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Development of a software tool for economic evaluation of health, safety, and environmental initiatives in a combined cycle power plant

Hossein Miri[1,2], **Reza Gholamnia**[1,2], **Amin Bagheri**[2,3], **Reza Saeedi**[1,2*]

[1]Workplace Health Promotion Research Center, Shahid Beheshti University of Medical Sciences, Tehran, Iran
[2]Department of Health, Safety and Environment (HSE), School of Public Health and Safety, Shahid Beheshti University of Medical Sciences, Tehran, Iran
[3]Environmental and Occupational Hazards Control Research Center, Shahid Beheshti University of Medical Sciences, Tehran, Iran

Abstract

Background: This study aimed to provide a comprehensive tool for the economic evaluation of investments in health, safety, and environment (HSE).

Methods: This developmental cross-sectional study was conducted on the costs and benefits of HSE investments in a combined cycle power plant in Gilan province, 2021. The components of preventive measure costs (PMCs) and occupational accidents, diseases, and environmental pollution costs (ADPCs) were determined by an expert panel and review of scientific literature. The HSE economic assessment tool (HSE-EAT) was developed in Microsoft Excel software using macro/visual basic coding. The tool was designed to determine the efficient measures using the cost-benefit analysis (CBA) and the combination of control measures with the highest financial benefits using the cost-effectiveness analysis (CEA).

Results: The application of the HSE-EAT in a combined cycle power plant showed the highest return on investment (ROI) for installation of drains for ducts of diesel fuel pipes and the lowest ROI value for renovation of emergency eyewash and shower. The ratio of indirect to direct benefits of implementing the preventive measures in the worst-case and best-case scenarios were 3.0 and 1.3, respectively.

Conclusion: The HSE-EAT exhibited the advantages of comprehensiveness, flexibility, being user-friendly, and faster and more accurate calculations and could be also used for economic evaluation of health, safety and environmental initiatives in other industries and organizations.

Keywords: Cost-benefit analysis, Environmental pollution, Occupational accidents, Power plants, Software

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***Correspondence to:**
Reza Saeedi,
Email: r.saeedi@sbmu.ac.ir

Introduction

The increasing development of industry and technology has created significant economic growth in the world. Despite these positive effects, lack of sufficient investment in the field of health, safety, and environment (HSE) in industry sector causes occupational accidents, diseases and environmental pollution, which in addition to threatening the employees' and public health and environmental sustainability, can lead to huge financial losses (1-3). According to the International Labor Organization (ILO), there are more than 2 million deaths due to work-related accidents and about 300 million non-fatal occupational accidents worldwide per year, which result in economic losses up to 4% of gross domestic products (GDP) worldwide (4). The results of a study by the Global Economic Forum also show that the cost of work-related accidents and diseases is about 3000 billion the United States dollar (USD) per year (5).

The adverse consequences of industrial accidents and pollution are not limited to the workplace and usually affect the surrounding environment. As a result, the public health and environmental sustainability are faced with complex and dangerous problems and significant costs and damages (6-10). Ambient air pollution is recognized as the fourth leading risk factor for premature death worldwide. In 2013, the amount of lost income due to air pollution in the world was estimated to be US$ 225 billion (11). According to the report of the Organisation for Economic Co-operation and Development (OECD) (12), the economic losses from air pollution is estimated to be 3500 billion USD per year. The adverse health and economic effects are much more evident in developing countries, in which the HSE standards in industry sector have been ignored to increase production and economic efficiency (13-19); therefore, the evaluation of the occupational accidents and pollution costs is one of the best approaches to convince top managers of organizations and industries for implementing the preventive measures (15,20-24). The preventive measures in the HSE management are very diverse and extensive, but the financial resources to implement these measures are limited, thus, the HSE manager should balance between the fields of health, safety and environment and select the control measures based on the economic assessments to achieve the most efficiency (25-27).

The economic evaluation of HSE initiatives is a time-consuming and complicated task due to numerous determinants and calculations as in most of the cases, the HSE administrations forgo to consider economic analyses for prioritizing preventive measure and persuading top managers for HSE investments; therefore, a software tool is urgently needed to facilitate the application of the economic evaluation in HSE management. So far, a software tool for economic analysis of the control measures in the HSE management and mutual benefits between the fields has not been presented (24,28-33); therefore, the objective of this study was to provide a comprehensive tool for economic evaluation of investments in the HSE management. After determining the components of the preventive measure costs (PMCs) and the occupational accident, disease and environmental pollution costs (ADPCs), the cost elements, and the shares of the employer, workers, government, and society in the costs, the HSE-EAT was developed in Microsoft Excel software using macro/visual basic coding. The HSE-EAT was then calibrated by applying the tool in a combined cycle power plant and the output was analyzed.

Materials and Methods

Study area

This study was conducted in a combined gas-steam cycle power plant in Gilan province, Iran. In the combined gas-steam cycle power plants, the hot gases from the exhaust of the gas turbine were used to generate steam in the steam's unit to prevent energy wastage (34-36). This power plant had six gas units and three steam units.

Determining the components of PMCs and ADPCs

The costs of implementation of preventive measures to improve the health, safety, and environmental conditions are considered as the PMCs. The ADPCs include all costs incurred by employer, workers, government, and society as a result of occupational accidents and diseases and environmental pollution. In this study, the components of PMCs and ADPCs were determined by a panel of experts in the fields of environmental health (2 persons), occupational safety and health (2 persons), HSE management (4 persons), economy (2 persons), and health economy (2 persons) as well as review of the scientific literatures.

According to the expert panel, the costs were classified into two categories of direct and indirect costs, and cost-bearing sectors were determined to be employer (industry), workers, government, and society. The data required for developing the HSE-EAT consisted of: (a) components of occupational accident costs, (b) components of occupational disease costs, (c) components of environmental pollution costs, (d) components of preventive measures costs, and (e) factors and constants of conversion of disease/injury to the monetary equivalent (Rials), and then, changing it to USD (1 USD = 250 000 Rials). The conversion rate of Rial to USD is not constant and can be changed by the users of the HSE-EAT. In order to calculate the monetary value of suffering from occupational injuries and diseases, the fatal and non-fatal health losses were converted to disability-adjusted life year (DALY). The DALY index is sum of the years of life lost due to premature mortality (YLLs) and years lived with disability (YLDs) explained in the previous studies (37-40). The monetary value of suffering from occupational injuries and diseases was calculated by multiplying DALY and value of statistical life (VSL) (30). In this study, the VSL was considered to be US$ 5000 per DALY. The factors and constants were extracted from the literature review, law and regulations of the Social Security Organization, Ministry of Cooperatives Labor and Social Welfare, and Department of Environment (41-48).

Developing the HSE-EAT

The HSE-EAT was developed based on the cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) using the components of PMCs and ADPCs and the definition of computational relationships by the expert panel. The CBA and CEA identify the efficient preventive measures and the most efficient combination of the preventive measures according to the existing limitations such as budget, respectively.

Cost-benefit analysis

The CBA determines the efficient use of financial and time resources by identification of the efficient preventive measures. The main purpose of this analysis was to collect information about the amount of costs and benefits of the investments. In the HSE-EAT, the CBA was performed based on the following three-step process:

(a) Identification of ADPCs and PMCs

(b) Calculation of the present values of costs and benefits: The ADPCs and most of the PMCs occurred over a period of time and the value of money decreases during the period; therefore, the discount rate was considered in the economic assessment. The present value of annual costs and benefits was calculated according to the following equation (19):

$$B = \frac{A}{(1+r)^n} \quad (1)$$

where A is the annual costs and benefits, B is the present value of the annual costs and benefits, n is the design period (equipment life), and r is the discount rate (0.03). The inflation rate was not considered in the calculations due to the same effect on both the benefits and costs. All the components of ADPCs occur during the life cycle of preventive measures; thus, the discount rate was used to calculate the present value of their costs. Among the components of PMCs, the discount rate was not applied to the initial purchase and installation costs.

(c) Comparing total costs and benefits: The return on investment (ROI) and net present value (NPV) of each preventive measure were calculated as the benefit to cost ratio and the difference between benefits and costs, respectively. The preventive measure benefits (PMBs) were calculated using the following equation (31):

$$\text{PMBs} = (\text{ADPCs}_a - \text{ADPCs}_b) \quad (2)$$

where $ADPCs_a$ and $ADPCs_b$ are the occupational accident, disease and environmental pollution costs after and before implementing the preventive measures, respectively. The below equations show the conditions for determining the efficient and inefficient preventive measures (31):

For efficient preventive measures:

$$(\text{NPV} = \text{PMCs} - \text{PMBs}) \geq 0 \text{ OR } \left(\text{ROI} = \frac{\text{PMBs}}{\text{PMCs}}\right) \geq 1 \quad (3)$$

For inefficient preventive measures:

$$(\text{NPV} = \text{PMCs} - \text{PMBs}) < 0 \text{ OR } \left(\text{ROI} = \frac{\text{PMBs}}{\text{PMCs}}\right) < 1 \quad (4)$$

Cost-effectiveness analysis

In practice, implementation of all the efficient preventive measures is not possible due to budget limitation, organizational priorities, and specific legal requirements. As a result, the optimal combination of preventive measures by taking into account all the existing limitations is determined by the CEA to maximize profits. When the budget ceiling is clear and there are several measures or programs, the financial resources are allocated to the measures with the lowest cost to benefit ratios until the budget is exhausted (49-51).

Depending on the accident occurrence scenario, a preventive measure is either taken completely or not at all. This optimization problem is called the "knapsack problem" and is limited to the following conditions (31):

$$Max\ B_i X_i \quad (5)$$

$$C_i X_i < Bu_{tot} \quad (6)$$

$$X_i \in \{0,1\} \quad (7)$$

where $Max\ B_i X_i$ is the maximum benefit from the implementation of the preventive measures, and $C_i X_i < Bu_{tot}$ shows the total costs of the preventive measures lower than the budget, and $X_i \in \}0,1\{$indicates the full implementation (1) or non-implementation (0) of a preventive measure.

Preparing the HSE-EAT software

The components and analyses explained in the previous steps were encoded in Microsoft Excel software. All the mathematical and computational relations were programmed in Microsoft Excel by taking into account the relationships among the cost-bearing groups. The tool was designed in three worksheets: ADPCs, PMCs & PMBs, and Analysis. After calculating the ADPCs in the first worksheet, the obtained PMBs along with the PMCs are listed in the next worksheet, and finally, the CBA and CEA are performed in the third worksheet (Analysis). Also, the overlaps between the benefits of implementing the preventive measures in the fields of HSE are given on the last worksheet.

Application of the HSE-EAT software in the combined cycle power plant

In the final step of the study, to evaluate the developed tool, fix possible problems, and also, its application in real conditions, the tool was used in the combined cycle power plant. During application of the HSE-EAT in the power plant, a number of errors in the calculation functions and cost components were found based on the manual calculation and expert opinions; therefore, the HSE-EAT was revised and validated based on the expert opinions in practice. In the power plant, the occupational accidents and diseases, environmental pollution, corrective measures, and related costs were recorded. The tool was used to perform the CBA and CEA in the power plant in the following four steps:

(a) HSE risk assessment: First, HSE risk assessment in the power plant was performed and the preventive measures were determined. Then, assuming the implementation of the proposed measures, a secondary risk assessment was performed to examine the impact of the measures. Because of the inherent uncertainty in the risk assessment, two boundary conditions of the best-case scenario (the lowest risk limit) and the worst-case scenario (the highest risk limit) were obtained as the output of the HSE risk assessment and were applied for the economic evaluation.

(b) Calculation of the ADPCs: The ADPCs were calculated based on the average costs of injuries and diseases in the community, environmental pollution penalties, and the prices of the power plant equipment.

(c) Calculation of the PMCs: The costs of the proposed preventive measures were calculated using the data of accounting unit and referring to the companies providing health, safety, and environmental services.

(d) Registering data in the software and performing the CBA and CEA: The data obtained in the second and third steps were entered into the software, and the NPV and effectiveness of the proposed measures were evaluated by performing the CBA and CEA. The PMCs were well-known and determined based on the current price of goods and services, but the ADPCs were estimated in a prospective approach based on the risk assessment of HSE hazards; therefore, due to the inherent uncertainty in the risk assessment results, the ADPCs as well as economic evaluation of HSE investments were provided as an interval between the best-case and the worst-case scenarios.

Results

Description of the HSE-EAT

The principles, components, and sub-components of the ADPCs and PMCs and their equations in the HSE-EAT and the user manual of the HSE-EAT are presented in Supplementary file 1. Supplementary file 1 consisted of three tables: Table S1 for the PMCs and their calculation methods, Table S2 for the occupational accidents and diseases costs and their calculation methods, and Table S3 for the environmental pollution costs and their calculation methods. The number of principles, components, and sub-components of the ADPCs and PMCs by cost-bearing group in the HSE-EAT are provided in Table 1.

The number of principles of ADPCs and PMCs in the HSE-EAT were 15 (nine direct and six indirect) and four (two direct and two indirect), respectively. The three worksheets of the HSE-EAT were named as ADPCs, PMCs & PMBs, and Analysis. The buttons were provided at the bottom of each worksheet to perform the commands and calculations.

In the ADPCs worksheet, the costs of sub-components, components, and principles of occupational accidents and diseases and environmental pollution are calculated through the equations that are coded in Microsoft Excel. In the PMCs and PMBs worksheet, the costs of preventive measures and the benefits of implementing them as a result of decreasing ADPCs were listed in two tables. The NPV is the final result of this worksheet. The specifications of the preventive measures in the PMCs and PMBs worksheet are title, field (health, safety, or environment), year of investment, and lifespan. In the Analysis worksheet, all the proposed preventive measures are listed and examined for both the CBA and CEA. The CBA provides the efficient measures and the CEA indicates the investment recommendations concerning maximum benefits and limitations. In the budget table, the user can specify the budget of each HSE field separately. The last table shows the overlap of benefits of the preventive measures among the HSE fields, indicating the profit of *integrated* HSE management system.

Economic evaluation of HSE investments in the combined cycle power plant

The economic evaluation of HSE investments in the combined cycle power plant was done with two scenarios (the worst-case and best-case scenarios). In the worst-case scenario, all the proposed preventive measures over their lifespan were determined to be efficient based on the CBA. After the HSE risk assessment and coordination with the HSE management unit, a number of nine preventive measures were proposed for high-risk hazards. The outputs of the CBA and CEA for the proposed preventive measures in the combined cycle power plant in the worst-case and the best-case scenarios using the HSE-EAT are presented in Table 2 and Figure 1.

Based on the CBA, all the proposed preventive measures during their lifespans were determined to be efficient. According to the CEA, by considering the allocated budget (US$ 14 000), the two proposed measures, renovation of diesel fuel pipes and installation of drains for ducts of diesel fuel pipes, were selected and recommended to invest. In the best-case scenario, renovation of diesel fuel pipes, renovation of ducts of diesel fuel pipes, and installation of drains for ducts of diesel fuel pipes were efficient, but only the renovation of diesel fuel pipes and installation of drains for ducts of diesel fuel pipes were again selected based on the CEA. The NPVs of the preventive measures in the worst-case scenario were higher than those in the best-case scenario, but in both the scenarios, the proposed measures for investment were the same. The highest NPV was related to the renovation of automatic fire extinguishing system (US$ 398 000) in

Table 1. Number of principles, components, and sub-components of the ADPCs and PMCs by cost-bearing group in the HSE-EAT

Cost-bearing group	ADPCs			PMCs		
	Principle	Component	Sub-component	Principle	Component	Sub-component
Worker	4	8	-	-	-	-
Employer	11	18	12	4	13	10
Government	6	4	-	-	-	-
Society	8	-	-	-	-	-

Table 2. Cost benefit analysis and cost effectiveness analysis of the proposed preventive measures in the combined cycle power plant in the worst-case and best-case scenarios by the HSE-EAT

Field	Measure	Cost (US$ 1000)	Worst–case Scenario				Best–case Scenario			
			Benefit (US$ 1000)	CBA		CEA	Benefit (US$ 1000)	CBA		CEA
				NPV (US$ 1000)	Efficient or Inefficient			NPV (US$ 1000)	Efficient or Inefficient	
Health, safety, and environment	Renovation of diesel fuel pipes	12.6	338.2	325.6	Efficient	Invest	36.5	23.9	Efficient	Invest
Health, safety, and environment	Renovation of ducts of diesel fuel pipes	2.2	327.4	325.2	Efficient	Not invest	24.1	21.9	Efficient	Not invest
Health, safety, and environment	Installation of drains for ducts of diesel fuel pipes	0.7	116.4	115.7	Efficient	Invest	13.7	13	Efficient	Invest
Health and safety	Renovation of automatic fire extinguishing system	86.9	485.2	398.3	Efficient	Not invest	10.0	-76.9	Inefficient	Not invest
Health and safety	Renovation of hot steam and water pipes	7.1	118.1	111	Efficient	Not invest	0.5	-6.6	Inefficient	Not invest
Health and safety	Renovation of ducts of hot steam and water pipes	5.8	29.5	23.7	Efficient	Not invest	0.3	-5.5	Inefficient	Not invest
Health and safety	Renovation of emergency eyewash and shower	1.5	68.3	66.8	Efficient	Not invest	0.1	-1.5	Inefficient	Not invest
Health, safety and environment	Renovation of gas unit scrubber	244.1	352.8	108.7	Efficient	Not invest	3.0	-241.1	Inefficient	Not invest
Health and safety	Renovation of amortized fans	3.3	103.8	100.5	Efficient	Not invest	0.5	-2.9	Inefficient	Not invest

CBA, Cost benefit analysis; CEA, cost effectiveness analysis; NPV, net present value.

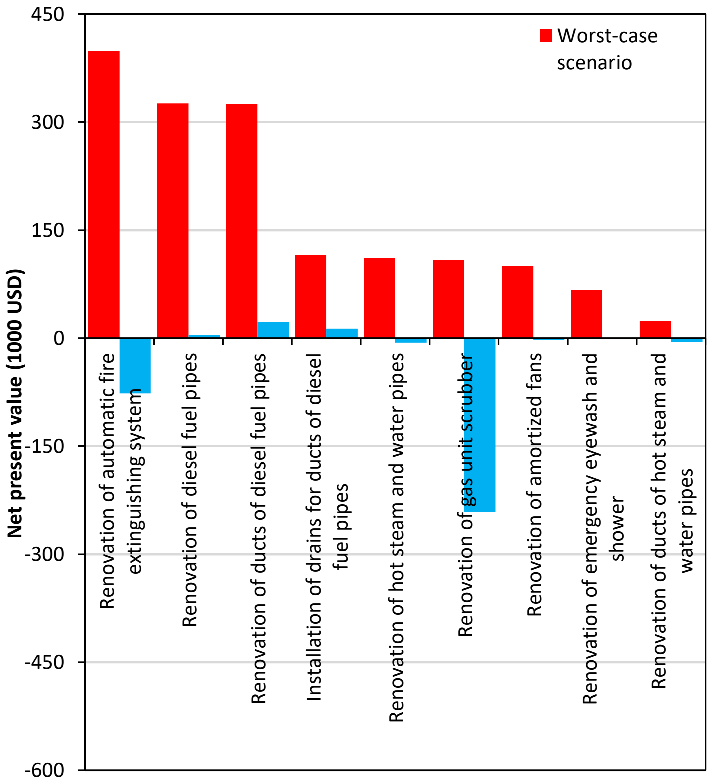

Figure 1. Net present value of the proposed preventive measures for the power plant in the worst-case and best-case scenarios based on the HSE-EA

the worst scenario, but its cost (US$ 86 900) was higher than the allocated budget.

The shares of the power plant, workers, and government in the total benefits of implementing the nine proposed measures in the worst-case scenario were 62.6%, 36.7%, and 0.7%, respectively. In the best-case scenario, almost 99.5% of the benefits of implementing the proposed measures belonged to the power plant and the share of the government was as low as 0.5%. In the best-case scenario, the severe occupational injuries and illnesses were not assumed; therefore, the implementation of the preventive measures did not cause considerable benefits for the workers. The shares of direct and indirect benefits in the total benefits of implementing the nine proposed measures were respectively 25% and 75% in the worst-case scenario and 43% and 57% in the best-case scenario. Table 3 provides the overlaps of the preventive measures benefits among the fields of HSE in the worst-case and best-case scenarios. According to Table 3, four measures were efficient in all the fields of HSE.

Discussion

Due to most of the equipment in the power plant exceeded their life cycle, the risk of HSE hazards was relatively high. As shown in Table 2, in the worst-case scenario, all the proposed measures were identified as efficient and in the best-case scenario, only three measures were efficient. In both the scenarios, the power plant (organization) would achieve the most benefits of the HSE investments. The main reason for the high share of the power plant was the expensiveness of equipment in the gas and steam units. The highest and lowest values of ROI in the worst-case scenario were related to the preventive measures of the installation of drains for ducts of diesel fuel pipes (165.3) and renovation of gas unit scrubber (0.4). The corresponding values in the best-case scenario were related to the installation of drains for ducts of diesel fuel pipes (18.6) and the renovation of emergency eyewash and shower (0.1). In the study of Rahimi et al (52), the social costs of emissions in a power plants were determined to be 1330 Rials per 1 kw.h electricity production. Zhang et al (53) developed a dynamic and integrated approach for decision-making about safety investment in power grid enterprises. According to the system dynamics-based model, the critical factors for power grid safety were determined to be risk assessment, safety training, organizational investment, and technological investment. Jiang et al (54) introduced a multivariate regression model for safety investment and accident control in coal mines. Based on the multivariate regression model, in the studied mining enterprise investment of 5 million yuan in safety was needed for a significant reduction in the casualty rate. Lebeau et al (30) evaluated the costs of occupational injuries and diseases in Québec during 2005–2007 to be 4.62 billion dollars annually.

The efforts and studies have been made to develop tools for economic analysis of industrial accidents, occupational diseases and injuries, and determining the financial equivalent of human health losses. In a previous study, Reniers and Brijs (31) developed a tool that performed the CBA and CEA for major accidents. Oxenburgh and Marlow (55) analyzed the occupational safety and health interventions in the workplace using the CBA. They only provided the CBA and did not determine the optimal combination of measures. They also calculated costs only for the employer and did not consider workers, government, and society groups. Bellamy et al (56) introduced a model called (Social Zaken en Werkgelegenheid) to create an active profile for classifying workers, comparing preventive measures, and determining the best cost-effectiveness approach to reduce risks. OSHA (57) provided a program in the form of a website called Safety Pays, which assesses the impact of occupational injuries and diseases on the company's profitability.

The HSE-EAT is designed in such a way that the user can quickly achieve the economic evaluation results. The final result of the tool (after the CBA and CEA) is the determination of efficient measures and the most efficient combination of measures according to the budget. The tool allows the user to select the obligate measures from the preventive measure list, and then, perform the CEA. The tool also shows the overlaps of the costs and benefits in the fields of HSE. The advantages of the HSE-EAT include comprehensiveness, considering the overlaps of costs and benefits in the fields of HSE, use of discount rate, faster and more accurate calculations, flexibility, user-friendliness, and considering obligate measures in the CEA. The HSE-EAT can be applied for economic evaluation of the HSE investments in both the workplaces and public environments. The economic evaluation of HSE initiatives can exhibit ROI and increase the motivation of top managers and policy makers for implementation of HSE interventions.

It is worth noting that some of aspects of the occupational accident, disease and environmental pollution such as destroying the company's reputation and destruction of the beauty of the environment and perspectives could not

Table 3. Overlaps of the preventive measures benefits among the fields of health, safety, and environment for the power plant in the worst-case and best-case scenarios

Preventive measure	Benefit (1000 USD)			
	Best-case scenario		Worst-case scenario	
	Health and safety	Environmental	Health and safety	Environmental
Renovation of diesel fuel pipes	16.4	0.1	338.1	0.1
Renovation of ducts of diesel fuel pipes	24.0	0.1	327.3	0.1
Installation of drains for ducts of diesel fuel pipes	13.6	0.1	116.3	0.1
Renovation of gas unit scrubber	2.7	0.3	352.5	0.3

be converted to monetary value and were not addressed in the HSE-EAT. The other limitation of this research was related to the inherent uncertainty in the risk assessment of HSE hazards that were transferred to the ADPCs and economic evaluation.

Conclusion

Although the capital costs of the HSE preventive measures in the power plant were relatively high, most of the measures were efficient due to their long lifespans. Based on the CBA, all the proposed measures were determined to be efficient in the worst-case scenario. The two measures, renovation of diesel fuel pipes and installation of drains for ducts of diesel fuel pipes, were selected to implement by the allocated HSE budget based on the CEA. In the worst-case scenario, the shares of the power plant, workers, and government in the total benefits of implementing the nine proposed measures were 62.6%, 36.7%, and 0.7%, respectively, but in the best-case scenario, almost all the benefits of implementing the proposed measures belonged to the power plant. The share of indirect benefits in the total benefits for implementing the proposed measures in the worst-case scenario was considerably higher than that in the best-case scenario. The HSE-EAT exhibited the advantages of comprehensiveness, flexibility, being user-friendly, and faster and more accurate calculations, and could be also used for economic evaluation of health, safety and environmental initiatives in other industries and organizations.

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Authors' contribution

Conceptualization: Hossein Miri, Reza Saeedi.
Data curation: Amin Bagheri.
Formal analysis: Hossein Miri.
Funding acquisition: Reza Saeedi.
Investigation: Hossein Miri.
Methodology: All the authors.
Project administration: Reza Saeedi, Reza Gholamnia, Amin Bagheri.
Resources: Hossein Miri.
Software: Hossein Miri.
Supervision: Reza Saeedi.
Validation: Reza Gholamnia.
Visualization: Hossein Miri.
Writing–original draft: All the authors.
Writing–review & editing: All the authors.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical issues

This study was approved by the Research Ethics Committee of School of Public Health and Neuroscience Research Center, Shahid Beheshti University of Medical Sciences in accordance with the declaration of Helsinki for human studies of the World Medical Association (Ethical code: IR.SBMU.PHNS.REC.1398.058). All the ethical guidelines and safety procedures were considered during the experimental period.

Supplementary files

Supplementary file contains Tables S1-S3.

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