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A workforce scheduling model to reduce occupational heat stress and labor cost

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Abstract

Excessive exposure to high temperatures in the workplace is a cause of heat stress, anxiety, and fatigue in industrial workers. In workplaces in which workers are surrounded by heat sources such as furnaces and boilers, the heat exposure levels may need to be administratively controlled to adequately protect workers from excessive heat exposure. This study integrates National Institute for Occupational Safety and Health (NIOSH) recommended heat stress limits into the design of workforce scheduling models in order to mitigate the heat exposure level of workers. A binary programming model is formulated to determine the optimal workforce schedule, where the objectives are to minimize the labor cost and to minimize the temperature difference between the actual exposure levels and the recommended exposure limit adopted by NIOSH. Additional considerations include the heat tolerance of workers and task workloads. The Epsilon constraints method is used to obtain the Pareto optimal solutions. Based on the results, this study demonstrates that the average heat stress level of workers can be reduced significantly by the use of a workforce scheduling approach. In the case presented, the difference between the actual exposure levels and the recommended exposure limits of the workforce can be reduced by about 0.73 ˚C per person.

Keywords: Occupational safety, Heat, Workforce scheduling, NIOSH, Workload

1. Introduction

The use of heat is a common practice in manufacturing processes, especially those that involve the alteration of the material’s structure, shape, and other physical properties. In workplaces with excessive heat emission or inadequate heat protection, the emission of radiant heat from these processes can expose workers to heat stress and heat-related illnesses such as excessive sweating, headache, rashes, and fatigue [1]. Aside from the health effects, exposure to excessive heat can affect a worker’s productivity [2]. To reduce heat exposure issues in a workplace, a hierarchy of hazard control measures recommended by the National Institute for Occupational Safety and Health (NIOSH) can be employed [3]. After identifying heat sources, especially those with a potential for causing heat stress, all heat control efforts should be designed with the priority of eliminating or to reducing heat at the source. This step typically involves the insulation of heat equipment, the use of reflective radiant heat shields, and the transfer of exhaust heat to designated areas. Then, engineering control measures can be implemented to transfer exhaust heat away from workers or to protect workers from excessive heat. In countries or places with humid and warm weather, the humidity and high ambient temperatures usually constrain the body’s ability to release excess heat. The use of air-conditioning and spot cooling to improve the thermal comfort of a workplace is a common engineering control practice [4]. When the aforementioned measures are still not sufficient to ensure worker safety, management can use administrative control to reduce the heat exposure of workers to safer levels. The control process usually involves scheduling workers to reduce their work time or reducing the number of workers required in high exposure areas. The use of scheduling has long been recognized as an effective and cost-effective supplemental solution to occupational safety and health problems. However, for occupational heat exposure, there remain unexplored areas of workforce scheduling practice that deserve attention. The details are given in the next section of this paper.

The use of scheduling-based administrative control techniques, such as job rotation, to prevent workers from excessive exposure to occupational hazards has been widely addressed in occupational safety literature, as shown in Table 1. In general, the main objective functions of job rotation modeling studies are to minimize either the number of workers exposed to hazards or the accumulated exposure of individuals. For instance, related to noise hazards, Yaoyuenyong and Nanthavanij 2008 propose a job rotation model and solution algorithms to keep the number of workers exposed to hazardous noise at a minimum [5]. The job rotation model by Tharmmaphornphilas et al., 2003 instead focuses on minimizing the maximum daily noise dose of workers [6]. During the past decade, safe workforce scheduling studies aimed to obtain optimal worker-task matching, while at the same time keeping workers safe from the health effects of exposure to occupational hazards. The combination of multiple operational objectives in safe workforce scheduling has been an ongoing research subject. Barrera et al., 2012 propose mixed-integer linear programming and heuristic approaches to minimize the number of workers needed for a service plan while simultaneously balancing the workload among workers [7]. A job-rotation model proposed by Yoon et al., 2016 deals with the cumulative workload both by eliminating high sequential workloads and balancing the cumulative daily workload among workers [8]. Multi-objective optimization techniques are used in job rotation studies. Rerkjirattikal and Olapiriyakul 2019 use the maximin technique to determine safe job-rotation plans with satisfactory levels of operating cost and workers' job satisfaction [9]. Sana, S.S., et al., 2018 formulate a multi-objective job rotation model and non-dominated sorting genetic algorithm to determine job rotation plans that consider multiple ergonomic risks [10].

In general, occupational hazards can be classified by whether their permissible limits of exposure are the same for every worker, or different from person to person depending on each person's capacity to withstand it. The two types of hazards are respectively referred to as single- and variable-limit hazards [5]. In the case of single-limit hazards, all workers can be considered identical under a job rotation plan in terms of exposure capacity [6]. The scheduling of workers under variable-limit hazards is a more complex task, due to the need to manage a heterogeneous workforce with varied ability to withstand hazards in day-to-day operations [11-13]. The impacts of workforce diversity on productivity, wage, and, most importantly, individual ability to withstand hazards, must be considered.

Heat is a variable-limit hazard whose ability to cause thermal discomfort and occupational injuries is dependent on many personal and environmental factors. The fundamentals of heat hazard and heat stress factors have been rigorously studied. Heat stress factors are comprised of the individual characteristics of workers (acclimatization), workload (metabolic rate), and ambient climatic conditions (air movement, humidity, and radiant heat) [14]. The impacts of clothing related to the heat exchange between the body and its immediate environment are also discussed by previous research [15]. Various heat management guidelines have been developed, as reviewed by Rowlinson, YunyanJia et al. 2014 [16]. Extensive research efforts have focused on how to develop heat stress indices as discussed in Edirisinghe and Andamon 2019 [17]. Based on these findings, there exist numerous research opportunities to transform the existing knowledge on heat hazard and heat exposure into engineering and management approaches. However, in the context of workforce scheduling, occupational heat exposure has received far less research attention than other variable-limit hazards.

Table 1 Literature review summary.

Occupational health burden	Modeling/solution approaches	Objectives	Previous studies
Single- and variable-limit hazards	Heuristic job rotation procedures	Minimizing the number of workers exposed to hazards	Yaoyuenyong and Nanthavanij, 2008 [5]
Noise	Multi-workday job rotation scheduling model	Minimizing the maximum daily noise exposure encountered among the workers	Tharmmaphornphilas et al., 2003 [6]
Workload	Mixed-integer linear programming and heuristic procedures	Minimizing the number of workers and balancing workloads	Barrera, Velasco, 2012 [7]
Daily cumulative workloads	Integer programming model	Eliminating sequential workloads and balancing daily cumulative workloads	Yoon, Ko, 2016 [8]

Occupational health burden	Modeling/solution approaches	Objectives	Previous studies
Noise	Multi-objective binary programming models	Controlling the noise exposure levels among workers, considering labor cost and workers' job satisfaction	Rerkjirattikal and Olapiriyakul, 2019 [9]
Ergonomic	Multi-objective programming and non-dominated sorting genetic algorithm	Reducing ergonomic risks	Ospina Mateus, Sana, 2018 [10]
Noise and low back injuries	Safe skill-based and multi-objective integer programming model	Minimizing exposure risks and workers' idleness	Deljoo, Al-e-hashem, 2009 [11]
Ergonomic risks	Mixed-integer linear programming models	Controlling workers' ergonomic risks and reducing daily production cycle time	Moussavi, Mahdjoub, 2016 [12]
Mental and physical workloads	Goal programming model	Balancing workloads	Dewi and Septiana, 2015 [13]

To fill these research gaps, this study develops a workforce scheduling approach for reducing the heat stress of workers. The proposed approach takes into account the acclimatization and workload of workers when assigning workers to tasks at different time intervals. The proposed model is validated using a real manufacturing case study, where the interactions between demand, productivity, skill, and safety, are considered. The situation in which multiple heat stress factors are considered when scheduling workers is presented. In our analysis, an epsilon-constraint method is adopted to generate the set of Pareto optimal solutions for minimizing labor cost and heat stress among workers. The proposed model and multi-objective approach are expected to enable decision makers to reach task assignment plans that are cost-effective while providing workers with low heat stress. In terms of technical contributions, the proposed model is the first effort to apply the NIOSH's recommended WBGT to a workforce scheduling problem. In the next section, research methodologies are presented.

2. Materials and methods

2.1. Heat stress at workplace

In this study, the wet-bulb globe temperature (WBGT) of a manufacturing system case study was measured. WBGT refers to the environmental thermal load imposed on a person, taking into consideration the effects of temperature, humidity, air movement, and solar radiation. The use of WBGT as an index for measuring heat stress in an industrial workplace is recommended by The American Conference of Governmental Industrial Hygienists (ACGIH) and the National Institute for Occupational Safety and Health (NIOSH). For our measurements, a Tenmars-188 Heat Stress WBGT meters is used to measure WBGT, which is computed based on the dry-bulb temperature, wet-bulb temperature, and black-globe temperature. The calculation formula for indoor WBGT used in this study is shown in Equation 1.

$$WBGT_{indoor} = 0.7T_{nwb} + 0.3T_g \tag{1}$$

where;

$WBGT_{indoor}$ = the Wet Bulb Globe Temperature (˚C)
T_{nwb} = the natural wet-bulb temperature (˚C)
T_g = the black globe temperature (˚C)

T_{nwb} is the temperature that indicates the amount of cooling provided to the human subject through evaporation. T_g is the temperature that indicates the mean radiant temperature of the environment. During the measurement, the meter was mounted at a height of 1.1 m for standing individuals and 0.6 m for seated individuals using a tripod stand. The meter was placed away from any barrier that might impede the flow of radiant heat.

2.2. *Recommended WBGT*

Our scheduling objective is to minimize the difference between the worker heat stress and the threshold limit value. In this paper, the heat stress imposed on workers measured in the unit of WBGT will be benchmarked against NIOSH recommended WBGT. As presented in Table 1, the recommended WBGT varies according to the level of workload, work-rest ratio, and the level of acclimatization to hot working conditions. The relationship between these variables and the recommended WBGT have long been publicized in an effort to mitigate heat exposure hazards in the workplace [14]. In our analysis, workers are subject to the recommended WBGT based on their tasks' workload. A constant workload with 75% to 25% work-rest ratio is assumed throughout the task assignment period of an 8-h shift.

Table 2 NIOSH recommended WBGT for 8-h of work for acclimatized and unacclimatized workers (˚C).

Work-Rest	Workload		
	Light (200 Kcal/h) (˚C)	Moderate (350 Kcal/h) (˚C)	Heavy (500 Kcal/h) (˚C)
Continuous	30 (27.5)	27 (25)	25 (21)
75% work-25% rest	31 (29)	28 (26)	26 (23)
50% work-50% rest	32 (30)	29 (28)	27.5 (26)
25% work-75% rest	33 (31)	31 (29.5)	30 (29)

*Figures in ( ) are for unacclimatized workers.

In this section two integer programming models are formulated to determine the optimal workforce schedule based on 1) cost minimization objective (O1) and 2) temperature difference minimization objective (O2). The cost minimization model is used to evaluate the level of heat stress of workers under a typical design goal. The second model aims to minimize the difference between the actual exposure temperature and the recommended exposure temperature adopted by NIOSH. In this study, the workforce consists of experienced and inexperienced workers. We assume that only experienced workers are acclimatized to heat. Inexperienced workers have lower wage and productivity rate and are not acclimatized to heat. The number of workers at each workstation can be varied according to the demand for labor. A worker can perform one task at a time. During any time interval, a workstation must be attended by at least one worker.

2.3. *Mathematical model formulation*

In this section two integer programming models are formulated to determine the optimal workforce schedule based on 1) cost minimization objective (O1) and 2) temperature difference minimization objective (O2). The cost minimization model is used to evaluate the level of heat stress of workers under a typical design goal. The second model aims to minimize the difference between the actual exposure temperature and the recommended exposure temperature adopted by NIOSH. In this study, the workforce consists of experienced and inexperienced workers. We assume that only experienced workers are acclimatized to heat. Inexperienced workers have lower wage and productivity rate and are not acclimatized to heat. The number of workers at each workstation can be varied according to the demand for labor. A worker can perform one task at a time. During any time interval, a workstation must be attended by at least one worker.

2.3.1. *Indices*

i Workstation ID $(i = 1,\ldots,I)$

n Worker ID $(n = 1,\ldots,N)$

2.3.2. *Parameters*

SE_i Temperature at workstation i (˚C)

SD_i Demand requirement of workstation i (Units)

$WP_{i,n}$ Productivity unit of worker n, at workstation i (Units)

$WT_{i,n}$ NIOSH recommended WBGT for 8-h work, for worker n, at workstation i (˚C)

$WC_{i,n}$ Labor cost for worker n, at workstation i (USD)

2.3.3. *Decision variable*

$X_{i,n}$ 1 if worker n works at workstation i, 0 otherwise.

2.3.4. Mathematical model

$$Minimize \sum_{n=1}^{N} \sum_{i=1}^{I} X_{i,n} \cdot WC_{i,n} \quad \text{(O1)}$$

$$Minimize \sum_{n=1}^{N} \sum_{i=1}^{I} \left(SE_i - WT_{i,n}\right) \cdot X_{i,n} \quad \text{(O2)}$$

2.3.5. Constraints

$$\sum_{n=1}^{N} X_{i,n} \geq 1 \qquad \forall i \quad \text{(C1)}$$

$$\sum_{i=1}^{I} X_{i,n} \leq 1 \qquad \forall n \quad \text{(C2)}$$

$$\sum_{n=1}^{N} \left(X_{i,n} \cdot WP_{i,n}\right) \geq SD_i \qquad \forall i \quad \text{(C3)}$$

$$X_{i,n} \in Bin \qquad \forall i, \forall n \quad \text{(C4)}$$

Constraint (C1) states that there is at least one worker at any workstation. (C2) ensures that any worker can perform a task at one workstation during any scheduling period. Constraint (C3) ensures that all workstations have a sufficient number of workers to fulfill their demand requirements. Constraint (C4) declares the binary characteristic of the decision variable. The current study focuses on the hot-climate case. Regarding the objective function (O2), SE_i is assumed to be always greater than $WT_{i,n}$. However, mathematically, SE_i may be strictly less than $WT_{i,n}$. In such cases, the difference between the two parameters needs to be set to 0.

2.4. Case study

A manufacturing case study with nine independent workstations was considered. The amount of workload, WBGTs, and demand levels of all workstations are shown in Figure 1. The amount of workload for the task at each workstation is estimated and assumed to be constant throughout an 8-h shift. The working postures and body movements required for workers to perform tasks are evaluated to determine the amount of heat load generated by workers and the corresponding amount of workload. In this study, workload is classified into three levels: light workload (200 kcal/h); moderate workload (200-350 kcal/h); and heavy workload (350 kcal/h). In our case, for all tasks, workers were in a sitting position with moderate arm-hand movements. A WBGT measurement was conducted to measure indoor WBGT during the hottest two h of a workday in April 2018, which is the hottest period in Thailand. The average WBGTs during the 2-h period are compared against the recommended WBGTs for workers to determine their individual and workforce heat-stress burden. In our manufacturing plant case study, workstations 3, 5, 8 and 9 consist of light workload tasks. Workstations 1, 2, 4, 6 and 7 contain tasks with moderate workloads. Regarding the WBGT, workstations 3, 5 and 9 use machines that act as radiant heat sources and have higher levels of WBGT than others.

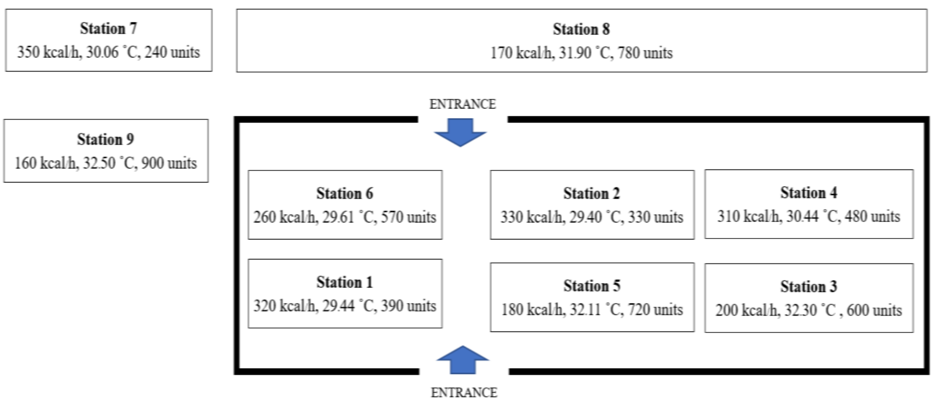
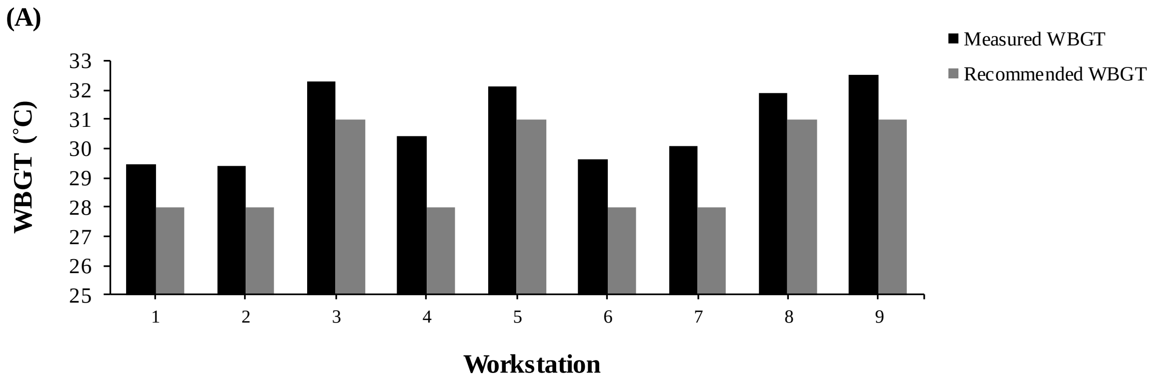


Figure 1 Workplace layout (Workload, WBGT, and demand).

In our case study, the workforce consists of 20 experienced workers and 20 inexperienced workers. It is assumed that experienced workers have worked in their current settings for a long time and they are acclimatized to working under high temperatures. Inexperienced workers are still unacclimatized to working in a high-temperature environment. To visualize the heat stress imposed on workers, we compare the recommended WBGTs of experienced and inexperienced workers against the WBGTs measured at workstations, as shown in Figure 2. For each workforce, the recommended WBGTs vary according to the level of the workload of tasks. The work-rest ratio is 75 to 25 for all workstations. The hiring of experienced workers allows us to have a workforce with higher heat tolerance, but it is a more costly option than hiring inexperienced workers. The cost of hiring experienced and inexperienced workers is shown in the appendix. It is expected that the proposed model will help determine the cost-effective and low-heat-stress task assignment plans.



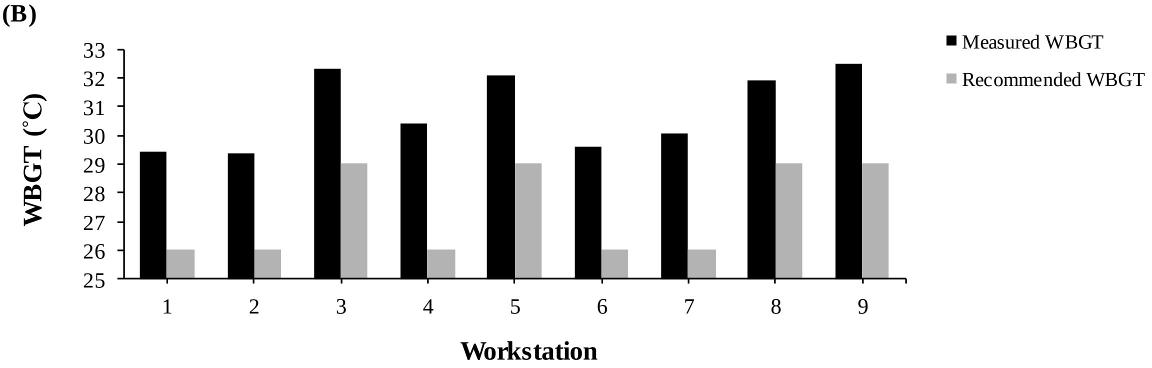


Figure 2 Measured and recommended WBGT. (A) WBGT for experienced workers. (B) WBGT for inexperienced workers.

3. Results

The scheduling of experienced and inexperienced workers to different workstations is made under the cost and heat stress mitigation objectives. It is expected that the heat-stress-mitigation model can lead to a significant reduction in heat stress among workers. The attempt to reduce heat stress may result in higher labor cost. However, it is anticipated that multi-objective techniques can enable us to reach a set of solutions with a good trade-off between cost and heat stress. The proposed model is formulated and solved using Opensolver 2.9.0. The scheduling plans for a workday is obtained as shown in Table 3 and 4. When the scheduling objective is to minimize the cost, the workforce is composed of 20 inexperienced workers and 11 experienced workers. The total cost is 407.41 USD (12,862 Thai Baht (THB)). The total WBGT difference is 74.0 ˚C. When the solving objective is to mitigate the overall heat stress, all 20 experienced workers are utilized due to their higher heat tolerance. Only 10 inexperienced workers are assigned to workstations with relatively lower heat stress. The total WBGT difference reduces to 49.9 ˚C with a labor cost of 462.08 USD (14,588 THB). The attempt to mitigate heat stress leads to the decision to employ all experienced workers, resulting in a much higher labor cost. Figure 3 shows the levels of WBGT difference experienced by the workforce under the cost minimization and temperature difference minimization plans. For each plan, the heat stress of the workers is listed in descending order.

Table 3 Optimal scheduling plans with cost minimization.

	Workstation								
	1	2	3	4	5	6	7	8	9
WBGT (˚C)	29.44	29.40	32.30	30.44	32.11	29.61	30.06	31.90	32.50
Throughput (units)	517	330	692	480	824	575	248	935	1,054
Number of experienced workers	4	3	0	0	0	0	4	0	0
Number of inexperienced workers	0	1	3	3	3	3	1	3	3
Total workers at workstation	4	4	3	3	3	3	5	3	3
Labor cost = 407.41 USD (12,862 THB)				Difference WBGT = 74.00 ˚C					

Table 4 Optimal scheduling plans with temperature difference minimization.

	Workstation								
	1	2	3	4	5	6	7	8	9
WBGT (˚C)	29.44	29.40	32.30	30.44	32.11	29.61	30.06	31.90	32.50
Throughput (units)	395	342	759	487	861	608	240	995	1,107
Number of experienced workers	2	2	3	1	2	1	3	3	3
Number of inexperienced workers	1	2	0	2	1	2	2	0	0
Total workers at workstation	3	4	3	3	3	3	5	3	3
Labor cost = 462.08 USD (14,588 THB)				Difference WBGT = 49.90 ˚C					

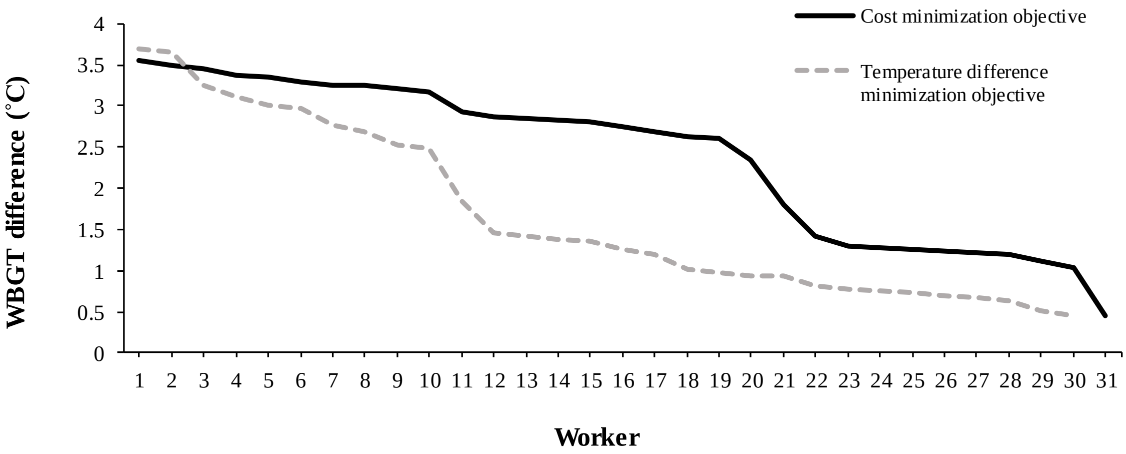


Figure 3 Heat stress of workers.

From the results, the study uses the ε-constraint method to find the trade-off solutions between cost and heat stress impacts. According to the ε-constraint method, the problem is solved based on the temperature different objective, while cost is considered as an additional constraint. The cost obtained from the objective function (O1) is regarded as the minimum cost threshold value. The cost obtained from the objective function (O2) is the maximum threshold value. We solve the problem again while varying the cost threshold value between the two threshold limits and explore the trade-off solutions as shown in Figure 4. In general, the lower-cost solutions make more use of inexperienced workers. Assigned workers have low heat tolerance limits and are subject to substantial heat stress. For lower temperature-difference solutions, more experienced workers with higher heat tolerance limits are employed. Decision makers can select the appropriate solutions from this Pareto frontier based on their budget and heat stress criteria.

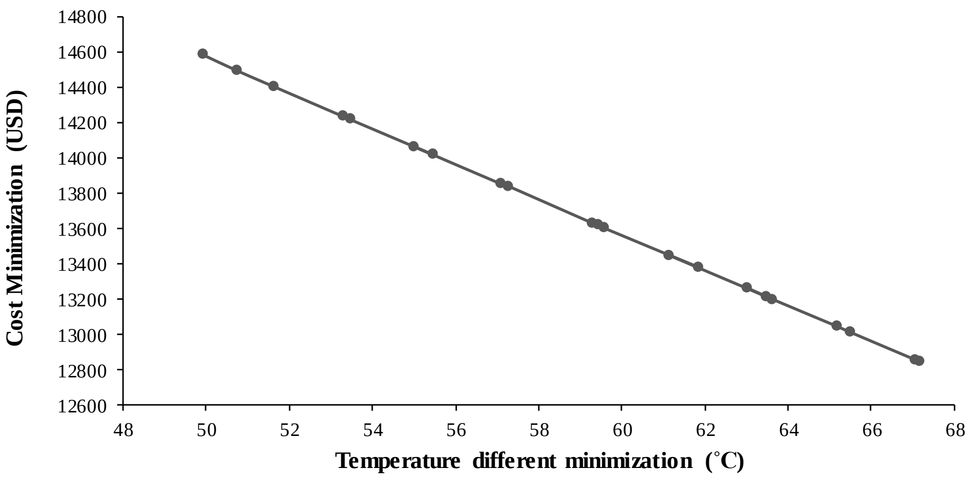


Figure 4 Pareto frontier showing the trade-off solutions.

4. Discussion

For traditional heat-stress mitigation practices, workers are typically assigned to perform tasks based on the permissible exposure duration. Workers are periodically allowed to rest in lower-temperature areas. The ability to monitor workers' heat stress and their progress in demand fulfillment is limited. The proposed job rotation approach offers several advantages over the traditional approach. First, the assignment of workers to tasks is made based on the objective of heat stress mitigation and demand fulfillment requirement. Decision-makers can keep track of individual worker's heat stress while ensuring that the demand is always satisfied. Second, when individual heat stress data are visible, supplemental hygienic practices can be adopted more efficiently within a group of workers requiring heat stress relief. This can lead to cost-saving opportunities since some hygienic practices such as acclimation training and medical screening can be costly in terms of time and money.

There are some limitations to the proposed heat-stress mitigation approach. The effective use of the approach can only be realized when there are significant temperature differences among different workstations. This can be difficult for cases where heat sources are uniformly distributed across all the work areas. Regarding the time period, the current model assumes that workers perform the same task for the entire workday. The current solution can be extended to deal with multiple time periods of a day in which workloads or work conditions may be different. With multiple scheduling periods, workers can be assigned to perform strenuous tasks during the lower temperature periods to attain lower heat stress. Instead of using the epsilon constraint method, goal programming can be used to deal with both objectives together, either in a preemptive/prioritized manner or in a weighted manner. The use of workload-relief and heat-relief equipment can be introduced into the scheduling problem. When using job rotation, skill mismatch is another issue to be addressed. Additional constraints can be formulated based on the need to match workers' skills to the tasks' skill requirements. Other constraints that are worth considering include worker availability, individual limitations, and task requirements.

5. Conclusion

The development of workforce scheduling to resolve heat stress issues at the workplace has received inadequate research attention. The present work is the first study that incorporates NIOSH recommended heat stress limits into a workforce scheduling decision support model to mitigate the heat stress of a workforce. A binary integer programming model is formulated to determine the optimal workforce schedule, where the objectives are to minimize the labor cost and to minimize the temperature difference between the actual exposure levels and the recommended exposure limits adopted by NIOSH. The proposed model incorporates several important heat stress factors, including the heat tolerance of workers, workstation WBGTs, task workloads, and work-rest ratio. The proposed model can serve as a basis for the development of production scheduling tools for improved thermal comfort.

To validate and demonstrate the use of the model from a manufacturing perspective, worker productivity and demand across different workstations are taken into account. As demonstrated by the case study analysis, when temperature difference minimization is the main goal, workers are assigned to perform tasks according to their heat tolerance and exposure temperature. Experienced workers are mainly used to fulfill demand. Inexperienced workers are assigned to perform tasks at workstations with lower temperatures. When compared to the cost minimization scenario, the heat stress of workers reduces by as much as about 0.73 ˚C per person. Given the warm climate in the studying area, this reduction is quite significant and comparable to the WBGT reduction achieved by using mist cooling equipment. The use of the proposed scheduling approach is expected to bring the thermal condition at the workplace closer to worker thermal comfort range.

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