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Implementation of Heart and Dematel Integration to Steam Boiler Working Process

Gulin Feryal Can[1]* and Elif Kilic Delice[2]

[1]Department of Industrial Engineering, Başkent University, Turkey

[2]Department of Industrial Engineering, Atatürk University, Turkey

***Corresponding author:** Gülin Feryal Can, Department of Industrial Engineering, Başkent University, Ankara, Turkey, Email: gfcan@baskent.edu.tr

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Abstract

Human Error Assessment and Reduction Technique (HEART) is a practical and powerful approach to prioritize errors related to human actions, based on probabilities. HEART can determine error producing conditions (EPCs) which cause human errors for different processes including main duties (MDs) and sub-duties (SDs). HEART can be applied quickly for any process where human reliability is important. In this study, HEART and advanced version of Decision Making Trial and Evaluation Laboratory (AV-DEMATEL) integration proposed by Can and Delice in 2018 was performed for evaluating human related errors in steam boiler working process. In this way, the interactions between MDs, SDs and EPCs in a steam boiler working process were considered to compute process error probability (PEP). Additionally, the applicability of the proposed approach by Can and Delice (2018) was demonstrated again.

Keywords: Heart; MCDM; Dematel; Error Assessment

Abbreviations: HEART: Human Error Assessment and Reduction Technique; MDs: Main Duties; EPCs: Error Producing Conditions; SDs: Sub-Duties; AV-DEMATEL: Advanced Version of Decision Making Trial and Evaluation Laboratory; PEP: Process Error Probability; HREs: Human Related Errors; HEP: Human Error Probability; MCDM: Multi-Criteria Decision Making; FTA: Fault Tree Analysis; CREAM: Cognitive Reliability and Error Analysis Method; AHP: Analytic Hierarchy Process; RARA: Railway Action Reliability Assessment; FANP: Fuzzy Analytic Network Process; GEP: Generic Error Probability.

Introduction

Human error is probably the most well-known and widely publicized of all human factors concepts. Human related errors (HREs) cause serious workplace injuries. Worker loss is immeasurable as it is known that a serious workplace injury can cause major damage. Major crisis can occur for the workers and their families and these crises can even lead to serious financial burdens. In this context, it has a vital place to determine HREs previously and to prevent workers and work places from these errors. The Human Error Assessment and Reduction Technique (HEART) first advanced by Williams in 1988 is one of the effective approach that frequently used for prioritizing and evaluating HREs [1].

HEART can determine the error-producing conditions (EPCs) that cause human errors for different operations. HEART has been successfully extended to a wide range of industries such as railway transportation, aviation, health services and nuclear energy in recent years [2]. The HEART assumes that the probability of human error occurrence may be revised based on the presence and strength of EPCs related to the process [3]. At the design phase, it can prevent potential human errors or reduce the effects of these errors with additional controls. HEART determines the possibility of nominal human unreliability to identify the most important human errors to be avoided. It can be performed quickly for any process to ensure human reliability. However, HEART has many deficiencies related to real-life applications [4]. The first problem is its mathematical procedure. In traditional HEART, by using this procedure, different decision makers (DMs)' assessments cannot be aggregated. Generally, error assessment applications are performed by a team including more than one DM and aggregation of different opinions is important for the final result. Secondly, traditional HEART cannot model effect relationships between the duties that make up a process. Additionally, any process include main duties (MDs) and sub-duties (SDs) so, there may be different EPCs that effect each MD and SD for each DM's view point. This brings with complex effect relations which occur between MDs, SDs and EPCs. At this point, HEART cannot model these complex relations. The fourth problem is related to GTTs. Any MD can be included in different GTTs for different DMs. Traditional version cannot reflect these differentiations. The final problem is only considering weights of EPCs in reliability assessment for a process. However, different errors may occur in any of MDs and SDs and these errors can affect process productivity in a negative manner. For this reason, the weights of MDs and SDs should be computed separately. In addition, weights of SDs are dependent on weights of MDs and these dependencies should be considered in process error probability computation.

To overcome the shortcomings of traditional HEART debated above and to suggest solutions for the related shortcomings, an advanced HEART approach proposed by Can [5] and Delice [6] was performed in this study. In the context of the advanced HEART approach carried out Can [5] and Delice [6], the Decision Making Trial and Evaluation Laboratory (DEMATEL) was implemented in an integrated manner to assess human error probability (HEP). In this way, effective usage of HEART could be improved for real life applications by implementing Multi-criteria Decision Making (MCDM) structure. In this study, the reason to implement Can [5] and Delice [6] approach for human related errors in steam boiler working process is, to show interactions between MDs, SDs and EPCs via structuring integrated effect matrix. Second is, to compute importance weights of MDs, SDs and EPCs with the support of integrated effect matrix. Third is, to classify each SD in more than one GTT for assessing HREs in a detailed manner. Fourth is, to determine the most dangerous EPC more accurately. Fifth is, to compute HEP in an integrated and more accurate way. Sixth is, to consider all different opinions of DMs related to GTTs and EPCs when making decision for the EPCs that should be prevented firstly. For these purposes, HEART and DEMATEL integration proposed by Can [5] and Delice [6] was preferred to use especially for modelling interactions between MDs, SDs and EPCs. The DEMATEL advanced by Fontela and Gabus [7], has long been used to determine the cause and effect relations between components of a system. These cause and effect relations between components form interactive relationships. DEMATEL can convert the interrelations between components into an intelligible structural model of the system to form an accurate decision [8].

Additionally, different from the other DEMATEL implementations, in Can [5] and Delice [6] approach, all components of the decision system were considered. The decision system covers all MDs, SDs and EPCs as components. This means that all MDs, SDs and EPCs take place in integrated effect matrix which is a new term for DEMATEL. In this way, all interactions between them can be evaluated. The decision shows which EPC should be prevented firstly and which SD(s), MD(s) should be improved primarily. In real error assessment cases, each SD in the same MD or each SD included in different MDs can affect each other. In terms of HEART, each EPC may occur in any of GTTs, MDs and SDs. According to GTTs, EPCs may change so these complex interactions should be considered in error assessments.

The proposed approach in the Can [5] and Delice [6] study was utilized for a steam boiler working process. A steam boiler is a device used to create steam by applying heat energy to water. Steam boiler can be used for different purposes such as generating power in steam engines or steam turbines, in process industries for various processes, for heating the buildings in cold weather and for producing hot water for hot water supply. For steam boiler working process, human errors have a vital role in terms of work health and safety. Industrial boilers are a potential bomb and they explode when they are not operated according to the rules. If the errors can determine previously, boiler explosions can always be prevented. The person who runs the boiler system to produce steam is called the boiler operator. Industrial boiler systems are operated at high pressure and temperature levels. For this reason, boiler operators have high risk level for burns and explosions. Thus, boiler operators must follow all safety measures for worker health and work safety.

The rest of the paper was organized as follows. Literature review related to HEART was given in the second section. Third section includes traditional HEART and the HEART and DEMATEL integration advanced by Can [5] and Delice [6]. Results were given in the fourth section and general comments and future research opinions are given in the fifth section.

Scientific Literature Review

Human error categories and weighting of EPCs are the important research issues for HEART related studies. These studies were debated below briefly.

Casamirra, et al. [9] and Castiglia and Giardina [10] determined the HEP for irradiation plants by combining fault tree analysis (FTA), fuzzy set theory and HEART. Castiglia, et al. [11] determined risk level for various accident scenarios by fuzzy FTA and HEART integration to consider the uncertainties for EPCs. Chadwick and Fallon [12] proposed a modified HEART for healthcare and Graphic Rating Scale was used to determine the weight for each EPC. Castiglia and Giardina [13] implemented Fuzzy HEART to determine operators' errors in hydrogen refueling stations and results of this method have been compared with the results of the Cognitive Reliability and Error Analysis Method (CREAM). Castiglia, et al. [3] suggested an approach with using the fuzzy HEART to compute the probability of medical personnel error. THERP is also used to determine the fuzzy interval of the error probabilities in the event-tree. Akyüz and Çelik [14] combined HEART and AHP method to calculate effect of EPCs. Akyüz, Çelik and Çebi [15] determined marine specific EPC values using Majority Rule, HEART, Human Factors Analysis and Classification System, Analytic Hierarchy Process (AHP), and validation techniques. Akyüz and Çelik [16] proposed an extended HEART with interval type-2 fuzzy sets to overcome the uncertainty of experts' judgments for the cargo operations. Islam, Islam, Abbassi, Garaniya and Khan [17], revised the conventional HEART to estimate the HEP for the maintenance procedures in marine operations. Kumar, Rajakarunakaran and Prabh [18] used the Fuzzy HEART and expert elicitation together for quantification of HEP with an application related to refueling operation. Wang, et al. [4] proposed a modified HEART based on Railway Action Reliability Assessment (RARA) Technique and Fuzzy Analytic Network Process (FANP) to assess HEP in high-speed railway dispatching tasks. Akyüz, et al. [19] presented a systematic HEP during bunkering operation at chemical tanker ship using the Shipboard Operation Human Reliability Analysis. Giardina, et al. [20] presented an integrated approach based on Hierarchical Task Analysis and three human error quantification methods as HEART, Standardized Plant Analysis Risk Human Reliability Analysis and the CREAM method integration. Proposed approach was implemented for an innovative plant as an advanced nuclear physic application. Sheikhalishahi, et al. [21] suggested an open shop scheduling model to take into account human error and preventive maintenance. Can [5] and Delice [6] first proposed integrated effect matrix for DEMATEL to advance HEART for steam boiler working process. Can and Delice [22] suggested HEART and advanced version of DEMATEL (AV-DEMATEL) integration to evaluate machine related errors and human related errors in a steam boiler working process. They also advanced a new aggregating operator to compute PEP.

As mentioned by Wang, et al. [4] not considering the dependent relationships between EPCs is an important deficiency in these studies. In this study, AV-DEMATEL based HEART approach was implemented to evaluate human related errors in a steam boiler working process effectively. In this manner, it is provided to model interrelations between MDs, SDs and EPCs. An integrated structure to form effect matrix was used as in Can [5] and Delice [6] study and the importance weight of each SD and EPC were computed with the support of this integrated approach. All DMs' different opinions related to GTTs and EPCs are taken into consideration as opposed to the traditional HEART and the studies related to HEART in the literature. The proposed approach is flexible to classify SDs based on GTTs.

There are no studies that integrate HEART and AV-DEMATEL to consider complex effect relations in different segments of decision hierarchy except Can [5] and Delice [6]. For these reasons, Can [5] and Delice [6] study and this study can contribute to the human error assessment applications to perform risk analysis in a detailed and accurate manner? The differences of this study from Can [5] and Delice [6] study are to only consider human related errors, to consider different DMS' evaluations for the steam boiler working process.

Method

This paper performs an advanced HEART by incorporating HEART and AV-DEMATEL suggested by Can [5] and Delice [6]. Therefore, the following sub-section only introduces the HEART methodology because DEMATEL is a frequently used method [7]. Also, in this study, research and publication ethics were considered.

Human Error Assessment and Reduction Technique (HEART)

The HEART includes two fundamental parameters as the Generic Error Probability (GEP) and EPCs. The GEP provides a probability which is carried out by DM for a selected GTT. HEART proposes nominal human unreliability values according to nine GTTs [23].

The EPCs can be any internal or external condition such as operator experience level, noise level, stress, age, appropriate time for duty, and time of day or organization quality which adversely affects human performance. While GTT enables the user to find the appropriate task in the process, EPC gives the performance that shapes the human factors that affect HEP for the respective task. Thus, any of EPCs may increase the HEP value in conjunction with GTT. HEART considers the list of 40 EPCs and HEART assumes that any predicted reliability of a task performance may be modified according to the presence of the identified EPCs [23]. The error rate in HEART is estimated by using Eq.(1) and Eq.(2).

$$HEP_{i_j} = \prod_{b=1}^{40}(((EF_b - 1) \times w_b) + 1) \quad (1)$$

$$GHEP_{i_j} = HEP_{i_j} \times NHU_Z \quad (2)$$

Where;
HEP_{i_j} is the HEP of *jth* SD in *ith* MD,
EF_b is the effect of *bth* EPC on any SD,
w_b is the importance weight of *bth* EPC,
$GHEP_{i_j}$ is the general HEP of *jth* SD in *ith* MD,
NHU_z is the nominal human unreliability for *zth* GTT.
NHU_z can change according to the selected GTT.

The Performed Approach and its Application

The steps of the AV-DEMATEL based HEART approach are given below with the support of the application related to steam boiler working process. A steam boiler is operated by using oil, coal or gas. It includes water and a heat source to turn the water into steam. This steam moves in a pipe to provide power for equipment, heat or cleaning.

Step 1: Determine MDs, SDs and DMs
MDs defined as MD_i; $i = 1, \ldots v, \ldots, n$ are the stages of the process and SDs indicated as SD_{i_j} $i = 1, \ldots v, \ldots n; j = 1, \ldots, u, \ldots m$ form MDs. SDs are the sub stages of MDs and they form the smallest parts of work flow named as process. *k* DMs denoted as DM_k; $k = 1, \ldots, t$ compose DM group. These are the experts who can define and evaluate the HREs in the process.

In steam boiler working process, three DMs DM_k; $k = 1,2,3$ form the DM group. While two of the DMs are mechanical engineers, one is an electrical engineer. In addition, DMs work as A and B class occupational health and safety experts. These DMs divided the work flow related to daily control tasks that must be performed before steam boiler works into 5 MDs, MD_i; $i = 1, \ldots, 5$. Each MD includes different numbers of SDs. First MD (MD_1) has one SD as . Second MD (MD_2) has two SDs as SD_{2_1}, SD_{2_2}. Third MD (MD_3) has four SDs as $SD_{3_1}, SD_{3_2}, SD_{3_3}, SD_{3_4}$. Fourth MD ($MD_4$) has five SDs as $SD_{4_1}, SD_{4_2}, SD_{4_3}, SD_{4_4}$. Fifth MD ($MD_5$) has three SDs as $SD_{5_1}, SD_{5_2}, SD_{5_3}$. The part of these MDs and SDs are given in Table 1.

MDs MT_i; $i = 1, \ldots, 5$	**Definition**	**SDs** SD_{i_j}; $j = 1, \ldots, m$	**Definition**
MD_1	Control Steam boiler water level indicator	SD_{1_1}	See if boiler water level is within desired range
MD_2	Control of Steam lines	SD_{2_1}	See that the Steam outlet valve on the boiler is open
		SD_{2_2}	See if the inlet and outlet valves in the vapor collector are open
⋮	⋮	⋮	⋮
MD_5	Security and warning system control	SD_{5_1}	Check whether the safety valves are easily opened or closed
		SD_{5_2}	Adjust safety ventilator settings to a pressure value above 10%
		SD_{5_a}	Check that the boiler presostalt settings are correct

Table 1: MDs and SDs in Steam Boiler Working Process.

Step 2: Determine the GTTs and EPCs for each SD

Each DM determines the GTTs GTT_z; z = 1, ..., 9 and EPCs EPC_b; b = 1, ...,40 as in HEART for each SD. GTT_1 presents A type GTT as an example. All different opinions of DMs for GTTs and EPCs related to each SD are considered and brought together. In Table 2, GTTs and EPCs related to SDs for DM_1 are given as an example.

MDs	SDs	GTTs	Definition	EPCs
MD_i	SD_{i_j}	GTT_z		EPC_b
MD_1	SD_{1_1}	GTT_5	E type	EPC_2, EPC_{15}
MD_2	SD_{2_1}	GTT_5	E type	EPC_2, EPC_{15}
	SD_{2_2}	GTT_5	E type	$EPC_{36}, EPC_{38}, EPC_{40}$
MD_3	SD_{3_1}	GTT_5, GTT_6	E and F types	$EPC_2, EPC_{15}, EPC_{37}$
	SD_{3_2}	GTT_5, GTT_6	E and F types	$EPC_{30}, EPC_{31}, EPC_{34}, EPC_{39}$
	SD_{3_3}	GTT_5, GTT_6	E and F types	$EPC_2, EPC_3, EPC_{15}, EPC_{37}$
	SD_{3_4}	GTT_5	E type	$EPC_{30}, EPC_{31}, EPC_{34}, EPC_{39}$
MD_4	SD_{4_1}	GTT_5, GTT_6	E and F types	$EPC_2, EPC_{15}, EPC_{37}$
	SD_{4_2}	GTT_5	E type	EPC_2, EPC_{15}
	SD_{4_3}	GTT_5	E type	$EPC_2, EPC_3, EPC_4, EPC_{15}, EPC_{37}$
	SD_{4_4}	GTT_8	H type	$EPC_2, EPC_{15}, EPC_{37}$
MD_5	SD_{5_1}	GTT_5	E type	EPC_2, EPC_4, EPC_6
	SD_{5_2}	GTT_6	F type	EPC_2, EPC_4
	SD_{5_3}	GTT_6	F type	$EPC_2, EPC_3, EPC_4, EPC_{15}$

Table 2: GTTs and EPCs related to SDs for DM_1.

Step 3: Form integrated effect matrix for each DM

Integrated effect matrix for each DM is formed by using effect scale as "0 (no effect), 1 (low effect), 2 (medium effect), 3 (high effect), 4 (very high effect) [7]. Matrix components affect each other mutually. Effect matrix for DM_1 is given in Table 3 as an example.

Step 4: Combine integrated effect matrix of all DMs

Integrated effect matrices of all DMs are combined by using arithmetic mean and combined integrated effect matrix is given in Table 4 for the steam boiler working process to show average effect values is formed.

Step 5: Form the normalized effect matrix

Normalized Effect Matrix is structured via computing the maximum values of rows and maximum values of columns in combined integrated effect matrix. These values shown in Table 4 are summed. Then, the minimum value named as "*k*" among summation of rows' maximum values denoted as s_r; $r = 1, \ldots, n+m+40$ and summation of columns'' maximum values s_c; $c = n+m+40$ are determined as in Eq.(3). Finally *k* is multiplied with combined integrated effect matrix to form Normalized Effect Matrix seen in Table 5 as in Eq.(4).

$$k = Min(\frac{1}{\max s_r}, \frac{1}{\max s_c}) \quad (3)$$

$$[N] = k \times [E] \quad (4)$$

Step 6: Form the total effect relation matrix

Total Effect Relation Matrix [*T*] given in Table 6 for steam boiler working process is formed as in Eq.(5).

$$T = N + N^2 + N^3 + \ldots = \sum_{f=1}^{\infty} N^f$$

$$T = N(I-N)^{-1} \quad (5)$$

Where;

[*I*] is the unit matrix.

	MT_1	MT_2	...	MT_5	SD_{1_1}	SD_{2_1}	SD_{2_2}	...	SD_{5_1}	SD_{5_2}	SD_{5_3}	EPC_2	...	EPC_{39}	EPC_{40}
MD_1	0.00	1.00	...	1.00	0.00	1.00	1.00	...	1.00	2.00	3.00	2.00	...	2.00	1.00
MD_2	1.00	0.00	...	3.00	2.00	0.00	0.00	...	4.00	2.00	4.00	2.00	...	1.00	1.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MD_5	4.00	2.00	...	0.00	4.00	2.00	1.00	...	0.00	0.00	0.00	2.00	...	2.00	1.00
SD_{1_1}	4.00	1.00	...	2.00	0,00	1.00	3.00	...	2.00	1.00	2.00	3.00	...	2.00	3.00
SD_{2_1}	4.00	4.00	...	2.00	2.00	0.00	1.00	...	3.00	2.00	4.00	2.00	...	1.00	1.00
SD_{2_2}	1.00	4.00	...	1.00	2.00	3.00	0.00	...	4.00	2.00	3.00	2.00	...	2.00	1.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
SD_{5_1}	2.00	1.00	...	4.00	4.00	1.00	2.00	...	0.00	2.00	4.00	3.00	...	1.00	3.00
SD_{5_2}	1.00	2.00	...	4.00	3.00	2.00	2.00	...	2.00	0.00	3.00	1.00	...	2.00	2.0
SD_{5_3}	1.00	2.00	...	4.00	3.00	2.00	2.00	...	4.00	3.00	0.00	2.00	...	1.00	2.00

EPC_2	2.00	4.00	...	2.00	1.00	2.00	4.00	...	4.00	2.00	4.00	0.00	...	2.00	2.00
EPC_3	2.00	4.00	...	2.00	1.00	2.00	2.00	...	2.00	4.00	2.00	2.00	...	1.00	2.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	4.00	2.00	...	2.00	1.00	1.00	2.00	...	2.00	3.00	4.00	4.00	...	2.00	1.00
EPC_{39}	2.00	4.00	...	2.00	1.00	2.00	2.00	...	2.00	3.00	4.00	4.00	...	0.00	1.00
EPC_{40}	2.00	1.00	...	4.00	4.00	1.00	2.00	...	2.00	3.00	2.00	4.00	...	3.00	0.00

Table 3: Integrated Effect Matrix for the First DM for the Steam Boiler Working Process.

	MD_1	MD_2	...	MD_5	SD_{1_1}	SD_{2_1}	SD_{2_2}	...	SD_{5_1}	SD_{5_2}	SD_{5_3}	EPC_2	...	EPC_{39}	EPC_{40}	Max
MD_1	0.00	1.00	...	1.00	0.00	1.00	1,00	...	1.00	2.67	3.00	2.00	...	2.00	1.67	4.00
MT_2	1.00	0.00	...	3.00	2.00	0.00	0,00	...	4.00	2.00	4.00	2.00	...	1.00	1.00	4.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
MT_5	3.33	2.00	...	0.00	4.00	2.00	1,00	...	0.00	0.00	0.00	0.00	...	2.00	1.00	4.00
	3.00	1.00	...	2.00	0.00	1.00	3,00	...	2.67	1.00	2.00	2.67	...	2.00	3.00	4.00
	4.00	4.00	...	2.00	2.00	0.00	1,00	...	3.67	2.67	4.00	3.67	...	1.00	1.00	4.00
	1.00	4.00	...	1.00	2.00	3.00	0,00	...	2.00	2.00	1.67	2.00	...	2.00	1.67	4.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	2.00	1.00	...	4.00	4.00	1.00	2,00	...	0.00	2.00	4.00	3.00	...	1.00	3.00	4.00
ST_{5_2}	1.00	2.00	...	4.00	2.00	2.00	2,67	...	2.00	0.00	3.00	1.00	...	2.00	2.00	4.00
ST_{5_3}	1.00	2.00	...	4.00	3.00	2.00	2,00	...	4.00	3.00	0.00	2.00	...	1.00	1.33	4.00
EPC_2	2.00	4.00	...	2.00	1.00	2.00	4,00	...	4.00	2.00	4.00	0.00	...	2.00	2.00	4.00
EPC_3	1.33	2.67	...	2.67	2.00	1.67	2,00	...	2.00	4.00	2.00	2.00	...	1.00	1.33	4.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	4.00	2.00	...	2.33	2.33	2.00	2,33	...	1.33	2.67	4.00	3.00	...	2.00	1.00	4.00
EPC_{39}	2.00	3.33	...	2.00	1.67	2.00	2,00	...	2.00	3.00	4.00	4.00	...	0.00	1.00	4.00
EPC_{40}	2.00	1.33	...	3.33	3.67	1.33	3,33	...	2.00	2.67	3.00	3.00	...	3.00	0.00	4.00
Max	4.00	4.00	...	4.00	4.00	4.00	4,00	4,00	4.00	4.00	4.00	4.00	4,00	3.00	3.00	

Table 4: Combined Integrated Effect Matrix for Steam Boiler Working Process.

	MT_1	MT_2	…	MT_5	ST_{1_1}	ST_{2_1}	ST_{2_2}	…	ST_{5_1}	ST_{5_2}	ST_{5_3}	EPC_2	…	EPC_{39}	EPC_{40}
MT_1	0.00	0.01	…	0.01	0.00	0.01	0.01	…	0.01	0.02	0.02	0.02	…	0.02	0.01
MT_2	0.01	0.00	…	0.02	0.02	0.00	0.00	…	0.03	0.02	0.03	0.02	…	0.01	0.01
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	0.03	0.02	…	0.00	0.03	0.02	0.01	…	0.00	0.00	0.00	0.02	…	0.02	0.01
ST_{1_1}	0.02	0.01	…	0.02	0.00	0.01	0.02	…	0.02	0.01	0.02	0.02	…	0.02	0.02
ST_{2_1}	0.03	0.03	…	0,02	0,.02	0.00	0.01	…	0.03	0.02	0.03	0.02	…	0.01	0.01
ST_{2_2}	0.01	0.03	…	0.01	0.02	0.02	0.00	…	0.02	0.02	0.01	0.02	…	0.02	0.01
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	0.02	0.01	…	0.03	0.03	0.01	0.02	…	0.00	0.02	0.03	0.02	…	0.01	0.02
ST_{5_2}	0.01	0.02	…	0.03	0.02	0.02	0.02	…	0.02	0.00	0.02	0.01	…	0.02	0.02
ST_{5_3}	0.01	0.02	…	0.03	0.02	0.02	0.02	…	0.03	0.02	0.00	0.02	…	0.01	0.01
EPC_2	0.02	0.03	…	0.02	0.01	0.02	0.03	…	0.03	0.02	0.03	0.00	…	0.02	0.02
EPC_3	0.01	0.02	…	0.02	0.02	0.01	0.02	…	0.02	0.03	0.02	0.02	…	0.01	0.01
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	0.03	0.02	…	0.02	0.02	0.02	0.01	…	0.01	0.02	0.03	0.02	…	0.02	0.01
EPC_{39}	0.02	0.03	…	0.02	0.01	0.02	0.02	…	0.02	0.02	0.03	0.03	…	0.00	0.01
EPC_{40}	0.02	0.01	…	0.03	0.03	0.01	0.02	…	0.02	0.02	0.02	0.02	…	0.02	0.00

Table 5: Normalized Effect Matrix for Steam Boiler Working Process.

	MT_1	MT_2	...	MT_5	ST_{1_1}	ST_{2_1}	ST_{2_2}	...	ST_{5_1}	ST_{5_2}	ST_{5_3}	EPC_2	...	EPC_{39}	EPC_{40}
MT_1	0.018	0.029	...	0.029	0.018	0.025	0.025	...	0.028	0.043	0.045	0.035	...	0.027	0.028
MT_2	0.024	0.019	...	0.042	0.032	0.015	0.016	...	0.048	0.035	0.050	0.033	...	0.019	0.021
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	0.043	0.036	...	0.020	0.046	0.031	0.024	...	0.021	0.022	0.022	0.035	...	0.027	0.022
ST_{1_1}	0.043	0.031	...	0.038	0.020	0.026	0.041	...	0.043	0.032	0.039	0.044	...	0.028	0.039
ST_{2_1}	0.048	0.050	...	0.037	0.033	0.016	0.024	...	0.048	0.042	0.053	0.035	...	0.020	0.023
ST_{2_2}	0.027	0.052	...	0.030	0.034	0.040	0.018	...	0.037	0.038	0.036	0.036	...	0.027	0.028
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	0.036	0.031	...	0.054	0.050	0.027	0.034	...	0.023	0.040	0.054	0.045	...	0.022	0.040
ST_{5_2}	0.028	0.038	...	0.053	0.035	0.033	0.038	...	0.037	0.024	0.046	0.030	...	0.028	0.031
ST_{5_3}	0.029	0.039	...	0.054	0.043	0.034	0.035	...	0.053	0.047	0.025	0.038	...	0.021	0.028
EPC_2	0.035	0.053	...	0.040	0.029	0.034	0.049	...	0.054	0.040	0.055	0.023	...	0.029	0.032
EPC_3	0.028	0.041	...	0.041	0.033	0.029	0.032	...	0.035	0.052	0.037	0.035	...	0.020	0.025
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	0.050	0.038	...	0.041	0.037	0.033	0.032	...	0.033	0.044	0.054	0.045	...	0.029	0.024
EPC_{39}	0.035	0.048	...	0.039	0.033	0.033	0.034	...	0.038	0.046	0.054	0.051	...	0.013	0.024
EPC_{40}	0.036	0.033	...	0.049	0.048	0.029	0.035	...	0.038	0.044	0.047	0.045	...	0.036	0.017

Table 6: Total Effect Relation Matrix for Steam Boiler Working Process.

Step 7: Compute the effect and relation values

The row summations of [*T*] indicated as D_s; $s = n+m+40$ and the column summations of [*T*] denoted as R_s; $s = n+m+40$ are computed. Then, D_s+R_s is relation level with the other components of the decision system and D_s-R_s is effect level between the components of the decision system. Some of the components which have positive D_s-R_s values have more effect than the others. Components with negative D_s-R_s values are affected by others. Additionally, the components which have higher D_s+R_s values are more related with the others. These values for the steam boiler working process are shown in Table 7.

	D_s	R_s	D_s+R_s	D_s-R_s
MD_1	1.165	1.168	2.333	-0.003
MD_2	1.047	1.168	2.359	-0.265
⋮	⋮	⋮	⋮	⋮
MD_5	1.119	1.326	2.675	-0.207
SD_{11}	1.270	1.326	2.596	0.140
SD_{21}	1.156	1.326	2.287	0.123
SD_{22}	1.198	1.326	2.231	0.127
⋮	⋮	⋮	⋮	⋮
SD_{51}	1.301	1.291	2.592	0.010
SD_{52}	1.257	1.291	2.631	-0.116
SD_{53}	1.323	1.291	2.722	-0.075
EPC_2	1.321	1.291	2.573	0.068
EPC_3	1.149	1.403	2.553	-0.254
⋮	⋮	⋮	⋮	⋮
EPC_{38}	1.283	1.077	2.360	0.207
EPC_{39}	1.271	1.077	2.038	0.505
EPC_{40}	1.295	1.077	2.234	0.357

Table 7: D_s, R_s, D_s+R_s and D_s-R_s values.

According to the Table 7, MT_4 has the lowest D_s-R_s value (-0.380) and EPC_{39} has the highest D_s-R_s value (0.505). In the same manner, SD_{32} has the highest D_s+R_s value (2.799) and EPC_{39} has the lowest D_s+R_s value (2.038).

Step 8: Compute the weights of MDs

To compute the weights of MDs denoted as W_i Eq.(6) is used [24]. The summations of W_i should be equal to 1.

$$W'_i = \sqrt{(D_s + R_s)^2 + (D_s - R_s)^2}$$

$$W_i = \frac{W'_i}{\sum_{i=1}^{n} W'_i} \quad (6)$$

Where, is the pre-weight value of each MD. The weights of MDs for steam boiler working process are shown in Table 8.

MDs	W'_i	W_i
MD_1	2.333	0.182
MD_2	2.374	0.186
MT_3	2.183	0.171
MT_4	2.395	0.187
MT_5	3.499	0.274

Table 8: The weights of MDs for Steam Boiler Working Process.

It can be seen from Table 8, MT_5 has the highest importance weight as 0.274.

Step 9: Compute the weights of SDs
To compute the weights of SDs, Eq.(7) is used [5,6,24].

$$W''_{ij} = \sqrt{(D_s + R_s)^2 + (D_s - R_s)^2}$$

$$W'_{ij} = \frac{W''_{ij}}{\sum_{j=1}^{m} W''_{ij}}$$

$$W_{ij} = W'_{ij} \times W_i \quad (7)$$

where W''_{ij} is the pre-weight value of each SD, W'_{ij} is the initial weight of each SD and W_{ij} is the importance weight of *jth* SD in *ith* MD. The weights of SDs for steam boiler working process are shown in Table 9.

SDs	W''_{ij}	W'_{ij}	W_{ij}
SD_{11}	2.600	1.000	0.182
SD_{21}	2.290	0.506	0.094
SD_{22}	2.234	0.494	0.092
SD_{31}	2.398	0.241	0.041
SD_{32}	2.801	0.282	0.048
SD_{33}	2.487	0.250	0.043
SD_{34}	2.250	0.226	0.039
SD_{41}	2.657	0.207	0.039
SD_{42}	2.424	0.189	0.035
SD_{43}	2.517	0.196	0.037

SD_{4_4}	2.606	0.203	0.038
SD_{4_5}	2.609	0.204	0.038
SD_{5_1}	2.592	0.326	0.089
SD_{5_2}	2.634	0.331	0.091
SD_{5_3}	2.723	0.343	0.094

Table 9: The Weights of SDs for Steam Boiler Working Process.

Step 10: Compute the Weights of EPCs
To compute the weights of EPCs Eq.(8) is used.

$$\ddot{w}_b = \sqrt{(D_s + R_s)^2 + (D_s - R_s)^2}$$

$$\dot{w}_b = \frac{\ddot{w}_b}{\sum_{b=1}^{40} \ddot{w}_b}$$

$$w_b = \dot{w} \times w_{i_j} \quad (8)$$

Where $\ddot{w}_b$ is the pre-weight value of each EPC, $\dot{w}_b$ is the initial weight of each EPC and w_b is the importance weight of *bth* EPC for the *jth* SD in *ith* MD. The parts of the weights of EPCs for steam boiler working process are shown in Table 10.

SDs			
SD_{1_1}			
EPCs	$\ddot{w}_b$	$\dot{w}_b$	w_b
EPC_2	2.574	0.153	0.028
EPC_{15}	2.497	0.148	0.027
EPC_{31}	2.601	0.154	0.028
EPC_{34}	2.283	0.135	0.025
EPC_{36}	2.272	0.135	0.025
EPC_{38}	2.369	0.141	0.026
EPC_{40}	2.262	0.134	0.024
⋮	⋮	⋮	⋮

ST_{5_1}			
EPCs	$\ddot{w}_b$	$\dot{w}_b$	w_b
EPC_2	2.574	0.174	0.016
EPC_4	2.597	0.175	0.016
EPC_6	2.482	0.168	0.015
EPC_{31}	2.262	0.153	0.014
EPC_{34}	2.601	0.176	0.016
EPC_{40}	2.283	0.154	0.014
SD_{5_2}			
EPCs	$\ddot{w}_b$	$\dot{w}_b$	w_b
EPC_2	2.574	0.259	0.024
EPC_4	2.597	0.261	0.024
EPC_{15}	2.497	0.251	0.023
EPC_{40}	2.262	0.228	0.021
SD_{5_3}			
EPCs	$\ddot{w}_b$	$\dot{w}_b$	w_b
EPC_2	2.574	0.107	0.010
EPC_3	2.565	0.106	0.010
EPC_4	2.597	0.108	0.010
EPC_{15}	2.497	0.104	0.010
EPC_{36}	2.272	0.094	0.009
EPC_{38}	2.369	0.098	0.009
EPC_{40}	2,262	0.094	0.009
EPC_{31}	2.601	0.108	0.010
EPC_{34}	2.283	0.095	0.009
EPC_{39}	2.099	0.087	0.008

Table 10: The weights of EPCs for Steam boiler working process.

Step 11: Compute HEP and GHEP for each SD

To calculate HEP and GHEP Eq.(1) and (2) are used respectively. Table 11 shows the HEP_{i_j} and $GHEP_{i_j}$ values for steam boiler working process.

Step 12: Compute the Total HEP for each MD

Total HEP for each MD ($THEP_i$) is obtained as in Eq.(9).

$$THEP_i = \sum_{j=1}^{n} GHEP_{ij} \quad (9)$$

Table 12 presents $THEP_i$ values for main tasks in Steam boiler working process.

SDs						
SD_{11}						
EPCs	GTT_z	NHE	EF_b	w_b	HEP_{ij}	$GHEP_{ij}$
EPC_2	GTT_5 E type GTT	0.02	11.00	0.028	0.028	0.001
EPC_{15}			3.00	0.027		
EPC_{31}			1.20	0.028		
EPC_{34}			1.05	0.025		
EPC_{36}			1.06	0.025		
EPC_{38}			1.16	0.026		
EPC_{40}			2.40	0.024		
⋮			⋮	⋮	⋮	
ST_{51}						
EPCs	GTT_z	NHE	EF_b	w_b	HEP_{ij}	$GHEP_{ij}$
EPC_2	GTT_5 E type GTT	0.02	11.00	0.016	1.470	0.029
EPC_4			9.00	0.016		
EPC_6			8.00	0.015		
EPC_{31}			2.40	0.014		
EPC_{34}			1.20	0.016		
EPC_{40}			1.10	0.014		
EPCs	GTT_z	NHE	EF_b	w_b	HEP_{ij}	$GHEP_{ij}$
EPC_2	GTT_6 F type GTT	0.007	11.00	0.024	1.581	0.011
EPC_4			9.00	0.024		
EPC_{15}			3.00	0.023		
EPC_{40}			2.40	0.021		
EPCs	GTT_z	NHE	EF_b	w_b	HEP_{ij}	$GHEP_{ij}$

EPC_2	GTT_6 F type GTT	0.007	2.592	0.010	1.376	0.010
EPC_3			2.577	0.010		
EPC_4			2.612	0.010		
EPC_{15}			2.510	0.010		
EPC_{36}			2.284	0.009		
EPC_{38}			2.379	0.009		
EPC_{40}			2.276	0.009		
EPC_{31}			2.616	0.010		
EPC_{34}			2.290	0.009		
EPC_{39}			2.114	0.008		

Table 11: HEP_{i_j} and $GHEP_{i_j}$ Values for Steam Boiler Working Process.

Step 13: Compute the HEP for work flow

HEP for work flow is denoted as HEP_{wf} and it is computed as in Eq.(10).

$$HEP_{wf} = \sum_{i=1}^{m} THEP_i \quad (10)$$

Table 12 shows that related Steam boiler working process has %81 HEP.

MDs	$THEP_i$
MD_1	0.001
MD_2	0.048
MD_3	0.345
MD_4	0.367
MD_5	0.050
HEP_{wf}	0.810

Table 12: $THEP_i$ Values for MDs.

Results

Results show that, the highest D_s-R_s value belongs to EPC_{39} defined as distraction or task interruption in HEART. This means that EPC_{39} has more effect to provide human error in steam boiler working process than the EPCs. EPC_{39} may induce the operators to forget the task which they must to do. Conversely, the lowest D_s+R_s value is related to the same EPC. This can be defined as EPC_{39} has lesser relations with the other MDs, SDs and EPCs than the other process components and EPC_{39} is not related with the steam boiler working process. EPC_{39} is only one of the potential human error causes and it has not been encountered where the application performed in the study. In this vein, it can be said that lesser relation result for EPC_{39} is logical.

A result related to MDs indicates that the lowest D_s-R_s value belongs to MT_4 defined as burners and fuel system control. This can be evaluated as MT_4 is effected the other MDs, SDs and EPCs more than the other process components. MT_4 has a vital role for steam boiler in term of explosion. Burners play a complementary role in oil and gas production. Burners produce the heat required to separate the oil, gas and water mixture. Burners hold the gases in vapor phase whilst transportation through pipelines. According to this, having lesser effect is a logical result for MT_4.

Another obtained result from the study is related to D_s+R_s values. In term of these values, has the highest value. This means that has more relation than the other components of the process. is explained as checking whether the water level of the degasser tank is within the marked range. If the water level is not within the marked range, the pumps feeding the degasser tank should be check whether they are working or not.

Additionally, MD_5 explained as control of safety and warning systems was determined as the most important MD. In steam boiler system, a wide range of safety and monitoring equipment were used to help protection of the boiler from operating outside the set parameters and shut it down to prevent a dangerous situation.

According to importance weights of SDs, it was found that SD_{5_3} determined as check whether the boiler presosat settings are correct has the highest importance weight in MD_5. In terms of EPCs in SD_{5_3}, it was identified as EPC_2, EPC_3, EPC_4, EPC_{15}, EPC_{31} have the highest importance according to DMs. EPC_2 is defined as a shortage of time available for error detection and correction, EPC_3 is explained as low signal to noise ratio, EPC_4 is determined as a means of suppressing or over-hiding information or features which is too easily accessible, EPC_{15} is described as an operator in experience,

EPC_{31} is designated as low work force morale in traditional HEART. According to these explanations, it can be said that these EPCs are the general problems in all process. These general problems becoming more important to check whether the boiler presosat settings are correct or not. If this SDs is not performed truly because of these EPCs, the steam boiler explosion may occur.

When THEP values are examined, it can be seen that MD_5 has the highest HEP because, the SDs in MD_5 has higher GHEP values than the other SDs in the other MDs. The importance weights of MDs demonstrate that, MD_5 has the highest importance. This means, according to the DMs, MD_5 is the most important stage of the steam boiler working process so the obtained THEP result is logical.

Final result is related to HEP value, this result presents that steam boiler working process has %81 probabilities in terms of human errors. In this result, MD_5 has the highest importance and it should be prevented firstly. Again in MD_5, necessary precautions should be taken about SD_{5_1} because according to GHEP, SD_{5_1} has the highest value among the other SDs in MD_5. For this aim firstly, measures for EPC_2 defined as a shortage of time available for error detection should be performed. This EPC is the most effective one among the other EPCs in SD_{5_1}.

Conclusion

This study has originality and contribution in terms of applying Can [5] and Delice [6] approach for steam boiler working process with different DMs. In this study, integrated effect matrix was used again to obtain different DMs' evaluations. All MDs, SDs and EPCs form integrated effect matrix. In this way, all interactions between MDs, SDs and EPCs can be evaluated and which EPC, SD(s), MD(s) should be improved can be determined easily. By modelling these complex interactions in error assessment, real life can be reflected more accurate manner. This is also a big improvement for human error assessment activities.

For the future studies, the advanced HEART suggested by Can [5] and Delice [6] can be implemented with fuzzy logic, intuitionistic fuzzy logic, hesitant fuzzy sets etc. The proposed advanced HEART can be performed for different ındustrial fields to define human error probability. Thus, the feasibility of the proposed approach is demonstrated more strongly.

Authors' Contributions

In this study, Author 1 made data collection, performed a part of data analysis and interpretated the results; Author 2 completed the rest of the data analysis, reviewed the literature and built the manuscript structure.

Conflict of Interest

No conflict of interest was declared by the authors.

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