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ORIGINAL ARTICLE

Fuzzy Logic in HEART and CREAM Methods to Assess Human Error and Find an Optimum Method Using a Hierarchical Fuzzy System: A Case Study in a Steel Factory

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ABSTRACT
Numerous studies have been conducted to assess the role of human errors in accidents in different industries. Human reliability analysis (HRA) has drawn a great deal of attention among safety engineers and risk assessment analyzers. Despite all technical advances and the development of processes, damaging and catastrophic accidents still happen in many industries. Human Error Assessment and Reduction Technique (HEART) and Cognitive Reliability and Error Analysis Method (CREAM) methods were compared with the hierarchical fuzzy system in a steel industry to investigate the human error. This study was carried out in a rolling unit of the steel industry, which has four control rooms, three shifts, and a total of 46 technicians and operators. After observing the work process, reviewing the documents, and interviewing each of the operators, the worksheets of each research method were completed. CREAM and HEART methods were defined in the hierarchical fuzzy system and the necessary rules were analyzed. The findings of the study indicated that CREAM was more successful than HEART in showing a better capability to capture task interactions and dependencies as well as logical estimation of the HEP in the plant studied. Given the nature of the tasks in the studied plant and interactions and dependencies among tasks, it seems that CREAM is a better method in comparison with the HEART method to identify errors and calculate the HEP.

KEYWORDS: HEART Method, CREAM Method, Steel Factory

INTRODUCTION
Numerous studies have been conducted to assess the role of human errors in different industrial accidents [1]. Human reliability analysis (HRA) is known as one of the most powerful methods in risk assessment among safety engineers [2]. Despite all technical advances and the development of processes, damaging and catastrophic accidents still happen in many industries [3-4].

Data analyses about HRA have shown that human errors are the main causes of accidents in complicated systems [5]. Among the accidents caused by human errors, Bhopal, Alpha Piper, Three Miles Island, and Chernobyl are some of the most catastrophic ones [3-4]. Analyzing human activity in different industrial processes demands studies including identifying, modeling, and measuring human error probability (HEP) [6-7].

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Therefore, such studies are suggested to follow an interdisciplinary approach including psychology, ergonomics, engineering, mathematics, etc. [8]. There is a wide range of methods enabling engineers and psychologists to work as a team to analyze human error and reliability. Among these methods are expert judgment methods, simulation, classic mathematical assessment, and other methods like error event tree [2]. Human error analysis (HEA) requires reliable data, quality data processing, and an efficient connection between different databases which constitute the major parts of any assessment [5].

A general review of HRA indicates that many methods are based on highly questionable assumptions about human behavior. On the other hand, the outcome of these methods may be accompanied by vagueness and subjectivity. Therefore, there needs a new technique to solve this problem. Fuzzy logic is able to represent vague information in systems that are difficult to define precisely. It can capture the phenomenon of uncertainty associated with information sources. Accordingly, recent studies tend to use the fuzzy approach [11-22-26] to minimize uncertainty related to expert judgment data and information sources in HEA methods like HEART and CREAM. HEART (representing the 1st generation) and CREAM (representing the 2nd generation). So that, these methods were selected to assess human error in a steel company. To capture uncertainties associated with the expert judgment and information source, fuzzy logic was used to improve these methods. However, the aim of the current study was to use fuzzy logic in the HEART and CREAM methods and compare them with each other to find a suitable method for human error detection in the studied industry. The HEART and CREAM were selected due to the familiarity of this steel company's operators with these methods.

This study was organized into the following sections. The relevant literature was reviewed in the introduction section. The HEART, CREAM description, and Fuzzy system development were described in section 2. Thereafter, section 3 provides the results, including the results of HEART and CREAM fuzzy. The outcomes of this study were discussed in Section 4. Finally, Section 5 offers some concluding remarks on the research.

MATERIALS AND METHODS

This study was conducted in 2020 in a steel company located in southwestern Iran. The HEART and CREAM methods were used for data collection in the steel plant. In this factory, more than 1000 employees are working in different production sections. The steps of implementing these two methods are as follows.

Heart description:

The HEART method is a way to assess HRA and functions based on the human performance. It evaluates the interaction between human, assigned tasks, and formation of operation/human factors or Error Producing Condition (EPC). The method is comprised of below steps.

Generic task unreliability:

Classifying the task based on the generic human unreliability into one of the nine generic task types [27].

Error Producing Condition (EPCs):

Identifying error-producing conditions that can have a negative effect on human performance.

Assessed effect ratio:

Estimating the effect of each EPC on the task based on experts' 0 and 1 judgment.

Assessed effect:

Obtaining as follows: (EPC -1) (assessed effect ratio) + 1

HEP calculation:

Calculating overall probability of failure of tasks as follows: (nominal human unreliability × assessed effect 1 × assessed effect 2 … etc. [27]

The HEART method is based on an expert's judgment. Therefore, uncertainties related to information source estimation of EPCs are quite obvious. Hence, unlike the original HEART method in identifying EPCs, the fuzzy rules was used to estimate the Maximum Nominal Predicted Effect Factor (MNPEF)[27]. This will reduce uncertainty and increase the reliability of the output data. Furthermore, 38 EPCs presented in the original HEART were used in the fuzzy system. The EPC value ranged between 0 to 20 in conventional HEART [27]. Given this range, there were three linguistic statements for each EPC including low, moderate, and high. Then, the data related to EPCs was processed by MATLAB software. To avoid increasing the rules due to a large number of inputs, Hierarchical Fuzzy System (HFS) was used to analyze the data so that the output of the previous level was taken as the input of the next level. As a result, 38 EPCs were categorized into the paired groups by experts' judgments. A part of the fuzzification of 38 EPCs has been shown in Figure1. In the end, the final value was calculated based on the 38 EPCs.

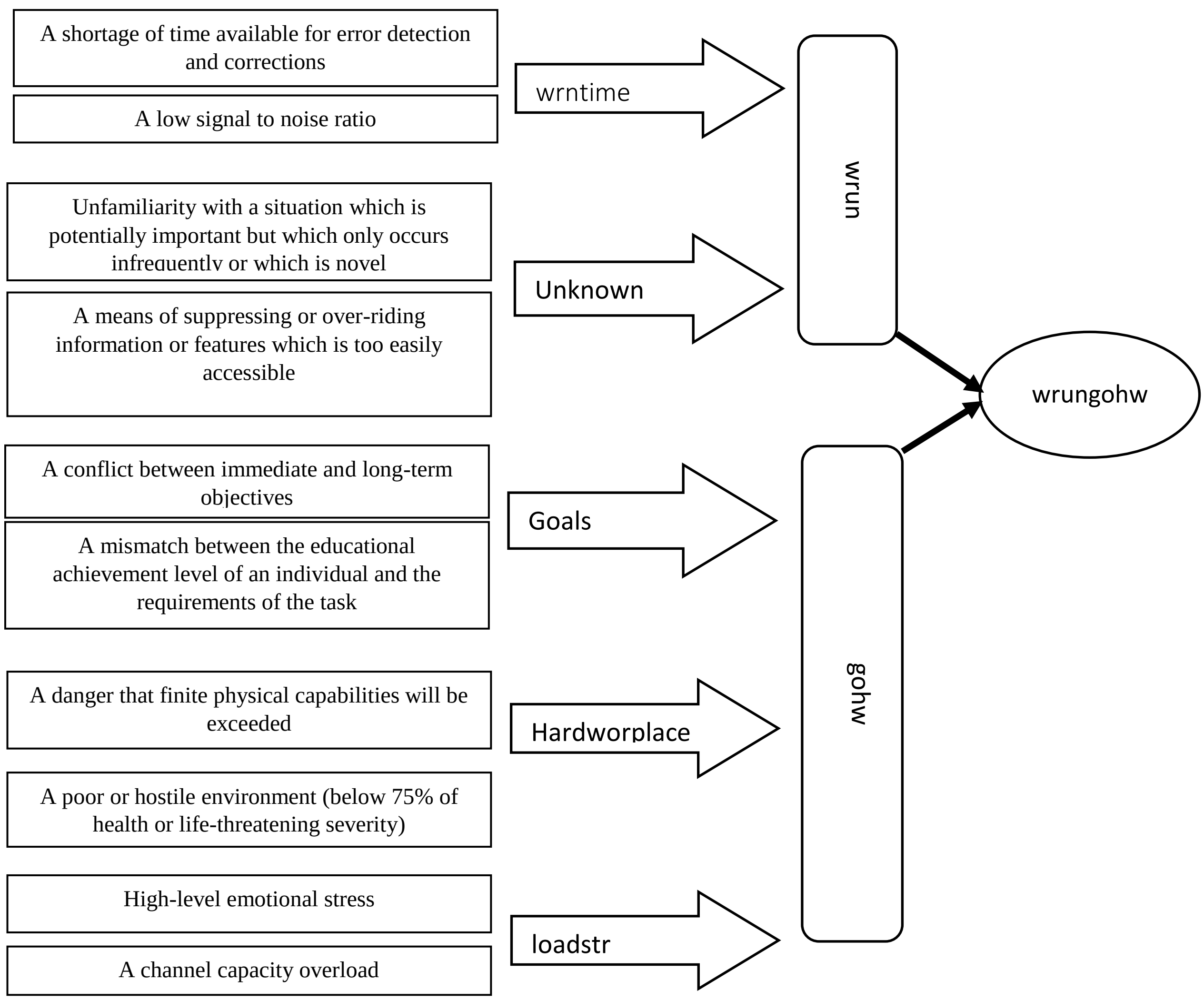

Fig 1. Hierarchical fuzzy system based on HEART method

Cream description:

The context is the main factor for the evaluation of HEP. The relationship between the context and HEP was specifically determined as Contextual Control Model (COCOM) in the CREAM method. Therefore, this method is based on the control degree that operators have over the context. Hence, the degree of control can be determined by the situations in which operators perform their tasks. According to the CREAM method, the degree of control was categorized into four levels.

- ***Scrambled:*** Background control so that operator works with a little attempt.
- ***Opportunistic:*** The operator works based on their habits and experiences without programing or predicting.
- ***Tactical:*** The operator works based on procedures or rules; although, there is no limitation for programing.
- ***Strategic:*** The operator does not have a good performance because of structural condition at workplace [23].

To describe the context impact on the HEP, nine Common Performance Conditions (CPCs) were used. Each one of CPCs has a score range from 0 to 100, which is determined based on the personnel's perception of the size of CPCs effect (see Table 1). Three CPCs were assigned with four affecting modes and six of those were assigned with three affecting modes. The work shift was defined as a three-item range namely morning (70-100), evening (20-80), and night (0-25) [28].

The effect of each CPC was categorized into three classes including improved (with positive effect on reliability), not significant (without effect on reliability), and reduced (adverse effect on reliability) [22]. Considering the level of each CPC (three of the CPCs contain 4 levels and sex of them include 3 levels), the number of fuzzy sets were determined (see Table 2). The algorithm of the fuzzification of the CREAM has been presented in Figure 2.

Table 1. Level of CPCs [28]

No.	CPC	Number of fuzzy set	CPC level	Effect
1	Adequacy of Organization	4 [0-100]	Deficient(0-25)	Reduced
			Inefficient(10-60)	Reduced
			Efficient(40-90)	Not significant
			Very efficient(70-100)	Improved
2	Working conditions	3 [0-100]	Incompatible(0-25)	Reduced
			Compatible(20-80)	Not significant
			Advantageous(70-100)	Improved
3	Adequacy of man machine interface (MMI) and operational Support	4 [0-100]	Inappropriate(0-25)	Reduced
			Tolerable(10-60)	Not significant
			Adequate(40-90)	Not significant
			Supportive(70-100)	Improved
4	Availability of procedures/plans	3 [0-100]	Inappropriate(0-25)	Reduced
			Acceptable(20-80)	Not significant
			Appropriate(70-100)	Improved
5	Number of simultaneous goals	3 [0-100]	More than actual capacity(0-25)	Reduced
			Matching current capacity(20-80)	Not significant
			Fewer than actual capacity(70-100)	Not significant
6	Available time	3 [0-100]	Continuously inadequate(0-25)	Reduced
			Temporarily inadequate(20-80)	Not significant
			Adequate(70-100)	Improved
7	Time of the day/circadian rhythm	3 [0-100]	(Night(unadjusted(0-25)	Reduced
			(Day (adjusted(20-80)	Not significant
			evening (unadjusted)(70-100)	Reduced
8	Adequacy of training and experience	3 [0-100]	Inadequate(0-25)	Reduced
			Adequate with limited experience(20-80)	Not significant
			Adequate with high(70-100) experience	Reduced
9	Crew collaboration Quality	4 [0-100]	Deficient(0-25)	Improved
			Inefficient(10-60)	Not significant
			Efficient(40-90)	Not significant
			Very efficient(70-100)	Improved

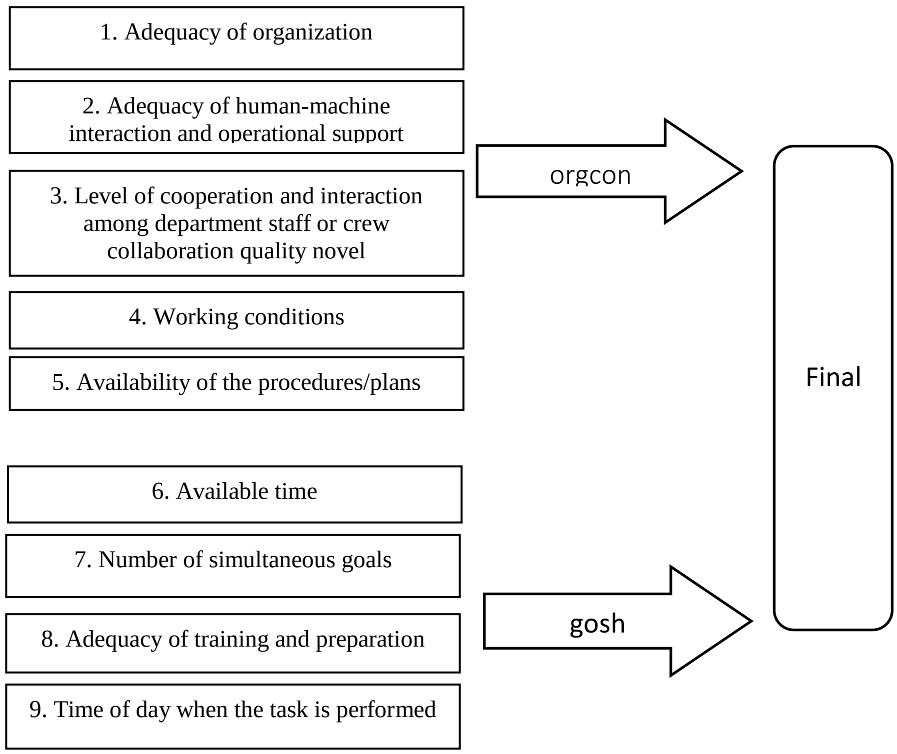

Fig 2. Hierarchical fuzzy system based on CREAM

Fuzzy system development:

Fuzzy theory is one of the methods to compensate probability [29]. This method is a set of linguistic statements like low, moderate, and high with specific ranges that cover complicated and ambiguous situations or knowledge and experiences that are realized quantitatively [30]. One of the first methods of fuzzy inferences is Mamdani's fuzzy inference method [31], which was used for developing control systems.

A membership function between 0 and 1 was defined for different elements in a fuzzy method ((MF) ≅ μ_A(x)), where (X) = 0 μ_A means that X is not part of the set and (X) = 1 μ_A means that X is a part of the set so that any X between 0 and 1 is a fuzzy expression. The applicable shapes for MF are bell form, trapezoid, sigmoidal, S shape, Z shape, or triangular. Currently, a triangular form is the best option [32].

Mamdani's fuzzy inference method was used in the current study, where the inputs were defined as linguistic statements that yield the input and output effects [31]. Given a large number of inputs, the number of rules was expected to be high so that some of the rules were not covered or the condition to define rules became more complicated. It means a hole in the rules' definition. In order to provide better control over inputs, HFS was used in this study. HFS, compared to an integrated fuzzy system prevents excessive growth in the number of rules so that every input was assumed as a layer, and the output of the previous layer produces the input of the next layer. The most important advantage of this system is less rules are assumed compared to the integrated system [33-35]. Indeed, the system has a layered structure, including several separate fuzzy inference systems. Thus, the output of each system was the input of the higher layer [36].

RESULTS

The present study was aimed to compare two human error methods which have been used in this steel plant to analyze human error. For this purpose, the casting ward section was selected with a total of 4 control rooms, 3 shifts, and 46 technicians and operators. After observing the work process, reviewing the documents, and interviewing each operator, the worksheets of each research method were completed. Then, the data related to each method were analyzed using HFS in the MATLAB software environment. The results of each method were separately presented as follows.

The results of heart:

As it was previously mentioned, to reduce uncertainty in estimating EPCs in the HAERT method, the linguistic statements was used to solve this problem. Hence, each EPC in the HEART method was defined with a specific membership function. For example, the membership function of EPC2 and EPC3 has been presented in Figure 3a and Figure 3b, respectively. As illustrated in Figure 3a,b the degree of membership EPC2 from 8 to 10 was low, 9.75 to 12.5 was regarded as medium and 11.5 to 14 was high. The membership function of the remaining EPCs was presented in Table 2. An example of these rules is provided in Table 3.

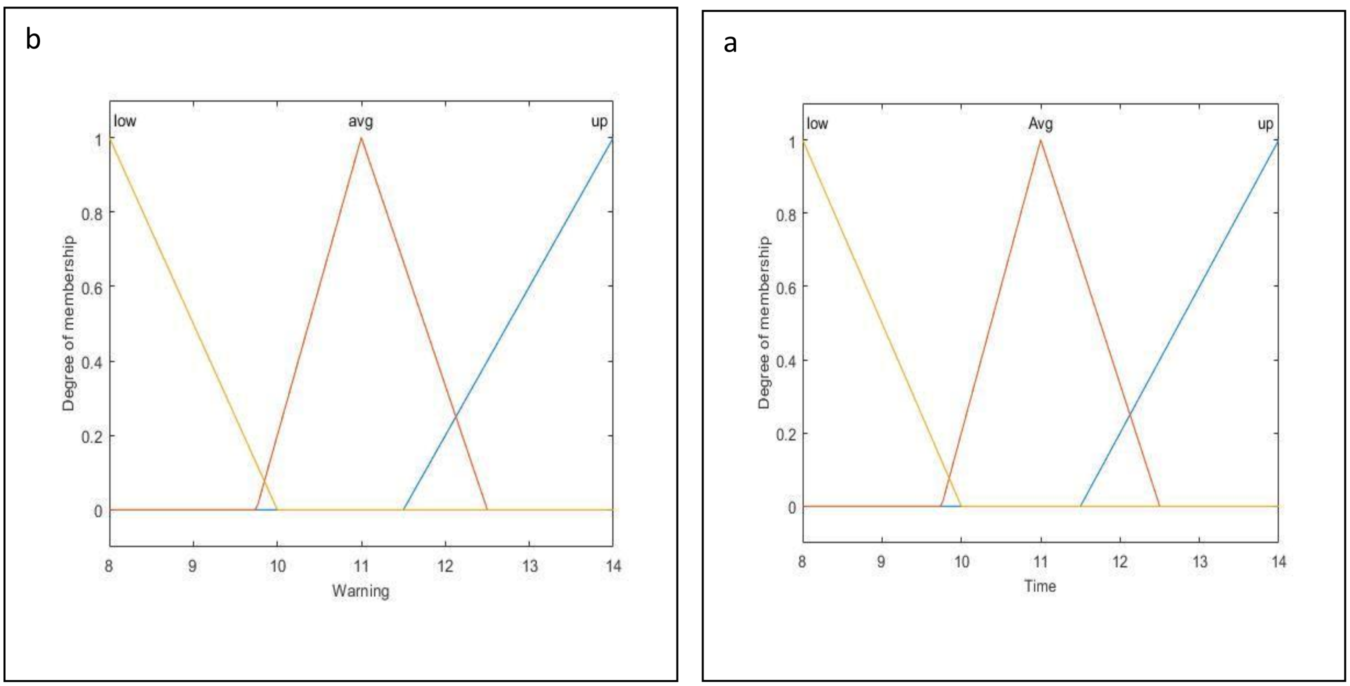

Fig 3. a,b. HEART inputs membership diagram

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Table 2. Degree of membership of EPCs

EPC	Maximum Nominal Predicted Effect Factor	Degree of Membership
1	15 – 20	L: 15-17.5; M:16.75-18.5; H:18.25-20
2	8 – 14	L: 8-10; M:9.75-12.5; H:11.5-14
3	8 – 14	L: 8-10; M:9.75-12.5; H:11.5-14
4	8 – 14	L: 8-10; M:9.75-12.5; H:11.5-14
5	6 – 10	L: 6-7.75; M:7.5-9; H:8.75-10
6	6 – 10	L: 6-7.75; M:7.5-9; H:8.75-10
7	6 – 10	L: 6-7.75; M:7.5-9; H:8.75-10
8	4 – 9	L: 4-6; M:5.75-8; H:7.5-9
9	4 – 8	L: 4-5; M:4.75-6; H:5.75-8
10	2 – 7	L: 2-4; M:3.75-5.5; H:5.25-7
11	3 – 8	L: 3-5; M:4.5-6.75; H:6.5-8
12	2 – 6	L: 2-4; M:3.5-4.5; H:4.75-6
13	2 – 6	L: 2-4; M:3.5-4.5; H:4.75-6
14	2 – 6	L: 2-4; M:3.5-4.5; H:4.75-6
15	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
16	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
17	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
18	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
19	0 – 5	L: 0-2.5, M:2.25-4; H:3.75-5
20	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
21	0 – 5	L: 0-2.5, M:2.25-4; H:3.75-5
22	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
23	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
24	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
25	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
26	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
27	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
28	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
29	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
30	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
31	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
32	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
33	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
34	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
35	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
36	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
37	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5
38	0 – 5	L: 0-2.5; M:2.25-4; H:3.75-5

Table 3. The fuzzy rules for EPC2 and EPC3

```
fis1=newfis('Time_War');
%input1:Time
fis1=addvar(fis1,'input','Time',[8 14]);
fis1=addmf(fis1,'input',1,'up','trimf',[11.5 14 14]);
fis1=addmf(fis1,'input',1,'Avg','trimf',[9.75 11 12.5]);
fis1=addmf(fis1,'input',1,'low','trimf',[8 8 10]);

%input2:Warning
fis1=addvar(fis1,'input','Warning',[8 14]);
fis1=addmf(fis1,'input',2,'up','trimf',[11.5 14 14]);
fis1=addmf(fis1,'input',2,'avg','trimf',[9.75 11 12.5]);
fis1=addmf(fis1,'input',2,'low','trimf',[8 8 10]);

%Output in first level:wrntime1
fis1=addvar(fis1,'output','wrntime1',[0 20]);
fis1=addmf(fis1,'output',1,'up','trimf',[13 20 20]);
fis1=addmf(fis1,'output',1,'Medium','trimf',[6 10 14.5]);
fis1=addmf(fis1,'output',1,'low','trimf',[0 0 8]);


%Add Rules in level 1
RuleList1=[1 3 2 1 1;
1 2 2 1 1;
1 1 1 1 1;
0 3 3 1 1;
0 2 2 1 1;
0 1 1 1 1;
2 1 2 1 1;
2 2 2 1 1;
2 3 3 1 1;
3 1 2 1 1;
3 2 3 1 1;
3 3 3 1 1;
1 0 1 1 1;
2 0 2 1 1;
3 0 3 1 1];

fis1=addrule(fis1,RuleList1);
Input1=xlsread('wrntime1.xlsx');
figure(1)
gensurf(fis1)
fiswrntime1=evalfis(Input1,fis1);
```

The results of the evaluation of the fuzzy rules were defined in Table 3. Figure 4 shows that if error detection and corrections time availability was short and if the signal to noise ratio was low (warning), the probability of human error (wrntime1) would be increased. Therefore, Figure 4 shows that the defined rules were correct.

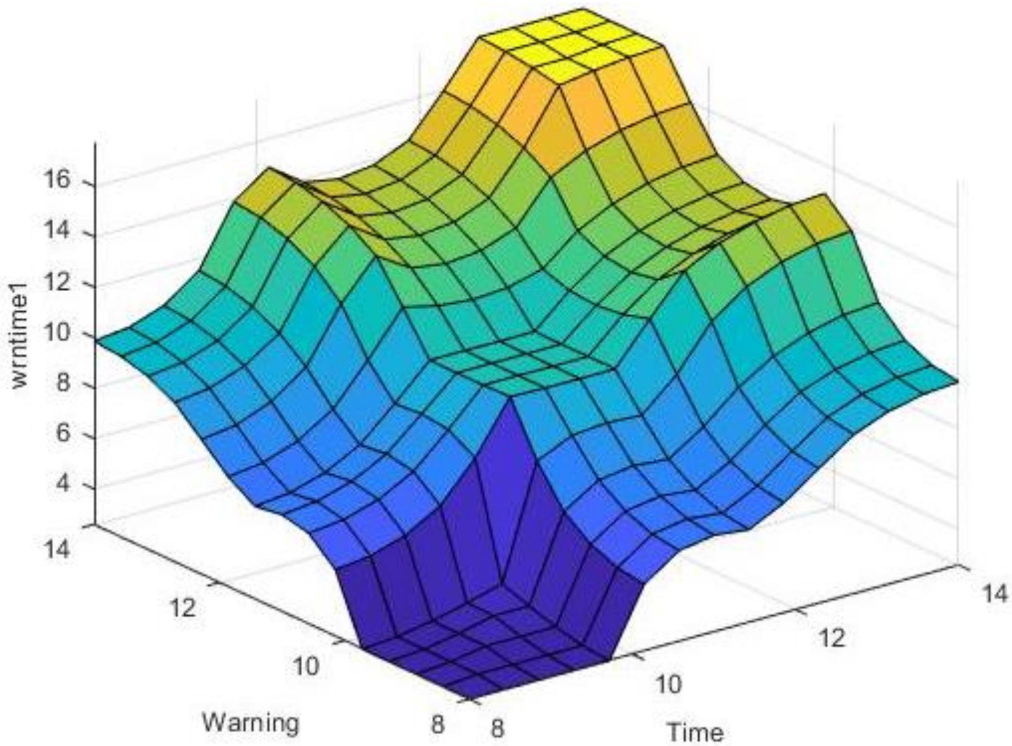


Fig 4. HEART fuzzy rules diagram

Finally, the results of human error computation in the HEART method based on the HFS approach for some tasks which were more critical have been presented in Table 4.

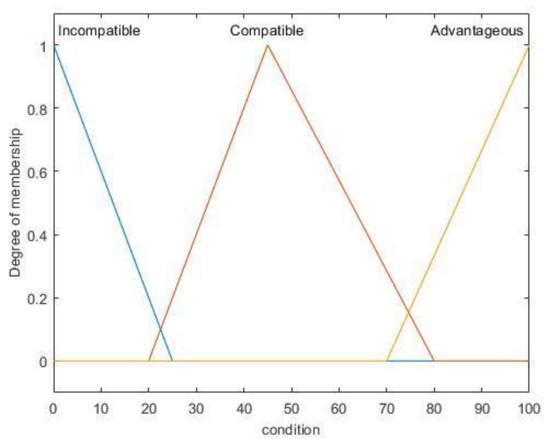
Table 4. Human error probability based on HFS in the HEART method

Percent of participant	Generic Task Unreliability*	Multiplier*	Assessed Proportion of Effect†	Assessed Effect	HEP
82.6%	0.16	10	0.4	3.6	0.57
4.4%	0.16	9	0.4	3.2	0.51
11%	0.16	8	0.4	2.8	0.45
2%	0.16	7	0.4	2.4	0.38

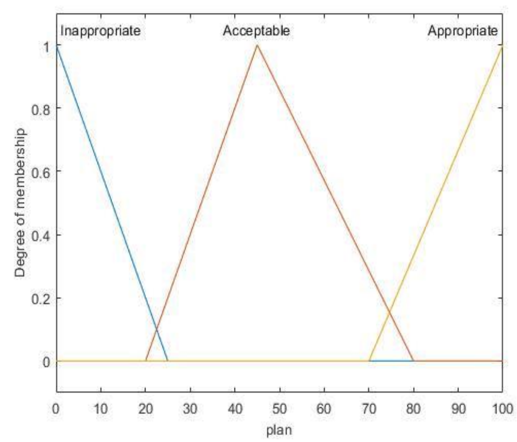
As showed in Table 4, the multiplier for 82.6% of the participants was equal to 10, for 4.4% of the participants was equal to 9, for 11% of the participant was equal to 8, and for 2% of the participants was equal to 7. The last column of Table 5 also provides the HEP value for each task.

The results of cream:

Based on the CREAM method, the membership function for each one of the CPCs was defined in a specific range, and then the rules were defined (Table 1). For instance, the inputs membership diagram of work condition and availability of plans has been illustrated in Figure 5a. and Figure 5b, respectively. As illustrated in Figure 5 a,b, the degree of membership work condition from 0 to 25 was incompatible, 20 to 80 compatible, and 70 to 100 advantageous. The membership function of the remaining CPCs has been presented in Table 2. Subsequently, fuzzy rules for nine CPCs were defined using Figure 2.



b



a

Fig 5. a,b. Membership diagram for each CREAM input

The results of the evaluation of the fuzzy rules have been presented in Figure 6. As it was shown in Figure 6, if work condition was incompatible (0-25) and the availability of plans was inappropriate (0-25), the probability of human error (condition1) would be increased. Therefore, Figure 6 shows that the rules defined were correct.

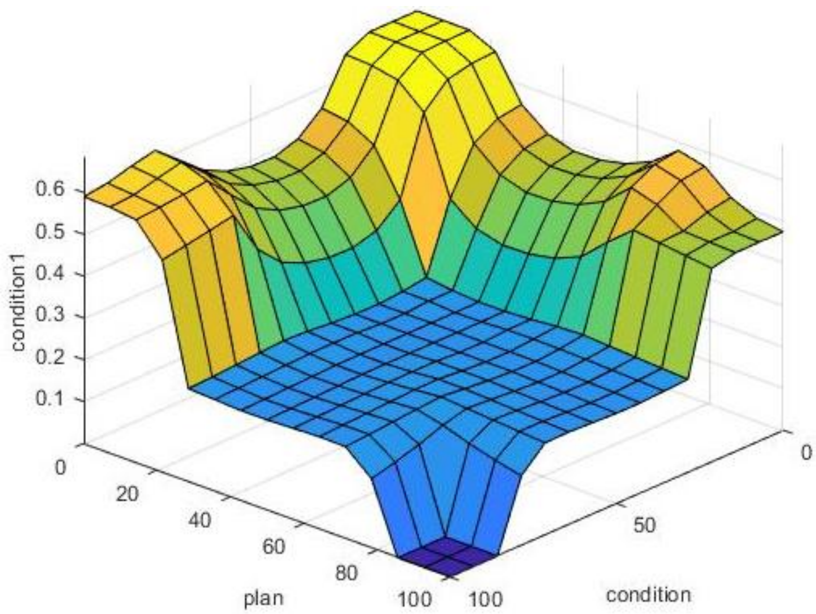


Fig 6. CREAM fuzzy rule diagram

Finally, the results of human error computation in the CREAM method based on the HFS approach for critical tasks showed that the control style of operators for the mentioned tasks was determined by opportunistic (100%) while the results of calculating control style based on the conventional CREAM indicated that tactical (13%), opportunistic (85%) and scrambled (2%) were effective.

The HEP obtained by the fuzzy HEART and fuzzy CREAM have been presented in Table 5.

Table 5. The HEP for fuzzy HEART and fuzzy CREAM

Fuzzy HEART		Fuzzy CREAM	
Percent of participant	HEP	Percent of participant	HEP
82.6	0.57	89	0.22
4.4	0.51	7	0.23
11	0.45	4	0.45
2	0.38		

DISCUSSION

The current study provided a comparison between the HEART and CREAM to find an optimum method using HFS in order to identify the human errors in a steel factory. According to Figure 1, the highest value of EPCs in the first layer of the HF- HEART was related to inputs of workload, stress, alarm buzz, and time needed to respond with MNPEF higher than 10. In addition, the values of inputs of exposure to unknown situations and unfamiliarity with potential situations were below 10 for most of the operators. Therefore, these inputs were entered in the second layer. Accordingly, the mean of the HEP calculation based on these assumptions (see Table 4) in the HF-HEART method revealed that the probability of error among operators of casting line was almost 0.48.

The results of fuzzy system analysis using CREAM method indicated that work shift, education, available time, and work condition had more effect on human error. The mean of HEP calculation using HF-CREAM was estimated around 0.30 for the Casting line.

The results obtained by two methods indicated that an improvement in work condition, giving more time to do the task, and choosing the suitable person for each work shift were the available options to prevent errors.

Given that the nature of the tasks, interactions, and dependencies in the studied plant, it seems that the CREAM was a better method in comparison with the HEART method for identification of errors and calculation of the HEP. It is due to HEART analyzing approach in which tasks are analyzed in isolation without consideration of task interaction and dependencies. These findings were in line with those of the study of Kumer et al. [20]. Furthermore, the empirical justification of the HEART error rate multiplier factors required validation which was subjective and depends significantly on the expertise of individuals. Finally, the results of Table 8 showed that the calculation of the HEP using the CREAM compared to the HEART was more logical and accommodates the conditions of the plant. On the other hand, the investigation of documents related to human error in the studied plant showed that the probability of human error considering existing conditions in the plant was much more consistent with the HEP values calculated by the CREAM method.

Limitations of the study:

In the current, only one unit's data was collected. It would be interesting for scholars to consider other sectors as well as industries to provide a broader view about these methods.

CONCLUSION

The current study provided a comparison between HEART and CREAM to find an optimum method using HFS in order to identify the human errors in a steel factory. The fuzzy logic concepts were applied in the conventional HEART and CREAM technique by considering abstract linguistic to calculate quantitative error probability. The findings of this study indicated that the CREAM compared to the HEART was more successful in capturing task interaction, dependencies, and logical estimation of the HEP at the studied plant.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest in this study.

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