CHAPTER 8

CONCLUSIONS

This chapter summarizes the contents of the research in this dissertation. Next, the key contributions are listed. The recommendations for future research are discussed as well.

8.1 Summary of the Research

8.1.1 Noise Hazard Prevention

Chapter 3 explains three analytical procedures for designing a noise hazard prevention program. The program must prevent the daily noise exposure at any worker location from exceeding 90 dB*A*. An engineering-based procedure emphasizes only engineering controls and, therefore, yields an upper bound of the total noise control cost. An HPD-based procedure, on the other hand, determines an appropriate set of HPDs and the worker locations where the HPDs must be worn. Thus, this procedure gives a lower bound of the total noise control cost. A mixed procedure that follows the OSHA's hierarchy of noise control is developed to design an optimal noise hazard prevention strategy. Depending on noise data, number of workers, feasible noise control methods, and allocated budget, the optimal strategy recommends a combination of engineering controls, job rotation, and/or the use of HPDs to prevent workers' daily noise exposures from exceeding 90 dB*A*. Six optimization models are developed, two for engineering controls, two for job rotation, and two for the use of HPDs. The order of application also follows the OSHA's hierarchy of noise control. The design procedure consists of 12 steps. The six optimization models are sequentially utilized in these steps to determine the optimal noise hazard control strategy.

For engineering controls, Model E1 is intended to find feasible engineering controls to reduce all workers' daily noise exposures to a safety level at a minimum cost. Model E2, on the other hand, is intended to determine engineering controls within the given budget that minimize the maximum daily noise exposure at any worker location. For job rotation, Model A1 is firstly applied to find the optimal work assignment solution based on the current workforce such that all daily noise exposures do not exceed 90 dB*A* and the total worker-location changeover is minimized. If no solution exists, Model A2 is then applied using the increased workforce to determine the minimum number of workers and their work assignments to achieve *safety* daily noise exposure. Models H1 and H2 consider both job rotation and the use of HPDs to find a safety work assignment solution with the minimum number of HPDs used in the facility. Two workforce sizes, $m = n$ and $n \leq m \leq M$, are assumed for the two models, respectively.

Readers should be reminded that the optimal strategies may differ based on the total noise control cost and/or the combination of noise controls to be implemented. In terms of their benefit, all feasible strategies will result in safety noise exposures in all workers. Based on the benefit/cost analysis, one might be tempted to choose the strategy that requires the lowest total cost, which normally is the strategy with job rotation and/or the use of HPDs. However, it has been long known that workers typically resist wearing

HPDs unless being strongly enforced and closely monitored. In practice, this behavior can make the implemented strategy ineffective. Thus, one needs to consider both total cost and effectiveness of the noise hazard control strategy before making a decision.

The optimization approach fails to find the optimal solution or sometimes cannot find the solution with the given computational time. Then, two GAs are developed to deal with the engineering control problem and to perform the workforce scheduling with minimum worker-location changeovers, respectively.

In Chapter 4, the selection of engineering controls for noise hazard prevention is presented. The engineering noise control problem (ENCP) is mathematically formulated as a *zero-one* nonlinear programming problem. The problem objective is to find a set of engineering noise controls, without exceeding the given budget, such that the maximum daily noise load is minimized. The ENCP is a variant of the knapsack problem. GA is developed to provide the optimal or near-optimal solution for the ENCP.

To select appropriate GA parameters and operations, two computational experiments are carried out. The first experiment investigates the effects of GA parameters, namely, crossover probability Pc, mutation probability Pm, population size $Popsize$, and maximum generation Max_gen on the maximum daily noise load $l_{\max}$. The results show that all of the above GA parameters have significant effects on $l_{\max}$. The second experiment is intended to find proper GA operations for solving the ENCP. Two repair procedures are developed to assist the GA in enhancing the quality of the solution. Four hundred and fifty problems (9 problem sizes $\times$ 5 sub-problems $\times$ 10 replicates) are analyzed by the GA. The problems are grouped into six combinations of selected GA operations (called treatments). It is found that the combination which employs enlarged sampling space, roulette wheel selection with elitist selection, single-point crossover, single-point mutation, and ordered repair procedure demonstrates the best performance (i.e., achieving the lowest average $l_{\max}$).

The comparison between the average $l_{\max}$'s obtained from the GA and LINGO confirm that the GA can effectively solve the ENCP. For small-sized problem, the GA is able to yield the average $l_{\max}$'s that are identical to those obtained from LINGO. When the problem size is very large, LINGO will have difficulty finding the optimal solution within the given time limit of 50,000 seconds. The GA, on the other hand, is able to yield the feasible solution in relatively short time irrespective of the problem size.

The given numerical example shows that the noise control budget has significant effect on the obtained engineering controls. If the budget is too low, the recommended engineering controls will not be able to completely reduce noise hazards to the permissible level. In most real situations, the noise control budget is limited and fixed. As such, other noise control approaches should be considered. In practice, a combination of noise control approaches should be implemented to keep the total noise control cost from exceeding the budget and to achieve safety daily noise exposures for all workers.

Chapter 5 demonstrates the application of genetic algorithms to determine daily work assignments for workers such that their hazard exposures do not exceed the permissible level. Although only noise hazard is discussed, the proposed heuristic GA can be modified to solve other occupational hazard problems. The work assignment solution generated by the heuristic GA also requires the minimum number of workers for job rotation and results in the minimum total worker-location changeover, which can help to promote the implementation of job rotation in real work situations.

Two mathematical models (Model A1 and A2) representing the administrative control for noise hazard prevention in this study are integer nonlinear programming models. As the size of the problem increases, it becomes impractical to solve the problem to optimality. That is, the optimization approach to safety-based workforce scheduling is limited in not only the problem size but also the computation time. The use of a GA is expected to be an alternative approach to this type of problem. By considering both the number of workers to safely attend all worker locations and the worker-location changeovers caused by job rotation, the heuristic GA can deal with job rotation in a quantitative manner and yield a productive work assignment solution.

In this research, the proposed heuristic crossover and heuristic mutation not only generate offspring based on some classical concepts but also are intended to improve the offspring so that they will be the best among all feasible offspring. The *Improvement* stage utilizes a specially developed procedure to evaluate the fitness of the offspring and seek the best offspring through a series of systematic exchanges of workers among worker locations. Moreover, with the swap and multi-start algorithms as the local improvement, it is expected to help the heuristic GA to effectively search for a better solution.

Three workplace noise problems are presented as examples to compare the solutions obtained from two solution approaches, i.e., optimization and heuristic GA. Each problem is solved for ten times and using the maximum generation or the termination time as the stopping condition. The results from the examples show that the heuristic GA can effectively find the optimal solution (as judged from m^* and F^*). In terms of the average hit time, the heuristic GA is significantly superior to LINGO.

Mathematical models of certain noise controls are available and they can be solved to determine an optimal noise hazard prevention solution. However, for large-sized problems, this optimal solution procedure is not practical. Thus, in Chapter 6, a Decision Support System is then developed by utilizing the proposed heuristics as shown in Chapter 4, 5, and 6 and by following the OSHA's hierarchy of noise controls.

The proposed noise hazard prevention (NHP) program is an alternative means to solving the workplace noise problem. It applies the concept of decision support systems to generate an effective NHP solution, along with the total required noise control cost and the resulting daily noise exposures of all workers. Through its four modules, the user can create a noise control project; input workplace, machine, noise controls, and HPD data; choose a preferred solution procedure; and view a detailed NHP solution report.

From the given example, a noise control project is created. Then, it is evaluated using seven different combinations of noise controls. The NHP is utilized to generate effective noise hazard prevention strategies, with all resulting daily noise exposures not exceeding the permissible level. For Case NC-5 in which only engineering controls are to be applied, the noise control budget of 30,000 baht is found to be insufficient. Nevertheless, by increasing the budget to 39,500 baht, it is possible to find a noise hazard prevention strategy that is effective. In practice, management can use the NHP to generate noise hazard prevention strategies based on different noise control budget levels and solution procedures. Then, the most preferred strategy can be chosen and implemented.

The NHP program helps to make designing a noise hazard prevention program easy and practical. The recommended NHP solution can be presented in a quantitative manner, making the implementation of the solution more convenient. Moreover, the effectiveness of the solution can be validated by the daily noise exposures of all workers that are computed by the NHP program.

8.1.2 Design of Auditory Warning System

In Chapter 7, the author explains an analytic procedure for evaluating an existing auditory warning system to determine if its alarm signal is adequately audible to alert workers to dangerous situations. The audibility requirement requires that the combined alarm signal sound level must exceed the combined noise level (from the ambient and all machines) by at least 15 dB*A* at any worker location. Two alarm location models are also presented. The model objective is to determine a minimum number of alarm devices and their locations such that a maximum combined alarm signal sound level at any worker location is minimized, yet still exceeding the combined noise level by at least 15 dB*A*. The first model is applicable for the problems in which the signal sound level of the alarm device is assumed to be unknown, while the second one is for those in which the signal sound level of the alarm device is specified. Then, a heuristic algorithm for solving the alarm location problem with known signal sound level of the alarm device is proposed.

Initially, the algorithm searches for the "most required" worker location and its "second most required" neighboring worker location. An alarm device is placed at a location (in between these two worker locations) that satisfies the audibility requirement at the "most required" worker location. After placing the alarm device, the audibility requirement is checked at every worker location. The placement of alarm devices continues until the combined alarm signal sound level exceeds the combined noise level by at least 15 dB*A* at every worker location. A computer program is written in Visual Basic application in Microsoft Excel to perform the computation steps.

For small alarm location problems, it is possible to solve the problem using an optimization approach. The solution (number of alarm devices and their locations) is a local optimum. For large alarm location problems, however, the heuristic approach is more practical than the optimization approach. Although the heuristic approach does not guarantee an optimal solution, it is able to yield a solution that is *near-optimal*. From the computational experiment, the heuristic approach can yield a *minimum* number of alarm devices in 81.25% of the test problems. When comparing the average "signal – noise" differences, the heuristic approach obtains a result that is larger than the *minimax* difference (from the optimization approach) by not more than 2 dB*A*. More interestingly, the efficiency of the heuristic approach is found to increase when the problem size increases.

With the analytic procedure presented in this research, safety practitioners will be able to assess the audibility of an existing auditory warning system in their workplaces. The heuristic procedure will also enable them to determine a minimum number of alarm devices and their locations so that workers can adequately hear the alarm signals. To further enhance the effectiveness of the auditory warning system, it is necessary to consider other issues, namely, cognitive, behavioral, and human factors, regarding the design of auditory warnings and human perception of signals. Furthermore, it is possible to use the heuristic algorithm discussed in Chapter 7 in conjunction with a computerized model called "Detectsound" to account for the effect of age on auditory sensitivity and frequency selectivity. Safety practitioners can firstly utilize the algorithm to determine the number and location of alarm devices and then use "Detectsound"

8.2 Key Contributions of the Research

In summary, key contributions of the research include the following points:

1. The mixed procedure for designing the optimal noise hazard prevention is able to determine a noise control strategy that prevents the workers' daily noise exposures from exceeding 90 dB*A* within a given budget. The resulting strategy follows the OSHA's hierarchy of noise control by applying engineering controls first, followed by administrative controls, and finally the use of HPDs.
2. The GA for the ENCP is able to yield the feasible solution in relatively short time irrespective of the problem size. These findings confirm the effectiveness of the GA in solving the ENCP.

3. Workers are commonly exposed to various occupational hazards such as chemical, radiation, noise, thermal, and physical loads. When job rotation is implemented, the heuristic GA can be used to determine the minimum number of workers and their safety work assignments. Additionally, the GA yields productive work assignments since the total worker-location changeover is minimized.
4. The proposed NHP program will enable ergonomists and safety engineers to evaluate several noise hazard prevention strategies based on different solution procedures and choose the strategy that satisfies the noise control budget and prevents the workers' daily noise exposure from exceeding the permissible level.
5. For the design of auditory warning systems, the proposed heuristic procedure will also enable safety practitioners to determine a minimum number of alarm devices and their locations so that workers can adequately hear the alarm signals. The heuristic is developed as a practical tool for engineers or safety practitioners.

8.3 Recommendations for Future Studies

For the noise hazard prevention problem, the future development of the NHP program may consider the following points:

1. To enhance the capability of the NHP program, the NHP program should be develop under a general language program (e.g., Visual Basic or C language).
2. For engineering controls, the calculation of the noise reduction rate or guideline for selection of the noise control techniques can be added to the NHP program.
3. Pictures of the application of the noise hazard prevention may be added to the NHP program in order to illustrate the noise control techniques to users.

For the design of the auditory warning system, future study may be required as follows:

1. To further enhance the effectiveness of the auditory warning system, it is necessary to consider other issues, namely, cognitive, behavioral, and human factors, regarding the design of auditory warnings and human perception of signals.
2. It is possible to use the heuristic algorithm discussed in this research in conjunction with a computerized model called "Detectsound" to account for the effect of age on auditory sensitivity and frequency selectivity. Safety practitioners can firstly utilize the algorithm to determine the number and location of alarm devices and then use "Detectsound" to make the resulting alarm system more effective for alerting workers to hazardous situations.