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Occupational Safety Assessment for Surface Mine Systems: The Case in Jordan

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Abstract: Surface mining is one of the hazardous industries that have several risky operations, including transportation, treatment, and mineral extraction. To avoid the risk of disaster, it is important to evaluate safety procedures and determine expected hazards. The aim of this study is to develop a thorough safety evaluation model for the surface mining industry based on the analytic hierarchy process (AHP), one important multi-criteria decision-making approach. A total of 11 criteria and 36 sub-criteria that are both independent and homogeneous were involved in the decision problem. Further, a deep sensitivity analysis was conducted to assess the stability of the ranking preference. The findings indicate that four out of the eleven criteria are particularly significant. To test the model's applicability and effectiveness, a case study was conducted involving three surface mining companies located in the north of Jordan. The results demonstrate that the model is reliable, applicable, and effective in addressing real-world problems.

Keywords: occupational safety and health; surface mining; multi-criteria decision making; AHP; Jordan

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1. Introduction

Occupational safety and health is an important issue in various industries, such as the mining, manufacturing, service, and construction sectors. Implementing a high level of safety management practices significantly improves moral and has economic and legal benefits. Thus, numerous firms around the world were established to monitor, enforce, and create occupational safety and health guidelines.

Implementing an occupational safety and health model is important in reducing accidents and disease rates and improving an organization's reputation. Furthermore, it has financial advantages, as it reduces costs associated with any accident, including property damage, injury compensation, sick pay, and the liability insurance of the employer. Thus, organizations must possess five crucial characteristics to maintain a safe work environment: safe equipment and machinery, a safe workplace, suitable training and supervision, secure work, and competent workers [1].

Multi-criteria decision-making (MCDM) methods help decision makers select the optimal choice from many feasible alternatives [2]. Currently, many MCDM approaches are available and used in multiple applications. Examples of MCDM approaches include the preference selection index (PSI), the Analytic Network Process (ANP), Elimination and Choice Expressing Reality (ELECTRE), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), grey theory, and the analytic hierarchy process

(AHP) [3]. The AHP approach was implemented in several applications, including strategic planning [4], sustainable development [5], safety against fire [6], safety benefit index and implementation [7], mining crusher selection [8], and the selection of optimal land to be used for surface mining [9], and was combined with Monte Carlo Simulation for optimal mining method selection [10].

The surface mining industry is recognized as one of the most hazardous industries around the world due to its operations, such as transporting, extracting, and processing minerals [11]. Surface mining is considered an important investment around the world as it provides high productivity at lower costs [12]. Statistics demonstrated the severity of nonfatal and fatal injuries among several sectors [13]. For example, in the mining industry in Turkey, statistics revealed a total of 7766 nonfatal injuries per 100,000 employees and 54.7 fatalities per 100,000 employees [13]. In Spain, there were 10,277.9 nonfatal injuries per 100,000 workers and 13.8 fatalities per 100,000 workers, while in Mexico, there were 4209 nonfatal injuries [13]. Statistics in the USA in 2016 revealed 12.7 fatalities per 100,000 workers and 600 injuries per 100,000 workers [14]. In 2022, statistics in the USA revealed 5486 fatal work injuries [15]. In Jordan, in 2015, there were 6 fatalities and 133 injuries, resulting in ratios of 68 fatalities per 100,000 workers and 14,780 injuries per 100,000 workers [16]. These injury ratios are high compared to most mine-producing countries, where the ratios do not exceed 2000 injuries and 54 fatalities per 100,000 workers [13]. Therefore, this study aims to develop a safety evaluation model that helps decision makers identify hazards and effectively assess safety outcomes and measures.

2. Literature Review

Several studies were conducted to assess and improve occupational safety and health in the mining sector. The occupational safety and health was assessed in surface mines in Turkey [17]. They improved the mining industry by analyzing the statistical data of accidents with multiple mine-producing countries. They found that Turkey has the highest of both accident rates and fatality to injury ratios. They also found that the important causes of fatal accidents were powered haulage, blasting operations, and the fall of face/high walls. Kania et al. [18] evaluated occupational risks in a specific hydraulic surface mine. They selected two workstations in the organization; these were hydraulic and storekeeper mining. Many types of hazards were found in this study based on the study of threat identification. These threats included electrical, explosive, fire, noise, radiation, hand tools, etc. They minimized the risks from higher to lower levels by implementing preventive and corrective plans. In addition, many studies developed a plan for mine ventilation [19].

On the other hand, Anderson [20] mentioned heat stress as a major parameter that influences workers in underground mines by proposing control measures required to mitigate hazards and decrease opportunities for workers' stress, which might reduce productivity. Multiple models were developed to predict hazard types in surface mining. Rezaei et al. [21] demonstrated a fuzzy model to predict hazards from fly rock during blasting in surface mines of iron. A total of 490 datasets were used, including 20% that were used for model testing. The developed fuzzy model was found to be more efficient when compared to the traditional statistical approaches. Moreover, Kerketta et al. [22] evaluated an open cast chromite mine to estimate the workers' hearing loss based on age, experience, and workstation. In China, Rui-xin et al. [23] evaluated surface mines in China based on two computer software tools called 3D MAX and Pro/E by building a simulation model. The model permitted the visual assessment of the mining operations' equipment. The model helped with training new miners and safety management, which reduced the number of accidents and injuries.

The AHP is a decision-making approach initiated by Saaty in 1980 [24]. The AHP approach was used in several safety evaluation studies in many areas. Silva et al. [25] developed an AHP model for ISO 9004: 2000 to assess the performance of two industrial firms based on the environment, quality, and occupational safety and health. They found that the most significant criteria were production operations and product manufacturing.

Shikha and Sharad [26] performed a thorough review of risk assessment approaches used in the mining industry around the world [26]. Su et al. [27] utilized safety accident reports in the coal mine industry to evaluate the safety risks. They used Monte Carlo Simulation to optimize the AHP for determining weight. They also utilized TOPSIS for building the safety assessment model. They found that the coal mine safety risk level is an orange risk, which is consistent with the real-life situation [27].

According to our knowledge, no studies were found on developing a comprehensive occupational safety and health evaluation model in the surface mining industry based on the AHP approach, which was the goal of this study.

3. Methodology

One of the powerful things about the AHP is the ability to deal with problems involving both quantitative and qualitative criteria. The AHP method involves two main items, criteria and alternatives. The AHP approach has a specific number of pairwise comparisons. Based on these pairwise comparisons, a mathematical analysis will result in helping the decision process [28].

The AHP approach in this study had three primary functions. These included structuring complexity, a ration scale measurement, and synthesis. The structuring complexity function was the process of constructing the decision problem hierarchy that involved, from the top down, the goal, criteria, sub-criteria, and alternatives. The measurement process compared criteria, sub-criteria, and alternatives relative to each other in a pairwise form. This comparison was performed based on a 1–9 ranking scale. Finally, synthesis involved combining the part of the criteria and sub-criteria that was associated with each alternative, which led to identifying the weight, priority, and rank of alternatives [29]. Table 1 and Figure 1 summarize both the criteria and sub-criteria.

Table 1. Defining the model criteria and sub-criteria.

Criteria (Code Title)	Sub-Criteria (Code Title)	Definition
System Safety (C1)	Management Commitment (S1)	Safety management duties: [1,11,30–33]
	Supervision (S2)	Safety, supervisor inspections, and auditing: [1,11,28,30,32]
	Worker Involvement (S3)	Employees' duties toward safety: [1,11,30–32]
	Safety Culture and Training (S4)	Firm's safety culture and employee training: [1,11,30–33]
Mine Planning (C2)	Surveying (S5)	Investigating the mine area safely: [23,30,32]
	Clearance (S6)	Cleaning hazards in the mine area: [1]
	Layout of the Mine (S7)	Safety consideration in planning the mine site and facilities: [31,32]
	Laying Out (S8)	Hazards while constructing the mine and its facilities: [1]
Facilities (C3)	Welfare Requirements (S9)	The presence of welfare facilities at the site: [1,28,30,32]
	First Aid Facilities (S10)	First aid facility availability: [28,32]
Excavation and Face Stability (C4)	Geotechnical Assessment (S11)	Conducting geological evaluations of the mine site: [11,31]
	Fall from the Face and Face Stability (S12)	Barriers' availability and the face conditions in the extraction area: [11,17,30,31]
	Mineral Extraction (S13)	Extracting minerals using safe tools: [11]
	Work Direction and Face Design (S14)	Using safe face design and safe methods in extracting: [11,31]

Table 1. *Cont.*

Criteria (Code Title)	Sub-Criteria (Code Title)	Definition
Explosives (C5)	Explosive Control (S15)	Storing, transporting, and securing explosives safely: [11,17,30–32]
	Blasting Operation Management (S16)	Highlighting the danger zones and the blasting time clearly: [11,31]
	Supervision after Blasting Operations (S17)	Safely performing post shot firing operations: [11,31,32]
Movements of People, Vehicles, and Materials (C6)	Movement of People (S18)	Safe movement of people at the mine site: [1,17,18,33]
	Movement of Vehicles (S19)	Movement of vehicle hazards in the mine: [1,18,31,33]
	Manual Handling (S20)	Manual handling with safe methods: [1,18,32]
	Mechanical Handling (S21)	Safe use of handling equipment: [1,17,32]
Machines, Equipment, and PPE (C7)	Mechanical Hazards (S22)	Mechanical equipment hazards: [1,17,18]
	Mechanical Hazard Supervision and Control (S23)	Utilizing safe machine design with caution and instructions, and performing periodic maintenance: [1,30,33]
	Portable Electrical Equipment and Hand Tools (S24)	Using suitable and safe hand tools along with portable electrical equipment, and conducting periodic maintenance: [1,17,18,30]
	Personal Protective Equipment (PPE) (S25)	Provide suitable PPE for all workers: [1,30,32,33]
Chemical and Biological Hazards (C8)	Chemical Hazards (S26)	The chemical hazards at the workplace: [1,18,28,30,32,33]
	Chemical Control (S27)	PPE for ventilation and chemical equipment considering the exposure time: [1,28,32,33]
	Biological Hazards (S28)	The hazards resulting from biological sources at the site: [1,18,28,32]
Ergonomics (C9)	Ambient Factors (S29)	Workplace environment effects on workers: [1,18,28,30,32,33]
	Physical Body Problems (S30)	Physical body problems when performing tasks: [1,18,28,30]
	Human Behavior (S31)	The human behavior problems affecting the workers when performing their jobs: [1,18]
Fire Fighting (C10)	Fire Initiation (S32)	The presence of fire initiation elements: [1,17,18,28,32,33]
	Fire Fighting Management (S33)	Procedures and caution in case of fire and fire drills: [1,30,32,33]
	Fire Fighting Equipment (S34)	The presence of well-maintained firefighting equipment: [1,32]
Electrical Hazards (C11)	Electricity Safety Plan (S35)	Well-designed electrical circuit: [1,30,33]
	Electrical Safety Management (S36)	Dealing with electricity and providing PPE for electricity following safe procedures: [1,17,18,33]

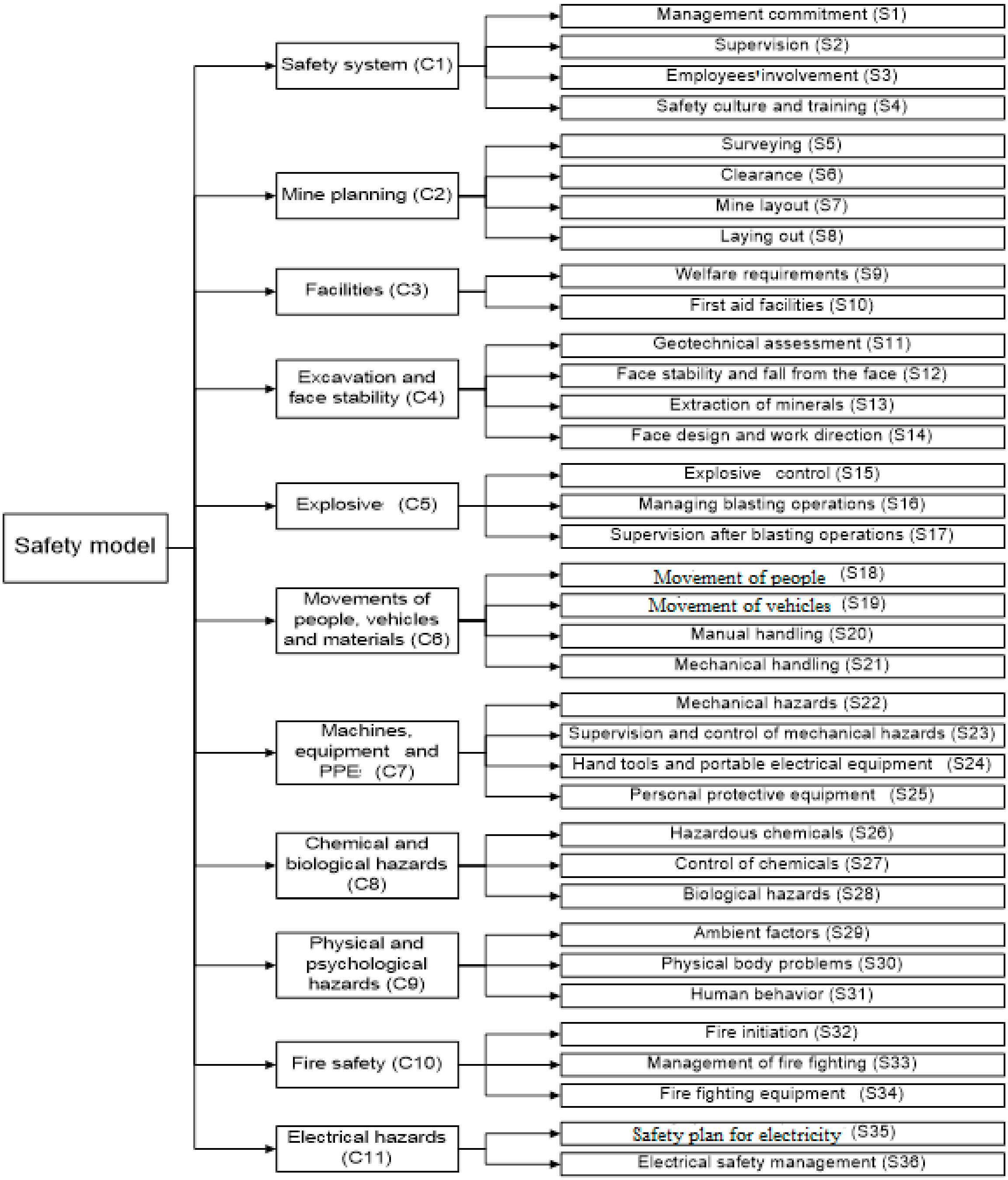

Figure 1. The structured safety model hierarchy.

3.1. Defining Safety Criteria and Sub-Criteria

Specifying the criteria and sub-criteria in the safety model was based on several sources; these included the International Labor Organization conventions and recommendations [30,32,34], the safety regulations of the Jordanian labor law [35], the United Kingdom Health and Safety Executive approved codes of practice [11,31,33], and sources from the literature [1,17,18]. In addition, to categorize the criteria, experts in safety training and evaluation were reached according to the modified Delphi method [36].

3.2. Comparison of Criteria, Sub-Criteria, and Alternatives

According to the AHP hierarchy, a pairwise comparison was conducted. Several comparison matrices were utilized. The number of comparison matrices must be equal to that of nodes in the hierarchy, excluding those at the lowest level. The matrix size varied based on the related node.

Table 2 presents the scale used in the AHP model. Based on Table 2, the value of 1 indicates that the two compared nodes are of equal importance. As the value increases, the preference of one node over the other increases until reaching extreme importance [24].

Table 2. The AHP rating scale [28].

Importance	Definition
1	The same
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2, 4, 6, 8	Intermediate values

3.3. Comparison to Weights and Priority Transformation

After performing all the pairwise comparisons, the values inside the matrices were transformed into weights; thus, priorities could be used to rank each item. First, to obtain the weight ratio, normalizing the columns in the matrix was performed. Afterward, the column was multiplied by a value that added the summation inside it to 1. After that, the average of the values in each row was obtained and then a new column was added to record averages. The averages summation must equal 1 for each matrix [28]. The normalization was conducted for each matrix in the AHP.

The final step in the AHP was ranking alternatives. The worst and the best alternatives could be identified, and the rest of the alternatives could be ranked to facilitate the decision-making problem [29]. Table 3 shows an example of a pairwise comparison matrix.

Table 3. An example of a pairwise comparison matrix.

	Safety System	**Mine Planning**	**Facilities**	**Face Stability and Excavation**	**Explosives**	**Movement of Vehicles, Materials and People**	**PPE, Machines, and Equipment**	**Biological and Chemical Hazards**	**Ergonomics**	**Fire Fighting**	**Electrical Hazards**
Safety System	1	1	2	2	1	1	1	1	2	2	2
Mine Planning	1	1	3	2	1	1	1	1	1	2	2
Facilities	1/2	1/3	1	1	1	1	1	1	1	1	1
Face Stability and Excavation	1/2	1/2	1	1	1	2	2	2	1	3	2
Explosives	1	1	1	1	1	2	4	2	2	1	2
Movement of Vehicles, Materials and People	1	1	1	1/2	1/2	1	1	1	1	1	1
PPE, Machines, and Equipment	1	1	1	1/2	1/4	1	1	1	2	1	1
Biological and Chemical Hazards	1	1	1	1/2	1/2	1	1	1	2	1	1
Ergonomics	1/2	1	1	1	1/2	1	1/2	1/2	1	1	1
Fire Fighting	1/2	1/2	1	1/3	1	1	1	1	1	1	1
Electrical Hazards	1/2	1/2	1	1/2	1/2	1	1	1	1	1	1

4. Results

In the developed AHP model, three surface mining companies in Jordan were considered. These were two cement manufacturing companies and one chemical fertilizer company (phosphate mining). These companies were the alternatives in the AHP model. Table 4 shows the results of weighting and normalizing the criteria, sub-criteria, and alternatives in the AHP model.

Table 4. Weights of criteria, sub-criteria, and the alternatives with the inconsistency ratio.

Criteria	Criteria Weight	Sub-Criteria	Sub-Criteria Weight	Synthesis Value	Cement Company 1	Cement Company 2	Fertilizer Company	Inconsistency Ratio	
								Sub-Criteria	Criteria
C1	0.1200	S1	0.3470	0.0420	0.4130	0.260	0.3270	0.050	0.020
		S2	0.2460	0.0300	0.3270	0.4130	0.2600	0.050	
		S3	0.2040	0.0240	0.3110	0.1960	0.4930	0.050	
		S4	0.2040	0.0240	0.3330	0.3330	0.3330	0.000	
		Synthesis value			0.3550	0.3040	0.3400		
C2	0.1210	S5	0.2000	0.0240	0.3270	0.4130	0.2600	0.050	0.000
		S6	0.2000	0.0240	0.3270	0.4130	0.2600	0.050	
		S7	0.4000	0.0480	0.3330	0.3330	0.3330	0.000	
		S8	0.2000	0.0240	0.3270	0.4130	0.2600	0.050	
		Synthesis value			0.3300	0.3770	0.2930		
C3	0.0740	S9	0.5000	0.0370	0.3270	0.4130	0.2600	0.050	0.000
		S10	0.5000	0.0370	0.3270	0.4130	0.2600	0.050	
		Synthesis value			0.3270	0.4130	0.2600		
C4	0.1140	S11	0.2460	0.0280	0.3110	0.1960	0.4930	0.050	0.020
		S12	0.3470	0.0400	0.3270	0.4130	0.2600	0.050	
		S13	0.2040	0.0230	0.4430	0.1690	0.3870	0.020	
		S14	0.2040	0.0230	0.4430	0.1690	0.3870	0.020	
		Synthesis value			0.3710	0.2660	0.3630		
C5	0.1320	S15	0.5400	0.0710	0.3330	0.3330	0.3330	0.000	0.010
		S16	0.2970	0.0390	0.3330	0.3330	0.3330	0.000	
		S17	0.1630	0.0220	0.3330	0.3330	0.3330	0.000	
		Synthesis value			0.3330	0.3330	0.3330		
C6	0.0760	S18	0.2980	0.0230	0.4430	0.1690	0.3870	0.020	0.020
		S19	0.2100	0.0160	0.5000	0.2500	0.2500	0.050	
		S20	0.2460	0.0190	0.3270	0.4130	0.2600	0.000	
		S21	0.2460	0.0190	0.3270	0.4130	0.2600	0.050	
		Synthesis value			0.3930	0.3110	0.2960		
C7	0.0790	S22	0.3950	0.0310	0.4930	0.3110	0.1960	0.050	0.020
		S23	0.2320	0.0180	0.5400	0.1630	0.2970	0.010	
		S24	0.2320	0.0180	0.4000	0.2000	0.4000	0.000	
		S25	0.1400	0.0110	0.5280	0.1400	0.3330	0.050	
		Synthesis value			0.4810	0.2270	0.2910		
C8	0.0820	S26	0.3300	0.0270	0.4000	0.4000	0.2000	0.000	0.000
		S27	0.3300	0.0270	0.4000	0.4000	0.2000	0.000	
		S28	0.3300	0.0270	0.3330	0.3330	0.3330	0.000	
		Synthesis value			0.3750	0.3750	0.2500		
C9	0.0690	S29	0.4000	0.0280	0.4000	0.4000	0.2000	0.000	0.000
		S30	0.4000	0.0280	0.4930	0.3110	0.1960	0.050	
		S31	0.2000	0.0140	0.4000	0.4000	0.2000	0.000	
		Synthesis value			0.4330	0.3690	0.1990		
C10	0.0690	S32	0.4000	0.0280	0.4000	0.4000	0.2000	0.000	0.000
		S33	0.4000	0.0280	0.3870	0.4430	0.1690	0.020	
		S34	0.2000	0.0140	0.3870	0.4430	0.1690	0.020	
		Synthesis value			0.3930	0.4250	0.1820		

Table 4. *Cont.*

Criteria	Criteria Weight	Sub-Criteria	Sub-Criteria Weight	Synthesis Value	Cement Company 1	Cement Company 2	Fertilizer Company	Inconsistency Ratio	
								Sub-Criteria	Criteria
C11	0.0650	S35	0.5000	0.0330	0.3870	0.4430	0.1690	0.020	0.000
		S36	0.5000	0.0330	0.3870	0.4430	0.1690	0.020	
		Synthesis value			0.3870	0.4430	0.1690		

4.1. Inconsistency Ratio

In order to obtain an accurate and a representative result, the constructed matrices must be consistent. A consistency measuring test is required for all the hierarchy matrices. Once the inconsistent matrices are identified, a revision and improvement must be performed [28]. After computing the consistency ratios of the comparison matrices in this study, all of the consistency ratios of all matrices were less than 0.05, which means that the evaluation was consistent.

4.2. Sensitivity Analysis

The sensitivity analysis was performed to study the effect of changing the priority of either the criteria or the sub-criteria on the alternatives' rank. Furthermore, the sensitivity analysis was used to understand the influence of changing the alternatives' ranking on the main goal accomplishment [29]. Figure 2 represents the alternatives' weights and rank before conducting the sensitivity analysis.

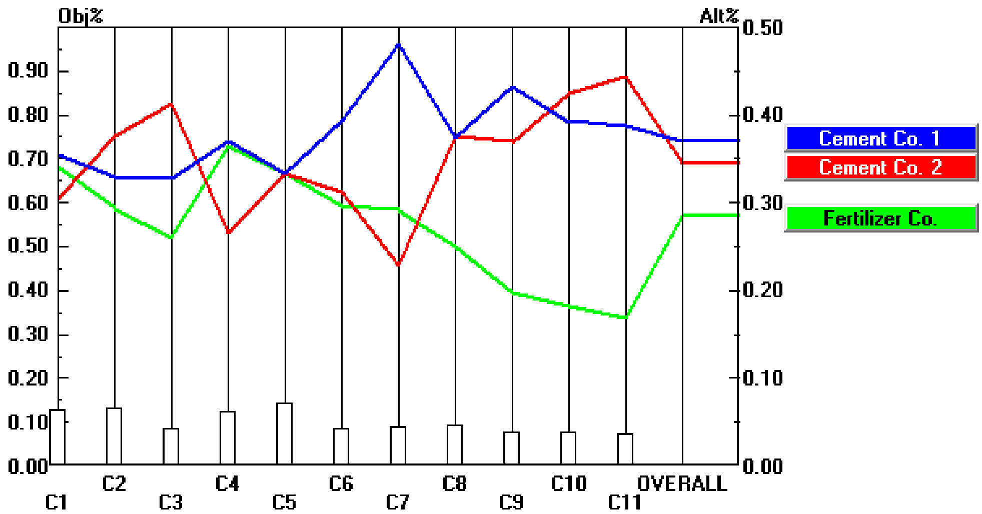

Figure 2. The alternatives' overall weights in the case study.

As shown in Figure 3, it can be clearly seen that the explosive weight criterion (C5) was increased from 0.132 to 0.172, which is a 30% increase in its priority. Furthermore, the resulting overall alternatives' weights were changed: for Cement Company 1, the change was from 0.370 to 0.368, Cement Company 2 changed from 0.286 to 0.288, and there was no change in the overall weights for the fertilizer company.

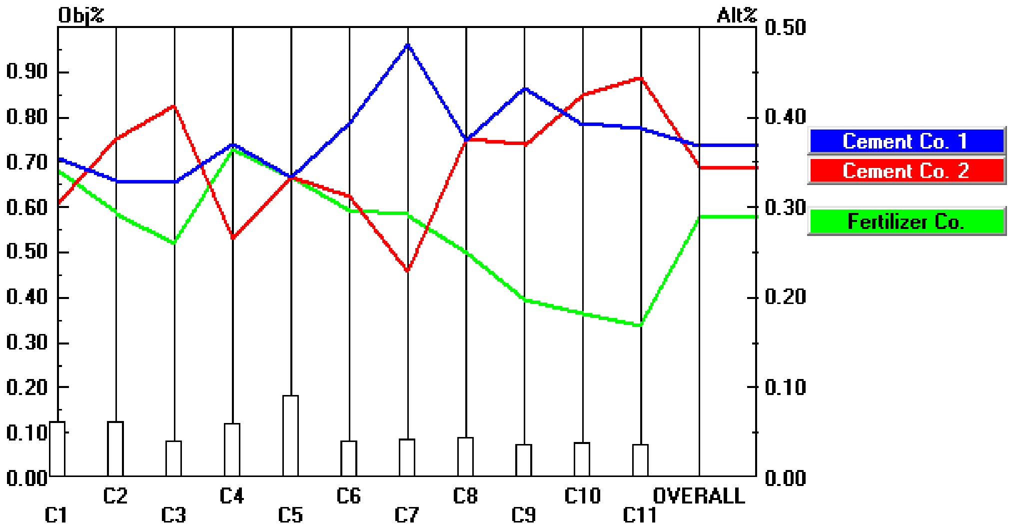

Figure 3. The weights and rank of alternatives with a 30% increase in the explosives criterion (C5).

Regarding the mine planning (C2) criterion, the overall weight was increased from 0.121 to 0.194, which represents an increase of 60%, as shown in Figure 4. The overall weights of alternatives were changed; they changed from 0.370 to 0.367 for Cement Company 1, from 0.344 to 0.347 for Cement Company 2, and no changes occurred for the fertilizer company.

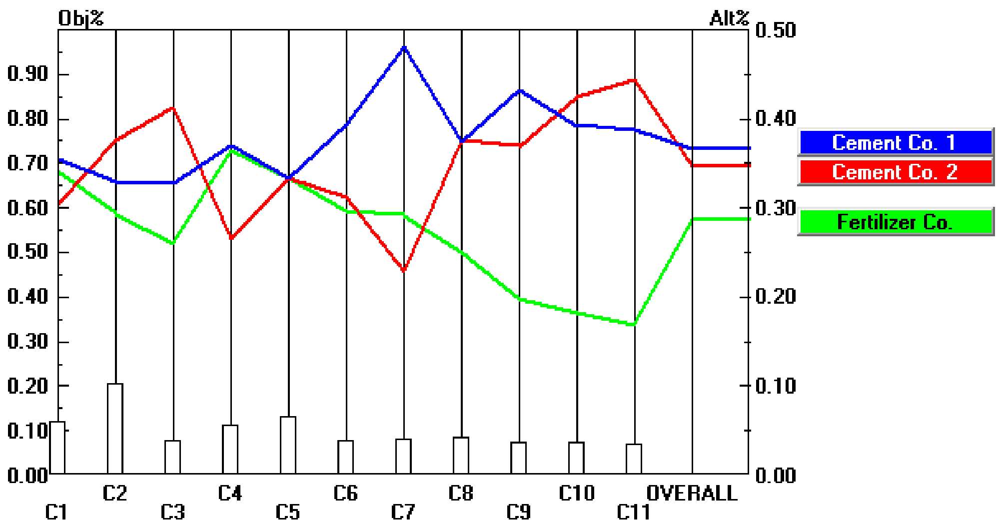

Figure 4. The weights and rank of alternatives with a 60% increase in the mine planning (C2) criterion.

As shown in Figure 5, the safety system (C1) weight was increased by 60% from 0.120 to 0.192. The overall weights of alternatives were changed in the following rank: Cement Company 1 from 0.370 to 0.369, Company 2 from 0.344 to 0.341, and the fertilizer company from 0.286 to 0.290.

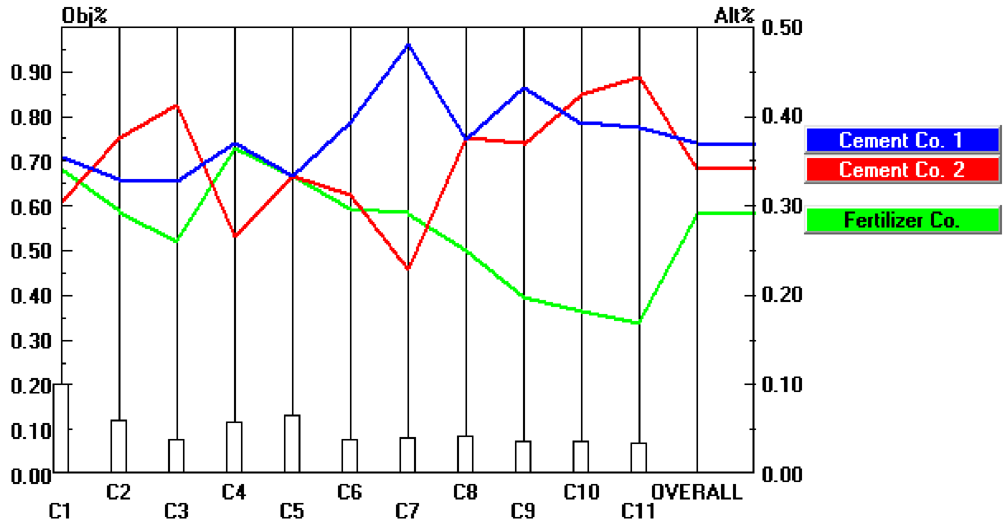

Figure 5. The weights and rank of alternatives with a 60% increase in the safety system (C1).

As shown in Figure 6, the weight of excavation and face stability (C4) was monitored, increasing 60% from 0.114 to 0.182. Overall, the alternatives' weights were changed as follows: Cement Company 2 changed from 0.344 to 0.338, the fertilizer company from 0.286 to 0.292, and Cement Company 1's weight did not change. Several other sensitivity tests were conducted on the results of this paper; overall, the best alternative is Cement Company 1.

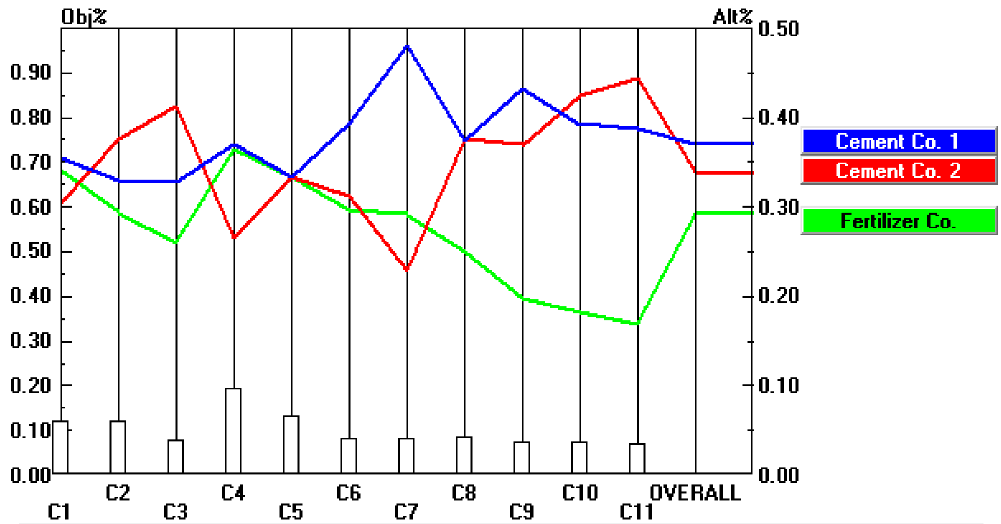

Figure 6. Weights and rank of alternatives with a 60% increase in excavation and face stability (C4).

5. Conclusions

Applying the AHP technique helps determine the priorities and weights of the criteria and sub-criteria. It also assists in identifying the alternatives' weights and ranking. Based on the AHP results, four out of eleven criteria were found to be significant in surface mining operations in Jordan. Those were, in descending order, explosives, mine planning, the safety system, and the excavation and face stability.

The AHP approach proved that it could be used in all decision-making problems, either for qualitative or quantitative criteria. In addition, the constructed health and safety model is applicable to any surface mining company. In this study, three companies were assessed: two cement companies and one chemical fertilizer company in Jordan. The best choice regarding the health and safety performance was Cement Company 1.

A sensitivity analysis was performed on this study. A high change in the most effective criteria caused a little change in the alternatives' weights, and their ranking remained the same. Therefore, the final decision was not changed or affected, which means that the study results are reliable.

One limitation of the AHP is the complexity of pairwise comparison, which might affect the decision. As a future study, and to overcome this problem, the case studied in this research could be performed using a different multi-criteria decision-making tool, such as the ANP, which could reduce biases in the pairwise comparison, allowing us to reach a better decision.

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