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Human Error Probability Determination in Blasting Process of Ore Mine Using a Hybrid of HEART and Best-Worst Methods

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ABSTRACT

Background: One of the important actions for enhancing human reliability in any industry is assessing human error probability (HEP). The HEART technique is a robust tool for calculating HEP in various industries. The traditional HEART has some weaknesses due to expert judgment. For these reasons, a hybrid model is presented in this study to integrate HEART with Best-Worst Method.
Materials Method: In this study, the blasting process in an iron ore mine was investigated as a case study. The proposed HEART-BWM was used to increase the sensitivity of APOA calculation. Then the HEP was calculated using conventional HEART formula. A consistency ratio was calculated using BWM. Finally, for verification of the HEART-BWM, HEP calculation was done by traditional HEART and HEART-BWM.
Results: In the view of determined HEPs, the results showed that the mean of HEP in the blasting of the iron ore process was 2.57E-01. Checking the full blast of all the holes after the blasting sub-task was the most dangerous task due to the highest HEP value, and it was found 9.646E-01. On the other side, obtaining a permit to receive and transport materials was the most reliable task, and the HEP was 8.54E-04.
Conclusion: The results showed a good consistency for the proposed technique. Comparing the two techniques confirmed that the BWM makes the traditional HEART faster and more reliable by performing the basic comparisons.

1. Introduction

The mining industry is one of the most dangerous work environments [1–3]. The main threat to the mining industry is mining accidents that lead to injury, death, property damage, and environmental pollution, and identification of accidents cause is an essential step to reduce these problems [4]. Human error has become a crucial concern in the mining industries as it is responsible for 85% of mining accidents [5,6]. Research on platinum mine accidents in South Africa found that unsafe acts were responsible for 98.9% of accidents [4]. Additionally, the evidence showed that the only way to improve safe operation in the mining industry is to evaluate and manage unsafe acts and reduce human error [7,8].

Human Reliability Analysis (HRA) [9] is the primary approach to prevent and reduce human error [9]. The HRA has three main steps: recognizing fundamental operations, analyzing relevant tasks, and determining human error probability (HEP) [10]. Several methods have been used to assess the human contribution to the accident, including Technique for Human Error Rate Prediction (THERP) [11], Simplified Plant Analysis Risk Human Reliability Assessment (SPAR-H) [12], Cognitive Reliability and Error Analysis Method (CREAM) [13], Information, Decision and Action in Crew context

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(IDAC) [14], Accident Sequence Evaluation Program (ASEP) [15], and Phoenix [16].

The human error assessment and reduction technique (HEART) is one of the most widespread techniques because it is easy to learn, reliable, and has a straightforward mechanism but has a moderate accuracy [17,18,24]. This technique is flexible and has been used to estimate the HEP in many industries, including railways [18,19], shipping [20,21], manufacturing [22], and information [23]. The HEP obtained by the HERAT has three parts including, Generic Task Type (GTT), Error-Producing Conditions (EPC), and Assessed Proportion of Affect (APOA). GTT and EPC are approximately structured affairs; the HEP is subjected to the precision of experts' judgment through APOA determination. In the APOA calculation, the weight of each EPC is obtained based on expert judgment. For this reason, it faces much uncertainty [24].

Many studies tried to improve the certainty of the HERAT technique. Fuzzy-HEART [24–26], a hybrid HEART based on AHP [20], Fuzzy analytic network process [27], HEART and AV-DEMATEL [22], HEART combined with improved analytic hierarchy process [28]. The classical fuzzy approach does not consider the self-confidence of experts and has an uncertainty in the extracted human opinions [29,30]. Therefore it cannot eliminate the traditional HERAT uncertainty [18]. In order to solve this problem, a hybrid technique was presented by Aghaei et al. by combining the HEART method with z-numbers. The researchers in the mentioned study enhanced the reliability of HEART using the z-numbers. For this purpose, experts were asked to rate their reliability on their opinions. Experts were also ranked based on education, experience, and job position. This study could overcome the disadvantages of traditional HEART but needed many inputs and calculations [9]. However, it is still necessary to provide a fast and user-friendly method that requires few inputs.

Few studies concern human error in the mining industries. To this, the present study aimed to use the advantages of HEART and also use the BWM to overcome the disadvantages of HEART. On the other hand, this study integrates these two techniques' strengths to calculate the HEP in mining industries with the least of comparisons and the most precision.

2. Materials and methods

This section briefly reviews the fundamental principles of the HEART technique and BWM method used in the following sections.

2.1. HEART approach

The HEART method is a technique to evaluate HEP, introduced by Williams [17]. Three fundamental parameters define the HEART: Generic Error Probability (GEP), EPCs, and APOA ([20,31]). The GEP is used to determination of the GTT. For each GEP value, a

qualitative description is provided, as shown in Table 1 [9]. The EPCs indicate the Performance Shaping Factors (PSF) that may influence the HEP, presented in Table 2 [9]. EPC can be any condition that negatively affects performance. One or more EPCs can be defined for each task. The theory of this approach is that while a task is completed, the reliability changes under the impact of the EPCs [32]. The APOA is the third parameter, which gives each EPC a weight according to its importance [9]. Finally, HEP is determined according to the following equation:

$$HEP = GEP \times \left\{ \prod_i \left[(EPC_i - 1)\, APOA_{pi} + 1 \right] \right\} \tag{1}$$

The HEP is human error probability, GEP shows the corresponding GTT error probability value, EPC is the ith error-producing condition, and APOA expresses the assessed proportion of affect of ith EPC.

2.2. The Best-Worst Method

The Best-Worst method is a multi-criteria decision-making (MCDM) approach presented by Rezaei [33]. This technique obtains weights according to a pairwise comparison of the best and worst criteria with other criteria in a 5-Step method. A consistency ratio is also defined to ensure the final results. The BWM technique is vector-based and requires less comparison than matrix-based MCDM methods such as AHP. Generally, 2n-3 comparisons are made in this technique. The final weights are reliable because the comparisons are more consistent than the AHP. This technique can be used independently to estimate and extract weights or combined with other MCDM methods [33].

2.3. Traditional HERAT calculations

In the present study, ten experts participated. These experts were randomly divided into two groups. The experts were matched in two groups regarding education, experience, and specialized field. The first group of experts performed the weighting for the assigned tasks and sub-tasks based on the traditional HEART technique. The calculation of the HEPs was done using Formula 1 and is shown in Table 6.

2.4. Proposed method

In the HEART technique, after determining GTT, the EPC must be defined for each of them. Sometimes more than one EPC may be specified for each GTT. In this case, the weighting of EPCs and determination of APOA should be done for them. This APOA is determined using the expert's opinions. The traditional HEART method usually does not take into account the knowledge and

Table 1
The generic task type

Code	Generic task type	GEP
A	Totally unfamiliar; performed at speed with no real idea of likely consequence	0.55
B	Shift or restore system to a new or original state on a single attempt without supervision or procedures	0.26
C	Complex task requiring a high level of comprehension and skill	0.16
D	Fairly simple task performed rapidly or given scant attention	0.09
E	Routine, highly practiced, rapid task involving relatively low level of skill	0.02
F	Restore or shift a system to original or new state, following procedures with some checking	0.003
G	Completely familiar, well designed, highly practiced task which is routine	0.0004
H	Respond correctly to system command even when there is an automated system providing accurate interpretation of system state	0.00002
M	Miscellaneous task for which no description can be found	0.03

Table 2
The error producing conditions

	Error producing conditions	Weight
A1	Unfamiliarity with a situation which is potentially important but only occurs infrequently or is novel	17
A2	A shortage of time available for error detection & correction	11
A3	A low signal-to-noise ratio	10
A4	A means of suppressing or overriding information or features which is too easily accessible	9
A5	No means of conveying spatial & functional information to operators in a form which they can readily assimilate	8
A6	A mismatch between an operator's model of the work & that imagined by a Designer	8
A7	No obvious means of reversing an unintended action	8
A8	A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information	6
A9	A need to unlearn a technique & apply one which requires the application of an opposing philosophy	6
A10	The need to transfer specific knowledge from task to task without loss	5.5
A11	Ambiguity in the required performance standards	5
A12	A mismatch between perceived & real risk	4
A13	Poor, ambiguous, or ill-matched system feedback	4
A14	No clear, direct, & timely confirmation of an intended action from the portion of the system over which control is to be exerted	4
A15	Operator inexperience (e.g., A newly-qualified tradesman, but not an "expert")	3
A16	An impoverished quality of information conveyed by procedures & person interaction.	3
A17	Little or no independent checking or testing of output.	3
A18	A conflict between immediate and long-term objectives	2.5
A19	No diversity of information input for veracity checks	2.5
A20	A mismatch between the educational achievement level of an individual and the requirements of the task	2
A21	An incentive to use other more dangerous procedures	2
A22	Little opportunity to exercise the mind and body outside the immediate confines of a job	1.8
A23	Unreliable instrumentation (enough that it is noticed)	1.6
A24	A need for absolute judgements which are beyond the capabilities or experience of an operator	1.6
A25	Unclear allocation of function and responsibility	1.6
A26	No obvious way to keep track of progress during an activity	1.4
A27	A danger that finite physical capabilities will be exceeded	1.4
A28	Little or no intrinsic meaning in a task	1.4
A29	High-level emotional stress	1.3
A30	Evidence of ill-health amongst operatives, especially fever	1.2
A31	Low workforce morale	1.2
A32	Inconsistency of meaning of displays and procedures	1.2
A33	A poor or hostile environment (below 75% of health or life-threatening severity)	1.15
A34	Prolonged inactivity or highly repetitive cycling of low mental workload tasks	1.1
A35	Disruption of normal work-sleep cycles	1.1
A36	Task pacing caused by the intervention of others	1.06
A37	Additional team members over and above those necessary to perform task normally and satisfactorily	1.03
A38	Age of personnel performing perceptual tasks	1.02

experience of the experts, so this can reduce the sensitivity in calculating APOA and reduce the reliability of the method. Various studies have been presented to solve this weakness of the HEART method [9,20]. The present study used the BWM technique to increase the sensitivity in calculating APOA. The BWM compares and weighs by selecting the best and the worst EPC and comparing them with other EPCs. This HEART-BWM hybrid technique increases the sensitivity of APOA calculation and the reliability of the proposed technique by combining the advantages of both methods. In this section of the study, a hybrid HEP measurement method is offered, in which the BWM was combined with the traditional HEART technique. The schematic of the study is shown in Fig. 1. This HEART-BWM consists of threesteps.

Step 1- **Identification of EPCs of sub-tasks:** This step aims to determine EPCs for each sub-task. Four steps step defined in the current study

Step 1-1-**Selection and analysis of a task:** A task was selected, and all the task activities were analyzed. The task was analyzed using the hierarchical task analysis (HTA) method

Step 1-2-**Determination of scenario**: This step aimed to describe original scenarios and point out all the factors leading to human error. These factors could include task type, physical workload, mental workload, working environment, individual characteristics of operators

Step 1-3-**Determination of GTT:** This step followed two goals; 1) to determine GTT using the results of steps 1-1 by the experts, and 2) to pick the proper value of GEP for each GTT

Table 3
Consistency index [35]

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency index (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Table 4
HTA of the blasting process in the iron ore mine

1-Preparation of explosive plan by engineering unit
  1-1 Assessing the blasting's location
    1-1-1 Evaluation of soil type and its moisture content
    1-1-2 Assessing the blasting's area and the height of the Step where the blasting takes place
  1-2 Mapping the blasting location
    1-2-1 Taking photos of the blast site
    1-2-2 Record the required dimensions and points using a mapping camera
  1-3 Map of explosive boreholes (holes)
    1-3-1 Determining the type and amount of explosives according to the humidity of the place
    1-3-2 Determining the diameter and depth of explosive holes
    1-3-3 Determining the layout and distances of the holes
  1-4 Map review and approval by the engineering unit

2- Drilling holes
  2-1 Evaluating the drilling site and implement the explosive plan

    2-1-1 Checking for cracks and fractures in walls and floor
    2-1-2 Leveling the surface of the drilling site
    2-1-3 Specify the drilling location of each hole according to the explosive design
  2-2 Checking the drilling machine
    2-2-1 Checking hydraulic system and jacks
    2-2-2 Checking the water level of the device
    2-2-3 Check the drilling rig
  2-3 Safe transfer of drilling machine to the site
    2-3-1 Choose the right way
    2-3-2 Accompany the car (avoid collisions with high-pressure cables)
    2-3-3 Place the machine in a suitable location for drilling in the hole
      2-3-3-1 Checking the distance of the car to the edge of the stairs
      2-3-3-2 Checking the location of the jacks
  2-4 drilling
    2-4-1 Choosing the headboard that fits the diameter of the hole and install it
    2-4-2 Drilling holes
    2-4-3 Approve drilling each hole according to its characteristics in the map

3- Loading and carrying explosives
  3-1 Obtaining a permit to receive and transport materials
  3-2 Checking the explosives truck
    3-2-1 Checking car anti-spark equipment
    3-2-2 Checking the gasoline tank and its connections
    3-2-3 Checking brake system, gearbox and tires
    3-2-4 Impermeability of car walls and roof
    3-2-5 Checking the condition of the car surge arrester
  3-3 Loading explosives
    3-3-1 Park the car at a distance of 10 meters from the warehouse and turn off the car
    3-2-2 Apply the parking brake and use the 5 front and rear gears of the tires
    3-2-3 Loading explosives accurately and without haste (transfer detonators by separate machine)
  3-4 Transfer of materials to the mine
    3-4-1 Escort car carrying explosives from back and front
    3-4-2 Park the car in a safe and pre-designated place in accordance with the standard
    3-4-3 Temporary storage of explosives in accordance with standards

4- Blast hole loading
  4-1 Final control of holes
    4-1-1 Checking the diameter and depth of the holes
    4-1-2 Checking seams and fractures in holes
    4-1-3 Checking the humidity and water content of the holes
  4-2 Transfer of explosives to the mine
    4-2-1 Transfer of powder materials with ANFO truck and waterproof materials with emulsion truck
    4-2-2 Transfer detonators, cables and wicks to the blast site by separate machine
    4-2-3 Transfer dynamite, explosive barrel and cortex to the blast site by separate machine
  4-3 Transfer of detonated dynamite to the bottom of the hole
    4-3-1 Pour some of the main load on the bottom of the hole
    4-3-2 Dynamite detonation
      4-3-2-1 Drilling dynamite with a wooden flag
      4-3-2-2 Putting nannies in dynamite
      4-3-2-3 Tighten the detonator in place and tie the detonator cable to the dynamite
    4-3-3 Transfer of detonated dynamite to the bottom of the hole
  4-4 Pour explosives into the hole and fill two-thirds of the hole volume
    4-4-1 Slowly and cautiously pour explosives on dynamite
    4-4-2 Condensate explosives to fill the entire space of the hole and seamlessly connect the materials
    4-4-3 Fill the remaining third with soil and clay without damaging the stuffing cable (flowering)

Table 4 (*continued*)

5- Connect the spark plug cables to each other
   5-1 Connect the spark plug cables to each other in parallel or sequentially depending on the need
   5-2 Connect the cables and pull the cable to the shelter

6- Blasting Process
   6-1 Final control of connections and wiring of the detonator circuit
   6-2 Evacuation of people and machines
     6-2-1 Announce the evacuation of the mine to all units
     6-2-2 Moving mining machinery to safe places
     6-2-3 Patrol to ensure evacuation of the mine
     6-2-4 Ring the special siren 15 minutes before the blasting three times
   6-3 Blasting
     6-3-1 The wicker goes to the shelter and lights the wick at a certain time
     6-3-2 Check the full blast of all the holes after the blasting
     6-3-3 White siren to inform personnel

Step 1-4-**Identification of EPCs:** EPCs are the factors affecting human error. Moreover, the experts are identifying the EPCs concerning the situation. If the experts select more than one EPC, the APOA should be calculated. In the case of this study, the APOA was calculated using BWM

Step 2- **Identification of APOA using BWM:** This step aimed to determine the assessed proportion of affect for each EPC. In the traditional HEART method, the expert performs the APOA calculation, and there is always unreliability in the expert's judgment. To deal with this, the present study presents a new technique based on BWM-HEART. This step has six steps

Step 2-1-**Determination a set of decision criteria:** In this step, experts determine the number of necessary criteria to make a decision. In the case of the present study, the criteria are the EPCs

Step 2-2-**Choosing the best and the worst:** The experts chose the best as the most important and the worst as the least important criteria

Step 2-3-**Determination the best to others (BO):** The best score compared to other criteria is determined in the range of 1-9. BO is obtained as follows:

$$A_B = (a_{B1},\ a_{B2},\ \ldots,\ a_{Bn}) \tag{2}$$

Where, a_{B1} is equal to the value of B relative to j and it is clear that. $A_{BB} = 1$.

Step 2-4-**Determination of others to worst (OW):** The other criteria score compared to worst is determined in the range of 1-9. OW is obtained as follows:

$$A_W = (a_{1W},\ a_{2W},\ \ldots,\ a_{NW}) \tag{3}$$

where, a_{jw} is equal to the value of j relative to W and it is clear that. $A_{ww} = 1$.

Step 2-5-**Finding the optimal weights:** The optimal weight for the criteria is obtained when we have $\frac{W_B}{W_J} = a_{BJ}$ and $\frac{W_J}{W_w} = a_{JW}$. In order to provide these conditions for all J, the maximum absolute difference between $\left|\frac{W_B}{W_J} - a_{BJ}\right|$ and $\left|\frac{W_J}{W_w} - a_{JW}\right|$ must be minimized for all J. Regarding the non-negativity and sum condition for the weights, the next problem results:

Min max j $\left\{\left|\frac{W_B}{W_J} - a_{BJ}\right|, \left|\frac{W_J}{W_w} - a_{JW}\right|\right\}$
s.t.

$$\sum_j w_j = 1$$

$$w_j \geq 0,\ for\ all\ j \tag{4}$$

The above problem can be expressed as follows:
min ξ.
S.t.

$$\left|\frac{W_B}{W_J} - a_{BJ}\right| \leq \xi, for\ all\ j$$

$$\left|\frac{W_J}{W_W} - a_{JW}\right| \leq \zeta, for\ all\ j$$

$$\sum_j w_j = 1$$

$$w_j \geq 0,\ for\ all\ j \tag{5}$$

By solving the above equation, the optimal weights (w_1^*, w_2^*, …, w_n^*) and ξ^* are obtained. The optimal weights are used as the APOA.

Step 2-6-**Calculation of Consistency Ratio (CR):** In this step, a CR for the proposed BWM was determined. The value of a_{BW} is the highest value given by the expert in weighting. The highest compatibility occurs when a_{Bj} and a_{jW} have the same value as a_{BW}, which leads to ξ. By solving the $a_{BW} \in \{1, 2, \ldots, 9\}$, we can get the highest possible value of ξ (maxξ). This maximum value is represented by the consistency index heading, which is shown in Table 3. Finally, the CR is calculated using the following equation:

$$Consistency\ ratio = \frac{\xi^*}{consistency\ index} \tag{6}$$

CR is in range of 0-1, 0 shows more consistency, while values close to1show less consistency. The CR values under 0.1 shows good consistency.

Step 3- **Calculation of HEP:** In the last step, the HEP is calculated for each sub-task according to the Equation (1).

3. Results

3.1. Case study

In this section of the study, a blasting process in an iron ore mine is displayed to illustrate the utilization and effectiveness of the HEART-BWM framework.

Table 5
The results of HEART-BWM

Sub-task	GTT	EPC	Priority Weight	A$_{BW}$	KSI	CI	CR
1-1-1	D	A3, A15, A16, A19, A23, A33	0.389, 0.219, 0.146, 0.049, 0.109, 0.087	7	0.048	3.73	0.013
1-1-2	E	A15	1	1	1	0	0
1-2-1	G	A3, A15. A23	0.111, 0.704, 0.185	6	0.037	3.00	0.012
1-2-2	D	A15, A23, A25	0.64, 0.1, 0.26	3	0.14	2.30	0.06
1-3-1	D	A11, A16, A19, A21	0.089, 0.473, 0.267, 0.178	5	0.062	2.30	0.027
1-3-2	C	A11, A15, A16, A19, A21	0.140, 0.460, 0.187, 0.072, 0.140	5	0.101	2.30	0.044
1-3-3	C	A11, A15, A16, A19, A21	0.24, 0.42, 0.16, 0.12, 0.06	6	0.06	3.00	0.02
1-4	G	A1, A8, A12, A16, A19, A22, A24	0.364, 0.132, 0.198, 0.099, 0.099, 0.041, 0.066	8	0.033	4.47	0.007
2-1-1	E	A1, A3, A12, A15, A31, A33	0.212, 0.142, 0.357, 0.142, 0.041, 0.106	7	0.066	3.73	0.017
2-1-2	F	A23, A31, A34	0.24, 0.2, 0.56	4	0.16	1.63	0.038
2-1-3	D	A15, A23, A34	0.312, 0.125, 0.563	4	0.062	1.63	0.038
2-2-1	E	A1, A3, A15, A31	0.214, 0.549, 0.161 0.076	6	0.092	3.00	0.031
2-2-2	G	A15, A31, A34	0.562, 0.125, 0.313	5	0.062	2.30	0.011
2-2-3	E	A3, A15, A31	0.583, 0.305, 0.111	5	0.028	2.30	0.012
2-3-1	E	A15, A16, A33	0.218, 0.077, 0.705	7	0.167	3.73	0.045
2-3-2	G	A3, A16, A28, A31	0.246, 0.434, 0.075, 0.245	5	0.057	2.30	0.025
2-3-3-1	E	A1, A15, A31	0.254, 0.654, 0.092	6	0.109	3.00	0.036
2-3-3-2	F	A1, A15, A31	0.244, 0.644, 0.112	5	0.089	2.30	0.038
2-4-1	D	A15, A16, A19	0.6, 0.17, 0.23	6	0.1	3.00	0.064
2-4-2	G	A15, A23, A25	0.542, 0.17, 0.292	4	0.042	1.63	0.035
2-4-3	G	A15, A23, A24	0.313, 0.562, 0.125	4	0.062	1.63	0.038
3-1	G	A19, A28, A32	0.625, 0.125, 0.25	5	0.125	2.30	0.061
3-2-1	F	A1, A3, A11, A12, A15, A20, A31	0.179, 0.179, 0.089, 0.325, 0.120, 0.036, 0.072	8	0.036	4.47	0.008
3-2-2	E	A1, A3, A11, A12, A15, A20, A31	0.178, 0.178, 0.089, 0.324, 0.118, 0.042, 0.071	7	0.031	3.73	0.008
3-2-3	E	A1, A3, A11, A12, A15, A20, A31	0.158, 0.158, 0.106, 0.294, 0.158, 0.045, 0.079	6	0.023	3.00	0.007
3-2-4	F	A1, A3, A11, A12, A15, A20, A31	0.164, 0.164, 0.109, 0.290, 0.139, 0.05, 0.08	5	0.038	2.30	0.016
3-2-5	E	A1, A3, A11, A12, A15, A20, A31	0.174, 0.174, 0.116, 0.31, 0.116, 0.039, 0.069	7	0.039	3.73	0.0104
3-3-1	G	A11, A13, A15, A28	0.276, 0.474, 0.184, 0.066	6	0.079	3.00	0.026
3-3-2	G	A11, A13, A15, A28	0.245, 0.434, 0.245, 0.075	5	0.057	2.30	0.025
3-3-3	D	A4, A11, A12, A15, A20, A27, A28	0.071, 0.324, 0.178, 0.178, 0.089, 0.042, 0.118	7	0.031	3.73	0.008
3-4-1	E	A1, A11, A12, A21, A25	0.227, 0.069, 0.152, 0.4, 0.152	5	0.055	2.30	0.024
3-4-2	G	A1, A12, A21, A28	0.254, 0.485, 0.169, 0.092	5	0.023	2.30	0.01
3-4-3	D	A11, A12, A15, A20, A21, A27, A28	0.141, 0.106, 0.141, 0.141, 0.343, 0.044, 0.084	6	0.053	3.00	0.018
4-4-1	E	A3, A11, A15, A20, A23, A31	0.375, 0.107, 0.214, 0.143, 0.053, 0.107	6	0.053	3.00	0.018
4-1-2	E	A3, A11, A15, A20, A23, A31	0.225, 0.113, 0.407, 0.113, 0.052, 0.09	7	0.043	3.73	0.011
4-1-3	E	A3, A11, A15, A20, A23, A31	0.362, 0.126, 0.189, 0.126, 0.069, 0.126	5	0.017	2.30	0.007
4-2-1	D	A1, A15, A31, A33	0.179, 0.268, 0.081, 0.47	5	0.065	2.30	0.028
4-2-2	D	A1, A15, A31, A33	0.176, 0.485, 0.073, 0.265	6	0.044	3.00	0.015
4-2-3	M	A1, A15, A31, A33	0.471, 0.268, 0.081, 0.179	5	0.065	2.30	0.028
4-3-1	D	A7, A15, A21, A22, A29	0.141, 0.211, 0.372, 0.064, 0.211	5	0.052	2.30	0.023
4-3-2-1	E	A1, A9, A15, A21, A29	0.227, 0.069, 0.151, 0.4, 0.152	5	0.055	2.30	0.024
4-3-2-2	E	A1, A9, A15, A21, A29	0.155, 0.055, 0.4, 0.233, 0.155	6	0.067	3.00	0.022
4-3-2-3	F	A15, A17, A21	0.7, 0.1, 0.2	6	0.1	3.00	0.033
4-3-3	D	A15, A21, A29, A36	0.268, 0.471, 0.179, 0.081	5	0.065	2.30	0.028
4-4-1	E	A1, A3, A7, A15, A21, A29	0.138, 0.13, 0.046, 0.207, 0.368, 0.138	7	0.046	3.73	0.012
4-4-2	E	A1, A15, A21, A29	0.196, 0.518, 0.196, 0.089	5	0.071	2.30	0.031
4-4-3	E	A1, A15, A21, A29	0.156, 0.594, 0.156, 0.094	6	0.031	3.00	0.01
5-1	E	A1, A15, A21, A23	0.549, 0.214, 0.16, 0.076	6	0.092	3.00	0.031
5-2	F	A1, A15, A21, A23	0.203, 0.559, 0.152, 0.085	6	0.051	3.00	0.017
6-1	E	A15, A19, A23	0.312, 0.125, 0.562	4	0.062	1.63	0.038
6-2-1	F	A16, A25, A36	0.704, 0.111, 0.185	6	0.037	3.00	0.012
6-2-2	E	A15, A21, A25	0.625, 0.125, 0.25	4	0.125	1.63	0.076
6-2-3	G	A12, A21, A23	0.583, 0.111, 0.305	5	0.027	2.30	0.012
6-2-4	G	A16, A21, A23	0.687, 0.125, 0.187	5	0.062	2.30	0.027
6-3-1	E	A15, A21, A29	0.325, 0.575, 0.1	5	0.075	2.30	0.033
6-3-2	C	A1, A3, A4, A12, A14, A15, A17, A24, A29	0.023, 0.028, 0.028, 0.037, 0.025, 0.205, 0.205, 0.224, 0.224	9	0.019	5.23	0.007
6-3-3	G	A16, A21, A25	0.628, 0.143, 0.229	4	0.057	1.63	0.035

3.2. The problem description

One of the fundamental and sensitive parameters which affect an ore mine is stone crushing using a blasting process. This process should be done without any accident or damage. Several factors influence the accident during the blasting, and according to studies, one of the most factors is human error [5,6].

Table 6
The HEP calculation results

Sub-task	GEP	HEP $_{HEART}$	HEP$_{BWM-HEART}$
1-1-1	0.09	7.820E-01	8.720E-01
1-1-2	0.02	6.000E-02	6.000E-02
1-2-1	0.0004	2.040E-03	2.140E-03
1-2-2	0.09	2.255E-01	2.514E-01
1-3-1	0.09	3.508E-01	3.837E-01
1-3-2	0.16	7.827E-01	8.328E-01
1-3-3	0.16	5.110E-01	5.359E-01
1-4	0.0004	8.796E-02	1.067E-01
2-1-1	0.02	4.395E-01	5.449E-01
2-1-2	0.003	3.902E-03	3.769E-03
2-1-3	0.09	1.561E-01	1.659E-01
2-2-1	0.02	6.306E-01	7.054E-01
2-2-2	0.0004	7.790E-04	8.980E-04
2-2-3	0.02	1.722E-01	2.056E-01
2-3-1	0.02	3.226E-02	3.665E-02
2-3-2	0.0004	2.051E-03	2.595E-03
2-3-3-1	0.02	1.781E-01	2.380E-01
2-3-3-2	0.003	2.671E-02	3.441E-02
2-4-1	0.09	3.456E-01	3.568E-01
2-4-2	0.0004	9.920E-04	1.080E-03
2-4-3	0.0004	8.610E-04	9.350E-04
3-1	0.0004	8.150E-04	8.540E-04
3-2-1	0.003	6.039E-02	1.056E-01
3-2-2	0.02	4.097E-01	6.994E-01
3-2-3	0.02	5.123E-01	6.397E-01
3-2-4	0.003	7.821E-02	9.855E-02
3-2-5	0.02	4.097E-01	7.120E-01
3-3-1	0.0004	1.219E-03	2.862E-03
3-3-2	0.0004	2.433E-03	2.798E-03
3-3-3	0.09	7.268E-01	7.815E-01
3-4-1	0.02	1.786E-01	2.629E-01
3-4-2	0.0004	4.790E-03	6.027E-03
3-4-3	0.09	3.572E-01	3.833E-01
4-1-1	0.02	1.882E-01	2.149E-01
4-1-2	0.02	1.627E-01	1.862E-01
4-1-3	0.02	1.758E-01	2.122E-01
4-2-1	0.09	3.662E-01	5.811E-01
4-2-2	0.09	4.127E-01	7.137E-01
4-2-3	0.03	2.969E-01	4.278E-01
4-3-1	0.09	3.109E-01	3.899E-01
4-3-2-1	0.02	2.142E-01	2.374E-01
4-3-2-2	0.02	1.719E-01	2.061E-01
4-3-2-3	0.003	1.008E-02	1.037E-02
4-3-3	0.09	1.806E-01	2.153E-01
4-4-1	0.02	3.598E-01	3.708E-01
4-4-2	0.02	1.289E-01	2.068E-01
4-4-3	0.02	1.224E-01	1.818E-01
5-1	0.02	2.784E-01	3.389E-01
5-2	0.003	3.048E-02	3.268E-02
6-1	0.02	4.950E-02	5.157E-02
6-2-1	0.003	7.481E-03	7.791E-03
6-2-2	0.02	3.115E-02	5.822E-02
6-2-3	0.0004	1.446E-03	1.309E-03
6-2-4	0.0004	1.188E-03	1.188E-03
6-3-1	0.02	4.390E-02	5.346E-02
6-3-2	0.16	6.182E-01	9.646E-01
6-3-3	0.0004	1.133E-03	1.179E-03

Step 1- **Identification of EPCs of human error**

This Step's primary aim was to perform a task analysis of the blasting process in the iron ore mine using the HTA technique (Table 4). A HTA was conducted. The blasting process in the iron ore mine process consists of six tasks: preparation of explosive plan by engineering unit, drilling holes, loading and carrying explosives, blast hole loading, connecting the spark plug cables, and blasting process. Then, all sub-tasks were classified using the HTA for each task. Finally, the GTT and EPCs of all sub-task were chosen by the five experts. In addition, the final GTT and EPCs of every sub-task are presented in Table 5.

Step 2- **Identification of APOA using BWM**

This step aimed to determine the assessed proportion of affect for each EPC using BWM. At first, we determined a set of decision criteria that, in the current case, they were the EPCs. For these, a questionnaire containing HTA and a list of 38 EPCs was given to the experts, and they were asked to choose EPCs for each sub-task. The EPCs for each sub-task were selected according to the majority rule among the expert's opinions. Then the experts scored the EPCs based on a Likert scale from 1 (least important) to 5 (most important). After that, the EPC, which had the higher mean, was chosen as best, and the one with the least mean was chosen as worst. Then, the best score compared to other criteria and the other criteria score compared to worst was determined in the range of 1-9. Then, the optimal weight for each criterion was obtained by solving Equation 5. Table 5 indicates the optimal weights (w_1^*, w_2^*, ..., w_n^*) and ξ^*. The optimal weights were used as the APOA. In the final step, a CR for the proposed BWM was determined using Equation 6 (Table 6), and the results showed that the CR is less than 0.1 (good consistency) [34].

Step 3- **Calculation of HEP**

In the last Step, the HEP of the blasting process in the iron ore mine was calculated for each sub-task according to Equation 1 based on traditional HEART and HEART-BWM. The results are shown in Table 6.

3.3. Sensitivity analysis

At this stage, after ensuring the reliable performance of the proposed model, sensitivity analysis was performed. Applying sensitivity analysis, researchers will evaluate the effects of changes in one variable on other variables. For this purpose, sub-task 3-1, which had the lowest HEP, and 6-3-2, which had the highest HEP, were selected. The procedure was that each time 1 point was added to each EPC in comparisons, the probability of human error was met. Overall, the number of reviews was 45 for the 3-1 sub-task and 125 for the 6-3-2 sub-task. The results of sensitivity analysis are shown in Figs. 2 and 3. According to figures, by changing the input variables, not much scattering was observed in the output results, and the results showed that the proposed method has acceptable certainty.

4. Discussion

In the view of determined HEPs, the results showed that the mean of HEP in the blasting of the iron ore process according to HEART-BWM was 2.57E-01, and according to HEART, it was 1.94E-01. The 6-3-2 sub-task, checking the full blast of all the holes after the blasting, was the most dangerous task due to the highest HEP value, and it was found 9.646E-01. Consequently, the necessary actions should be considered to increase human reliability in this task. On the other side, obtaining a permit to receive and transport materials was the most reliable task, and the HEP was 8.54E-04. This task gives the least HEP because the only human error could be to forget receiving a work permit. Nevertheless, if the permit is not received leads to insecure transport of materials, which means that the experts misunderstood this task.

The HEP of all sub-tasks are shown in Table 6 and Fig. 4. The task analysis was done using traditional HEART and the HEART-BWM to

1- Identification of EPCs of human error

```
┌─────────────────────────┐
│ Selection and analysis a task │
└─────────────────────────┘
            ↓
┌─────────────────────────┐
│ Determination of scenario │
└─────────────────────────┘
            ↓
┌─────────────────────────┐
│ Determination of GTT │
└─────────────────────────┘
            ↓
┌─────────────────────────┐
│ Identification of EPCs │
└─────────────────────────┘
```

2- Identification of APOA using BWM

```
┌─────────────────────────┐
│ Determination a set of decision criteria │
└─────────────────────────┘
            ↓
┌─────────────────────────┐
│ Choosing the best and the worst │
└─────────────────────────┘
            ↓
┌─────────────────────────┐
│ Determination the best to others (BO) │
└─────────────────────────┘
            ↓
┌─────────────────────────┐
│ Determiation of others to worst (OW) │
└─────────────────────────┘
            ↓
┌─────────────────────────┐
│ Finding the optimal weights │
└─────────────────────────┘
            ↓
┌─────────────────────────┐
│ Calculation of Consistency Ratio (CR) │
└─────────────────────────┘
```

3- Calculation of HEP
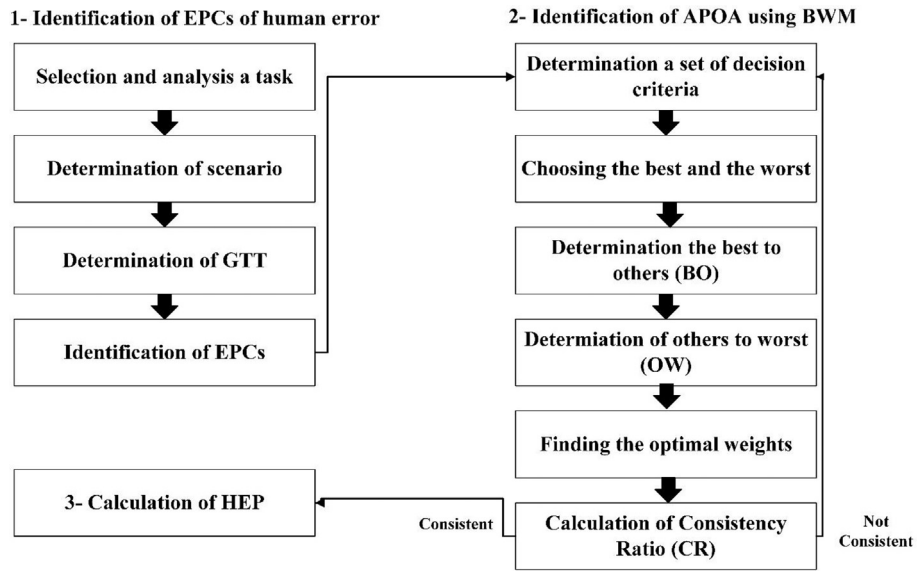
Consistent / Not Consistent

Fig. 1. The schematic of the present study.
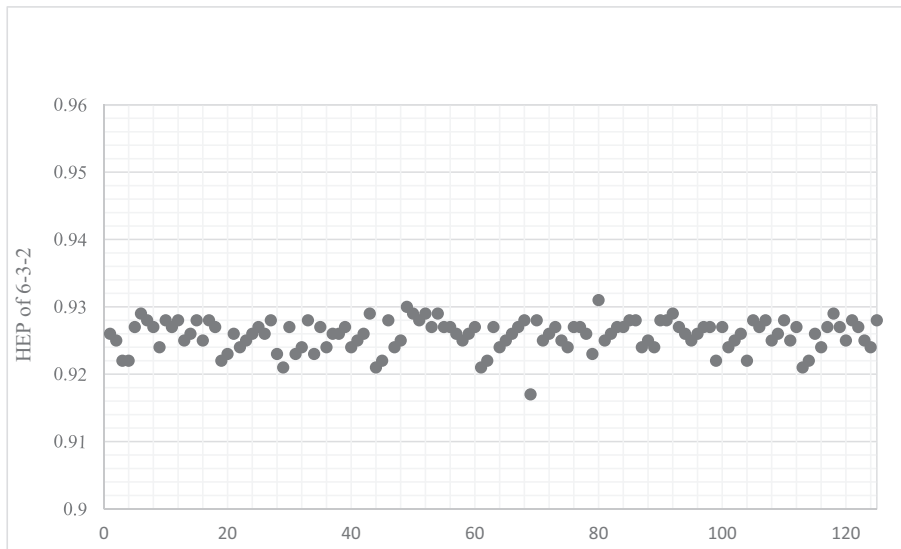

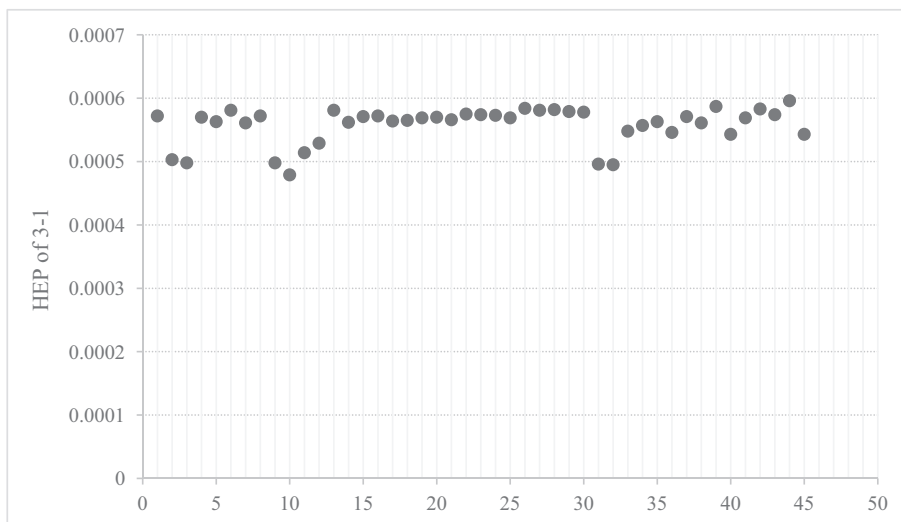**Fig. 2.** The results of sensitivity analysis for 6-3-2 sub-task.

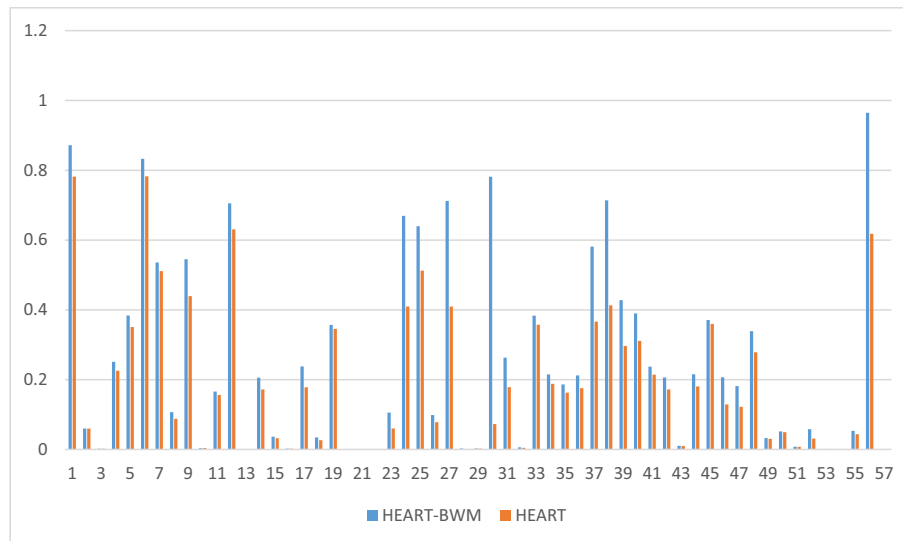**Fig. 3.** The results of sensitivity analysis for 3-1 sub-task.

Fig. 4. Comparing the traditional HEART and HEART-BWM. HEART, Human Error Assessment and Reduction Technique.

compare the results, and the HEP was calculated using both techniques. Fig. 4 shows the HEP distribution graph of both techniques. There are some differences between HEP derived from the traditional HEART and those calculated by the HEART−BWM. The results showed that in all sub-tasks, the HEPs of the traditional HEART were lower than the HEART−BWM.

An accident in the blasting process in the studied iron ore mine was analyzed. The explosives in one of the holes did not work, and the workers in charge of investigating the absolute blasting of all the holes did not notice this. The error puts the excavator operator in a dangerous position after removing the debris after the blasting. Adaptation of this accident to the HTA of the blasting process showed that the blasting team's negligence in performing the complete and accurate sub-task 6-3-2 caused this accident. The probability of human error obtained for this sub-task using the proposed technique is 9.646E-01. However, among the 57 sub-tasks under consideration, this amount is the first in terms of size. The high probability of this sub-task can be due to various reasons such as high sensitivity of the sub-task, direct exposure of people to explosives, and causing high human and financial losses.

This study aimed to introduce a novel approach to investigate the HEP in the blasting process in the iron ore mine based on HEART-BWM. Concerning the results, the BWM technique, with decreasing the comparison pairs, showed a high sensitivity in calculating the assessed proportion of affect. Reducing the number of comparisons significantly affects the experts' performance, making comparisons more accurate. The greater the number of comparisons, the greater the expert's confusion and the greater the likelihood of error. In addition, the proposed method has advantages like increasing reliability and eliminating the disadvantages of HERAT in APOA calculation. Several studies used the AHP technique to overcome the weaknesses of traditional HEART [20,32]. There are generally two types of comparisons, including basic and supportive comparisons. Basic comparisons compare the best and worst criteria with or against other criteria, and supportive comparisons compare all criteria except the best and worst [34]. The disadvantage of the AHP is its high number of comparisons, and this technique uses both basic and supportive comparisons. Based on Rezaei [34], the BWM technique reduces the number of comparisons and only performs the basic comparisons. The BWM makes the traditional HEART faster and more reliable by performing the basic comparisons.

5. Conclusion

This study presented a new approach to assess HEP by integrating the HEART and BWM techniques. HEART is a robust tool to determine the HEP value systematically, but in calculating the assessed proportion of affect, it has some weaknesses. In the present study, to solve this problem and improve the APOA calculation consistency, the BWM technique was used. To show the model in the blasting process in the iron ore mine was chosen. The proposed approach by determining HEP determines the sub-tasks with the most HEP and helps the safety practitioners to find the solutions. The HEART-BWM can apply in various industries such as maritime, petrochemical, railways, nuclear industries.

Authorship

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Conflicts of interest

The authors confirm that they dont have any conflict of interests.

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