demands are known in advance is less than that of the other two cases. Comparing the maximum number of worker lost days in the cases of known real-time task demands and known historical task demands, the case of known real-time task demands performs better in 979 out of 1,000 scenarios or 98% of the time. The average maximum number of worker lost days in the case that only the historical task demands are known is 7.2 days more than the average maximum number of worker lost days in the case that task demands are known in real time and the average maximum number of worker lost days in the case that task demands are known in real time is 5.7 days more than the average maximum number of worker lost days in the case that task demands are known in advance.

Table 2 Experimental results comparing three levels of task demand information.

	Historical task demand				Real-time task demand				Known task demand			
Problem	Min	Avg	Max	s	Min	Avg	Max	s	Min	Avg	Max	s
1	23.7	50.6	57.6	5.5	13.6	41.3	54.8	12.1	13.2	31.5	52.7	13.5
2	51.8	55.0	58.2	1.5	51.4	53.4	56.6	1.2	34.9	50.8	54.8	4.1
3	13.5	50.8	58.0	6.5	13.7	40.8	55.0	12.0	13.4	31.2	52.6	13.2
4	11.9	15.7	53.4	6.6	11.5	12.8	16.2	0.6	11.0	11.8	12.8	0.4
5	13.3	52.0	57.1	6.4	13.3	34.7	53.7	13.8	12.8	22.4	51.8	11.2
6	8.6	9.2	10.3	0.4	8.2	8.8	9.4	0.3	7.9	8.6	9.0	0.2
7	12.5	14.4	49.1	5.4	11.9	12.7	13.4	0.3	11.6	12.4	13.1	0.3
8	12.7	15.1	37.2	4.4	12.5	13.1	13.8	0.3	12.2	12.7	13.4	0.3
9	13.7	46.7	55.1	9.7	13.6	30.4	52.3	11.4	13.4	21.7	51.6	9.2
10	24.2	49.1	54.9	6.1	18.4	38.4	52.8	10.2	13.5	26.3	51.5	10.0

A comprehensive analysis of the value of information is performed. Figure 1 presents the average maximum number of worker lost days for the three different levels of task demand information. The results indicate that the test problems fall into two groups. The first group includes problems 2, 4, 6, 7, and 8 and the second includes problems 1, 3, 5, 9 and 10. As

more task demand information is made available for scheduling the average maximum number of worker lost days for the first group decreases slightly while the average maximum number of worker lost days for the second group decreases significantly.

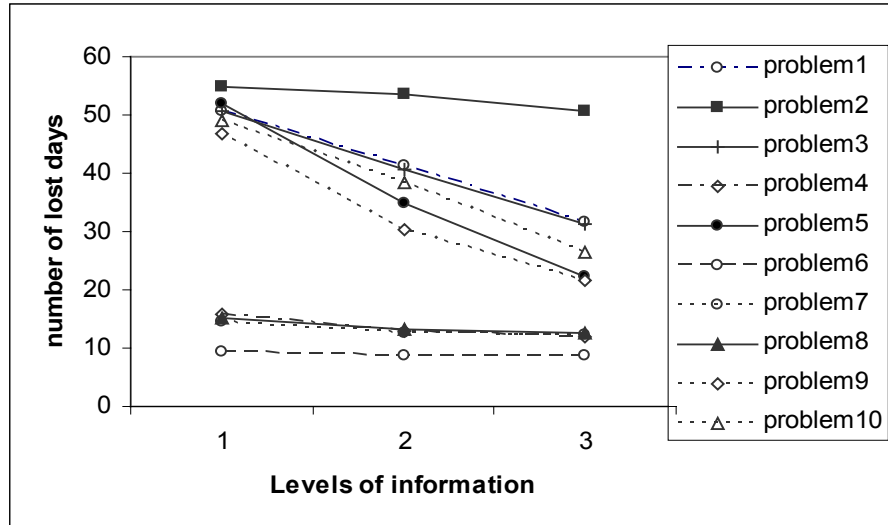


Figure 1 Graphical comparisons of three levels of task demand information

What is the source of the difference in the two groups of problems? Exploring the task demands of each problem, we found that the task demands of the problems in the first group are less variable compared to the task demands of the problems in the second group. Table 2 indicates that the standard deviations (s) of the maximum number of lost days in the case of known task demand for the first group ranges from 0.2 days to 4.1 days with an average of 1.1 days while the standard deviations of the maximum number of lost days in the case of known task demand for the second group ranges from 9.2 days to 13.5 days with an average of 11.42 days. Thus, there is much more inherent task variability in the second group. When task demands have high variability, utilizing task demand information to generate worker schedules is more helpful as compared to the case when task demands do not vary significantly.

2.3 Phase 2: Mathematical models to develop worker schedules considering worker skills.

2.3.1 Problem statement

Generally, worker assignment models are proposed to improve companies' performance. However, statistics show that occupational injuries are one of the major sources of companies' cost. Some worker assignment models are proposed to reduce the potential of these occupational injuries. These models allow workers to change their tasks during a day in order to reduce their task exposures, which is a concept of job rotation. However, these models did not consider worker skills to develop worker schedules and they can only be applied when the number of workers and tasks are equivalent. Therefore, this research proposes worker assignment models considering worker skills to perform tasks and their potential of injury resulting from performing those tasks. Lifting tasks and low back injury are utilized in the proposed models. However, similar models can be applied to various kinds of tasks and their corresponding injuries.

Problems considered in the proposed worker assignment model include n tasks and m workers, where the number of tasks is less than or equals to the number of workers $n \leq m$. All tasks are different in their task intensities, and the task intensities of each task are varied from period to period. Task intensities can be classified by the frequency of lifting, the horizontal lifting distance, the lifting weight, and the lifting height. Workers are also different in lifting capacities and genders. Male workers tend to have higher lifting capacity than female workers do, and workers at higher percentile tend to have higher lifting capacity than ones at lower percentile do.

During each working period, all tasks must be performed but a worker may or may not be chosen to perform a task. A worker can be assigned to a task only if he/she has higher skill level than the skill level requirement of that task. If a worker is assigned to at least one task, he/she will be in the payment list. Otherwise that worker is out of the payment list. Each worker must work individually. No more than one worker performs the same task and no

more than one task is assigned to a worker during the same time duration. However, workers can be rotated to perform different tasks at the end of each hour. Rotating workers could be a way to reduce the potential of worker injury.

2.3.2 Solution methodology

This research proposes two stage mixed integer programming model to determine worker rotation schedule. When the number of workers is equivalent to the number of tasks, the first stage is used to develop worker schedule that minimizes the maximum JSI value (model I). Then the second stage is applied to minimize the total number of worker lost day while keeping all JSI values below the maximum value of the first stage or 1.5, which is the threshold (model II). In case of the maximum JSI value that is greater than 1.5, an additional number of workers should be considered. When the number of workers is greater than the number of tasks, the proper number of workers should be determined. Using a large number of workers increases the total labor cost while using a small number of workers increases the injury loss. The first stage model is proposed to minimize the total labor cost while maintain the JSI value of workers to be below the threshold of 1.5 (model III). After the total labor cost is determined, an improved worker assignment can be developed by the second stage model, which is minimizing the total number of worker lost day while keeping the maximum JSI value to be below the threshold and the total labor cost to be below the value from the first stage (model IV).

Before the details of mathematical models are illustrated, model notation and definitions are described.

Model notation and definitions

Model parameters

I Set of workers $i = 1, 2, \dots, n$

J Set of jobs $j = 1, 2, \dots, m$

K Set of periods $k = 1, 2, \dots, p$

O Set of break points of a piecewise linear function $o = 1, 2, \dots, a$

L Set of straight line segments of a piecewise linear function $l = 1, 2, \dots, a-1$

W_i Set of random variables w_{oi}

WW_i Set of binary 0-1 variables w_{li}

$labor_cost_i$ = Labor cost of worker i ,

$worker_skill_i$ = Skill level of worker i ,

job_skill_j = Skill requirement for job j ,

sub_jsi_{ijk} = JSI value of worker i perform job j at period k ,

M = A large positive number

Decision variables

x_{ijk} = 1 if worker i performs job j during period k ,

0 otherwise,

y_i = 1 if worker i is chosen to be in the payment list,

0 otherwise,

jsi_i = An entire day JSI value of worker i ,

z_{ij} = A (0,1) decision variable,

$max\ jsi$ The maximum JSI value among all workers

$injury_loss_i$ The number of lost days of worker i

Model I

min *max jsi*

subject to

$$\sum_{i=1}^n x_{ijk} = 1 \quad \forall j, k$$

$$\sum_{j=1}^m x_{ijk} \leq 1 \quad \forall i, k$$

$$\sum_{j=1}^m \sum_{k=1}^p x_{ijk} \leq 8 \quad \forall i$$

$$job_skill_j - worker_skill_i \leq M \cdot (1 - z_{ij}) \quad \forall i, j$$

$$\sum_{k=1}^p x_{ijk} \leq M \cdot z_{ij} \quad \forall i, j$$

$$max\ jsi \geq \sum_{j=1}^m \sum_{k=1}^p sub_jsi_{ijk} \cdot x_{ijk} \quad \forall i$$

$$x_{ijk} = 0 \text{ or } 1 \quad \forall i, j, k$$

$$z_{ij} = 0 \text{ or } 1 \quad \forall i, j$$

$$jsi_i \geq 0 \quad \forall i$$

Model II

$$\begin{aligned}
\min \quad & \sum_{i=1}^n injury_loss_i \\
& \sum_{i=1}^n x_{ijk} = 1 & \forall j,k \\
& \sum_{j=1}^m x_{ijk} \leq 1 & \forall i,k \\
& \sum_{j=1}^m \sum_{k=1}^p x_{ijk} \leq 8 & \forall i \\
& job_skill_j - worker_skill_i \leq M \cdot (1 - z_{ij}) & \forall i,j \\
& \sum_{k=1}^p x_{ijk} \leq M \cdot z_{ij} & \forall i,j \\
& jsi_i = \sum_{j=1}^m \sum_{k=1}^p sub_jsi_{ijk} \cdot x_{ijk} & \forall i \\
& jsi_i \leq max_jsi & \forall i \\
& injury_loss_i = 0.888 \cdot w_{0i} + 13.8375 \cdot w_{1i} + 51.2627 \cdot w_{2i} + 117.5967 \cdot w_{3i} & \forall i \\
& jsi_i = 0 \cdot w_{0i} + 1.5 \cdot w_{1i} + 1.6 \cdot w_{2i} + 5 \cdot w_{3i} & \forall i \\
& w_{0i} \leq ww_{0i} & \forall i \\
& w_{1i} \leq ww_{0i} + ww_{1i} & \forall i \\
& w_{2i} \leq ww_{1i} + ww_{2i} & \forall i \\
& w_{3i} \leq ww_{2i} & \forall i \\
& \sum_{o=1}^a w_{oi} = 1 & \forall i \\
& \sum_{l=1}^{a-1} ww_{li} = 1 & \forall i \\
& x_{ijk} = 0 \text{ or } 1 & \forall i,j,k \\
& z_{ij} = 0 \text{ or } 1 & \forall i,j \\
& jsi_i \geq 0 & \forall i \\
& injury_loss_i \geq 0 & \forall i \\
& w_{oi} \geq 0 & \forall i,o \\
& ww_{li} = 0 \text{ or } 1 & \forall i,l
\end{aligned}$$

Model III

$$\min \quad \sum_{i=1}^n labor_cost_i y_i$$

subject to

$$\sum_{i=1}^n x_{ijk} = 1 \quad \forall j, k$$

$$\sum_{j=1}^m x_{ijk} \leq 1 \quad \forall i, k$$

$$\sum_{j=1}^m \sum_{k=1}^p x_{ijk} \leq 8 \cdot y_i \quad \forall i$$

$$job_skill_j - worker_skill_i \leq M \cdot (1 - z_{ij}) \quad \forall i, j$$

$$\sum_{k=1}^p x_{ijk} \leq M \cdot z_{ij} \quad \forall i, j$$

$$max\ jsi \geq \sum_{j=1}^m \sum_{k=1}^p sub_jsi_{ijk} \cdot x_{ijk} \quad \forall i$$

$$x_{ijk} = 0 \text{ or } 1 \quad \forall i, j, k$$

$$y_i = 0 \text{ or } 1 \quad \forall i$$

$$z_{ij} = 0 \text{ or } 1 \quad \forall i, j$$

$$jsi_i \geq 0 \quad \forall i$$

Model IV

$$\begin{aligned}
\min \quad & \sum_{i=1}^n injury_loss_i \\
& \sum_{i=1}^n x_{ijk} = 1 & \forall j,k \\
& \sum_{j=1}^m x_{ijk} \leq 1 & \forall i,k \\
& \sum_{j=1}^m \sum_{k=1}^p x_{ijk} \leq 8y_i & \forall i \\
& job_skill_j - worker_skill_i \leq M \cdot (1 - z_{ij}) & \forall i,j \\
& \sum_{k=1}^p x_{ijk} \leq M \cdot z_{ij} & \forall i,j \\
& jsi_i = \sum_{j=1}^m \sum_{k=1}^p sub_jsi_{ijk} \cdot x_{ijk} & \forall i \\
& jsi_i \leq max\ jsi & \forall i \\
& injury_loss_i = 0.888 \cdot w_{0i} + 13.8375 \cdot w_{1i} + 51.2627 \cdot w_{2i} + 117.5967 \cdot w_{3i} & \forall i \\
& jsi_i = 0 \cdot w_{0i} + 1.5 \cdot w_{1i} + 1.6 \cdot w_{2i} + 5 \cdot w_{3i} & \forall i \\
& w_{0i} \leq ww_{0i} & \forall i \\
& w_{1i} \leq ww_{0i} + ww_{1i} & \forall i \\
& w_{2i} \leq ww_{1i} + ww_{2i} & \forall i \\
& w_{3i} \leq ww_{2i} & \forall i \\
& \sum_{o=1}^a w_{oi} = 1 & \forall i \\
& \sum_{l=1}^{a-1} ww_{li} = 1 & \forall i \\
& \sum_{i=1}^n labor_cost_i y_i \leq total_labor_cost \\
& x_{ijk} = 0 \text{ or } 1 & \forall i,j,k \\
& z_{ij} = 0 \text{ or } 1 & \forall i,j \\
& jsi_i \geq 0 & \forall i \\
& injury_loss_i \geq 0 & \forall i \\
& w_{oi} \geq 0 & \forall i,o \\
& ww_{li} = 0 \text{ or } 1 & \forall i,l
\end{aligned}$$

2.3.3 Experimental results

The models are tested with 2 different sizes of problems defined by the number of tasks. Sixteen 4-task problems and eight 8-tasks problems are generated and used in the experiment. Task intensities are varied and are classified into 4 groups: easy, moderate, difficult, and very difficult. Task intensities are determined by measuring the JSI value accrues to the 50th percentile male if he works all day on that task. If the 50th percentile male works on an easy task all day, the JSI value accrues to this worker is less than 1.0. If he works on a moderate task all day, the JSI value accrues to this worker is between 1.0 and 1.5. If he works on a difficult task all day, the JSI value accrues to this worker is between 1.5 and 2.0 and if he works on a very difficult task all day, the JSI value accrues to this worker is greater than 2.0. The detail descriptions of each test problems are illustrated in table 3.

Table 3. Descriptions of the 20 test problems

Problems	Total number of tasks	Number of easy tasks	Number of moderate tasks	Number of difficult tasks	Number of very difficult tasks
Problems 1-8	4	2	2		
Problems 9-12	4		2	2	
Problems 13-16	4	2			2
Problems 17-18	8	4	4		
Problems 19-20	8		4	4	
Problems 21-22	8	4			4
Problems 23-24	8		4		4

Workers are different in their genders, skill levels and percentiles. This work considers a skill at 2 levels; however, the model can also be applied to more than 2 skill levels. Worker percentiles used in the experiment range from 0.2–0.9. Each test problem is experimented with 2 group sizes of workers. The 4-task problems are applied to 4 workers and 6 workers. The 8-task problems are applied to the 8 workers and 12 workers.

All problems are solved by CPLEX 7.0 on Pentium 4, 2.6 GHz. The results are illustrated in tables 4 and 5.

Table 4. The experimental results from model I and model II

Problems	Model I		Model II	
	MaxJSI	Total lost days	Total lost days	
			Model I	1.5
1	2.07	94.26		
2	1.29	43.59	43.55	43.51
3	1.84	128.88		
4	1.49	49.94	49.62	49.62
5	1.45	52.94	52.94	52.83
6	1.93	131.67		
7	1.56	97.66		
8	1.72	162.12		
9	2.95	218.21		
10	2.96	216.88		
11	2.93	245.60		
12	3.12	246.15		
13	2.41	243.47		
14	2.99	184.73		
15	4.82	277.60		
16	3.59	229.67		
17	1.29	93.09	92.23	90.33
18	1.29	94.80	94.78	92.15
19	2.08	428.41		
20	2.20	401.16		
21	2.85	400.53		
22	2.33	442.08		
23	2.99	443.81		
24	2.48	462.06		

Table 4 illustrates the experimental results from model I and model II. The results from the first model show that 5 out of 24 test problems obtain the maximum JSI value below 1.5. These test problems are solved again in the second model. The maximum JSI value constraint in the second model is assigned to 2 different values. For the first case, the maximum JSI value equals the objective function value obtained from model I, and for the second case the maximum JSI value equals 1.5. The total number of lost days from the second model decrease, compared to the ones from the first model, in all test problems except for the first case of problem 5. In the first case the total number of lost day reduces on average 0.25 days, and in the second case, the total number of lost day reduces on average 1.18 days.

Additional number of workers is included in other test problems, which the maximum JSI values are above 1.5. These test problems are applied again in the third and forth models. Table 5 illustrates the experimental results from model III and model IV. The third model aims to minimize the total labor cost while maintaining the JSI values of all workers below 1.5. Columns 4-6 in table 5 show the total labor cost, maximum JSI value, and the total number of lost days resulted from model III. Numbers in parentheses in column 4 are the number of workers chosen to perform tasks in each problem. The total number of lost days from model III decrease in all problems compared to the ones from model I. The total number of lost days decreases on average 182.65 days. This number is huge due to worker schedules keeping all JSI values below 1.5.

However, the total labor cost may increase, decrease or remain the same. The total labor cost increase when extra number of workers is needed to perform task in order to keep JSI value below 1.5. The total labor cost remains the same or decrease when proper groups of workers are chosen to perform tasks while keeping the number of workers the same. For example, problem 1 contains 4 tasks, which one requires skill level 2 and others require skill level 1. Among the 4 current workers, 2 workers have skill level 1 and others have skill level 2. Workers with higher skill level are more expensive than worker with lower skill level.

When 2 extra workers are introduced, one is at skill level 1 and the other is at skill level 2. The better worker schedule chooses 3 workers at skill level 1 and 1 workers at skill level 2, which provides cheaper labor cost. Since the extra worker at skill 1 is stronger than the current worker at skill level 2, the maximum JSI value can be kept below 1.5 using 4 workers.

Considering identical criteria as model III, model IV provides improved worker schedules. Columns 7 and 8 in table 5 show the maximum JSI value and the number of lost days from model IV. The labor cost from model IV is equivalent the labor cost from model III. However, the number of lost days reduces in all problems and it decreases on average 5.26 days. The maximum JSI values from these 2 models are not statistically different.

Table 5. The experimental results from model III and model IV

Problems	Model I		Model III			Model IV	
	Labor cost (no. workers)	Lost days	Labor cost (no. workers)	MaxJSI	Lost days	MaxJSI	Lost days
1	800 (4)	94.26	700 (4)	1.49	43.28	1.09	41.33
3	800 (4)	128.88	700 (4)	1.47	53.58	1.31	44.20
6	800 (4)	131.67	700 (4)	1.50	56.97	1.47	50.81
7	800 (4)	97.66	800 (4)	1.49	50.67	1.49	42.75
8	800 (4)	162.12	800 (4)	1.49	50.67	1.49	42.75
9	800 (4)	218.21	950 (5)	1.47	68.38	1.49	58.93
10	800 (4)	216.88	1200 (6)	1.45	77.78	1.49	66.64
11	800 (4)	245.60	950 (5)	1.43	61.45	1.50	57.83
12	800 (4)	246.15	1050 (5)	1.47	67.74	1.50	57.35
13	800 (4)	243.47	950 (5)	1.50	63.56	1.49	60.85
14	800 (4)	184.73	1050 (5)	1.47	65.38	1.49	61.93
15	800 (4)	277.60	1300 (6)	1.49	79.36	1.49	74.49
16	800 (4)	229.67	950 (5)	1.48	68.67	1.49	66.68
19	1700 (8)	428.41	2100 (10)	1.49	133.07	1.50	125.53
20	1700 (8)	401.16	1750 (9)	1.50	120.67	1.50	116.96
21	1500 (8)	400.53	1750 (9)	1.50	121.27	1.50	117.00
22	1700 (8)	442.08	1850 (9)	1.50	123.60	1.50	121.02
23	1600 (8)	443.81	2100 (11)	1.50	139.27	1.50	138.70
24	2000 (8)	462.06	2200 (11)	1.49	139.26	1.50	138.97

3. ผลที่ได้จากโครงการวิจัย

3.1 ผลจากโครงการระยะที่ 1 (Phase 1)

3.1.1 The experimental results from this study show that when more information is known better worker schedules can be developed. This was shown by comparing three levels of task demand information. When task demands are known in advance, the problem characteristics are deterministic and workers can be assigned to tasks during each period optimally. Therefore, the average maximum number of worker lost days is the least among the three cases considered for all scenarios. When task demands are known right after they have occurred, worker schedules can be adjusted based upon the known task demands that have already occurred. The average maximum number of worker lost days is less than the average for the case where the worker schedule is only based upon the historical task demands.

3.1.2 When task demands have high variability, utilizing task demand information to generate worker schedules is more helpful as compared to the case when task demands do not vary significantly. Thus, if one is scheduling workers in a highly variable environment it is important to have as much task demand information as possible in order to be able to develop better schedules.

3.1.3 The experimental results clearly indicate that when more task demand information is known better worker schedules can be developed and this helps reduce the injury potential. However, different levels of effort are needed in order to obtain these three different levels of task demand information. Therefore, depending on the variability and difficulty of the lifting tasks involved in a company's operations, the company may want to consider having more task demand information available. In particular, when task demands vary significantly the company should consider implementing more advanced information systems in order to provide more timely task demand data. A company would have to weigh the costs of having more enhanced information systems to gather better task demand information with the

benefits of reducing the potential for worker injuries along with other benefits that may be obtained such as reducing inventory levels.

3.2 ผลจากโครงการระยะที่ 2 (Phase 2)

3.2.1 There are different methods to deal with multi-objective. One way is developing only one model and minimizing the total cost including the total labor cost and the total injury cost. However, this research uses the 2-stage method due to difficulty of transferring the number of lost days to injury costs. Moreover, from the company perspective, labor cost is more interesting to be reduced than the injury cost since it is more direct cost.

3.2.2 The two-stage mixed integer programming can be a guideline for a company to choose proper group of workers to perform tasks by considering worker skill requirement with the minimum labor cost. Moreover, with the same labor cost, this method can provide worker schedules that minimize worker injury.

4. ผลงานที่ส่งเพื่อตีพิมพ์

4.1 Wipawee Tharmmaphornphilas, and Bryan A. Norman, "Job Rotation Plans for Reducing Low Back Injuries with Real-Time Information," Proceedings of the 13rd Industrial Engineering Research Conference, May 16-19, 2004, Houston, Texas, USA, CD Rom format. (ภาคผนวก ก.)

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4.3 Wipawee Tharmmaphornphilas, "A Multi-Objective Mixed Integer Programming to Develop Worker Schedules Considering Worker Injury," submitted to International Journal of Production Research. (ภาคผนวก ค.)

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Job rotation plans for reducing low back injuries with real-time information

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Abstract

In manual material-handling environments, a large number of workforce injuries are sustained each year and these injuries are often of a severe nature. This paper is concerned with finding a job rotation methodology to reduce the potential of workforce injuries. Under varied conditions of lifting task demands, a single deterministic rotation plan may not be a desirable solution. The importance of obtaining task demand information at different decision stages and properly integrating it with worker rotation plans is illustrated with a number of example problems. The results show that real-time information provides substantial benefits in reducing the maximum number of worker lost days due to low back injuries.

Keywords: Job Rotation, Value of Information, Low Back Injury

1. Introduction

Low back pain is a major safety issue in material handling settings. Reducing the incidence of low back injury significantly reduces the corresponding expenses. Generally, the overexertion prevention strategies that may help eliminate or reduce the incidence and severity of workplace injuries can be categorized into 3 classes: 1) engineering solutions such as job redesign, workplace redesign, tool redesign, and automation, 2) administrative controls such as revision of work-rest schedules, rotating workers among jobs, training, exercises, and job/career changes, and 3) personal protective equipment [1]. In this paper, job rotation, which is an administrative control method, is applied to reduce the potential for low back injuries. Job rotation is a method of assigning workers to different tasks during a day allowing workers to change postures so that their stress may be reduced. Job rotation has been applied to many settings in both the service and manufacturing sectors [2-5]. While these authors claim that it was implemented successfully, no specific methods for constructing the job rotation plans were described.

The problem of constructing good job rotation plans is complicated by uncertainty in the work setting. Uncertainty may originate from different sources such as machine breakdowns, material delays, and worker absenteeism. A worker schedule developed by assuming that parameters are precisely specified may be effective for one scenario but not for another. A robust method, which is less sensitive to the input parameters, can often be more effective to solve uncertain problems [6]. A robust approach can be developed based upon historical task data. It may not provide an optimal result for each individual scenario; however, it works well across different scenarios.

Job rotation schedules may be improved by the use of real-time data from the work setting if appropriate information technology tools are utilized. Currently, information technology is improving at a rapid pace

and data can be collected easier, cheaper, and faster than before. Therefore, instead of using only historical data to develop a robust worker schedule, better worker schedules can be developed based upon real-time information. The value of information for production planning and inventory control has been shown in many supply chain papers. Information may yield benefits to human safety as well. This paper proposes a method of using information to develop better worker schedules to reduce worker injuries.

2. Problem Statement

We apply job rotation to reduce the potential for low back injuries due to lifting. Uncertain task demands and different workers' profiles are considered. We assume that the number of tasks and the number of workers are equivalent. Each worker can perform only one task and a task can only be done by one worker at a time. Workers are allowed to move to perform other tasks at the end of each hour. Workers are assumed to have enough rest at the end of each day so that all stress is relieved. Workers return to a normal condition at the beginning of each day. This paper considers a methodology to generate a one-day job rotation schedule to reduce the potential of worker low back injury based upon different levels of information knowledge.

Lifting task demands are simulated similarly to the previous work developed by Carnahan et al [7]. The lifting task demands include the lifting weight, the lifting frequency, the lifting height, and the horizontal lifting distance. Task demands except the lifting height are uniformly distributed with different ranges during each period. Each lifting task may be comprised of small subtasks determined by the lifting height. The number and types of subtasks can be different. An example of lifting task demands is illustrated in Table 1. This task is composed of 2 subtasks determined by the lifting heights, FK and SR. Subtask FK is the task of lifting from floor level to knuckle height, and subtask SR is the task of lifting from shoulder height to reach height. The lifting weight, the lifting frequency, and the horizontal lifting distance are uniformly distributed with different ranges during each period. For example, the lifting weights of subtask FK are uniformly distributed between 20-23 kg during 8 am to 12 pm and between 30-35 kg during 1 pm to 5 pm.

Table 1 An example of lifting task demand descriptions

Task descriptions	Duration	Subtasks (Lifting height)	
		FK	SR
Lifting Weight (kg)	8:00-12:00	20-23	20-25
	1:00-5:00	30-35	27-31
Lifting Frequency (lifts/min)	8:00-10:00	5-8	10-15
	10:00-12:00	7-9	8-9
	1:00-5:00	4-5	4-7
Horizontal lifting distance (cm)	8:00-12:00	30-40	15-20
	1:00-5:00	18-20	17-22

Workers vary in gender, anthropometry, age, strength, etc. We differentiate workers by considering their genders and lifting capacities. Lifting capacity is determined by the maximum acceptable weight that workers can lift repeatedly for long periods without undue stress or over-tiring [8-9].

Since task demands and work profiles are different. Stress accrued varies when different workers perform the same task during the same hour in the same day and also varies when a worker performs the same task during the same hour but on different days. Some tasks require high physical strength and are considered to be difficult tasks. Some tasks require low physical strength and are considered to be easy tasks. Job rotation may be applied to move workers from difficult tasks to easy tasks to reduce workers' stress.

We have developed a method to incorporate real-time information knowledge to generate better worker schedules to reduce the potential for worker low back injuries. The real-time information referred in this paper is the lifting task demands illustrated in Table 1. For example, in many settings one could know in real-time the weight, the lifting frequency, and the lifting distance of the material that is being lifted.

3. Solution Methodology

The methodology starts by identifying a proper objective function to assess the potential for worker low back injuries. Then we develop a heuristic method to include real-time information to generate dynamic worker schedules. Detailed descriptions are included in the following subsections

3.1 Objective Function

The main purpose of job rotation in this paper is to reduce the potential for worker low back injury due to lifting. The potential for worker low back injury can be assessed using the Job Severity Index (JSI) [8]. The JSI is a unit-less ratio relating the required lifting tasks for a job to the ability of a worker to satisfy those requirements. For instance, when a male workers at the 50th percentile lifting capacity performs the same lifting task as a female worker at the 50th percentile lifting capacity, the JSI value of the male worker is less than that of the female one. From worker low back injury statistics, low JSI values imply low injury potential and high JSI values imply high injury potential. The potential incidence and severity of back injuries dramatically increases among workers who have JSI values more than 1.5 compared to workers who have JSI values less than or equal to 1.5.

Even though the JSI can assess worker stress, it does not clearly identify economic loss. Therefore, a more tangible objective function - minimizing the maximum number of worker lost days is applied. The number of worker lost days can be determined as a function of JSI values [10] and is shown below. Variable x in the model is a random variable representing the JSI value.

$$\begin{aligned} \text{Number of lost day} &= 0.89 + 8.63x && \text{if } 0 \leq x \leq 1.5 \\ &= -547.54 + 374.25x && \text{if } 1.5 \leq x \leq 1.6 \\ &= 20.05 + 19.51x && \text{if } x \geq 1.6 \end{aligned} \quad (1)$$

3.2 A Heuristic Search Method Based Upon Real-Time Information

Using the minimizing the maximum number of worker lost days objective function, a heuristic is developed to generate dynamic worker schedules. Previous work has presented a greedy with diversification heuristic based upon a historical data to generate robust worker rotation schedules [10]. This paper extends the greedy with diversification heuristic by integrating real-time information to generate dynamic worker schedules.

The heuristic based upon using real-time information also includes a greedy method and a diversification technique. The greedy method is used to find a local optimal solution while the diversification technique is used as a mechanism to escape from the local optimum by perturbing the local optimal solution. This heuristic method is run at the end of every period right after real task demands are known in order to update worker schedules.

The method starts by using a robust worker schedule developed by Tharmmaphornphilas [10] as an initial solution. The number of lost days for each worker is calculated based upon only historical data. During the first period, workers are assigned to tasks based on this robust schedule. Since we assume that real-time information can be obtained, real task demands including the lifting weight, the lifting frequency, the lifting height, the horizontal lifting distance, that have occurred during the first period are known at the end of the first period. Therefore, the number of lost days of each worker is recalculated based upon the real task demands of period 1 and historical task demands of other periods.

The heuristic method tries to improve the solution by exploring neighboring solutions by rotating the worker with the highest number of lost days to perform other tasks one period at a time from period 2 to period 8. The initial solution is replaced if one of its neighbors provides a better objective function value. This stage of the heuristic method is a greedy search.

For example, assume the initial worker schedule given in Table 2. This schedule includes 4 workers and 4 tasks. Workers' percentiles identify their lifting capacities. Higher percentile workers have higher lifting capacities than lower percentile workers do. Once the worker schedule is obtained, the expected number

of worker lost days for each worker based upon historical data is then calculated. From the schedule in Table 2, the number of worker lost days for the 50th percentile male, the 95th percentile male, the 50th percentile female, and the 95th percentile female are 10, 9, 18, and 15 days consecutively.

At the end of the first period, real task demands for period 1 are known. Therefore, the number of lost days is recalculated using the real task demands of period 1 and historical data for the other periods. The updated number of lost days for the 50th percentile male, the 95th percentile male, the 50th percentile female, and the 95th percentile female are 10, 11, 20, 17 days.

Since the 50th percentile female has the maximum number of worker lost days (20 days), neighboring solutions of this initial solution are determined by swapping the 50th percentile female to perform other tasks one at a time from periods 2 to 8. For example, a new assignment from 9 to 10 a.m. can be the 50th percentile male performs task D and the 50th percentile female performs task B while keeping all of the other assignments the same. For n workers, n tasks, and m periods, if r periods have already occurred, there will be $(m-r)(n-1)$ neighboring solutions. The best solution among these $(m-r)(n-1)$ neighbors, if it is better than the current solution, will replace the current solution. This process is continued until there is no improvement and a local optimum is found.

Table 2 An example of worker rotation schedule.

Periods	50%tile male	95%tile male	50%tile female	95%tile female
8:00-9:00	Task A	Task B	Task C	Task D
9:00-10:00	Task B	Task A	Task D	Task C
10:00-11:00	Task B	Task A	Task D	Task C
11:00-12:00	Task C	Task D	Task A	Task B
1:00-2:00	Task B	Task A	Task D	Task C
2:00-3:00	Task B	Task A	Task D	Task C
3:00-4:00	Task A	Task B	Task D	Task C
4:00-5:00	Task A	Task D	Task B	Task C
No. of lost days	10	9	18	15

Once a local optimum is found, a diversification technique is applied. The diversification technique is a way to help escape from the local optimum and drive the search to new regions of the search space. The diversification technique used in this heuristic method is allowing swapping between two arbitrary workers with a probability of 0.4 during each period. For example, assuming that the local optimal solution is found and the real task demands of the first r periods have already occurred. The diversifying process can be performed by randomly generating a number ranging from 0 to 1. If the number is less than 0.4, we randomly select 2 workers and swap their tasks during the $(r+1)^{th}$ period. This process is repeated through the m^{th} period. The solution from the diversification is accepted regardless of its results and then the improvement process or greedy procedure starts again from this solution. The greedy and diversification processes are repeated until the stopping criterion is met. In the experiments, 50-150 non-improving consecutive moves were used as a stopping criterion.

The heuristic method is repeated at the end of every period and a worker schedule is adjusted based upon actual task demands that have already occurred. This type of method is sometimes called scheduling with recourse.

4. Experimental Results

To determine the effect of scheduling workers based upon real-time information knowledge, 10 test problems were generated. Two problem sizes are used containing 4 workers and 4 tasks and 8 workers and 8 tasks. Each problem size is composed of 5 problem sets differentiated by worker profiles and task demands. Since this paper considers uncertain task demands, 100 scenarios are generated for each test problem to test the quality of the generated schedules.

We compare the results of a dynamic worker schedule based upon real-time information with a robust worker schedule based upon historical data. Since robust worker schedules work well with various scenarios of task demands, the robust schedule for each test problem is applied to all 100 scenarios. The maximum number of worker lost days for each scenario is measured. The minimum, average, maximum, and standard deviation of the maximum number of lost days is shown in Table 3. Since worker schedules may be adjusted based upon actual information when real-time information can be obtained. The worker schedules for each test problem across various scenarios may not be the same. The maximum number of worker lost days for each scenario is measured. The minimum, average, maximum, and standard deviation of the maximum number of lost days is shown in Table 3.

Comparing the maximum numbers of worker lost days in the cases of known real-time task demands and known historical task demands, the case of known real-time task demands performs better 979 out of 1,000 scenarios or 98% of the time. The average maximum number of worker lost days in the case that task demands are not known in real-time is 7.22 days greater than the average maximum number of worker lost days in the case that task demands are known in real-time.

Table 3 Experimental results

Problem	Historical Task Demand				Real-Time Task Demand			
	Min	Avg	Max	s	Min	Avg	Max	s
1	23.7	50.6	57.6	5.5	13.6	41.3	54.8	12.1
2	51.8	55	58.2	1.5	51.4	53.4	56.6	1.2
3	13.5	50.8	58	6.5	13.7	40.8	55	12
4	11.9	15.7	53.4	6.6	11.5	12.8	16.2	0.6
5	13.3	52	57.1	6.4	13.3	34.7	53.7	13.8
6	8.6	9.2	10.3	0.4	8.2	8.8	9.4	0.3
7	12.5	14.4	49.1	5.4	11.9	12.7	13.4	0.3
8	12.7	15.1	37.2	4.4	12.5	13.1	13.8	0.3
9	13.7	46.7	55.1	9.7	13.6	30.4	52.3	11.4
10	24.2	49.1	54.9	6.1	18.4	38.4	52.8	10.2

5. Conclusions and Future Work

Combining information knowledge to develop worker schedules can be a way to reduce the potential for worker injuries. The experimental results show that better worker schedules can be developed if more information is known. When task demands are known right after they have occurred, worker schedules can be adjusted based upon the actual task demands. The average maximum number of worker lost days is less than if only historical task demand information is used.

From the above ten test problems, the number of lost days dramatically decreases in problems 1, 3, 5, 9, and 10, but marginally decreases in all the others. Therefore, it is possible that the knowledge of additional real-time information only benefits some particular problem structures. Future research should explore such problem structures in order to provide a guideline as to whether real-time information gathering systems should be implemented.

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ภาคผนวก ข.

The Value of Information to Develop Job Rotation Plans to

Reduce Worker Low Back Injuries

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Abstract

In manual material-handling environments, a large number of workforce injuries are sustained each year and the injuries are often of a severe nature. This paper investigates a job rotation methodology to reduce the potential for workforce injuries. Under conditions where lifting task demands vary a single deterministic rotation plan may not always be the best solution. Moreover, different job rotation scheduling methods are best for different levels of task demand information. This paper considers the cases where 1) only historical task demand information is known, 2) task demand information is known in real-time as the tasks are completed, and 3) where task demands are known in advance. The importance of obtaining task demand information for these three cases and properly integrating it within the worker rotation plans is illustrated with a number of example problems. The results show that real-time and advance task demand information can provide significant benefits with regard to reducing the maximum number of worker lost days due to low back injuries.

Keywords: Job Rotation, Real-time Information, Low Back Injury

2. Introduction

Workplace injuries and illnesses are major problems that companies face. Repetitive motion and overexertion are principal causes of workplace injuries and illnesses and contribute primarily to injuries affecting the lower back [1]. Worker compensation claim statistics indicate that low back injuries constitute 16% of all claims but 33% of the total

cost of all claims [2]. However, worker compensation claim statistics in manual material handling show that low back injuries account for 29.5% of all claims and 41.6% of the total cost of these claims [3]. Moreover, low back injury is one of the most frequent problems treated by orthopedic surgeons and is the second most frequent cause of lost working days in people under age 45 [4].

Since low back injury is a major safety issue. Reducing the incidence of low back injury significantly reduces its corresponding expenses. Generally, overexertion prevention strategies that may help eliminate or reduce the incidence and severity of workplace injuries can be categorized into 3 classes: 1) engineering solutions such as job redesign, workplace redesign, tool redesign, and automation, 2) administrative controls such as revision of work-rest schedules, rotating workers among jobs, training, exercises, and job/career changes, and 3) personal protective equipment [5]. Engineering solutions are often used in industries to reduce worker overexertion; however, it requires a significant amount of money. Moreover, no perfect workplace can be achieved within reasonable financial constraints, or even if there are no financial limits [6]. In the case of manual lifting, not many personal protective devices can be applied to prevent workers from accruing stress. Therefore, job rotation, which is an administrative control, is investigated in this paper as a cost effective method for reducing the potential for lifting injuries.

Job rotation is a method of assigning workers to different tasks during a day allowing workers to change postures so that their stress may be reduced. Job rotation has been

applied to many settings in both service and manufacturing industries [7-10]. Although these authors claim that job rotation was implemented successfully, the methods for constructing job rotation plans were not described in these papers. One of the goals of this research is to address this shortcoming in the literature. Section 3 of this paper describes a method for creating job rotation plans to minimize the potential for worker injuries due to manual lifting.

A significant complicating factor in determining a job rotation plan is uncertainty. In real settings, uncertainty may originate from different sources such as machine breakdowns, material delays, and worker absenteeism. For manual material handling, uncertainty in task demands is a significant consideration. Task demands often cannot be known in advance or they may change over time. For example, unexpected orders may enter into the process, orders may change, or orders with high priority may enter into the process. In this research we examine uncertainty arising from task demand variability.

Decision making under uncertainty is difficult. Applying the same action to different scenarios may result in different outcomes. A deterministic method, which assumes that all parameters are precisely specified and the outcomes of any decisions can be determined exactly, cannot be applied effectively. A robust method, which is less sensitive to the input parameters, can often be more effective for solving problems characterized by uncertainty [11]. Often, a robust approach can be developed based upon a historical data. It may not provide an optimal result for each individual scenario; however, it usually works well across different scenarios. Consider the case of using job

rotation to reduce the potential for worker low back injuries. Considering uncertain lifting task demands, a robust approach generates a worker schedule that may not be the best solution when task demands are at the minimum, maximum or even average levels. However, if there is not too much variability a robust worker schedule will usually provide minimal or near minimal potential for worker injuries. A number of authors have applied robust approaches to deal with uncertainty [12, 13].

With the advent of better information technology it may be possible to reduce task uncertainty. Currently, information technology is improving dramatically. Data can be collected easier, cheaper, and faster. The value of information for production planning and inventory control is discussed in many supply chain papers [14-16]. However, production planning information that is obtained may also yield benefits to human safety as well. This paper proposes a method for using this information to develop better worker schedules in order to reduce the likelihood of worker injuries.

2. Problem Statement

We consider the problem of assigning workers to tasks in a manual-lifting environment where the number of lifting tasks and the number of workers are equivalent. During each period, a worker can perform only one task and a task can be done by only one worker. To simulate real settings, the lifting task demands may change over time and workers' lifting profiles vary. This paper presents a methodology to generate a job rotation schedule to reduce the potential for worker low back injury based upon levels of task demand information.

Lifting task demands are simulated in a manner similar to that of the previous work developed by Carnahan et al [17]. The lifting task demands include the lifting weight, the lifting frequency, the lifting height, and the horizontal lifting distance. Task demands, except the lifting height, are uniformly distributed with different ranges during each period. Each lifting task may be comprised of small subtasks determined by the lifting height. The number and types of subtasks can be different. Six different types of subtasks are considered: subtask FK is the task of lifting from floor level to knuckle height, subtask FS is the task of lifting from floor level to shoulder height, subtask FR is the task of lifting from floor level to reach height, subtask KS is the task of lifting from knuckle height to shoulder height, subtask KR is the task of lifting from knuckle height to reach height, and subtask SR is the task of lifting from shoulder height to reach height.

Example lifting task demands are illustrated in Table 2.1. This task is composed of 2 subtasks determined by the lifting heights, FK and SR. The lifting weight, the lifting frequency, and the horizontal lifting distance are uniformly distributed with different ranges during each period. For example, the lifting weights of subtask FK are uniformly distributed between 20-23 kg during 8 am to 12 pm and between 30-35 kg during 1 pm to 5 pm. The lifting frequencies are 5 to 8 lifts/minute during 8 am to 10 am, 7 to 9 lifts/minute during 10 am to 12 pm, etc. Working hours are 8 hours from 8 AM to 5 PM with a one hour lunch break. Other lifting tasks may be comprised of different numbers and types of subtasks but simulated similarly.

Table 2.1 Example lifting task demand descriptions

Task descriptions	Duration	Subtasks (Lifting height)	
		FK	SR
Lifting Weight (kg)_	8:00-12:00	20-23	20-25
	1:00-5:00	30-35	27-31
Lifting Frequency (lifts/min)	8:00-10:00	5-8	10-15
	10:00-12:00	7-9	8-9
	1:00-5:00	4-5	4-7
Horizontal lifting distance (cm)	8:00-12:00	30-40	15-20
	1:00-5:00	18-20	17-22

Another aspect of the problem that is considered to make it realistic is that there are different worker profiles. Non-identical workers are considered, i.e. they may have different genders, anthropometry, ages, strengths, etc. Workers are grouped into percentiles based upon their genders and lifting capacities. Lifting capacity is determined by the maximum acceptable weight that workers can lift repeatedly for long periods without undue stress or over-tiring [18-19]. Table 2.2 presents examples of the maximum acceptable lifting weight for different percentile male and female workers at 2 different lifting heights, FK and SR. Data in the table is based on Table 1 in Liles (1986) [20]. Generally, higher percentile workers have higher lifting capability than lower percentile workers, i.e. from Table 2.2, a 50th percentile male is capable of lifting 23.4 kg repeatedly without undue stress from floor level to knuckle height while a 95th percentile male is capable of lifting 35.4 kg from floor level to knuckle height. At the same percentile, male workers have higher lifting capability than female workers, i.e. from Table 2.2, a 50th percentile male is capable of lifting 23.4 kg repeatedly from floor level to knuckle height while a 50th percentile female is capable of lifting only 11.6 kg. This research assumes that workers perform lifting with two hands in the sagittal plane.

Table 2.2 Sample maximum acceptable lifting weights (kg)

Lifting heights	50%tile male	95%tile male	50%tile female	95%tile female
FK	23.4	35.4	11.6	21.6
SR	14.3	25.6	7.3	16.8

Since the task demands and work profiles are different. Stress accrued varies when different workers perform the same task during the same hour in the same day and also varies when a worker performs the same task during the same hour but on different days. Some tasks require high physical strength and are considered to be difficult tasks. Some tasks require low physical strength and are considered to be easy tasks. Job rotation may be applied to move workers from difficult tasks to easy tasks to reduce workers' stress.

Balanced rotation, which assumes that the number of workers and the number of tasks are equivalent, is considered in this study. A worker performs one task and a task can be done by only one worker at a time. However, workers can be rotated to perform different tasks at the end of each hour. Workers are assumed to have enough rest at the end of each day so that all stress is relieved. Workers return to a normal condition at the beginning of each day. Therefore, an 8-hour shift or a 1-day interval is simulated.

Because the task demands vary daily, a job rotation schedule that performs the best on one day may not do well on another. An approach to manage this uncertainty is to generate a job rotation schedule that performs well across all different daily demand scenarios. But today, due to dramatic improvements in information technology, information can be obtained easier and with lower cost than in the past. For example,

with a bar coding system, task demands can be known once orders arrive. Therefore, this paper develops a method to incorporate different levels of task demand information when generating worker schedules. Thus, one can determine the value of different levels of task demand information with regard to their potential for reducing low back injuries in workers.

There are 3 levels of task demand information considered in this paper: 1) task demands that are known from history, 2) task demands that are collected right after they have occurred in real time, and 3) task demands that are known in advance. The first case has no information flow from the customer or the source of the task demand to the production setting and no real-time information collecting tools. However, historical data is available for decision-making and can be used to try and create a good job rotation plan. The second case has no information flow from customers to the setting. However, the production setting is capable of collecting real-time information. Therefore, task demands are known once they have occurred. In the third case there is information flow from customers to the production setting. The production setting will know how many and which types of orders or task demands will occur throughout the day at the beginning of the day so workers can be properly scheduled to perform the tasks. Job rotation plans for all three levels of task demand information will be created and compared later in this paper.

3. Solution Methodology

The methodology starts by identifying a proper objective function to assess the potential for worker low back injuries due to lifting. Then a heuristic method is developed to generate robust rotation schedules based upon the three different levels of task demand information. Detailed descriptions are included in the following subsections.

3.1 Objective function

The objective of the job rotation is to reduce the potential for worker low back injury due to lifting. To assess worker stress due to lifting, the Job Severity Index (JSI) that has been proposed by Ayoub et al. is applied [18]. The JSI is a function of lifting weight to worker lifting capacity. From worker low back injury statistics and studies, tasks that have low JSI values imply low injury potential and tasks that have high JSI values imply high injury potential. However, economical loss due to low back injuries is not linearly dependent on JSI. For example, the injury expense for workers working at JSI levels above 1.5 is \$60,000 per 100 FTE (200,000 exposure hours) as compared with an injury expense of only \$1,000 per 100 FTE for workers working at JSI levels of 1.5 and below [21]. Therefore, an objective function based upon the number of lost working days due to lifting is developed. The number of lost days can be represented as a piecewise linear function of JSI as in equation (1). The model is based upon the data from Liles et al. [21] and is fitted with an R-square of 0.98.

$$\begin{aligned}
 \text{Number of lost days} &= 0.89 + 8.63x && \text{if } 0 \leq x \leq 1.5 \\
 &= -547.54 + 374.25x && \text{if } 1.5 \leq x \leq 1.6 \\
 &= 20.05 + 19.51x && \text{if } x \geq 1.6
 \end{aligned} \tag{1}$$

The number of lost days function is composed of three non-decreasing linear regressions. Variable x in equation (1) is a random variable representing the JSI value. If the JSI values fall between 0 and 1.5, the first equation is active. If the JSI value falls between 1.5 and 1.6, the second equation is active; otherwise the third function is active. The objective is then to minimize the maximum JSI, and subsequent number of lost days, for any of the workers.

3.2 The Heuristic Search Method

After developing a specific objective function, which is minimizing the maximum number of worker lost days for any of the workers, a greedy with diversification heuristic is developed to create job rotation schedules based upon three levels of task demand information: 1) task demands that are known from history, 2) task demands that are collected right after they have occurred in real-time, and 3) task demands that are known in advance.

The greedy with diversification heuristic includes a greedy method and a diversification technique. The greedy method is used to find a local optimal solution while the diversification technique is used as a mechanism to escape from the local optimum by perturbing the local optimal solution. The method starts by randomly generating an initial solution and then calculating the number of lost days of each worker. Neighboring solutions are explored by rotating the worker with the highest JSI value to perform other

tasks one period at a time. The current solution is replaced if its neighbor provides a better objective function value.

For example, consider a 4-worker and 4-task problem where the workers include a 50th percentile male, a 25th percentile male, a 90th percentile female and a 50th percentile female and the four tasks include Tasks A, B, C and D. The initial worker schedule is randomly generated and is shown in Table 3.1. During 8 to 9 a.m., the 50th percentile male performs task A, the 25th percentile male performs task B, the 90th percentile female performs task C and the 50th percentile female performs task D. The workers may be assigned to other tasks during the seven other time intervals during the day as shown in Table 3.1. After assigning all of the workers to tasks in each period, the number of worker lost days for each worker based upon the complete schedule is calculated. From the schedule in Table 3.1, the number of worker lost days for the 50th percentile male, the 25th percentile male, the 90th percentile female, and the 50th percentile female are 32, 47, 70, and 61 days, respectively.

Since the 90th percentile female has the maximum number of work lost day (70 days), the heuristic investigates changing some of her tasks to reduce her total JSI for the day. The new assignments considered from 8 to 9 a.m. are schedules 1, 2, and 3 shown in Table 3.2. Schedule 1 swaps the task of the 50th percentile male with the task of the 90th percentile female so the 50th percentile male performs task C and the 90th percentile female performs task A. This is similar to schedules 2 and 3, which swap the task assignment of the 90th percentile female with the 25th percentile male and with the 50th

percentile female, respectively. The swapping technique is applied to every period in a similar manner to find the assignment that results in the greatest reduction in the maximum number of lost days for any of the workers. For n workers, n tasks, and m periods, there are $m(n-1)$ neighbor solutions. The best solution among these $m(n-1)$ neighbors, if it is better than the current solution, will replace the current solution. This process is continued until no further improvement is possible and a local optimum is found.

Table 3.1 Example worker rotation schedule.

Periods	50%tile male	25%tile male	90%tile female	50%tile female
8:00-9:00	Task A	Task B	Task C	Task D
9:00-10:00	Task B	Task A	Task D	Task C
10:00-11:00	Task B	Task A	Task D	Task C
11:00-12:00	Task A	Task B	Task C	Task D
1:00-2:00	Task D	Task C	Task B	Task A
2:00-3:00	Task B	Task A	Task D	Task C
3:00-4:00	Task D	Task A	Task B	Task C
4:00-5:00	Task B	Task C	Task A	Task D
No. of lost days	32	47	70	61

Table 3.2 Example neighboring solutions for the 8:00-9:00 a.m. interval

Schedules	50%tile male	25%tile male	90%tile female	50%tile female
1	Task C	Task B	Task A	Task D
2	Task A	Task C	Task B	Task D
3	Task A	Task B	Task D	Task C

Once a local optimum is found, a diversification technique is applied. The diversification technique is a way to help the procedure escape from the locally optimal solution. The diversification technique used in this heuristic method is randomly swapping two workers with a probability of 0.4 during each period (the value of 0.4 was based on a preliminary study and is further justified in [22]). Diversification is used to drive the search to explore new areas of the search space. The solution from the diversification is assigned to be the current solution regardless of its results and then the improvement process or greedy procedure starts again from this solution. The greedy and diversification processes are repeated until a stopping criterion is met. In the experiments, 50 non-improving consecutive moves was used as a stopping criterion for small problems, which have 4 workers and 4 tasks and 150 non-improving consecutive moves was used as a stopping criterion for big problems, which have 8 workers and 8 tasks. The effectiveness of this heuristic approach is discussed in Section 4.

3.3 Accounting for Different Levels of Task Demand Information

The heuristic method is adjusted for each level of task demand information. In the case where the current task demands are unknown but the historical task demands are known, a simulation program is used to generate task demands in advance based on historical task demand data. The lifting task demands are simulated to calculate the corresponding JSI values for each worker task and hour combination. A thousand JSI values of each worker task and hour combination are used to calculate their means and standard deviations. These means and standard deviations are used as representatives of different

scenarios that may occur. Then, the heuristic method searches for a robust worker schedule for this set of information.

In the case that task demands are obtained once they have already occurred, a robust worker schedule generated from historical task demand data is used as an initial solution for the heuristic method. Once the actual task demands during the first time interval have already occurred, the heuristic method adjusts the workers' schedules for the remaining hours based upon the actual task demands during the previous hour. This is done by treating the first interval's task demands as known and then using the simulated values for the remaining periods applying the heuristic to schedule the remaining periods. This process is repeated every hour when more actual task demand information is acquired.

For the case where all task demands are known in advance, the problem characteristics change from stochastic to deterministic. A mathematical programming model can be formulated to find the optimal solution [22]. However, its computational time grows exponentially with the problem size. Therefore, the heuristic method is also applied to this deterministic case to generate worker schedules that minimize the maximum number of worker lost days for any of the workers.

4. Experimental Results

To determine the performance of worker schedules based upon the three levels of task demand information, 10 test problems are generated. The test problems differ in their sizes. Two problem sizes are used: 4 workers and 4 tasks and 8 workers and 8 tasks.

Each problem size is composed of 5 problem sets differing in their worker profiles and task demands. Problems 1-5 in Table 4.1 have 4 workers and 4 tasks and problems 6-10 have 8 workers and 8 tasks. Since this paper considers uncertain task demands, 100 scenarios of each test problem are generated for evaluation purposes.

In the case of having historical task demands, a robust worker schedule for each test problem is developed based upon a thousand JSI values of each worker task and hour combination. Since robust worker schedules work well with various scenarios of task demands, the robust schedule for each test problem is applied to all 100 scenarios. The maximum number of worker lost day for each scenario is measured. The minimum, average, and maximum for the maximum number of lost days objective are shown in Table 4.1

In the case when task demands are known once they have already occurred, robust worker schedules based upon the historical data are used as an initial worker schedule. Then, worker schedules are adjusted due to the demand patterns that occur in the different problem scenarios. Therefore, worker schedules for the same test problem may vary for different scenarios. The maximum number of worker lost days for each scenario is measured. The minimum, average, and maximum of the maximum number of lost days are shown in Table 4.1

In the case where task demands are known in advance, 100 scenarios of each problem are generated. Then a worker schedule for each problem scenario is developed and the

maximum number of worker lost day for each scenario is measured. As previously noted, for this level of information, task demands are known in advance and the problems become deterministic. Therefore, optimal solutions can be found from a mathematical programming model. However, due to the long computation times the heuristic method was used to solve the problems. In order to verify the effectiveness of the heuristic method, four scenarios of each problem set are chosen to compare the heuristic solutions with the optimal solutions from the math programming model. For the 4-worker and 4-task problems, the average percent difference from the optimal solution is 0.31% and for the 8-worker and 8-task problems, the average percent different from the optimal solution is 0.74%. These results indicate that the heuristic is effective at solving these deterministic problems and therefore it was used to solve the remaining problems that have demands known in advance. The minimum, average, and maximum of the maximum number of lost days for the problems where the demands are known in advance are shown in Table 4.1.

Table 4.1 Experimental results comparing three levels of task demand information.

	Historical task demand				Real-time task demand				Known task demand			
Problem	Min	Avg	Max	s	Min	Avg	Max	s	Min	Avg	Max	s
1	23.7	50.6	57.6	5.5	13.6	41.3	54.8	12.1	13.2	31.5	52.7	13.5
2	51.8	55.0	58.2	1.5	51.4	53.4	56.6	1.2	34.9	50.8	54.8	4.1
3	13.5	50.8	58.0	6.5	13.7	40.8	55.0	12.0	13.4	31.2	52.6	13.2
4	11.9	15.7	53.4	6.6	11.5	12.8	16.2	0.6	11.0	11.8	12.8	0.4
5	13.3	52.0	57.1	6.4	13.3	34.7	53.7	13.8	12.8	22.4	51.8	11.2
6	8.6	9.2	10.3	0.4	8.2	8.8	9.4	0.3	7.9	8.6	9.0	0.2
7	12.5	14.4	49.1	5.4	11.9	12.7	13.4	0.3	11.6	12.4	13.1	0.3
8	12.7	15.1	37.2	4.4	12.5	13.1	13.8	0.3	12.2	12.7	13.4	0.3
9	13.7	46.7	55.1	9.7	13.6	30.4	52.3	11.4	13.4	21.7	51.6	9.2
10	24.2	49.1	54.9	6.1	18.4	38.4	52.8	10.2	13.5	26.3	51.5	10.0

For all 1000 scenarios (100 scenarios for each problem), the maximum number of worker lost days in the case where task demands are known in advance is less than that of the other two cases. Comparing the maximum number of worker lost days in the cases of known real-time task demands and known historical task demands, the case of known real-time task demands performs better in 979 out of 1,000 scenarios or 98% of the time. The average maximum number of worker lost days in the case that only the historical task demands are known is 7.2 days more than the average maximum number of worker lost days in the case that task demands are known in real time and the average maximum number of worker lost days in the case that task demands are known in real time is 5.7 days more than the average maximum number of worker lost days in the case that task demands are known in advance.

A comprehensive analysis of the value of information is performed. Figure 4.1 presents the average maximum number of worker lost days for the three different levels of task demand information. The results indicate that the test problems fall into two groups. The first group includes problems 2, 4, 6, 7, and 8 and the second includes problems 1, 3, 5, 9 and 10. As more task demand information is made available for scheduling the average maximum number of worker lost days for the first group decreases slightly while the average maximum number of worker lost days for the second group decreases significantly. For the first group, the average maximum number of worker lost days in the case that only the historical task demands are known is 1.7 days more than the average maximum number of worker lost days in the case that task demands are known

in real time and the average maximum number of worker lost days in the case that task demands are known in real time is 0.9 days more than the average maximum number of worker lost days in the case that task demands are known in advance. For the second group, the average maximum number of worker lost days in the case that only the historical task demands are known is 12.7 days more than the average maximum number of worker lost days in the case that task demands are known in real time and the average maximum number of worker lost days in the case that task demands are known in real time is 10.5 days more than the average maximum number of worker lost days in the case that task demands are known in advance.

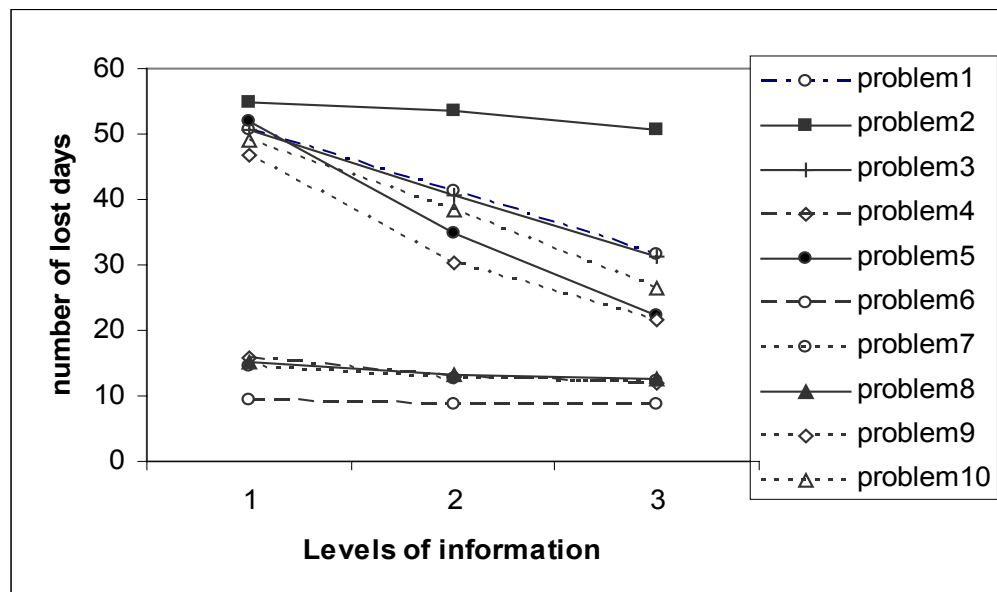


Figure 4.1 Graphical comparisons of three levels of task demand information

What is the source of the difference in the two groups of problems? Exploring the task demands of each problem, we found that the task demands of the problems in the first

group are less variable compared to the task demands of the problems in the second group. Table 4.1 indicates that the standard deviations (s) of the maximum number of lost days in the case of known task demand for the first group ranges from 0.2 days to 4.1 days with an average of 1.1 days while the standard deviations of the maximum number of lost days in the case of known task demand for the second group ranges from 9.2 days to 13.5 days with an average of 11.42 days. Thus, there is much more inherent task variability in the second group. The implications of this difference in inherent task variability are discussed in the next section.

5. Discussion and Conclusions.

Utilizing task demand information to develop worker schedules can be an effective way to reduce the potential for worker injuries. The experimental results from this study show that when more information is known better worker schedules can be developed. This was shown by comparing three levels of task demand information. When task demands are known in advance, the problem characteristics are deterministic and workers can be assigned to tasks during each period optimally. Therefore, the average maximum number of worker lost days is the least among the three cases considered for all scenarios. When task demands are known right after they have occurred, worker schedules can be adjusted based upon the known task demands that have already occurred. The average maximum number of worker lost days is less than the average for the case where the worker schedule is only based upon the historical task demands.

When task demands have high variability, utilizing task demand information to generate worker schedules is more helpful as compared to the case when task demands do not vary significantly. For example, comparing test problem 1 where task demands fluctuate significantly to test problem 6 where task demands do not fluctuate significantly, in test problem 1 the average maximum number of worker lost days reduces from 50.6, when only the historical task demands are known, to 41.3, when real-time task demands are known, to 31.5, when all task demands are known in advance while in test problem 6 the average maximum number of worker lost days reduce from 9.2, when only the historical task demands are known, to 8.8, when real-time task demands are known, to 8.6, when all task demands are known in advance. Thus, if one is scheduling workers in a highly variable environment it is important to have as much task demand information as possible in order to be able to develop better schedules.

The experimental results clearly indicate that when more task demand information is known better worker schedules can be developed and this helps reduce the injury potential. However, different levels of effort are needed in order to obtain these three different levels of task demand information. Therefore, depending on the variability and difficulty of the lifting tasks involved in a company's operations, the company may want to consider having more task demand information available. In particular, when task demands vary significantly the company should consider implementing more advanced information systems in order to provide more timely task demand data. A company would have to weigh the costs of having more enhanced information systems to gather better task demand information with the benefits of reducing the potential for worker

injuries along with other benefits that may be obtained such as reducing inventory levels. There are many other issues that should also be considered when evaluating a new information system such as the willingness of users to accept changes to the system. For more information concerning the evaluation of information technology see Milis et al. [23].

Finally, the results in this paper focused on minimizing the maximum injury potential for any of the workers in a group. An alternative objective would be to minimize the total number of lost days across the entire group of workers. However, this objective was not chosen because schedules that minimize the total number of lost days may be “unfair” because one worker may be put at significant risk of injury while the other workers have minimal risk of injury. Future work could examine using this objective and imposing additional constraints to limit the degree of “unfairness” by limiting the variation in JSI levels experienced by the different workers.

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ภาคผนวก ค.

**A multi-objective mixed integer programming to develop worker
schedules considering worker injury**

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A multi-objective mixed integer programming to develop worker schedules considering worker injury

Abstract

This paper proposes a quantitative method to determine the worker rotation schedules by considering the total labor cost, the potential of worker injury and the capability of workers to perform tasks. The 2-stage MIP models are formulated and can be applied when the number of workers is greater than or equivalent to the number of tasks. The first stage aims to minimize the maximum potential of worker injury when the number of workers and tasks are equivalent, and determines the proper number of workers to minimize the total labor cost when the number of workers is greater than the number of tasks. Then the second stage improves worker schedules by minimizing the total injury loss. The results show that when the number of workers and tasks are equivalent, if the maximum potential of injury determined by JSI value from the first stage is less than the threshold value of 1.5, the total injury loss is on average 0.25 days reduced. However, if this value is greater than 1.5, the total injury loss is on average 182.65 days reduced by increasing the number of workers. With the same total labor cost, applying the second stage decreases the total injury loss on average 5.26 days

Keywords

Worker Assignment Model, Low Back Injury, Worker Skill, and Job Rotation

1. Introduction

The human element is one of the most valuable assets in any manufacturing companies. The manner in which workers are assigned to tasks affects the companies' performance.

Many of the previous works considered assigning workers based upon their labor capacity and/or skills in order to improve profit, productivity, or reduce cost (Askin and Huang 1997, Billionnet 1999, Norman 2002). Assigning workers base upon their skills can improve companies' performances. However, workers are always assigned to tasks that they perform the best. Performing the same tasks repetitively may increase worker stress, fatigue and induce boredom. Moreover, it can be the cause of occupational injury. The models for assigning workers to tasks in order to reduce the potential of worker injuries have been proposed (Tharmmapornphilas et al. 2003, Carnahan et al. 2000). However, these models did not consider worker skills to develop worker schedules and they can only be applied when the number of workers and tasks are equivalent. Therefore, this paper proposes worker assignment models considering worker skills to perform tasks and their potential of injury resulting from performing those tasks. The proposed models can be applied when the number of workers is greater than or equals to the number of tasks. Lifting tasks and low back injury are utilized in the proposed models. However, similar models can be applied to various kinds of tasks and their corresponding injuries.

The remainder of this paper is organized as follows: section 2 provides background on low back pain and a method to assess the potential of low back pain, as well as the previous worker assignment models. Section 3 presents a statement of the problem, all assumptions used in this research, and also the proposed worker assignment models. Test problems are developed and the experimental results are illustrated in section 4. Then, the paper conclusion is in section 5.

2. Background

2.1 Low Back Pain and Lifting Equation

Back problem is a leading cause of work disability and productivity losses in industrialized countries. The cost for occupational low back pain in the United States is approximate \$100 billion per year and continues to rise (Frymoyer 1997). It is estimated that low back pain causes 149 million lost workdays annually, with 102 million lost workdays due to work-related back pain (Guo et al. 1999). Low back injury may occur by direct trauma, a single overexertion, or repetitive trauma. Approximate 90-95% of back pain resolves within 4-6 weeks and only 5-10% of those become chronically disabled and do not resolve for longer than 6 months. However, the group of chronically disabled is accounted for 70-90% of the total cost (Kelsey et al. 1998). A report of The Bureau of Labor Statistics (Bernard and Fine 1997) agrees with other studies that back injury is one of the most serious occupational injuries and the highest proportion of back injury is in the low back area. It also reports that lifting tasks are the major cause of low back injury in manual material handling.

Since lifting overexertion is one of the major causes of low back pain, there is considerable research mentioning ways to control this overexertion. Herrin et al. (1874) proposed four factors that need to be considered in the prevention of musculoskeletal injuries related to manual material-handling. The factors include worker characteristics, material-container characteristics, task-workplace characteristics, and work practice characteristics. The National Institute for Occupational Safety and Health (NIOSH)

developed a guidebook on manual lifting practices (Waters et al. 1993). In case of repetitive lifting with two hands in the sagittal plan, Ayoub et al. (1978) developed the job severity index (JSI) as a method to assess the potential for low back injury due to stress that workers receive while lifting.

The job severity index is based upon the required weight of lift and capacity of the worker who performs that lifting task (Liles 1986).

$$JSI = f\left(\frac{\text{required weight of lift}}{\text{worker capacity}}\right)$$

The validity of the JSI depends upon the accurate assessment of job characteristics and worker capacity. The job characteristics include lifting frequency, exposure time, and task geometry. Worker capacity is estimated from the maximum acceptable weight that worker can lift repeatedly for long period without undue stress or over-tiring. The detail of JSI equation can be found from Liles (1986). This paper utilizes the JSI as a way to assess the potential of low back injury. From Liles et al. (1984), the potential of worker injury increases as the JSI increases. However, the injury threshold appears to exist at a JSI value of 1.5. Workers working at JSI levels greater than 1.5 should expect to be injured much more frequently and more severely than those working at JSI levels less than 1.5. Tharmmaphornphilas and Norman (2004) maps the JSI values to the number of lost days using a continuous piecewise linear regression model, which is presented as the following.

$$\begin{aligned} \text{Number of lost days} &= 0.888 + 8.633 \cdot jsi & \text{if } 0 \leq jsi \leq 1.5 \\ &= -547.5405 + 374.252 \cdot jsi & \text{if } 1.5 \leq jsi \leq 1.6 \\ &= 20.0467 + 19.51 \cdot jsi & \text{if } jsi \geq 1.6 \end{aligned}$$

The number of lost days gradually increases with the JSI values when the JSI values are below 1.5. It sharply increases when the JSI values are between 1.5 and 1.6. Then the increasing rate of the number of lost days reduces when the JSI values are above 1.6.

2.2 Worker Assignment Models

Worker assignment models, which are different in the model objectives and constraints, have been proposed. Many papers propose worker assignment models considering worker technical skills such as CNC lathe operation, machine setup, and inspection and human skills such as communication, problem solving, and teamwork. Askin and Huang (1997) propose a model to minimize training cost incurred while adhering to the skill requirement constraints. Norman et al. (2002) propose a model to maximize profit considering productivity, cost of poor quality, and training cost. Billionnet (1999) applies integer programming to minimize labor cost considering worker ability. Van Oyen et al. (2001) propose models to investigate the environments where multiple workers can collaborate to complete a single task and environments where workers work individually.

Most of the worker assignment models are proposed to improve companies' performance. Then, workers are mostly assigned to tasks based upon their skills. Performing the same task with the same posture repetitively, worker stress can be increased and may lead to occupational injury. Statistics show that occupational injuries are one of the major sources of companies' cost. Some worker assignment models are proposed to reduce the potential of these occupational injuries. These models allow workers to change their

tasks during a day in order to reduce their task exposures, which is a concept of job rotation. Tharmmaphornphilas et al. (2003) applies an integer programming to minimize occupational noise exposure. Carnahan et al. (2000) and Tharmmaphornphilas and Norman (2004) are interested in reducing the potential of low back injury. Carnahan et al. proposed a genetic algorithm as a solution methodology while Tharmmaphornphilas et al. formulate an integer programming model and propose a robust heuristic technique using the central limit theorem of sums to solve the problem. However, these models never consider other companies' performance except for the potential of worker injury. Therefore, this paper proposed the multi-objective worker assignment model that considers the total labor cost, the potential of worker injury, and the worker skill requirement to perform tasks.

3. Proposed worker rotation models

The proposed models are applied in manual lifting environment, where workers perform lifting tasks. Low back injury may accrue to the workers performing lifting tasks with intensive task demands. Job Severity Index (JSI) is used to assess the potential of low back injury. Remind that workers with high JSI values have more potential of low back injury than workers with low JSI values and the threshold of JSI value is 1.5.

Problems considered in the proposed worker assignment model include n tasks and m workers, where the number of tasks is less than or equals to the number of workers $n \leq m$. All tasks are different in their task intensities, and the task intensities of each task are varied from period to period. Task intensity includes the lifting frequency, the

horizontal lifting distance, the lifting weight, and the lifting height. Workers are also different in lifting capacities and genders. Male workers tend to have higher lifting capacity than female workers do, and workers at higher percentile tend to have higher lifting capacity than ones at lower percentile do.

During each working period, all tasks must be performed but a worker may or may not be chosen to perform a task. A worker can be assigned to a task only if he/she has higher skill level than the skill level requirement of that task. If a worker is assigned to at least one task, he/she will be in the payment list. Otherwise that worker is out of the payment list. Each worker must work individually. No more than one worker performs the same task and no more than one task is assigned to a worker during the same time duration. However, workers can be rotated to perform different tasks at the end of each hour. Proper worker rotation could be a way to reduce the potential of worker injury.

Two aspects can be considered to minimize the potential of low back injury including minimizing the maximum injury potential among all workers and minimizing the total injury potential of all workers (Tharmmaphornphilas and Norman 2004). In order to maintain the maximum injury potential to be low, minimizing the maximum JSI value can be used as an objective function of the model. However, minimizing the total JSI value may not be proper to present the total injury potential since the injury loss is not linearly related to the JSI value. Workers with JSI values greater than 1.5 expect to be injured much more frequently and more severely than those with JSI values less than 1.5. For example, the total injury loss of two workers with the JSI value of 0.9 and 2.0 is

greater than the total injury loss of other two workers with the JSI value of 1.4 and 1.5 even though the total JSI values of these 2 groups are the same. Therefore, the total number of worker lost day is applied to quantify the total injury potential.

This paper proposes two stage mixed integer programming model to determine worker rotation schedule. When the number of workers is equivalent to the number of tasks, the first stage objective function is to minimize the maximum JSI value. Minimizing the maximum JSI value would develop worker schedule that the injury potential of each worker is low. Then the second stage is applied to minimize the total number of worker lost day while keeping all JSI values below the maximum value from stage 1 or 1.5. With this objective, the total potential of all workers will be at minimum.

Since the worker injury would be dramatically increased if the JSI value is greater than 1.5. In case of the maximum JSI value that is greater than 1.5, an additional number of workers should be considered. The detail of the first stage model is in figure 1 and the detail of the second stage model is in figure 2.

When the number of workers is greater than the number of tasks, the proper number of workers should be determined. Using a large number of workers increases the total labor cost while using a small number of workers may increase the injury loss. The first stage model is proposed to minimize the total labor cost while maintain the JSI value of workers to be below the threshold of 1.5. The detail of this model is in figure 3. After the total labor cost is determined, an improved worker assignment can be developed by

the second stage model, which is minimizing the total number of worker lost day while keeping the maximum JSI value to be below the threshold and the total labor cost to be below the value from the first stage.

Model notation and definitions

Model parameters

I Set of workers $i = 1, 2, \dots, n$

J Set of jobs $j = 1, 2, \dots, m$

K Set of periods $k = 1, 2, \dots, p$

$labor_cost_i$ = Labor cost of worker i ,

$worker_skill_i$ = Skill level of worker i ,

job_skill_j = Skill requirement for job j ,

sub_jsi_{ijk} = JSI value of worker i perform job j at period k ,

M = A large positive number

Decision variables

x_{ijk} = 1 if worker i performs job j during period k ,

0 otherwise,

jsi_i = An entire day JSI value of worker i ,

z_{ij} = A (0,1) decision variable,

$maxjsi$ = The maximum JSI value among all worker

[INSERT FIGURE 1 ABOUT HERE]

The model to minimize the maximum JSI value is presented in figure 1. Constraints 1 and 2 are worker assignment constraints. Constraint 1 ensures that during each working period, a job is performed by one worker. Constraint 2 ensures that during each working period, a worker is assigned to only one job. Constraint 3 ensures that a worker works at most 8 hours during a day. Constraints 4 and 5 are skill level requirement constraints. Workers must have higher skill level than the skill level requirement of jobs that they perform. Constraint 6 is applied to compute the maximum JSI value among all workers. This model can be used when the number of workers and the number of tasks are equivalent or the number of workers is greater than the number of tasks. If the number of workers and the number of jobs are equivalent, constraints 2 and 3 can be replaced by constraint 7.

$$\sum_{j=1}^m x_{ijk} = 1 \quad \forall i, k \quad (7)$$

Since the objective of this model is to minimize the maximum JSI value among all workers, the injury potential of each worker tends to be low. The severe low back injury may accrue to the workers who work at the JSI value that is greater than 1.5. Therefore, if the maximum JSI value is greater than this threshold, an additional number of workers should be considered in the model.

Once the maximum JSI value is obtained, an improved worker assignment can be developed from the second model, which is shown in figure 2. Before describing the model in detail, additional model parameters should be introduced.

Model parameters

O Set of break points of a piecewise linear function $o = 1, 2, \dots, a$

L Set of straight line segments of a piecewise linear function $l = 1, 2, \dots, a-1$

W_i Set of random variables w_{oi}

WW_i Set of binary 0-1 variables ww_{li}

Decision variable

$injury_loss_i$ The number of lost days of worker i

This model minimizes the total injury loss represented by the number of worker lost days. Constraints 8-12 are similar to constraints 1-5 from the first model. Similarly to the first model, if the number of workers and the number of jobs are equivalent, constraints 9 and 10 can be replaced by constraint 7. Constraint 13 is used to compute the JSI value of each worker. Constraint 14 limits the maximum JSI value of each worker to be below $maxjsi$, which can be 1.5 or the objective function value from the first model. This model determines losses due to low back injury by applying the number of lost day function from Tharmmaphornphilas et al. and Norman (2004). This piecewise function is also illustrated in section 2.1. Constraint 15 is used to calculate the number of lost days corresponding to the daily JSI value. The number of lost days in constraint 15 is calculated based upon random variables in the set W_i , which can be obtained from constraint 16.

Constraint 16 is used to link the daily JSI value from constraint 14 to the random variables in the set W_i . Constraints 17-20 are used to link random variables in the set W_i to binary variables in the set WW_i . Constraint 21 guarantees that the summation of

random variable in the set W_i equals to 1 while constraint 22 guarantees that the summation of binary variable in the set WW_i equals to 1.

When the JSI value of worker i lines on the first straight line segment, ww_{0i} equals 1 and only w_{0i} and w_{1i} can be positive. When the JSI value of worker i lines on the second straight-line segment, ww_{1i} equals 1 and only w_{1i} and w_{2i} can be positive. When the JSI value of worker i lines on the third straight-line segment, ww_{2i} equals 1 and only w_{2i} and w_{3i} can be positive. For example, when the JSI value of worker 1 is 1.55, ww_{11} will be 1, w_{11} and w_{21} will be 0.5. The number of lost day of this worker equals to 32.55 days.

[INSERT FIGURE 2 ABOUT HERE]

When the number of workers is greater than the number of tasks, minimizing the total labor cost objective is used to determine the number of workers that should be employed in order to keep the JSI value of each worker below 1.5. The detail of this model is in figure 3. This model is similar to the first model that is minimizing the maximum JSI value. However, constraint 25 is different from constraint 3, which the right hand side of this constraint contains variable y_i . Variable y_i equals 1 if worker i is assigned to any tasks during any periods; otherwise, it equals 0. Constraint 25 ensures that a worker will be in the payment list if he/she is assigned to at least one job. If a worker is in the payment list, his/her labor cost will be computed in the objective function. If workers are not allowed to work at the JSI value above 1.5, the parameter $maxjsi$ in constraint 28 is 1.5.

Once the minimum of the total labor cost is obtained from the third model, an improved worker schedule can be obtained from the forth model. This model is similar to the second model; however, an additional constraint, which is constraint 29, should be incorporated.

$$\sum_{i=1}^n labor_cost_i y_i \leq total_labor_cost \quad (29)$$

The parameter *total_labor_cost* is the objective function value from the third model. Also, constraint 10 should be substituted by constraint 25. Worker schedule obtained from this model may contain the smaller number of lost days than worker schedule obtained from the third model, which each worker has the JSI value below 1.5 and the total labor costs are equivalent.

The models that contain the constraint of limiting the daily JSI value of each worker to be below a threshold may bring about infeasible solutions. One way to construct feasible solutions is to increase the number of workers or workers should collaborate to complete a task during the same time duration. However, this paper considers problems where the number of worker is large enough in order to obtain a feasible solution.

[INSERT FIGURE 3 ABOUT HERE]

4. Computational Results

The models are tested with 2 different sizes of problems defined by the number of tasks. Sixteen 4-task problems and eight 8-tasks problems are generated and used in the experiment. Task intensities are varied and are classified into 4 groups: easy, moderate, difficult, and very difficult. Task intensities are determined by measuring the JSI value accrues to the 50th percentile male if he works all day on that task. If the 50th percentile male works on an easy task all day, the JSI value accrues to this worker is less than 1.0. If he works on a moderate task all day, the JSI value accrues to this worker is between 1.0 and 1.5. If he works on a difficult task all day, the JSI value accrues to this worker is between 1.5 and 2.0 and if he works on a very difficult task all day, the JSI value accrues to this worker is greater than 2.0. The detail descriptions of each test problems are illustrated in table 1.

[INSERT TABLE 1 ABOUT HERE]

Task intensity is determined by the lifting frequency, the lifting weight, the lifting distance, the lifting height. Task intensities during a day of each task are varied. The lifting frequency, the lifting weight, and the lifting distance are uniformly distributed during each time interval. The lifting height is identified by subtask. An example of task characteristic is illustrated in Table 2. If the 50th percentile male working on this task during 8-9, the JSI value accrues is 0.06, but it is 0.11 if he works on this task during 2-3 pm.

[INSERT TABLE 2 ABOUT HERE]

Workers are different in their genders, percentiles and skill levels. This research considers 2 levels of worker skill; however, the model can also be applied to more than 2 skill levels. Workers with skill level 2 are more expensive than worker with skill level 1. Workers with the same skill level get paid at the same rate. Worker percentiles used in the experiment range from 0.2–0.9. The 4-task problems are applied to workers of sizes 4 and 6. The 8-task problems are applied to workers of sizes 8 and 12.

In case of equivalent number of workers and tasks, the first model is applied to find the least maximum JSI value. With this model, the potential of injury for each worker is reduced. If the least maximum JSI value is less than 1.5, the second model is applied to find a worker schedule that minimizes the total number of lost days while keeping the maximum JSI value to be below a threshold. The mathematical models were solved using CPLEX 7.0. The results are illustrated in table 3.

If the least maximum JSI value is greater than 1.5, an additional number of workers are recommended. For 4-task problems, 2 extra workers are added into the model and for 8-task problems, 4 extra workers are added into the model. Since the number of workers is greater than the number of tasks, the third model is applied to find a proper group of workers that provides the minimum total labor cost while maintaining the maximum JSI value below 1.5. Then the improved worker schedule is obtained from the forth model.

The mathematical models were solved using CPLEX 7.0. The results are illustrated in table 4.

[INSERT TABLE 3 ABOUT HERE]

Table 3 illustrates the experimental results from model I and model II. The results from the first model show that 5 out of 24 test problems obtain the maximum JSI value below 1.5. These test problems are solved again in the second model. The maximum JSI value constraint in the second model is assigned to 2 different values. For the first case, the maximum JSI value equals the objective function value obtained from model I, and for the second case the maximum JSI value equals 1.5. The total number of lost days from the second model decrease, compared to the ones from the first model, in all test problems except for the first case of problem 5. In the first case the total number of lost day reduces on average 0.25 days, and in the second case, the total number of lost day reduces on average 1.18 days.

Additional number of workers is included in other test problems, which the maximum JSI values are above 1.5. These test problems are applied again in the third and forth models. Table 4 illustrates the experimental results from model III and model IV.

[INSERT TABLE 4 ABOUT HERE]

The third model aims to minimize the total labor cost while maintaining the JSI values of all workers below 1.5. Columns 4-6 in table 4 show the total labor cost, maximum JSI value, and the total number of lost days resulted from model III. Numbers in parentheses in column 4 are the number of workers chosen to perform tasks in each problem. The total number of lost days from model III decrease in all problems compared to the ones from model I. The total number of lost days decreases on average 182.65 days. This number is huge due to worker schedules keeping all JSI values below 1.5.

However, the total labor cost may increase, decrease or remain the same. The total labor cost increase when extra number of workers is needed to perform task in order to keep JSI value below 1.5. The total labor cost remains the same or decrease when proper groups of workers are chosen to perform tasks while keeping the number of workers the same. For example, problem 1 contains 4 tasks, which one requires skill level 2 and others require skill level 1. Among the 4 current workers, 2 workers have skill level 1 and others have skill level 2. Workers with higher skill level are more expensive than worker with lower skill level. When 2 extra workers are introduced, one is at skill level 1 and the other is at skill level 2. The better worker schedule chooses 3 workers at skill level 1 and 1 workers at skill level 2, which provides cheaper labor cost. Since the extra worker at skill 1 is stronger than the current worker at skill level 2, the maximum JSI value can be kept below 1.5 using 4 workers.

Considering identical criteria as model III, model IV provides improved worker schedules. Columns 7 and 8 in table 4 show the maximum JSI value and the number of

lost days from model IV. The labor cost from model IV is equivalent the labor cost from model III. However, the number of lost days reduces in all problems and it decreases on average 5.26 days. The maximum JSI values from these 2 models are not statistically different with $\alpha = 0.05$.

5. Conclusion

Occupational injury could be one of significant sources of cost in companies. The occupational injury can be controlled by different methodologies: engineering solutions, administrative controls and personal protective equipment. This paper utilizes lifting tasks as examples and proposes multi-objective mixed integer programming models to develop worker rotation schedules considering worker skills. The proposed methodology includes 2 stages to solve the problems and can be applied when the number of workers and tasks are equivalent or when the number of workers is greater than the number of tasks.

For the first case, the first stage develops worker schedules that minimize the maximum potential of injury among all workers. This objective function develops worker rotation schedules that not allow any workers to have high risk of injury. If the objective function values (the maximum JSI values) are less than 1.5, worker schedules are improved by the second stage; otherwise additional workers are recommended. The second stage aims to reduce the total injury loss determined by the total number of lost days. With identical criteria as in the first stage, the second stage decreases the number of lost day on average 0.25 days. However, if the maximum number of lost day is allowed to be 1.5, the second

stage decreases the number of lost day on average 1.18 days. A small amount of the number of lost days is decreased since JSI value of each worker is already below the threshold. Therefore, there is rare event of injury and the injury is not severe.

For the second case where the number of workers is greater than the number of tasks, the first stage is used to determine a proper group of workers with the minimum total labor cost. This group of workers must have enough skill levels to operate tasks and their potential of injury due to operating tasks must be below the threshold. Once the minimum labor cost is obtained, the worker schedules are improved by the second stage. A group of workers chosen from the second stage may not be exactly the same as the one from the first stage. With the same labor cost as in the first stage, the second stage develops worker schedules that the total injury loss is reduced on average 5.26 days. This number is larger than the average number from the first case due to more different workers can be chosen to perform tasks.

One way to deal with multi-objective is developing only one model and minimizing the total cost including the total labor cost and the total injury cost. However, this research uses the 2-stage method due to difficulty of transferring the number of lost days to injury costs. Moreover, from the company perspective, labor cost is more interesting to be reduced than the injury cost since it is more direct cost.

Considering computational time, all problems are solved using CPLEX 7.0 on Pentium 4, 2.6 GHz. For all 4-task problems, the average computational time is 1.5 seconds.

However, the computational time dramatically increase when the number of tasks is 8. For the 8-task problems, the average computational time is 7 hours. Therefore, mathematical models may not be proper to solve bigger problems. Heuristic method should be developed in the future to solve bigger problems.

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Figure 1 A mixed integer programming to minimize the maximum JSI value

min $maxjsi$

subject to

$$\sum_{i=1}^n x_{ijk} = 1 \quad \forall j, k \quad (1)$$

$$\sum_{j=1}^m x_{ijk} \leq 1 \quad \forall i, k \quad (2)$$

$$\sum_{j=1}^m \sum_{k=1}^p x_{ijk} \leq 8 \quad \forall i \quad (3)$$

$$job_skill_j - worker_skill_i \leq M \cdot (1 - z_{ij}) \quad \forall i, j \quad (4)$$

$$\sum_{k=1}^p x_{ijk} \leq M \cdot z_{ij} \quad \forall i, j \quad (5)$$

$$maxjsi \geq \sum_{j=1}^m \sum_{k=1}^p sub_jsi_{ijk} \cdot x_{ijk} \quad \forall i \quad (6)$$

$$x_{ijk} = 0 \text{ or } 1 \quad \forall i, j, k$$

$$z_{ij} = 0 \text{ or } 1 \quad \forall i, j$$

$$jsi_i \geq 0 \quad \forall i$$

$$maxjsi \geq 0$$

Figure 2 A mixed integer programming to minimize the total number of lost days

$$\begin{aligned}
 \min \quad & \sum_{i=1}^n injury_loss_i \\
 & \sum_{i=1}^n x_{ijk} = 1 \quad \forall j, k \quad (8) \\
 & \sum_{j=1}^m x_{ijk} \leq 1 \quad \forall i, k \quad (9) \\
 & \sum_{j=1}^m \sum_{k=1}^p x_{ijk} \leq 8 \quad \forall i \quad (10) \\
 & job_skill_j - worker_skill_i \leq M \cdot (1 - z_{ij}) \quad \forall i, j \quad (11) \\
 & \sum_{k=1}^p x_{ijk} \leq M \cdot z_{ij} \quad \forall i, j \quad (12) \\
 & jsi_i = \sum_{j=1}^m \sum_{k=1}^p sub_jsi_{ijk} \cdot x_{ijk} \quad \forall i \quad (13) \\
 & jsi_i \leq \max jsi \quad \forall i \quad (14) \\
 & injury_loss_i = 0.888 \cdot w_{0i} + 13.8375 \cdot w_{1i} + 51.2627 \cdot w_{2i} + 117.5967 \cdot w_{3i} \quad \forall i \quad (15) \\
 & jsi_i = 0 \cdot w_{0i} + 1.5 \cdot w_{1i} + 1.6 \cdot w_{2i} + 5 \cdot w_{3i} \quad \forall i \quad (16) \\
 & w_{0i} \leq ww_{0i} \quad \forall i \quad (17) \\
 & w_{1i} \leq ww_{0i} + ww_{1i} \quad \forall i \quad (18) \\
 & w_{2i} \leq ww_{1i} + ww_{2i} \quad \forall i \quad (19) \\
 & w_{3i} \leq ww_{2i} \quad \forall i \quad (20) \\
 & \sum_{o=1}^a w_{oi} = 1 \quad \forall i \quad (21) \\
 & \sum_{l=1}^{a-1} ww_{li} = 1 \quad \forall i \quad (22) \\
 & x_{ijk} = 0 \text{ or } 1 \quad \forall i, j, k \\
 & z_{ij} = 0 \text{ or } 1 \quad \forall i, j \\
 & jsi_i \geq 0 \quad \forall i \\
 & injury_loss_i \geq 0 \quad \forall i \\
 & w_{oi} \geq 0 \quad \forall i, o \\
 & ww_{li} = 0 \text{ or } 1 \quad \forall i, l
 \end{aligned}$$

Figure 3 A mixed integer programming to minimize the total labor cost

$$\min \sum_{i=1}^n labor_cost_i y_i$$

subject to

$$\sum_{i=1}^n x_{ijk} = 1 \quad \forall j, k \quad (23)$$

$$\sum_{j=1}^m x_{ijk} \leq 1 \quad \forall i, k \quad (24)$$

$$\sum_{j=1}^m \sum_{k=1}^p x_{ijk} \leq 8 \cdot y_i \quad \forall i \quad (25)$$

$$job_skill_j - worker_skill_i \leq M \cdot (1 - z_{ij}) \quad \forall i, j \quad (26)$$

$$\sum_{k=1}^p x_{ijk} \leq M \cdot z_{ij} \quad \forall i, j \quad (27)$$

$$max\ jsi \geq \sum_{j=1}^m \sum_{k=1}^p sub_jsi_{ijk} \cdot x_{ijk} \quad \forall i \quad (28)$$

$$x_{ijk} = 0 \text{ or } 1 \quad \forall i, j, k$$

$$y_i = 0 \text{ or } 1 \quad \forall i$$

$$z_{ij} = 0 \text{ or } 1 \quad \forall i, j$$

$$jsi_i \geq 0 \quad \forall i$$

Table 1. Descriptions of the 20 test problems

Problems	Total number of tasks	Number of easy tasks	Number of moderate tasks	Number of difficult tasks	Number of very difficult tasks
Problems 1-8	4	2	2		
Problems 9-12	4		2	2	
Problems 13-16	4	2			2
Problems 17-18	8	4	4		
Problems 19-20	8		4	4	
Problems 21-22	8	4			4
Problems 23-24	8		4		4

Table 2. An example of task characteristic

Task descriptions	Subtasks	Duration	
		8-10	10-12 & 1-5
Lifting weight (kg.)	Floor to Knuckle	U(5,10)	U(15,20)
	Floor to Shoulder	U(5,10)	U(5,15)
Lifting rate (lifts/min)	Floor to Knuckle	U(5,10)	U(5,10)
	Floor to Shoulder	U(5,8)	U(5,8)
Lifting distance (cm)	Floor to Knuckle	U(5,10)	U(10,15)
	Floor to Shoulder	U(5,10)	U(10,15)

Table 3. The experimental results from model I and model II

Problems	Model I		Model II	
	MaxJSI	Total lost days	Total lost days	
			Model I	1.5
1	2.07	94.26		
2	1.29	43.59	43.55	43.51
3	1.84	128.88		
4	1.49	49.94	49.62	49.62
5	1.45	52.94	52.94	52.83
6	1.93	131.67		
7	1.56	97.66		
8	1.72	162.12		
9	2.95	218.21		
10	2.96	216.88		
11	2.93	245.60		
12	3.12	246.15		
13	2.41	243.47		
14	2.99	184.73		
15	4.82	277.60		
16	3.59	229.67		
17	1.29	93.09	92.23	90.33
18	1.29	94.80	94.78	92.15
19	2.08	428.41		
20	2.20	401.16		
21	2.85	400.53		
22	2.33	442.08		
23	2.99	443.81		
24	2.48	462.06		

Table 4. The experimental results from model III and model IV

Problems	Model I		Model III			Model IV	
	Labor cost (no. workers)	Lost days	Labor cost (no. workers)	MaxJSI	Lost days	MaxJSI	Lost days
1	800 (4)	94.26	700 (4)	1.49	43.28	1.09	41.33
3	800 (4)	128.88	700 (4)	1.47	53.58	1.31	44.20
6	800 (4)	131.67	700 (4)	1.50	56.97	1.47	50.81
7	800 (4)	97.66	800 (4)	1.49	50.67	1.49	42.75
8	800 (4)	162.12	800 (4)	1.49	50.67	1.49	42.75
9	800 (4)	218.21	950 (5)	1.47	68.38	1.49	58.93
10	800 (4)	216.88	1200 (6)	1.45	77.78	1.49	66.64
11	800 (4)	245.60	950 (5)	1.43	61.45	1.50	57.83
12	800 (4)	246.15	1050 (5)	1.47	67.74	1.50	57.35
13	800 (4)	243.47	950 (5)	1.50	63.56	1.49	60.85
14	800 (4)	184.73	1050 (5)	1.47	65.38	1.49	61.93
15	800 (4)	277.60	1300 (6)	1.49	79.36	1.49	74.49
16	800 (4)	229.67	950 (5)	1.48	68.67	1.49	66.68
19	1700 (8)	428.41	2100 (10)	1.49	133.07	1.50	125.53
20	1700 (8)	401.16	1750 (9)	1.50	120.67	1.50	116.96
21	1500 (8)	400.53	1750 (9)	1.50	121.27	1.50	117.00
22	1700 (8)	442.08	1850 (9)	1.50	123.60	1.50	121.02
23	1600 (8)	443.81	2100 (11)	1.50	139.27	1.50	138.70
24	2000 (8)	462.06	2200 (11)	1.49	139.26	1.50	138.97