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Optimizing Noise Control Strategy in a Forging Workshop

Hamideh Razavi
Ehsan Ramazanifar
Jalal Bagherzadeh

Engineering Faculty, Ferdowsi University of Mashhad, Mashhad, Iran

In this paper, a computer program based on a genetic algorithm is developed to find an economic solution for noise control in a forging workshop. Initially, input data, including characteristics of sound sources, human exposure, abatement techniques, and production plans are inserted into the model. Using sound pressure levels at working locations, the operators who are at higher risk are identified and picked out for the next step. The program is devised in MATLAB such that the parameters can be easily defined and changed for comparison. The final results are structured into 4 sections that specify an appropriate abatement method for each operator and machine, minimum allowance time for high-risk operators, required damping material for enclosures, and minimum total cost of these treatments. The validity of input data in addition to proper settings in the optimization model ensures the final solution is practical and economically reasonable.

noise control   noise exposure   industrial noise pollution   genetic algorithm

1. INTRODUCTION

The deafening sound of forging strokes by heavy machines threatens both the physical and mental health of many industrial workers. Even though administrations are obliged to control the noise according to safety rules, the situation in some workshops is still frustrating [1]. In addition to noise levels themselves, the working hours in which each operator is exposed to loud noise should be controlled. According to the National Institute for Occupational Safety and Health (NIOSH), the workplace where any worker's daily noise exposure exceeds 85 dB(*A*) is required to have a noise hazard protection strategy implemented [2]. However, data collected for this study show that all operators in a press department are subjected to sound levels over 85 dB(*A*). For companies operating in similar fields, noise standards highlight the need for protection and control devices to improve the acoustic conditions and eliminate the noise risk [3].

In spite of costly damages resulting from noise contamination, including physical and mental injuries, some managers are not willing to attend to noise control techniques. This could be explained by unplanned and unorganized control efforts that fail to prove both efficient and economic. Therefore, a few methods have been suggested to find optimum combinations of noise control and to achieve a desired level of abatement. Sanders and McCormick searched for an appropriate combination, disregarding budget constraint and permissible exposure level [4]. Asawarungsaengkul and Nanthavanij proposed various models to be solved with numerical techniques [5, 6, 7]. In one of their approaches, they investigated minimizing the maximum noise load for operators in regard to budget and noise load constraints. Control means were limited to

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Correspondence should be sent to Hamideh Razavi, Engineering Faculty, Ferdowsi University of Mashhad, P.O. Box:91775-1111, Mashhad, Iran. E-mail: h-razavi@um.ac.ir.

sources and transmissions, and they did not consider protection aids for operators or time allowances.

Another approach Asawarungsaengkul and Nanthavanij proposed included six different models in three categories: engineering control, job rotation, and hearing protection device [5]. They did not discuss the solution for each single model. However, they later suggested that a genetic algorithm (GA) should be applied to the problems of job rotation and protection aids. Their methodology did not concern the least costly objective for each single model, and employed a stepwise solution for the whole model.

Studying background research reveals the lack of an integrated model that can simultaneously observe the permitted noise load and budget limits [8, 9, 10, 11]. Therefore, this study develops a thorough mathematical model to find the optimum noise control strategy. Using GA in MATLAB, this model can be run for different settings. This study investigates the real case of a forging workshop. Initially, the layout of the workshop, labor information, machine dimensions, and noise specifications are collected and entered into the model. Next, the parameters are defined and assumptions are made. Finally, the program is run and the solutions are presented and discussed.

2. OPTIMIZATION MODEL

This study develops an integrated model so that noise control methods for emission, transmission, and exposure are optimized simultaneously. The model minimizes the total cost of the strategy in respect to budget limitations as well as related standards. It uses integer programming with multidimensional variables and nonlinear constraints [13]. Since deterministic techniques cannot solve the model, a heuristic method based on GA is applied. The mathematical representation of the model is described here:

$$\min \sum_{i=1}^{op}\sum_{j=1}^{p} \propto_{ij} c_j + \sum_{j=1}^{son}\sum_{k=1}^{w} \beta_{jk} c_k + \sum_{j=1}^{son}\sum_{k=1}^{\upsilon} \gamma_{jk} c_k + \sum_{i=1}^{op} \frac{T_i}{t_i} \times b_i, \qquad (1)$$

subject to

$$D_i = \frac{480 - T_i}{\dfrac{480}{{}_2(L_i - 85)/3.01}} < 1, \qquad (2)$$

$$\sum_{i=1}^{op}\sum_{j=1}^{p} \propto_{ij} c_j + \sum_{j=1}^{son}\sum_{k=1}^{w} \beta_{jk} c_k + \sum_{j=1}^{son}\sum_{l=1}^{\upsilon} \gamma_{jl} c_l + \sum_{i=1}^{op} \frac{T_i}{t_i} \times b_i < \text{investment}, \qquad (3)$$

where

op = number of exposed operators (according to NIOSH [2], this is a person with $D_i > 1$)

p = total number of types of personal protective equipment (PPE)

α_{ij} = binary coefficient (1 = *used*, 0 = *not used*) of *j*th PPE for the *i*th operator

C_j = unit cost of *j*th PPE

son = number of noise sources

w = total number of dedicated protective equipment for source

β_{jk} = binary coefficient (1 = *used*, 0 = *not used*) of *k*th dedicated protective equipment for *j*th source

C_k = unit cost of *k*th dedicated protective equipment for source

v = total number of isolation material types for source

γ_{jl} = binary coefficient (1 = *used*, 0 = *not used*) of *l*th type of isolation material for the *j*th source

C_l = unit cost of *l*th type of the isolation material for source

T_i = exposed time in the range of 0–480 min (for a typical 8-h shift)

t_i = working time for *i*th operator

b_i = added value by *i*th operator working, i.e., hourly rate of payments for *i*th operator

L_i = sound pressure level (SPL) in *A*-weighted decibels which is received by *i*th operator

D_i = total noise dose for sound level of L_i at corresponding T_i for *i*th operator

The first set of constraints (Equation 2) ensures that the maximum allowable time of exposure at each noise pressure level for each operator is observed. The second set of constraints (Equation 3) establishes a budget limit for the total expenditure in the objective function.

2.1. GA

GA is a heuristic technique which employs inheritance, mutation, selection, and crossover operators to generate solutions for optimization problems [14]. In GA, a gene represents each variable. Strings of genes, i.e., chromosomes, can encode candidate solutions and gradually evolve towards better solutions. A population is formed by random and feasible chromosomes and generations consist of new populations through mutation or crossover between last populations. In each generation, a fitness function is used to evaluate the solution domain. GA initializes the process by random generation, then improves the solution reiteratively using fitness criteria. It continues until a solution which satisfies the "stop" condition is obtained. This algorithm is especially useful for large and nonlinear problems which cannot be solved with analytical and deterministic methods.

For most optimization problems, the number of feasible solutions increases exponentially by the number of parameters [15]. Since it is not possible to check all of these solutions, random generation of solutions is usually preferred. This way, the optimum result will hopefully be found among the random solutions. Similarly, the large number of parameters presented in the mathematical model of this research entails an algorithm to produce random solutions and obtain the optimum result using minimum iterations. Among heuristic methods, GA has the potential to manage such problems and is best fitted to the requirements of this research.

2.2. MATLAB

Computer programming for the model of this research has been performed in the MATLAB 2009A environment [16]. In spite of the versatility of MATLAB, the GA toolbox, in its general structure, is subject to several limitations and cannot be used for solving the model. Firstly, in the GA toolbox, iterative solutions are directly checked by the constraint, whereas in the presented model, these solutions have to be converted into noise reduction values to be later used for evaluation of noise exposure. Secondly, some controllers are used in the written program to exclude infeasible solutions from extra computations and speed up the running of the program. Finally, different parts of the hybrid chromosomes in the model can be treated separately in crossover steps. These capabilities do not exist in the GA toolbox; therefore, a customized program was developed. The following sections explain the details of the program.

3. CASE STUDY

To verify the model and its results, a forging press shop was selected as a pilot plant. Forging plants are among the most polluted areas in industries that propagate 85–110 dB(*A*) SPL [17, 18, 19]. In the pilot workshop, the process consisted of four stages: hot forging, cold forging, cutting, and hydraulic pressing. It is assumed that other sources of noise, e.g., air ventilating facilities, can be ignored in this study, due to their insignificant SPL in comparison to production machineries. Twenty operators worked in the area. Figure 1 shows the layout of the machines in this workshop.

3.1. Input Data

The required data for the model were inserted into Excel spreadsheets, as described in the following sections.

3.1.1. SPL measurements

SPL was measured with a Testo 815 (Testo, Germany) instrument at 1-m distance from the sources in accordance with the NIOSH criteria [2]. For each source, SPL was measured independently when other sources were not working. Table 1 shows SPL measured in a two-frequency scale (*A*- and *C*-weighted decibels) for the active machineries. Then, the decibel addition technique was applied to these individual SPL measures and the program derived resultant SPL [2].

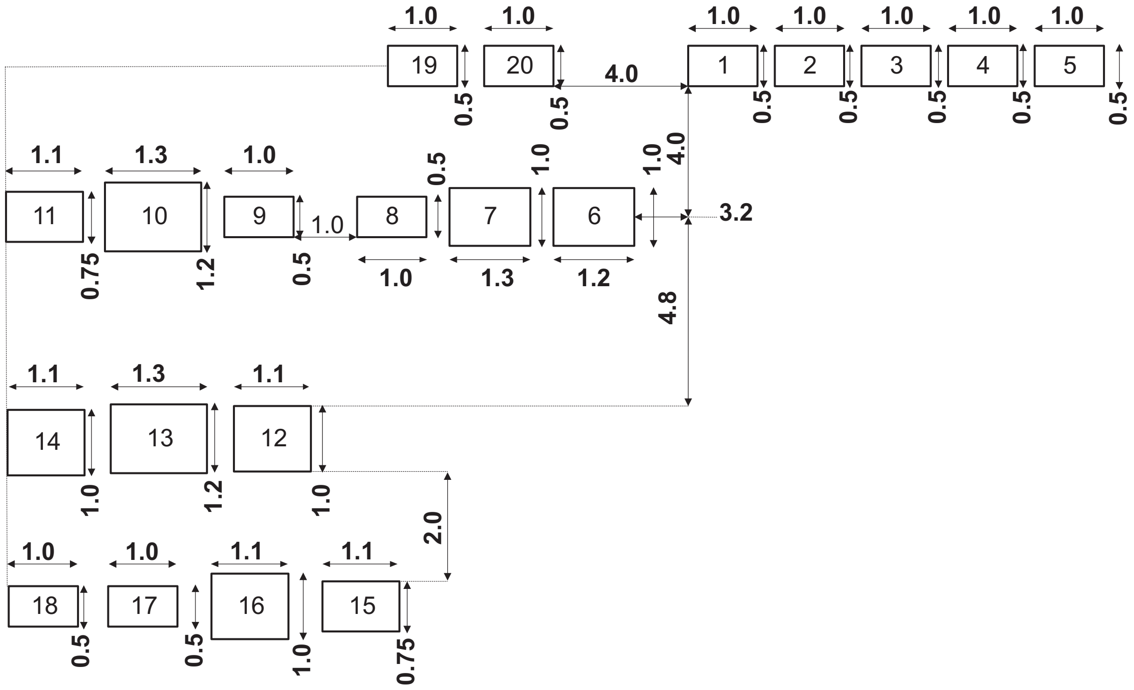

Figure 1. Layout of the forging workshop. *Notes.* 1–18 = machines, for description, see Table 1. All measurements (in bold) are in meters.

TABLE 1. Machine Specifications With Corresponding Sound Pressure Level (SPL) Measurements

Machine ID	Type of Machine	Side Area (m^2)	Function	SPL dB(*A*)	SPL dB(*C*)
1	PH-press 40T (M-C)	7.50	cutting (bar diameter 35 mm)	100.3	104.6
2	PH-press 40T (M-C)	7.50	cutting (bar diameter 16 mm)	100.3	104.6
3	PH-press 40T (M-C)	7.50	cutting (bar diameter 16 mm)	100.3	104.6
4	PZ-press 40T (M-C)	7.50	cutting (bar diameter 24 mm)	94.1	97.8
5	PZ-press 120T (H-F)	15.00	cutting (bar diameter 24 mm)	113.4	115.2
6	PZ- press 120T (H-F)	22.00	pre-form for 250T press	97.7	101.3
7	PZ-press 250T (H-F)	25.30	original shape	86.2	105.4
8	PZ-press 40T (H-F)	7.50	additional operations	80.0	87.0
9	PZ- press 40T (H-F)	7.50	pre-form for 500T press	94.1	97.8
10	PZ-press 500T (H-F)	27.50	original shape	94.0	101.0
11	PZ-press 80T (H-F)	9.25	additional operations	102.0	106.0
12	PZ- press 100T (H-F)	12.60	pre-form for 1000T press	93.0	100.0
13	PZ-press 400T (H-F)	25.00	original shape	96.0	103.0
14	PZ-press 100T (H-F)	10.50	additional operations	98.0	100.0
15	PZ-press 80T (H-F)	9.25	additional operations	96.3	101.2
16	PZ- press 1000T (H-F)	21.00	pre-form for 400T press	101.0	105.0
17	PZ-press 40T (H-F)	7.50	original shape	80.0	87.0
18	PH-press 40T (H-F)	7.50	additional operations	80.0	87.0
19	PZ-press 40T (C-F)	7.50	additional operations	102.0	106.0
20	PH-press 40T (C-F)	7.50	small parts	80.0	87.0

Notes. M-C = metal cutting, H-F = hot forging, C-F = cold forging.

3.1.2. Machine specifications

The dimensions of the machines are required to calculate the dimensions of the isolation materials. Table 1 lists this information. Figure 1 reports the Euclidean distances between the 20 machines in Table 1. These data were gathered in a 20 × 20 sheet and inserted into the model.

3.1.3. Labor information

From the 20 operators working in the workshop, 15 have a production cycle time of 0.5 min, and for the rest, the cycle time is 1 min. Each operator earns 10 300 per shift but the added value is 5 639 250. There is no need to specify the unit of the monetary values because it has no effect on the outputs. However, to interpret the results and report them to management, a uniform and suitable monetary unit should be applied throughout the study.

3.1.4. Equipment and material specifications

Three different classes of noise control facilities are defined for the model. Tables 2–4 contain the specifications for various types of each class for

TABLE 2. Specifications of Noise Control With Personal Protective Equipment (PPE)

PPE ID	Noise Reduction (dB)	Price	Model
1	0	0	nothing
2	2	3000	ear plug type1
3	5	6000	ear plug type 2
4	7	8700	ear plug type 3
5	8	9500	ear plug type 4
6	3	4000	ear muff type 1
7	4	5500	ear muff type 2
8	6	7900	ear muff type 3
9	9	11 500	ear plug type 2 + ear muffle 2

TABLE 3. Specifications of Noise Control With Protective Equipment for Source

Protective Equipment ID	Noise Reduction (dB)	Price	Model
1	0	0	none
2	20	1 000 000	fabric wrapped acoustic panel
3	24	1 250 000	partial enclosure type 1
4	30	1 500 000	partial enclosure type 2
5	32	1 600 000	partial enclosure type 3
6	37	1 750 000	partial enclosure type 4
7	40	2 000 000	partial enclosure type 5
8	47	2 500 000	total enclosure type 1
9	50	3 000 000	total enclosure type 2

TABLE 4. Specifications of Isolation Materials

Isolation Material ID	Type of Material	Absorption Coefficient	Price	Noise Reduction (dB)
1	none	0	0	none
2	foam type 1	0.50	70 000	20
3	foam type 2	0.70	90 000	25
4	blanket type 1	0.76	100 000	30
5	vinyl	0.83	120 000	37
6	louver	0.88	150 000	45
7	blanket type 2	0.92	170 000	50

PPE, protective equipment for source, and isolation materials. These tables include the "nothing" option to allow the program to select this choice for its cost advantages if justified.

3.1.5. Room constant

Room constant was calculated on the basis of the following information:

Section area (m^2)	50	110	40	30	20
Absorption coefficient	0.10	0.15	0.20	0.19	0.25
Room constant ($m^2 \cdot$ Sabine)	5.0	16.5	8.0	5.7	5.0

Based on these data, the sum of room constant is 40 $m^2 \cdot$ Sabine.

3.2. Model Assumptions and Parameters

To evaluate equivalent labor cost that is lost as a result of noise disturbances, a few parameters and assumptions need to be defined.

- Each operator works with a single machine; his/her position is fixed.
- The cost of personnel is considered to be 1.5 times their salary.
- A working shift is 480 min.
- The wage for a shift is 10 300.
- The budget limit is 100 000 000.

3.3. Running and Solutions

The program has been run for 100 000 generations with a population of 100. The mutation probability is set to 0.1, and the crossover probability to 0.9. The program has been executed several times. The final trial has taken 16 h and 30 min with a dual core 2.2 processor. Although in an optimum solution, no isolation material has been assigned to machines, and the limitation of control equipment causes the solution to be infeasible. Hence, dummy constraints are added to the problem so that control equipment is replaced with isolation materials. This modification leads the solution to get a little away from the least

TABLE 5. Results of the Model: Personal Protective Equipment (PPE) and Time Allowances Assigned to Each Operator

Personnel ID	PPE ID	Time Allowance (min)
1001	3	20
1002	3	4
1003	2	4
1004	3	4
1005	3	4
1006	3	4
1007	3	4
1008	2	4
1009	3	4
1010	2	4
1011	3	20
1012	7	4
1013	7	11
1014	2	4
1015	3	4
1016	2	4
1017	3	31
1018	3	20
1019	3	4
1020	3	4

TABLE 6. Results of the Model: Protective Equipment and Isolation Material Assigned to Each Machine

Machine ID	Protective Equipment ID	Isolation Material ID
1	1	5
2	1	2
3	1	3
4	1	3
5	1	3
6	1	3
7	1	2
8	1	3
9	1	5
10	1	2
11	1	3
12	1	5
13	1	2
14	1	5
15	1	2
16	1	3
17	1	3
18	1	2
19	1	3
20	1	2

cost, whereas large initial investment helps the program to converge to its optimum results more quickly. Nonetheless, the solution remains practical and the cost surplus is still conceivable for the management. Tables 5–6 show the final results. Table 5 includes the optimum set of PPE and time allowances for the high-risk operators, and Table 6 includes the optimum set of protective equipment for source and isolation materials for covering the noise sources. The total minimum cost for the optimum noise control strategy is 27 000 000.

4. MODEL VERIFICATION AND SENSITIVITY ANALYSIS

The model was executed for sample data collected from the noisy press shop, and the results were presented to the managers. The method was generally preferred due to its flexibility and ease of use. The managers can either define their ideal cost as a budget input to the model, or try different cost levels and compare the results. The final decision can then be made using a sensitivity analysis of the results against parameter variations. The sensitivity analysis for the case study revealed that the number of generation has the most significant effect on the results, among other parameters. Figure 2 shows that the total cost of the control strategy can be reduced, particularly when the number of generation increases from 100 000 to 150 000. However, above this range, the total cost remains almost constant. Using both crossover and mutation techniques in GAs ensures the optimum solution to be global. The large number of generation is reasonable because of the large number of the possible solution, in other words, 4.9714e+108; from which only 15e+6 (number of generation × population) are investigated.

5. CONCLUSION

Noise control strategies need to be integrated and economically feasible. This paper proposes a new optimization model for noise control integration in a forging press shop. It defines a thorough mathematical model that optimizes the set of noise reduction techniques while determining necessary work allowances. A computer program based on GA was then developed, and the model was solved for the data collected from a sample forging press shop. The results were classified into assigned equipment and allowances for operators, as well as assigned equipment and isolation material for sources. The output of the model was analyzed for sensitivity to parameter variations. It revealed that the genetic model parameters considerably affect the results. However, above a certain range, i.e., 150 000 for the number of generation which was carefully observed in this analysis, the deviations are negligible.

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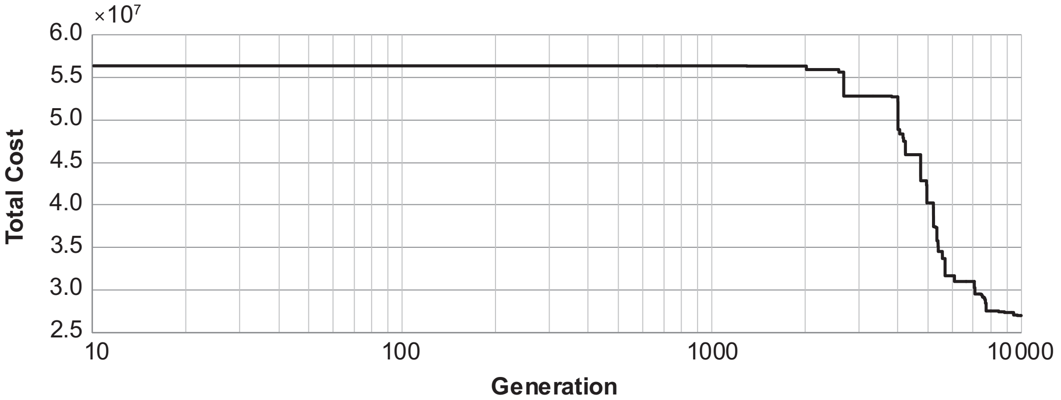

Figure 2. Sensitivity of total cost to the variation in the number of generation.

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