Received: 30 January 2019 | Revised: 17 June 2019 | Accepted: 6 September 2019
DOI: 10.1002/hfm.20819

WILEY

An advanced human error assessment approach: HEART and AV-DEMATEL

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Abstract

Human error assessment and reduction technique (HEART) is one of the most commonly used human error assessment approaches which computes human error probability (HEP) to prioritize errors related to human actions. HEART is a powerful tool considering error producing conditions (EPCs) which increase the HEP for generalized task versions named as generic task types (GTTs). HEART can give a solution including prevention of human-related errors (HREs) and reduction of the HREs' impacts via implementing additional controls. However, it has many short-comings for real-life error assessments. In this context, this study aims to improve effective usage of HEART through an advanced version of decision-making trial and evaluation laboratory (AV-DEMATEL). The reason to perform AV-DEMATEL is to show the complex effect relations between main tasks (MTs), subtasks (STs), and EPCs in a process. For this aim, an integrated effect relation matrix is proposed for DEMATEL and importance weights of MTs, STs, and EPCs are computed based on this matrix. In addition, not only HREs are considered but also machine-related errors (MREs) are taken into account to make error assessment for the process. The proposed approach also provides flexibility to categorize STs in different GTTs. Finally, a new term "process error probability" including HREs' probabilities and MREs' probabilities is recommended to compute error probability in an integrated manner for the process. To utilize the proposed approach, an example of a steam boiler daily control process is given.

KEYWORDS
DEMATEL, error assessment, HEART, HREs, MREs

1 | INTRODUCTION

Human error assessment (HEA) aims to find how likely it is that a process may be failed by potential human errors. This estimation is concluded with a human reliability assessment (HRA). In this way, types of human errors can be defined, estimated probability of each error can be obtained, influencing factors for the probability can be determined and finally, the recommendations for preventing these errors can be formed.

Human errors can be classified as unintended and intended actions (Reason, 1990). Unintended actions generally consist of skill-based errors as slips of action, lapses of memory. Intrusion, misordering, omission, reversal, mistiming can be given as examples for slips of action. Omissions, repetitions, reduced intentionality can be given as an example for lapses of memory. Slips and lapses generally comprise in very familiar tasks that can be applied without much conscious attention, for example, driving a vehicle. These types of tasks are very undefended to slips and lapses when humans' attentions are diverted even for a moment. Intended actions include mistakes and violations. Mistakes can occur as knowledge-based mistakes and rule-based mistakes. Misapplication of a good rule, application of a bad rule can be given as examples for rule-based mistakes. Confirmation bias, selectivity, vagabonding can be categorized as knowledge-based mistakes. Mistakes are related to decision-making failures. Mistakes arise when a human does the wrong thing, believing it to be true. Violations cover routine violation, exceptional violation, and acts of sabotage. These are intentional human failures “deliberately doing the wrong thing.” The violation of health and safety rules or procedures is one of the biggest reasons for accidents and injuries at work. These human errors classifications are based on the Generic Error Model System advanced by Reason (1990). This system is analyzed for any process by using HRA approaches. HRA is related to the human factors and it has been defined as the implementation of relevant information about human characteristics and behavior to the design of processes, objects, facilities, and environments that people benefit (Grandjean, 1980). HRA approaches are performed for the analysis of incidents of human-related errors (HREs) and examining a system, process, product or environment. The purpose of examining the process, system, and so forth is to find where weakness may lie or create a vulnerability to errors, not to find fault or apportion blame (Lyons, Adams, Woloshynowych, & Vincent, 2004). When a work accident causes in a process are reviewed, HREs are seen as the main factors. Therefore, to have an effective process, factors related to human errors need to be evaluated and quantified. In addition, all factors affecting human performance must be defined and quantified for the various phases of the process. Any system can be analyzed in which humans are involved with any of HRA approaches.

There are many different approaches that investigate HREs such as human error assessment and reduction technique (HEART; Swain & Guttmann, 1983), technique for human error rate prediction (THERP; Hannaman & Spurgin, 1984), A technique for human error analysis (Cooper, Ramey-Smith, Wreathall, & Parry, 1996), cognitive reliability and error analysis method (CREAM; Hollnagel, 1998), and so forth. Among these approaches HEART advanced by Williams (1988) is the most common used one. HEART considers the types of potential human errors, the estimated probability of such errors being made, factors may influence this probability (e.g., time pressure, stress, poor working environment, low morale), prevention ways of identified human errors in the design and additional mitigating controls that can be needed for reducing their impact. The HEART is based on human performance literature; it has been used to quantify human error probabilities (HEPs) related to any system, environment, product or process. HEART evaluates the interactions between humans, their specific tasks and human performance shaping factors or error producing conditions (EPCs; Williams, 1988). HEART matches tasks in a process with generic task types (GTTs) included in its structure. These GTTs are the types of tasks that often encountered in different work areas. For this reason, any of the tasks in the related process can be represented by one of GTTs in HEART. Because HEART has applicability for different areas, it can compute HEP for any process. It considers EPCs that can increase HEP up to a certain level. These EPCs are also generalized as negative conditions that can be encountered in any process. On the other hand, HEART has some shortcomings related to reflecting the real-life error assessments for processes. First of all, the mathematical procedure of HEART cannot consider the aggregated evaluations of different experts. In real-life cases, there may be more than one expert who tries to make a risk assessment for the related process. Second, in real error assessment cases, tasks in a process can affect each other. These effect relations cannot be modeled with traditional HEART. In addition, the process can be divided into main tasks (MTs) and subtasks (STs). There may be different EPCs that effect each MT and ST for each expert. According to this, complex effect relations may occur among MTs, STs, and EPCs. Third, any MT can be matched with different GTTs by different experts. This differentiation also cannot be modeled with traditional HEART procedure. As a fourth item, there are not only HREs in processes, there may be machine-related errors (MREs) in the related process. These types of errors should be considered to compute process error probability (PEP). Finally, the weights of EPCs are only considered in traditional HEART. However, for any process errors that may occur in any of MTs and STs can affect negatively process effectiveness. In this term, these MTs and STs should have importance weights for the process separately. In addition, STs are dependent on MTs, importance weights of MTs should have impacts on the importance weights of STs and these dependencies should be reflected in PEP.

Hence, to avoid the inadequacies of traditional HEART approach and to provide solutions to the problems mentioned above, this study proposes an improved version of HEART. For this aim, the advanced version of decision-making trial and evaluation laboratory (AV-DEMATEL) with integrated effect matrix is proposed. DEMATEL is one of the multi-criteria decision making (MCDM) methods that can measure the effect degree between criteria (Fontela & Gobus, 1974). In its most basic form, MCDM is called as a selection process of experts from alternatives when qualifications of alternatives are known. It is aimed in the proposed version of HEART to identify which EPC should be prevented first and which ST/STs, MT/MTs should be improved. Therefore, MCDM structure was found very suitable for HEA. The proposed integrated effect matrix for DEMATEL includes effect relations among MTs, STs, and EPCs. This is a new challenge for HEART. This means that all interactions among MTs, STs, and EPCs can be considered in HEA. These interactions can be reflected in computing weights of MTs, STs, and EPCs. Then, the weights of these components are considered in PEP value. Different from the traditional HEART implementation, all different viewpoints of experts for GTTs and EPCs related to each ST are considered and brought together. This action reflects the real-life more truly because any ST may be classified in more than one different GTTs and different EPCs may occur while performing each ST according to different experts. In addition, each ST has a certain error probability owing to HREs and MREs. Therefore, EPCs related to HREs and EPCs related to MREs for each expert are analyzed separately in the proposed methodology. At the end of the analysis, PEP, a new term for HEA is computed considering both HREs and MREs. In this way, an integrated error assessment approach has been advanced. Finally, the proposed approach is performed for a steam boiler daily control process. HEA is much more important for this process than the other processes in different working areas. Boilers may explode, damage plant and create negative conditions for production. Especially, boilers operated and maintained incorrectly, designed inadequately, sited wrongly may cause accidents. It is vital to check the risk level of the boiler if it is in an acceptable condition or if any measures are required or not. The proposed approach is practical and a suitable tool to perform this check. In this term, this study can provide detailed analysis support to the experts who perform HEA.

The other sections of the study are organized as follows. Section 2 includes a literature review. Section 3 contains the presentation of HEART, the proposed advanced version of HEART and its application to steam boiler working process. Section 4 covers results obtained from the application of the proposed approach and discussion related to the results and suggested approach. Opinions for future research are also given.

2 | LITERATURE REVIEW

There are limited studies in the literature that implement HEART to determine HREs and to make reductions for them. Information related to these studies are given below.

Casamirra, Castiglia, Giardina, and Tomarchio (2009) and Castiglia and Giardina (2011) determined the HEP for irradiation plants by combining fault tree analysis, fuzzy set theory, and HEART. Castiglia, Giardina, and Tomarchio (2010) explored potential exposure of medical operators working in a brachytherapy irradiation plant. The risk level for various accident scenarios was determined by fuzzy fault tree and HEART integration modified on the basis of fuzzy set concepts to consider the uncertainties for EPCs. Castiglia and Giardina (2013) used Fuzzy HEART to evaluate operators' errors in hydrogen refueling stations. The obtained results have been compared with the results obtained using CREAM. Chadwick and Fallon (2012) proposed a modified HEART for healthcare. To obtain the weight for each EPC graphic rating scales were utilized in the modified HEART. Castiglia, Giardina, and Tomarchio (2015) suggested an approach by using the fuzzy HEART to determine the probability of medical personnel error during the treatment process. Also, THERP is used to determine the fuzzy interval of the error probabilities in the event-tree. Akyuz and Celik (2015) integrated HEART and analytic hierarchy process (AHP) method for calculating the effect of EPCs. Akyuz, Celik, and Cebi (2016) produced marine-specific EPC values based on a multidimensional approach using majority rule, HEART, human factors analysis and classification system, AHP, and validation techniques. Akyuz and Celik (2016) suggested an extended HEART using interval type-2 fuzzy sets (IT2FS) to handle the uncertainties of experts' judgments. Islam, Abbassi, Garaniya, and Khan (2017) developed a new HEP assessment methodology by revising the conventional HEART to estimate the HEP for the maintenance procedures in marine operations. Kumar, Rajakarunakaran, and Prabhu (2017) presented an approach using the fuzzy HEART and expert elicitation for performing quantification of HEP with an application related to refueling operation. Wang, Liu, and Qin (2018) proposed a modified HEART with railway action reliability assessment technique and fuzzy analytic network process (FANP) to determine HEP in high-speed railway dispatching tasks. The FANP was used to overcome the problems of interdependences among EPCs and the uncertainties that existed in experts' judgments. Akyuz, Celik, Akgun, and Cicek (2018) presented a systematic HEP during bunkering operation at chemical tanker ship using the shipboard operation human reliability analysis which is a marine specific method to quantify the human error. Giardina et al. (2018) presented an integrated approach of hierarchical task analysis and three human error quantification methods as enhanced HEART, standardized plant analysis risk human reliability analysis, and the CREAM. This approach was implemented for an innovative plant for advanced nuclear physic applications. Sheikhalishahi, Eskandari, Mashayekhi, and Azadeh (2019) proposed an open shop scheduling model to take into account human error and preventive maintenance. The suggested mathematical model is integrated with HEART including makespan, human error, machine availability, and the relationship between human factors and production planning.

As a result of the literature review, advances in HEART were tried by combining different approaches for different areas and results produced from HEART was compared to other HEA approaches. However, none of the researchers have paid attention to increase effective usage of HEART especially in terms of complex effect relations among MTs, STs, and EPCs. As mentioned by Wang et al. (2018) not considering the dependent relationships between EPCs is an important deficiency in these studies. This study not only considers the dependent relationships between EPCs but also takes into accounts the dependent relationships among MTs, STs, and EPCs. In this term and the other terms emphasized in the introduction section, this study has originality for HEA.

In term of DEMATEL, there many studies in literature covering the application of DEMATEL for different decision processes, focusing on the integration of DEMATEL with different approaches and so forth. In this study, literature belongs to 2018 and 2019 for DEMATEL is introduced briefly. Liu, Deng, and Chan (2018) suggested a new methodology to address supplier management under uncertain environment. In the context of the proposed methodology, analytic network process (ANP) and entropy weight were employed to obtain the subjective and objective criteria weights. On the basis of DEMATEL and game theory, the comprehensive weight of ANP and entropy weight can be determined. Game theory was applied to combine the merits of subjective weight and objective weight, and DEMATEL was utilized to adjust the weight of criteria to make the result more reasonable. Finally, evidence theory was used to deal with the uncertainties of input data and get the supplier selection result. Abdel-Basset, Manogaran, Gamal, and Smarandache (2018) combined the neutrosophic set and DEMATEL to analyze and determine the factors influencing the selection of suppliers. Lin, Tseng, and Pai (2018) advanced the approximate fuzzy DEMATEL to evaluate uncertain influential factors for sustainable supply chain management by using the approximate fuzzy arithmetic operations under the weakest t norm

(T_ω). Zhang and Deng (2018) modified the source model of evidence by proposing a new method based on DEMATEL to take the weight of each evidence into consideration. They determined the total-relation matrix by the similarity among evidence and prominence and importance were calculated. Finally, they used Dempster's rule of combination to obtain the weighted average combination result. Lo, Liou, and Tzeng (2019) discussed a published paper titled "Sustainable recycling partner selection using fuzzy DEMATEL-AEW-fuzzy Vise Kriterijumska Optimizacija I Kompromisno Resenj (FVIKOR): A case study in small-and-medium enterprises (SMEs)", by Zhou et al. (2018). In their study, the crucial weights generated using the DEMATEL technique are questionable, may not be accurate to obtain the subjective weights of criteria. Asan, Kadaifci, Bozdag, Soyer, and Serdarasan (2018) new interval-valued hesitant fuzzy DEMATEL approach to deal with hesitancy in expert assessments. They compared the proposed approach with the classical and fuzzy DEMATEL approaches. Ding and Liu (2018) proposed 2-dimension uncertain linguistic variables and DEMATEL integration to identify critical success factors in emergency management.

Lo et al. (2019) proposed to use VIKOR together with an aspiration level concept for determining management implications. Mousavizade and Shakibazad (2019) studied the critical success factors of knowledge in Iranian urban water and sewage companies using interpretive structural modeling and DEMATEL method. Tian et al. (2019) proposed a unique model to solve take-back patterns of scrap cars systematically. They combined the gray method and DEMATEL to compute the weights of nine criteria, and FVIKOR was adopted to rank the three patterns based on expert evaluations. Yang, Lan, and Tseng (2019) determined the influencing criteria of coordinated development between metropolitan economy and logistics and revealed the logical relationships among the various influence criteria based on the DEMATEL. In addition, the DEMATEL–Bayesian network (BN) model was performed to obtain the key influence criteria and driving path of the coordinated development. Chen, Ming, Zhang, Yin, and Sun (2019) suggested rough-fuzzy DEMATEL-ANP integration to evaluate sustainable value requirement. They aimed to overcome vagueness and diversity in the decision process by implementing integrated rough-fuzzy number. Acuña-Carvajal et al. (2019) performed fuzzy DEMATEL and linear programming to support the design of a strategy map for the overall process of planning, structuring and validating a business unit strategy considering the subjectivity of decision making in the construction of strategy map. Dinçer, Yüksel, and Martínez (2019) advanced a novel evaluation method based on a hybrid methodology covering DEMATEL-ANP and multi-objective optimization by ratio analysis (MOORA). They applied their proposed approach for evaluation of the financial service performance in the emerging seven (E7) economies. They combined DEMATEL-ANP and MOORA integration with IT2FS to model modeling uncertainty of appraisers. Majumdar, Kapur, and Khatri (2019) investigated the software upgradation aspects of industries via performing the DEMATEL and then they found the optimal release time of the upgraded software using multi-attribute utility theory to remain competitive in the market. Liu and Ming (2019) used revised rough-DEMATEL to capture and evaluate requirements for smart industrial product-service system of systems. To model the interrelation between requirements of a smart industrial product-service system of systems and uncertainty of expert judgments, rough-DEMATEL was adopted. Kaya and Yet (2019) advanced a novel and systematic way of building causal decision support models based on DEMATEL in BNs. Their proposed approach elicits causal knowledge from multiple experts based on DEMATEL and transforms it to a BNs structure. Shakerian, Choobineh, Jahangiri, Alimohammadlou, and Nami (2019) introduced a new model for individual cognitive factors influencing human error by determining the interactions between the factors and their intensity using DEMATEL. They performed a qualitative study to determine and to elicit the individual cognitive factors influencing human error among the workers of different industries then, the experts' opinion was applied for these cognitive factors via utilizing DEMATEL. At the same time, it was provided via using DEMATEL that understanding the interactions among the individual cognitive factors influencing human error.

As seen from the brief literature review for DEMATEL, this method was combined with different theories like fuzzy sets, intuitionistic fuzzy sets, hesitant sets, rough sets, BNs, and so forth. Although there is no study that integrates HEART and DEMATEL. In addition, there is no study that advances DEMATEL in term of complex effect relations in different segments of decision hierarchy. For these reasons, this study can contribute to the literature especially HEA literature to perform risk analysis in a detailed and accurate manner.

3 | METHODOLOGY

This study suggests a novel HEART by integrating AV-DEMATEL in HEART. DEMATEL is a frequently used and well-known method. For this reason, no information about the implementation stages of DEMATEL is included in this paper. Readers can look at the study of Fontela and Gobus (1974) to seek information for DEMATEL. The traditional HEART, the proposed approach's implementation steps and the application for the proposed approach related to the steam boiler working process are introduced in the following sub-sections.

3.1 | Human error assessment and reduction technique (HEART)

The HEART can be described by two fundamental parameters as GTTs and EPCs. There are nine different GTTs considered in HEART as encountered tasks in workplaces generally. These are denoted by ranking A to M. Each GTT has a different HEP named as nominal human unreliability (NHU). This probably means that if any of GTT occurs, the HEP that may occur can be defined as the NHU value for this GTT. GTTs are matched with the tasks related to a process evaluated by an expert or experts. Indicators for GTTs, definitions of these and their related NHU values are given in Table 1.

TABLE 1 Generic task types, definitions and related nominal human unreliability values (William, 1988)

Generic tasks	Definitions	Nominal human unreliability (5th–95th percentile boundaries)
A	Totally unfamiliar, performed at speed with no real idea of likely consequences	0.55 (0.35–0.97)
B	Shift or restore the system to a new or original state on a single attempt without supervision or procedures	0.26 (0.14–0.42)
C	Complex task requiring a high level of comprehension and skill	0.16 (0.12–0.28)
D	Fairly simple task performed rapidly or given scant attention	0.09 (0.06–0.13)
E	Routine, highly practiced, a rapid task involving a relatively low level of skill	0.02 (0.007–0.045)
F	Restore or shift a system to original or new state following procedures, with some checking	0.003 (0.0008–0.0035)
G	Completely familiar, well-designed, highly practiced, routine task occurring several times per hour, performed to highest possible standards by a highly motivated, highly trained and experienced person, totally aware of implications of failure, with time to correct a potential error, but without the benefit of significant job aids	0.0004 (0.00008–0.009)
H	Respond correctly to system command even when there is an augmented or automated supervisory system providing an accurate interpretation of system stage	0.00002 (0.000006–0.00009)
M	Miscellaneous task for which no description can be found (Nominal 5th to 95th percentile data spreads were chosen on the basis of experience suggesting log normality)	0.03 (0.008–0.11)

The EPCs can be defined as any internal or external conditions such as operator experience level, noise level, operator morale disruption, age, appropriate time for duty, time of day, and so forth which affects human performance negatively. These different conditions are also met in any workplaces as GTTs. EPCs show the affect levels of these conditions that increase HEP in the respective task. Thus, EPCs can increase the HEP values for GTTs. HEART includes 40 different EPCs. The effect of EPCs can modify the

TABLE 2 The part of EPCs (Williams, 1988)

EPCs		Maximum predicted nominal amount
1.	Unfamiliarity with a situation which is potentially important but which only occurs infrequently or which is novel	×17
2.	A shortage of time available for error detection and correction	×11
3.	A low signal-to-noise ratio	×10
4.	A means of suppressing or overriding information or features which is too easily accessible	×9
5.	No means of conveying spatial and functional information to operators in a form which they can readily assimilate	×8
6.	A mismatch between an operator's model of the world and that imagined by the designer	×8
7.	No obvious means of reversing an unintended action	×8
8.	A channel capacity overload, particularly one caused by simultaneous presentation of nonredundant information	×6
9.	A need to unlearn a technique and apply one which requires the application of an opposing philosophy	×6
10.	The need to transfer specific knowledge from task to task without loss	×5.5
11.	Ambiguity in the required performance standards	×5
12.	A mismatch between perceived and real risk	×4
13.	Poor, ambiguous, or ill-matched system feedback	×4
14.	No dear direct and timely confirmation of an intended action from the portion of the system over which control is to be exerted	×3
15.	Operator inexperienced (e.g., a newly qualified tradesman, but not an "expert")	×3
16.	An impoverished quality of information conveyed by procedures and person–person interaction	×3
17.	Little or no independent checking or testing of output	×3

Abbreviation: EPC, error producing condition.

predicted reliability of task performance. EPCs are ranked as 1, 2, ..., 40 in HEART. The first 17 EPCs are shown in Table 2 as an example.

The error rate for a task is estimated as in Equations (1) and (2) in HEART procedure.

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

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

where

HEP_{i_j} is the HEP of jth subtask (ST_j) in ith main task (MT_i).

EF_b is the effect of bth EPC on any ST_j.

w_b is the importance weight of bth EPC.

$GHEP_{i_j}$ is the general HEP of jth ST in ith MT.

NHU_z is the nominal human unreliability for zth GTT. NHU_z can change according to the selected GTT as in Table 2.

3.2 | The proposed advanced version of HEART and its application to steam boiler daily control process

A steam boiler is powered by oil, coal, or gas. It is a vessel that contains water and a heat source. The boiler is used to transfer heat from the heat source to the water vessel. It turns the water into steam. This steam exits the vessel through a pipe and is transported to another location where it can be used. The steam boiler can be used for cleaning, to power equipment, to provide heat or for a number of other functions. The steam boiler in this particular scenario is to be discussed is used for providing heat in the company where the application was performed. This company produces medium voltage cells.

DEMATEL can only model direct effect relationships between criteria in the same hierarchical level; it cannot model effect relationships between criteria at different hierarchical levels. Different levels are formed by main and subcriteria as in MTS, STs, and EPCs. In addition, indirect relations occur between these different levels. In error assessment activities, it is a well-known fact that main and subcriteria may affect each other directly or indirectly. A direct effect relation means that the subcriteria included in the same main criterion affect each other. According to the proposed approach in this study, STs included in the same MT have direct effect relations. An indirect relation implies that a subcriterion included in the main criterion influences other main criteria. For the proposed approach, according to this explanation, STs in an MT can affect the other MTs or EPCs in an ST can affect the other STs or MTs. The proposed AV-DEMATEL can analyze such relationships, and thus, the initial direct relation matrix in traditional DEMATEL is transformed to an integrated effect matrix. As such, MTs, STs, and EPCs are integrated in the same matrix and their importance weights are computed considering direct and indirect effect relations. The implementation procedure of the AV-DEMATEL based HEART approach is given below. After that, the proposed integrated approach is applied for a steam boiler daily control process.

Step 1. Define the MTs, STs and form the expert group

MTs are denoted as MT_i; $i = 1, ..., v, ..., n$. These are the phases of the process. STs formed the smallest parts of a process are presented as ST_{i_j}; $i = 1, ..., v, ..., n$; $j = 1, ..., u, ..., m$. These are depended on MTs. STs formed MTs are the sub-phases of MTs. k experts denoted as E_k; $k = 1, ..., t$ compose the expert group. These are the decision-makers that have the abilities to define and evaluate the HREs and MREs in the process.

In term of steam boiler daily control process, three experts E_k; $k = 1, 2, 3$ form the expert group to evaluate HREs and MREs. The first expert (E_1) is an electronic engineer who has 14 years of working experience related to steam boiler systems. The second expert (E_2) is a mechanical engineer who has 13 years of experiences related to medium voltage cell manufacturing. He works as A class occupational health and safety expert. The third expert (E_3) is a mechanical engineer who has 17 years of working experiences in this company and he is a B class occupational health and safety expert.

These experts evaluated steam boiler working process in terms of daily control tasks that must be performed before steam boiler works as five MTs MT_i; $i = 1, ..., 5$. First MT (MT_1) covers one ST as ST_{1_1}. The second MT (MT_2) includes two STs as ST_{2_1} and ST_{2_2}. ST_{3_1}, ST_{3_2}, ST_{3_3}, and ST_{3_4} form the third MT (MT_3). ST_{4_1}, ST_{4_2}, ST_{4_3}, ST_{4_4}, and ST_{4_5} form the fourth MT (MT_4). Fifth MT (MT_5) contains three STs as ST_{5_1}, ST_{5_2}, and ST_{5_3}. Table 3 shows the part of MTs and STs.

Step 2. Match the GTTs with each ST and determine EPCs related to each ST

Each expert specifies the GTTs GTT_2; $z = 1, ..., 9$ and EPCs EPC_b; $b = 1, ..., 40$ for each ST. For example, the first GTT (GTT_1) shows A type GTT. GTTs, HREs' EPCs and MREs' EPCs for STs in the steam boiler daily control process according to E_1 are given as an example.

As seen from Table 4, checking the water level of the condensate tank to determine if it is in the marked range or not and if it is not then controlling the water pump and condensate return lines feeding the condensate tank (ST_{3_1}) task is effected by HREs and MREs separately. In terms of HREs, EPC_2, EPC_{15}, and EPC_{37} were considered by the first expert and in terms of MREs EPC_1, EPC_2, EPC_3, and EPC_6 are taken into account by the same expert. The MRE defined for ST_{3_1} is that the water pump feeding the condensate tank is defective and condensate return line has a problem.

Step 3. Structure the integrated effect matrix of HREs and MREs for each expert

Two different integrated effect matrices for each expert is formed for HREs and MREs. Integrated effect matrix for each expert for HREs is denoted as $[E]_k^h$ and the integrated effect matrix for each expert for MREs is indicated as $[E]_k^{mc}$. Table 5 shows the structure of $[E]_k^h$ for the first expert ($k = 1$) for HREs. $[E]_k^h$ and $[E]_k^{mc}$ are structured by using effect scale as "0 (no effect), 1 (low effect), 2 (medium effect), 3 (high

TABLE 3 The part of MTs and STs in daily control tasks for steam boiler

MTs		STs	
$MT_i; i = 1, ..., 5$	Definition	STs$ST_{i_j}; j = 1, ..., m$	Definition
MT_1	Control steam boiler water-level indicator	ST_{1_1}	See if boiler water level is within desired range
MT_2	Control of steam lines	ST_{2_1} ST_{2_2}	See that the steam outlet valve on the boiler is open See if the inlet and outlet valves in the vapor collector are open
⋮	⋮	⋮	⋮
MT_5	Security and warning system control	ST_{5_1} ST_{5_2} ST_{5_3}	Check whether the safety valves are easily opened or closed Adjust safety ventilator settings to a pressure value above 10% Check that the boiler presostalt settings are correct

Abbreviations: MT, main task; ST, subtask.

effect), 4 (very high effect)" which is used in traditional DEMATEL (Fontela & Gobus, 1974).

The effect of each MT on the other MTs for the kth expert is indicated as $(e_{il})^{k(h)}$ for HREs and $(e_{il})^{k(mc)}$; $i = 1, 2, ..., n$ and $l = 1, 2, ..., n$, $i \neq l$ for MREs. The effect of each MT on each ST is denoted as $(e_{i i_j})^{k(h)}$ and $(e_{i i_j})^{k(mc)}$; $i = 1, ..., v, ..., n$; $j = 1, ..., u, ... m$. The effect of each ST on MTs are indicated as $(e_{i_j i})^{k(h)}$ and $(e_{i_j i})^{k(mc)}$. This can be defined as the effect of jth ST included in ith MT on ith MT. The effect of each ST on the other STs is proven as $(e_{i_j i_{i_j}})^{k(h)}$ and $(e_{i_j i_{i_j}})^{k(mc)}$. The effect of each EPC on each MT is presented as $(e_{b_i})^{k(h)}$ and $(e_{b_i})^{k(mc)}$; $b = 1, ..., 40$ and the effect of each EPC on each ST is represented as $(e_{b_{i_j}})^{k(h)}$ and $(e_{b_{i_j}})^{k(mc)}$. The effect of each MT on each EPC is demonstrated as $(e_{i_b})^{k(h)}$ and $(e_{i_b})^{k(mc)}$. The effect of each ST on EPCs is proven as $(e_{i_{j_b}})^{k(h)}$, $(e_{i_{j_b}})^{k(mc)}$ and finally the effect of each EPC on the other EPCs is denoted as $\left(e_{b_z}\right)^{k(h)}$ and $(e_{b_z})^{k(mc)}$ $b = 1, 2, ..., 40$ and $z = 1, 2, ..., 40$, $b \neq z$. For example, $(e_{1 5_3})^{1(h)}$ shows that the first MT effects the third ST in the fifth MT at medium level according to the first expert for HREs as seen in Table 6 for steam boiler daily control process.

Table 7 shows integrated effect matrix for the first expert for the MREs for steam boiler working process.

TABLE 4 GTTs and EPCs for STs for daily control process according to E_1

MTs	STs	GTTs		EPCs for HREs	
MT_i $i = 1, ..., 5$	ST_{i_j} $j = 1, ..., m$	GTT_z $z = 1, ..., 9$	Definition	EPC_b $b = 1, ..., 40$	EPCs for MREs
MT_1	ST_{1_1}	GTT_5	E type GTT	EPC_2, EPC_{15}	–
MT_2	ST_{2_1}	GTT_5	E type GTT	EPC_2, EPC_{15}	–
	ST_{2_2}	GTT_5	E type GTT	EPC_{36}, EPC_{38}, EPC_{40}	–
MT_3	ST_{3_1}	GTT_5, GTT_6	E and F types GTTs	EPC_2, EPC_{15}, EPC_{37}	EPC_1, EPC_2, EPC_3, EPC_6, EPC_{12}, EPC_{13}, EPC_{14}, EPC_{15}, EPC_{20}, EPC_{25}, EPC_{26}, EPC_{31}, EPC_{36}
	ST_{3_2}	GTT_5, GTT_6	E and F types GTTs	EPC_{30}, EPC_{31}, EPC_{34}, EPC_{39}	EPC_1, EPC_2, EPC_3, EPC_6, EPC_{12}, EPC_{13}, EPC_{14}, EPC_{15}, EPC_{20}, EPC_{25}, EPC_{26}, EPC_{31}, EPC_{36}
	ST_{3_3}	GTT_5, GTT_6	E and F types GTTs	EPC_2, EPC_3, EPC_{15}, EPC_{37}	–
	ST_{3_4}	GTT_5	E type GTT	EPC_{30}, EPC_{31}, EPC_{34}, EPC_{39}	–
MT_4	ST_{4_1}	GTT_5, GTT_6	E and F types GTTs	EPC_2, EPC_{15}, EPC_{37}	EPC_1, EPC_2, EPC_3, EPC_6, EPC_{12}, EPC_{13}, EPC_{14}, EPC_{15}, EPC_{20}, EPC_{25}, EPC_{26}, EPC_{31}, EPC_{36}
	ST_{4_2}	GTT_5	E type GTT	EPC_2, EPC_{15}	–
	ST_{4_3}	GTT_5	E type GTT	EPC_2, EPC_3, EPC_4, EPC_{15}, EPC_{37}	EPC_1, EPC_2, EPC_3, EPC_6, EPC_{12}, EPC_{13}, EPC_{14}, EPC_{15}, EPC_{20}, EPC_{25}, EPC_{26}, EPC_{31}, EPC_{36}
	ST_{4_4}	GTT_8	H type GTT	EPC_2, EPC_{15}, EPC_{37}	–
	ST_{4_5}	GTT_6	F type GTT	EPC_2, EPC_{15}, EPC_{31}, EPC_{34}, EPC_{37}, EPC_{36}, EPC_{38}, EPC_{40}	EPC_1, EPC_2, EPC_3,EPC_{12}, EPC_{13}, EPC_{14}, EPC_{15}, EPC_{20}, EPC_{25}, EPC_{26}
MT_5	ST_{5_1}	GTT_5	E type GTT	EPC_2, EPC_4, EPC_6	–
	ST_{5_2}	GTT_6	F type GTT	EPC_2, EPC_4	–
	ST_{5_3}	GTT_6	F type GTT	EPC_2, EPC_3, EPC_4, EPC_{15}	EPC_1, EPC_2, EPC_3,EPC_{12}, EPC_{13}, EPC_{14}, EPC_{15}, EPC_{20}, EPC_{25}, EPC_{26}

Abbreviations: EPC, error producing condition; GTT, generic task type; MRE, machine-related error; MT, main task; ST, subtask.

TABLE 5 Structure of $[E]_1^h$

Components	MT_1	MT_2	…	MT_5	ST_{1_1}	…	ST_{5_3}	EPC_2	…	EPC_{39}	EPC_{40}
MT_1	0.00	$(e_{1_2})^{1(h)}$	…	$(e_{1_5})^{1(h)}$	$(e_{1_{1_1}})^{1(h)}$	…	$(e_{1_{5_3}})^{1(h)}$	$(e_{1_2})^{1(h)}$	…	$(e_{1_{39}})^{1(h)}$	$(e_{1_{40}})^{1(h)}$
MT_2	$(e_{2_1})^{1(h)}$	0.00	…	$(e_{2_5})^{1(h)}$	$(e_{2_{1_1}}^{1(h)})$	…	$(e_{2_{5_3}})^{1(h)}$	$(e_{2_2})^{1(h)}$	…	$(e_{2_{39}})^{1(h)}$	$(e_{2_{40}})^{1(h)}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	$(e_{5_1})^{1(h)}$	$(e_{5_2})^{1(h)}$	…	0.00	$(e_{5_{1_1}})^{1(h)}$	…	$(e_{(5(5_3))})^{(1(h))}$	$(e_{5_2})^{1(h)}$	…	$(e_{5_{39}})^{1(h)}$	$(e_{5_{40}})^{1(h)}$
ST_{1_1}	$(e_{1_{1_1}})^{1(h)}$	$(e_{1_{1_2}})^{1(h)}$	…	$(e_{1_{1_5}})^{1(h)}$	0.00	…	$(e_{1_{1_{5_3}}})^{1(h)}$	$(e_{1_{1_2}})^{1(h)}$	…	$(e_{1_{1_{39}}})^{1(h)}$	$(e_{1_{1_{40}}})^{1(h)}$
ST_{2_1}	$(e_{2_{1_1}})^{1(h)}$	$(e_{2_{1_2}})^{1(h)}$	…	$(e_{2_{1_5}})^{1(h)}$	$(e_{2_{1_{1_1}}})^{1(h)}$	…	$(e_{2_{1_{5_3}}})^{1(h)}$	$(e_{2_{1_2}})^{1(h)}$	…	$(e_{2_{1_{39}}})^{1(h)}$	$(e_{2_{1_{40}}})^{1(h)}$
ST_{2_2}	$(e_{2_{2_1}})^{1(h)}$	$(e_{2_{2_2}})^{1(h)}$	…	$(e_{2_{2_5}})^{1(h)}$	$(e_{2_{2_{1_1}}})^{1(h)}$	…	$(e_{2_{2_{5_3}}})^{1(h)}$	$(e_{2_{2_2}})^{1(h)}$	…	$(e_{2_{2_{39}}})^{1(h)}$	$(e_{2_{1_{40}}})^{1(h)}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	$(e_{5_{1_1}})^{1(h)}$	$(e_{5_{1_2}})^{1(h)}$	…	$(e_{5_{1_5}})^{1(h)}$	$(e_{5_{1_{1_1}}})^{1(h)}$	…	$(e_{5_{1_{2_3}}})^{1(h)}$	$(e_{5_{1_2}})^{1(h)}$	…	$(e_{5_{1_{39}}})^{1(h)}$	$(e_{5_{1_{40}}})^{1(h)}$
ST_{5_2}	$(e_{5_{2_1}})^{1(h)}$	$(e_{5_{2_2}})^{1(h)}$	…	$(e_{5_{2_3}})^{1(h)}$	$(e_{5_{2_{1_1}}})^{1(h)}$	…	$(e_{5_{2_{5_3}}})^{1(h)}$	$(e_{5_{2_2}})^{1(h)}$	…	$(e_{5_{2_{39}}})^{1(h)}$	$(e_{5_{2_{40}}})^{1(h)}$
ST_{5_3}	$(e_{5_{3_1}})^{1(h)}$	$(e_{5_{3_2}})^{1(h)}$	…	$(e_{5_{3_5}})^{1(h)}$	$(e_{5_{3_{1_1}}})^{1(h)}$	…	0.00	$(e_{5_{3_2}})^{1(h)}$	…	$(e_{5_{3_{39}}})^{1(h)}$	$(e_{5_{3_{40}}})^{1(h)}$
EPC_2	$(e_{2_1})^{1(h)}$	$(e_{2_2})^{1(h)}$	…	$(e_{2_5})^{1(h)}$	$(e_{2_{1_1}})^{1(h)}$	…	$(e_{2_{5_3}})^{1(h)}$	0.00	…	$(e_{2_{39}})^{1(h)}$	$(e_{2_{40}})^{1(h)}$
EPC_3	$(e_{3_1})^{1(h)}$	$(e_{3_2})^{1(h)}$	…	$(e_{3_5})^{1(h)}$	$(e_{3_{1_1}})^{1(h)}$	…	$(e_{3_{5_3}})^{1(h)}$	$(e_{3_2})^{1(h)}$	…	$(e_{3_{39}})^{1(h)}$	$(e_{2_{40}})^{1(h)}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	$(e_{38_1})^{1(h)}$	$(e_{38_2})^{1(h)}$	…	$(e_{38_5})^{1(h)}$	$(e_{38_{1_1}})^{1(h)}$	…	$(e_{38_{5_2}})^{1(h)}$	$(e_{38_2})^{1(h)}$	…	$(e_{38_{39}})^{1(h)}$	$(e_{38_{40}})^{1(h)}$
EPC_{39}	$(e_{39_1})^{1(h)}$	$(e_{39_2})^{1(h)}$	…	$(e_{39_5})^{1(h)}$	$(e_{39_{1_1}})^{1(h)}$	…	$(e_{39_{5_3}})^{1(h)}$	$(e_{39_2})^{1(h)}$	…	0.00	$(e_{39_{40}})^{1(h)}$
EPC_{40}	$(e_{40_1})^{1(h)}$	$(e_{40_2})^{1(h)}$	…	$(e_{40_5})^{1(h)}$	$(e_{40_{1_1}})^{1(h)}$	…	$(e_{40_{2_2}})^{1(h)}$	$(e_{40_2})^{1(h)}$	…	$(e_{40_{39}})^{1(h)}$	0.00

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

TABLE 6 $[E]_1^h$ for steam boiler daily control process

Components	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	1.00	...	1.00	0.00	1.00	1.00	...	1.00	2.00	3.00	2.00	...	0.00	0.00
MT_2	1.00	0.00	...	3.00	2.00	0.00	0.00	...	4.00	2.00	4.00	2.00	...	0.00	1.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	4.00	2.00	...	0.00	4.00	2.00	1.00	...	0.00	0.00	0.00	2.00	...	0.00	0.00
ST_{1_1}	4.00	1.00	...	2.00	0,00	1.00	3.00	...	2.00	1.00	2.00	3.00	...	0.00	0.00
ST_{2_1}	4.00	4.00	...	2.00	2.00	0.00	1.00	...	3.00	2.00	4.00	2.00	...	0.00	0.00
ST_{2_2}	1.00	4.00	...	1.00	2.00	3.00	0.00	...	4.00	2.00	3.00	0.00	...	0.00	1.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	2.00	1.00	...	4.00	4.00	1.00	2.00	...	0.00	2.00	4.00	3.00	...	0.00	0.00
ST_{5_2}	1.00	2.00	...	4.00	3.00	2.00	2.00	...	2.00	0.00	3.00	1.00	...	0.00	0.00
ST_{5_3}	1.00	2.00	...	4.00	3.00	2.00	2.00	...	4.00	3.00	0.00	2.00	...	0.00	0.00
EPC_2	2.00	4.00	...	2.00	1.00	2.00	0.00	...	4.00	2.00	4.00	0.00	...	2.00	2.00
EPC_3	0.00	0.00	...	2.00	0.00	0.00	0.00	...	0.00	0.00	2.00	2.00	...	1.00	2.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	0.00	2.00	...	0.00	0.00	0.00	2.00	...	0.00	0.00	0.00	4.00	...	2.00	1.00
EPC_{39}	0.00	0.00	...	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00	4.00	...	0.00	1.00
EPC_{40}	0.00	1.00	...	0.00	0.00	0.00	2.00	...	0.00	0.00.	0.00	4.00	...	3.00	0.00

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

Step 4. Combine integrated effect matrix of all experts for HREs and MREs

$[E]_k^h$ and $[E]_k^{mc}$ of all experts are combined by using arithmetic mean and the structure of combined integrated effect matrix for HREs ($[E]^h$) is shown in Table 8. The average effect of each MT on the other MTs is indicated as e_{il}^h for HREs and e_{il}^{mc}; $i = 1, 2, ..., n$ and $l = 1,2, ..., n, i \neq l$ for MREs. The average effect of each MT on each ST is denoted as $e_{i_{l_j}}^h$ and $e_{i_{l_j}}^{mc}$; $i = 1, ..., v, ..., n$; $j = 1, ..., u, ..., m$. The average effect of each ST on MTs are shown as $e_{i_{j_l}}^h$ and $e_{i_{j_l}}^{mc}$. The

TABLE 7 $[E]_1^{mc}$ for steam boiler working process

Components	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	1.00	...	1.00	0.00	1.00	1.00	...	1.00	2.00	3.00	2.00	...	2.00	1.00
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
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_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
ST_{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
ST_{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
ST_{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
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
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
ST_{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
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	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

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

TABLE 8 Structure of $[E]^h$

Components	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	e^h_{12}	…	e^h_{15}	$e^h_{11_1}$	$e^h_{12_1}$	$e^h_{12_2}$	…	$e^h_{15_1}$	$e^h_{15_2}$	$e^h_{15_3}$	e^h_{12}	…	e^h_{139}	e^h_{140}
MT_2	e^h_{21}	0.00	…	e^h_{25}	$e^h_{21_1}$	$e^h_{22_1}$	$e^h_{22_2}$	…	$e^h_{25_1}$	$e^h_{25_2}$	$e^h_{25_3}$	e^h_{22}	…	e^h_{239}	e^h_{240}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	e^h_{51}	e^h_{52}	…	0.00	$e^h_{51_1}$	$e^h_{52_1}$	$e^h_{52_2}$	…	$e^h_{55_1}$	$e^h_{55_2}$	$e^h_{55_3}$	e^h_{52}	…	e^h_{539}	e^h_{540}
ST_{1_1}	$e^h_{1_11}$	$e^h_{1_12}$	…	$e^h_{1_15}$	0.00	$e^h_{1_12_1}$	$e^h_{1_12_2}$	…	$e^h_{1_15_1}$	$e^h_{1_15_2}$	$e^h_{1_15_3}$	$e^h_{1_12}$	…	$e^h_{1_139}$	$e^h_{1_140}$
ST_{2_1}	$e^h_{2_11}$	$e^h_{2_12}$	…	$e^h_{2_15}$	$e^h_{2_11_1}$	0.00	$e^h_{2_12_2}$	…	$e^h_{2_15_1}$	$e^h_{2_15_2}$	$e^h_{2_15_3}$	e^h_{212}	…	e^h_{2139}	e^h_{2140}
ST_{2_2}	$e^h_{2_21}$	$e^h_{2_22}$	…	$e^h_{2_25}$	$e^h_{2_21_1}$	$e^h_{2_22_1}$	0.00	…	$e^h_{2_25_1}$	$e^h_{2_25_2}$	$e^h_{2_25_3}$	e^h_{222}	…	e^h_{2239}	e^h_{2240}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	$e^h_{5_11}$	$e^h_{5_12}$	…	$e^h_{5_15}$	$e^h_{5_11_1}$	$e^h_{5_12_1}$	$e^h_{5_12_2}$	…	0.00	$e^h_{5_15_2}$	$e^h_{5_12_3}$	$e^h_{5_12}$	…	$e^h_{5_139}$	$e^h_{5_140}$
ST_{5_2}	$e^h_{5_21}$	$e^h_{5_22}$	…	$e^h_{5_23}$	$e^h_{5_21_1}$	$e^h_{5_22_1}$	$e^h_{5_22_2}$	…	$e^h_{5_25_1}$	0.00	$e^h_{5_25_3}$	$e^h_{5_22}$	…	$e^h_{5_239}$	$e^h_{5_240}$
ST_{5_3}	$e^h_{5_31}$	$e^h_{5_32}$	…	$e^h_{5_35}$	$e^h_{5_31_1}$	$e^h_{5_32_1}$	$e^h_{5_32_2}$	…	$e^h_{5_35_1}$	$e^h_{5_35_2}$	0.00	$e^h_{5_32}$	…	$e^h_{5_339}$	$e^h_{5_340}$
EPC_2	e^h_{21}	e^h_{22}	…	e^h_{25}	$e^h_{21_1}$	$e^h_{22_1}$	$e^h_{22_2}$	…	$e^h_{25_1}$	$e^h_{25_2}$	$e^h_{25_3}$	0.00	…	$e^h_{5_439}$	$e^h_{5_440}$
EPC_3	e^h_{31}	e^h_{32}	…	e^h_{35}	$e^h_{31_1}$	$e^h_{32_1}$	$e^h_{32_2}$	…	$e^h_{35_1}$	$e^h_{35_2}$	$e^h_{35_3}$	$e^h_{35_4}$	…	$e^h_{5_539}$	$e^h_{5_540}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	e^h_{381}	e^h_{382}	…	e^h_{385}	$e^h_{381_1}$	$e^h_{382_1}$	$e^h_{382_2}$	…	$e^h_{385_1}$	$e^h_{385_1}$	$e^h_{385_2}$	e^h_{382}	…	e^h_{3839}	e^h_{3840}
EPC_{39}	e^h_{391}	e^h_{392}	…	e^h_{395}	$e^h_{391_1}$	$e^h_{392_1}$	$e^h_{392_2}$	…	$e^h_{395_1}$	$e^h_{395_2}$	$e^h_{395_3}$	e^h_{392}	…	0.00	e^h_{3940}
EPC_{40}	e^h_{401}	e^h_{402}	…	e^h_{405}	$e^h_{401_1}$	$e^h_{402_1}$	$e^h_{402_2}$	…	$e^h_{401_1}$	$e^h_{402_1}$	$e^h_{402_2}$	e^h_{402}	…	e^h_{4039}	0.00

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

average effect of each ST on the other STs is proven as $e^h_{i_{j_{i_j}}}$ and $e^{mc}_{i_{j_{i_j}}}$. The average effect of each EPC on each MT is presented as $e^h_{b_i}$ and $e^{mc}_{b_i}$; $b = 1, \ldots, 40$ and the average effect of each EPC on each ST is represented as $e^h_{b_{i_j}}$ and $e^{mc}_{b_{i_j}}$. The average effect of each MT on each EPC is demonstrated as $e^h_{i_b}$ and $e^{mc}_{i_b}$. The average effect of each ST on EPCs is proven as $e^h_{i_{j_b}}$ and $e^{mc}_{i_{j_b}}$. Finally, the average effect of each EPC on the other EPCs is denoted as $e^h_{b_z}$ and $e^{mc}_{b_z}$; $b = 1, 2, \ldots, 40$ and $z = 1, 2, \ldots, 40, b \neq z$.

$[E]^h$ is given in Table 9 for steam boiler daily control process. The same matrix is formed for MREs.

Step 5. Form the normalized combined effect relation matrix for HREs and MREs

Normalized effect matrix $[N]^h$ and $[N]^{mc}$ are structured via computing the maximum values of rows and maximum values of columns in $[E]^h$ and $[E]^{mc}$ for in order of HREs and MREs. Then, the minimum value named as "x" 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 Equation (3). Finally, x is multiplied with $[E]^h$ and $[E]^{mc}$ to form $[N]^h$ and $[N]^{mc}$ seen in Tables 10 and 11 as in Equation (4) and (5).

$$x = \text{Min}\left(\frac{1}{\max s_r}, \frac{1}{\max s_c}\right). \quad (3)$$

$$[N]^h = x \times [E]^h. \quad (4)$$

$$[N]^{mc} = x \times [E]^{mc}. \quad (5)$$

For HREs and MREs, the normalized effect of each MT on the other MTs is indicated as d^h_{il} and d^{mc}_{il}; $i = 1, 2, \ldots, n$ and $l = 1, 2, \ldots, n, i \neq l$ and the normalized effect of each MT on each ST is denoted as $d^h_{ii_j}$ and $d^{mc}_{ii_j}$; $i = 1, \ldots, v, \ldots, n$; $j = 1, \ldots, u, \ldots m$. The normalized effect of each ST on MTs are shown as $d^h_{i_{ji}}$ and $d^{mc}_{i_{ji}}$. The normalized effect of each ST on the other STs is proven as $d^h_{i_{j_{i_j}}}$ and $d^{mc}_{i_{j_{i_j}}}$. The normalized effect of each EPC on each MT is presented as $d^h_{b_i}$ and $d^{mc}_{b_i}$; $b = 1, \ldots, 40$ and the normalized effect of each EPC on each ST is represented as $d^h_{b_{i_j}}$ and $d^{mc}_{b_{i_j}}$. The normalized effect of each MT on each EPC is demonstrated as $d^h_{i_b}$ and $d^{mc}_{i_b}$. The normalized effect of each ST on EPCs is proven as $d^h_{i_{j_b}}$ and $d^{mc}_{i_{j_b}}$ and finally the normalized effect of each EPC on the other EPCs is denoted as $d^h_{b_z}$ and $d^{mc}_{b_z}$; $b = 1, 2, \ldots, 40$ and $z = 1, 2, \ldots, 40, b \neq z$. Structure of normalized combined effect matrix is shown in Table 10 for HREs.

TABLE 9 $[E]^h$ for steam boiler daily control process

Components	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}	Max
MT_1	0.00	1.00	…	1.00	0.00	1.00	1.00	…	1.00	2.67	3.00	0.67	…	0.00	1.00	4.00
MT_2	1.00	0.00	…	3.00	2.00	0.00	0.00	…	4.00	2.00	4.00	1.33	…	0.33	0.67	4.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
MT_5	3.33	2.00	…	0.00	4.00	2.00	1.00	…	0.00	0.00	0.00	0.67	…	0.67	0.67	4.00
ST_{1_1}	4.00	1.00	…	2.00	0.00	1.00	3.00	…	2.67	1.00	2.00	1.00	…	0.00	1.00	4.00
ST_{2_1}	4.00	4.00	…	2.00	2.00	0.00	1.00	…	3.67	2.67	4.00	1.33	…	0.33	0.33	4.00
ST_{2_2}	1.00	4.00	…	1.00	2.00	3.00	0.00	…	2.00	2.00	1.67	0.00	…	0.67	0.33	4.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	2.00	1.00	…	4.00	4.00	1.00	2.00	…	0.00	2.00	4.00	1.00	…	0.00	1.00	4.00
ST_{5_2}	1.00	2.00	…	4.00	2.00	2.00	2.67	…	2.00	0.00	3.00	0.33	…	0.00	0.67	4.00
ST_{5_3}	1.00	2.00	…	4.00	3.00	2.00	2.00	…	4.00	3.00	0.00	0.67	…	0.33	0.33	4.00
EPC_2	0.67	2.67	…	0.67	0.33	0.67	1.33	…	1.33	0.67	1.33	0.00	…	2.00	2.00	4.00
EPC_3	0.00	0.00	…	0.67	0.00	0.00	0.00	…	0.00	0.00	0.67	1.33	…	1.00	1.33	4.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	1.33	1.33	…	1.00	1.33	1.33	0.67	…	0.00	0.00	1.33	3.00	…	2.00	1.00	4.00
EPC_{39}	0.00	0.67	…	0.67	0.00	0.00	0.67	…	0.00	0.00	1.33	4.00	…	0.00	1.00	4.00
EPC_{40}	0.67	0.67	…	2.00	1.00	0.33	0.67	…	0.67	0.67	2.33	3.00	…	3.00	0.00	4.00
Max	4.00	4.00	…	4.00	4.00	4.00	3.00	…	4.00	4.00	4.00	4.00	4.00	3.00	3.00	

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

$[N]^h$ is given in Table 11 for steam boiler daily control process. The same matrix is structured for MREs.

Step 6. Form the total effect relation matrix for HREs and MREs

Total Effect Relation Matrices $[T]^h$ and $[T]^{mc}$ are formed as in Equations (6) and (7) for in order of HREs and MREs. The structure of $[T]^h$ is given in Table 12.

$$[T]^h = [N]^h + N^{2h} + N^{3h} + \cdots = \sum_{f=1}^{\infty} N^{fh}, \qquad (6)$$
$$[T]^h = [N]^h (I - [N]^h)^{-1}.$$

$$[T]^{mc} = [N]^{mc} + N^{2mc} + N^{3mc} + \cdots = \sum_{f=1}^{\infty} N^{fmc}, \qquad (7)$$
$$[T]^{mc} = [N]^{mc} (I - [N]^{mc})^{-1},$$

where $[I]$ is the unit matrix.

The total effect relation of each MT on the other MTs for HREs and MREs is indicated as g_{il}^h and g_{il}^{mc}; $i = 1, 2, \ldots, n$ and $l = 1, 2, \ldots, n, i \neq l$, respectively. and the total effect relation of each MT on each ST is denoted as $g_{i_{i_j}}^h$ and $g_{i_{i_j}}^{mc}$; $i = 1, \ldots, v, \ldots n$; $j = 1, \ldots, u, \ldots m$. The total effect relation of each ST on MTs are shown as $g_{i_{ji}}^h$ and $g_{i_{ji}}^{mc}$. The total effect relation of each ST on the other STs is proven as $g_{i_{i_{j_{l_j}}}}^h$ and $g_{i_{i_{j_{l_j}}}}^{mc}$. The total effect relation of each EPC on each MT is presented as g_{bi}; $b = 1, \ldots, 40$ and the total effect relation of each EPC on each ST is represented as $g_{b_{i_j}}^h$ and $g_{b_{i_j}}^{mc}$. The total effect relation of each MT on each EPC is demonstrated as g_{ib}. The total effect relation of each ST on EPCs is proven as $g_{i_{j_b}}^h$ and $g_{i_{j_b}}^{mc}$ and finally the total effect relation of each EPC on the other EPCs is denoted as $g_{b_z}^h$ and $g_{b_z}^{mc}$; $b = 1, 2, \ldots, 40$ and $z = 1, 2, \ldots, 40$, $b \neq z$. Table 13 presents $[T]^h$ for the steam boiler working process.

Step 7. Compute the effect and relation values for HREs and MREs

The row summations of $[T]^h$ indicated as D_s^h;$s = n + m + 40$ and the column summations of $[T]^{mc}$ denoted as R_s^h;$s = n + m + 40$ are computed. Then, $D_s^h + R_s^h$ named as relation level with the other components of the decision system and $D_s^h - R_s^h$ values called an effect level between the components of the decision system are obtained. Some of the components have positive $D_s^h - R_s^h$ values. These have more effect than others. The components which have negative $D_s^h - R_s^h$ values are affected more by the others. In addition, the components which have higher $D_s + R_s$ values are more related to the others. As opposed to, the components which have lower $D_s^h + R_s^h$ values than the others are lesser related to the others. D_s^h,R_s^h, $D_s^h + R_s^h$, and $D_s^h - R_s^h$ for HREs and D_s^{mc},R_s^{mc}, $D_s^{mc} + R_s^{mc}$, and $D_s^{mc} - R_s^{mc}$ for MREs for the steam boiler working process are shown in Table 14.

According to Table 14, MT_4 has the lowest $D_s^h - R_s^h$ value (−0.249) and EPC_{39} has the highest $D_s^h - R_s^h$ value (0.198). In the same manner, MT_5 has the highest $D_s^h + R_s^h$ value (1.810) and EPC_{37} has the lowest $D_s^h + R_s^h$ value (0.627).

TABLE 10 Structure of $[N]^h$

Components	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	d^h_{12}	...	d^h_{15}	$d^h_{11_1}$	$d^h_{12_1}$	$d^h_{12_2}$	...	$d^h_{15_1}$	$d^h_{15_2}$	$d^h_{15_3}$	d^h_{12}	...	d^h_{139}	d^h_{140}
MT_2	d^h_{21}	0.00	...	d^h_{25}	$d^h_{21_1}$	$d^h_{22_1}$	$d^h_{22_2}$	...	$d^h_{25_1}$	$d^h_{25_2}$	$d^h_{25_3}$	d^h_{22}	...	d^h_{239}	d^h_{240}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	d^h_{51}	d^h_{52}	...	0.00	$d^h_{51_1}$	$d^h_{52_1}$	$d^h_{52_2}$	...	$d^h_{55_1}$	$d^h_{55_2}$	$d^h_{55_3}$	d^h_{52}	...	d^h_{539}	d^h_{540}
ST_{1_1}	$d^h_{11_1}$	$d^h_{11_2}$	...	$d^h_{11_5}$	0.00	$d^h_{112_1}$	$d^h_{112_2}$	...	$d^h_{115_1}$	$d^h_{115_2}$	$d^h_{115_3}$	d^h_{112}	...	d^h_{1139}	d^h_{1140}
ST_{2_1}	$d^h_{21_1}$	$d^h_{21_2}$	...	$d^h_{21_5}$	$d^h_{211_1}$	0.00	$d^h_{212_2}$	...	$d^h_{215_1}$	$d^h_{215_2}$	$d^h_{215_3}$	d^h_{212}	...	d^h_{2139}	d^h_{2140}
ST_{2_2}	$d^h_{22_1}$	$d^h_{22_2}$	...	$d^h_{22_5}$	$d^h_{221_1}$	$d^h_{222_1}$	0.00	...	$d^h_{225_1}$	$d^h_{225_2}$	$d^h_{225_3}$	d^h_{222}	...	d^h_{2239}	d^h_{2240}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	$d^h_{51_1}$	$d^h_{51_2}$	...	$d^h_{51_5}$	$d^h_{511_1}$	$d^h_{512_1}$	$d^h_{512_2}$	...	0.00	$d^h_{515_2}$	$d^h_{512_3}$	$d^h_{51_2}$	...	d^h_{5139}	d^h_{5140}
ST_{5_2}	$d^h_{52_1}$	$d^h_{52_2}$	...	$d^h_{52_3}$	$d^h_{521_1}$	$d^h_{522_1}$	$d^h_{522_2}$	...	$d^h_{525_1}$	0.00	$d^h_{525_3}$	$d^h_{52_2}$	...	d^h_{5239}	d^h_{5240}
ST_{5_3}	$d^h_{53_1}$	$d^h_{53_2}$	...	$d^h_{53_5}$	$d^h_{531_1}$	$d^h_{532_1}$	$d^h_{532_2}$	...	$d^h_{535_1}$	$d^h_{535_2}$	0.00	$d^h_{53_2}$	...	d^h_{5339}	d^h_{5340}
EPC_2	d^h_{21}	d^h_{22}	...	d^h_{25}	$d^h_{21_1}$	$d^h_{22_1}$	$d^h_{22_2}$	...	$d^h_{25_1}$	$d^h_{25_2}$	$d^h_{25_3}$	0.00	...	d^h_{239}	d^h_{240}
EPC_3	d^h_{31}	d^h_{32}	...	d^h_{35}	$d^h_{31_1}$	$d^h_{32_1}$	$d^h_{32_2}$	...	$d^h_{35_1}$	$d^h_{35_2}$	$d^h_{35_3}$	d^h_{32}	...	d^h_{339}	d^h_{340}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	d^h_{381}	d^h_{382}	...	d^h_{385}	$d^h_{381_1}$	$d^h_{382_1}$	$d^h_{382_2}$	...	$d^h_{385_1}$	$d^h_{385_1}$	$d^h_{385_2}$	d^h_{382}	...	d^h_{3839}	d^h_{3840}
EPC_{39}	d^h_{391}	d^h_{392}	...	d^h_{395}	$d^h_{391_1}$	$d^h_{392_1}$	$d^h_{392_2}$	...	$d^h_{395_1}$	$d^h_{395_2}$	$d^h_{395_3}$	d^h_{392}	...	0.00	d^h_{3940}
EPC_{40}	d^h_{401}	d^h_{402}	...	d^h_{405}	$d^h_{401_1}$	$d^h_{402_1}$	$d^h_{402_2}$	...	$d^h_{401_1}$	$d^h_{402_1}$	$d^h_{402_2}$	d^h_{402}	...	d^h_{4039}	0.00

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

TABLE 11 $[N]^h$ for steam boiler working process

Components	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	0.01	...	0.00	0.01
MT_2	0.01	0.00	...	0.02	0.02	0.00	0.00	...	0.03	0.02	0.03	0.01	...	0.00	0.01
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	0.03	0.02	...	0.00	0.03	0.02	0.01	...	0.00	0.00	0.00	0.01	...	0.01	0.01
ST_{1_1}	0.03	0.01	...	0.02	0.00	0.01	0.02	...	0.02	0.01	0.02	0.01	...	0.00	0.01
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	0.01	...	0.00	0.00
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	0.02	0.01	...	0.03	0.03	0.01	0.02	...	0.00	0.02	0.03	0.01	...	0.00	0.01
ST_{5_2}	0.01	0.02	...	0.03	0.02	0.02	0.02	...	0.02	0.00	0.02	0.00	...	0.00	0.01
ST_{5_3}	0.01	0.02	...	0.03	0.02	0.02	0.02	...	0.03	0.02	0.00	0.01	...	0.00	0.00
EPC_2	0.01	0.02	...	0.01	0.00	0.01	0.01	...	0.01	0.01	0.01	0.00	...	0.02	0.02
EPC_3	0.00	0.00	...	0.01	0.00	0.00	0.00	...	0.00	0.00	0.01	0.01	...	0.01	0.01
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	0.01	0.01	...	0.01	0.01	0.01	0.01	...	0.00	0.00	0.01	0.02	...	0.02	0.01
EPC_{39}	0.00	0.01	...	0.01	0.00	0.00	0.01	...	0.00	0.00	0.01	0.03	...	0.00	0.01
EPC_{40}	0.01	0.01	...	0.02	0.01	0.00	0.01	...	0.01	0.01	0.02	0.02	...	0.02	0.00

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

TABLE 12 Structure of $[T]^h$

Components	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	$g^h_{1_2}$	…	$g^h_{1_5}$	$g^h_{1_{1_1}}$	$g^h_{1_{2_1}}$	$g^h_{1_{2_2}}$	…	$g^h_{1_{5_1}}$	$g^h_{1_{5_2}}$	$g^h_{1_{5_3}}$	$g^h_{1_2}$	…	$g^h_{1_{39}}$	$g^h_{1_{40}}$
MT_2	$g^h_{2_1}$	0.00	…	$g^h_{2_5}$	$g^h_{2_{1_1}}$	$g^h_{2_{2_1}}$	$g^h_{2_{2_2}}$	…	$g^h_{2_{5_1}}$	$g^h_{2_{5_2}}$	$g^h_{2_{5_3}}$	$g^h_{2_2}$	…	$g^h_{2_{39}}$	$g^h_{2_{40}}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	$g^h_{5_1}$	$g^h_{5_2}$	…	0.00		$g^h_{5_{2_1}}$	$g^h_{5_{2_2}}$	…	$g^h_{5_{5_1}}$	$g^h_{5_{5_2}}$	$g^h_{5_{5_3}}$	$g^h_{5_2}$	…	$g^h_{5_{39}}$	$g^h_{5_{40}}$
ST_{1_1}	$g^h_{1_{1_1}}$	$g^h_{1_{1_2}}$	…	$g^h_{1_{1_5}}$	0.00	$g^h_{1_{1_{2_1}}}$	$g^h_{1_{1_{2_2}}}$	…	$g^h_{1_{1_{5_1}}}$	$g^h_{1_{1_{5_2}}}$	$g^h_{1_{1_{5_3}}}$	$g^h_{1_{12}}$	…	$g^h_{1_{139}}$	$g^h_{1_{140}}$
ST_{2_1}	$g^h_{2_{1_1}}$	$g^h_{2_{1_2}}$	…	$g^h_{2_{1_5}}$	$g^h_{2_{1_{1_1}}}$	0.00	$g^h_{2_{1_{2_2}}}$	…	$g^h_{2_{1_{5_1}}}$	$g^h_{2_{1_{5_2}}}$	$g^h_{2_{1_{5_3}}}$	$g^h_{2_{12}}$	…	$g^h_{2_{139}}$	$g^h_{2_{140}}$
ST_{2_2}	$g^h_{2_{2_1}}$	$g^h_{2_{2_2}}$	…	$g^h_{2_{2_5}}$	$g^h_{2_{2_{1_1}}}$	$g^h_{2_{2_{2_1}}}$	0.00	…	$g^h_{2_{2_{5_1}}}$	$g^h_{2_{2_{5_2}}}$	$g^h_{2_{2_{5_3}}}$	$g^h_{2_{22}}$	…	$g^h_{2_{239}}$	$g^h_{2_{240}}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_1}	$g^h_{5_{1_1}}$	$g^h_{5_{1_2}}$	…	$g^h_{5_{1_5}}$	$g^h_{5_{1_{1_1}}}$	$g^h_{5_{1_{2_1}}}$	$g^h_{5_{1_{2_2}}}$	…	0.00	$g^h_{5_{1_{5_2}}}$	$g^h_{5_{1_{2_3}}}$	$g^h_{5_{1_2}}$	…	$g^h_{5_{139}}$	$g^h_{5_{140}}$
ST_{5_2}	$g^h_{5_{2_1}}$	$g^h_{5_{2_2}}$	…	$g^h_{5_{2_3}}$	$g^h_{5_{2_{1_1}}}$	$g^h_{5_{2_{2_1}}}$	$g^h_{5_{2_{2_2}}}$	…	$g^h_{5_{2_{5_1}}}$	0.00	$g^h_{5_{2_{5_3}}}$	$g^h_{5_{2_2}}$	…	$g^h_{5_{239}}$	$g^h_{5_{240}}$
ST_{5_3}	$g^h_{5_{3_1}}$	$g^h_{5_{3_2}}$	…	$g^h_{5_{3_5}}$	$g^h_{5_{3_{1_1}}}$	$g^h_{5_{3_{2_1}}}$	$g^h_{5_{3_{2_2}}}$	…	$g^h_{5_{3_{5_1}}}$	$g^h_{5_{3_{5_2}}}$	0.00	$g^h_{5_{3_2}}$	…	$g^h_{5_{339}}$	$g^h_{5_{340}}$
EPC_2	$g^h_{2_1}$	$g^h_{2_2}$	…	$g^h_{2_5}$	$g^h_{2_{1_1}}$	$g^h_{2_{2_1}}$	$g^h_{2_{2_2}}$	…	$g^h_{2_{5_1}}$	$g^h_{2_{5_2}}$	$g^h_{2_{5_3}}$	0.00	…	$g^h_{2_{39}}$	$g^h_{2_{40}}$
EPC_3	$g^h_{3_1}$	$g^h_{3_2}$	…	$g^h_{3_5}$	$g^h_{3_{1_1}}$	$g^h_{3_{2_1}}$	$g^h_{3_{2_2}}$	…	$g^h_{3_{5_1}}$	$g^h_{3_{5_2}}$	$g^h_{3_{5_3}}$	$g^h_{3_2}$	…	$g^h_{3_{39}}$	$g^h_{3_{40}}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{38}	$g^h_{38_1}$	$g^h_{38_2}$	…	$g^h_{38_5}$	$g^h_{38_{1_1}}$	$g^h_{38_{2_1}}$	$g^h_{38_{2_2}}$	…	$g^h_{38_{5_1}}$	$g^h_{38_{5_1}}$	$g^h_{38_{5_2}}$	$g^h_{38_2}$	…	$g^h_{38_{39}}$	$g^h_{38_{40}}$
EPC_{39}	$g^h_{39_1}$	$g^h_{39_2}$	…	$g^h_{39_5}$	$g^h_{39_{1_1}}$	$g^h_{39_{2_1}}$	$g^h_{39_{2_2}}$	…	$g^h_{39_{5_1}}$	$g^h_{39_{5_2}}$	$g^h_{39_{5_3}}$	$g^h_{39_2}$	…	0.00	$g^h_{39_{40}}$
EPC_{40}	$g^h_{40_1}$	$g^h_{40_2}$	…	$g^h_{40_5}$	$g^h_{40_{1_1}}$	$g^h_{40_{2_1}}$	$g^h_{40_{2_2}}$	…	$g^h_{40_{1_1}}$	$g^h_{40_{2_1}}$	$g^h_{40_{2_2}}$	$g^h_{40_2}$	…	$g^h_{40_{39}}$	0.00

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

TABLE 13 $[T]^h$ for the steam boiler working process

Components	MT_1	MT_2	…	MT_5	ST_{1_1}	…	ST_{5_1}	ST_{5_2}	ST_{5_3}	EPC_2	…	EPC_{39}	EPC_{40}
MT_1	0.008	0.016	…	0.017	0.007	…	0.015	0.029	0.031	0.009	…	0.002	0.010
MT_2	0.016	0.009	…	0.032	0.023	…	0.038	0.024	0.038	0.015	…	0.005	0.008
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
MT_5	0.033	0.023	…	0.008	0.036	…	0.008	0.008	0.009	0.010	…	0.008	0.008
ST_{1_1}	0.038	0.017	…	0.024	0.007	…	0.028	0.016	0.024	0.012	…	0.002	0.010
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
ST_{5_3}	0.018	0.026	…	0.042	0.032	…	0.040	0.033	0.011	0.011	…	0.005	0.006
EPC_2	0.009	0.026	…	0.012	0.007	…	0.016	0.010	0.017	0.006	…	0.018	0.019
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
EPC_{40}	0.010	0.011	…	0.021	0.012	…	0.010	0.010	0.023	0.029	…	0.026	0.004

Abbreviations: EPC, error producing condition; MT, main task; ST, subtask.

TABLE 14 Effect and Relation values for HREs and MREs

Components	D_s^h	R_s^h	$D_s^h + R_s^h$	$D_s^h - R_s^h$	Components	D_s^{mc}	R_s^{mc}	$D_s^{mc} + R_s^{mc}$	$D_s^{mc} - R_s^{mc}$
MT_1	0.529	0.593	1.122	−0.065	MT_1	0.521	0.551	1.072	−0.031
MT_2	0.555	0.593	1.245	−0.134	MT_2	0.506	0.551	1.009	0.002
⋮	⋮	⋮	⋮	⋮	⋮				
MT_5	0.558	0.719	1.810	−0.160	MT_5	0.687	0.707	1.696	−0.020
ST_{11}	0.563	0.719	1.282	0.025	ST_{11}	0.465	0.437	1.172	0.028
ST_{21}	0.672	0.719	1.210	0.148	ST_{21}	0.548	0.564	0.985	−0.016
ST_{22}	0.564	0.719	1.088	0.043	ST_{22}	0.544	0.444	1.108	0.100
⋮	⋮	⋮	⋮	⋮	⋮				
ST_{51}	0.672	0.615	1.287	0.058	ST_{51}	0.822	0.606	1.428	0.215
ST_{52}	0.623	0.615	1.250	−0.004	ST_{52}	0.769	0.518	1.287	0.251
ST_{53}	0.688	0.615	1.396	−0.019	ST_{53}	0.844	0.679	1.524	0.165
EPC_1	0.529	0.615	1.041	0.017	EPC_2	0.439	0.711	1.150	−0.273
EPC_2	0.303	0.615	1.287	0.058	EPC_3	0.456	0.579	1.035	−0.122
⋮	⋮	⋮	⋮	⋮	⋮				
EPC_{38}	0.505	0.406	0.911	0.100	EPC_{26}	0.509	0.556	1.103	−0.085
EPC_{39}	0.469	0.406	0.740	0.198	EPC_{31}	0.400	0.594	0.998	−0.198
EPC_{40}	0.527	0.406	0.867	0.187	EPC_{36}	0.366	0.598	0.844	−0.113

Abbreviations: EPC, error producing condition; HRE, human-related error; MRE, machine-related error; MT, main task; ST, subtask.

Step 8. Compute the weights of MTs for HREs and MREs

To compute the weights of MTs denoted as W_i^h and W_i^{mc} for in order of HREs and MREs Equations (8) and (9) are used. The summations of W_i^h and W_i^{mc} should be equal to 1 separately.

$$W'^h_i = \sqrt{(D_s^h + R_s^h)^2 + (D_s^h - R_s^h)^2},$$
$$W_i^h = \frac{W'^h_i}{\sum_{i=1}^n W'^h_i}. \quad (8)$$

$$W'^{mc}_i = \sqrt{(D_s^{mc} + R_s^{mc})^2 + (D_s^{mc} - R_s^{mc})^2},$$
$$W_i^{mc} = \frac{W'^{mc}_i}{\sum_{i=1}^n W'^{mc}_i}, \quad (9)$$

where W'^h_i is the preweight value of each MT for HREs. W'^{mc}_i is the preweight value of each MT for MREs. The weights of MTs for steam boiler working process in the context of HREs and MREs are shown in Table 15.

It can be seen from Table 15, MT_5 has the highest importance weight as 0.271, MT_1 has the lowest importance weight (0.168) for

TABLE 15 The weights of MTs for steam boiler daily control process

MTs	W'^h_i	W_i^h	MTs	W'^{mc}_i	W_i^{mc}
MT_1	1.124	0.168	MT_1	1.072	0.160
MT_2	1.252	0.187	MT_2	1.009	0.151
MT_3	1.209	0.180	MT_3	1.368	0.204
MT_4	1.296	0.194	MT_4	1.557	0.232
MT_5	1.818	0.271	MT_5	1.696	0.253

Abbreviation: MT, main task.

TABLE 16 The weights of STs for daily control process of steam boiler

STs	w''^h_{ij}	w'^h_{ij}	w^h_{ij}	w''^{mc}_{ij}	w'^{mc}_{ij}	w^{mc}_{ij}
ST_{11}	1.282	1.00	0.168	1.172	1	0.160
ST_{21}	1.219	0.528	0.099	0.985	0.469	0.071
ST_{22}	1.089	0.472	0.088	1.113	0.531	0.080
ST_{31}	1.231	0.244	0.044	1.159	0.226	0.046
ST_{32}	1.424	0.283	0.051	1.364	0.266	0.054
ST_{33}	1.238	0.246	0.044	1.359	0.265	0.054
ST_{34}	1.146	0.227	0.041	1.253	0.244	0.050
ST_{41}	1.314	0.2062	0.040	1.466	0.2096	0.049
ST_{42}	1.228	0.1926	0.037	1.443	0.2063	0.048
ST_{43}	1.228	0.1926	0.037	1.190	0.1701	0.040
ST_{44}	1.276	0.2001	0.039	1.411	0.2016	0.047
ST_{45}	1.328	0.2084	0.040	1.485	0.337	0.085
ST_{51}	1.288	0.327	0.089	1.444	0.306	0.077
ST_{52}	1.250	0.318	0.086	1.311	0.357	0.090
ST_{53}	1.396	0.355	0.096	1.533	0.337	0.085

Abbreviation: ST, subtask.

TABLE 17 The parts of w_b^h values

STs			
EPCs	$\ddot{w}_b^h$	$\dot{w}_b^h$	w_b^h
ST_{1_1}			
EPC_2	1.042	0.161	0.027
EPC_{15}	0.951	0.147	0.025
EPC_{31}	1.012	0.156	0.026
EPC_{34}	0.851	0.131	0.022
EPC_{36}	0.829	0.128	0.021
EPC_{38}	0.917	0.141	0.024
EPC_{40}	0.887	0.137	0.023
⋮	⋮	⋮	⋮
ST_{5_1}			
EPC_2	1.042	0.197	0.018
EPC_4	0.776	0.147	0.013
EPC_6	0.714	0.135	0.012
EPC_{31}	1.012	0.168	0.015
EPC_{34}	0.851	0.192	0.017
EPC_{40}	0.887	0.161	0.014
ST_{5_2}			
EPC_2	1.042	0.285	0.025
EPC_4	0.776	0.212	0.018
EPC_{15}	0.951	0.260	0.022
EPC_{40}	0.887	0.243	0.021
ST_{5_3}			
EPC_2	1.042	0.119	0.011
EPC_3	0.752	0.086	0.008
EPC_4	0.776	0.088	0.009
EPC_{15}	0.951	0.108	0.010
EPC_{36}	0.829	0.094	0.009
EPC_{38}	0.917	0.104	0.010
EPC_{40}	0.887	0.101	0.010
EPC_{31}	1.012	0.115	0.011
EPC_{34}	0.851	0.097	0.009
EPC_{39}	0.766	0.087	0.008

Abbreviations: EPC, error producing condition; ST, subtask.

HREs. On the other hand, MT_5 is the most important MT, MT_2 is the most important MT for MREs.

Step 9. Compute the weights of STs for HREs and MREs

To compute the weights of STs w_{ij}^h for HREs and w_{ij}^{mc} for MREs, Equations (10) and (11) are used (Can and Delice 2018).

TABLE 18 The parts of w_b^{mc} values

STs			
EPCs	$\ddot{w}_b^{mc}$	$\dot{w}_b^{mc}$	w_b^{mc}
ST_{3_1}			
EPC_1	1.182	0.092	0.004
EPC_2	1.042	0.081	0.004
EPC_3	1.116	0.086	0.004
EPC_6	0.859	0.067	0.003
EPC_{12}	1.034	0.080	0.004
EPC_{13}	0.874	0.068	0.003
EPC_{14}	0.867	0.067	0.003
EPC_{15}	0.968	0.075	0.003
EPC_{20}	0.983	0.076	0.004
EPC_{25}	1.014	0.078	0.004
EPC_{26}	1.106	0.086	0.004
ST_{3_2}			
EPC_1	1.182	0.092	0.004
EPC_2	1.042	0.081	0.004
EPC_3	1.116	0.086	0.004
EPC_6	0.859	0.067	0.003
EPC_{12}	1.034	0.080	0.004
EPC_{13}	0.874	0.068	0.003
EPC_{14}	0.867	0.067	0.003
EPC_{15}	0.968	0.075	0.003
EPC_{20}	0.983	0.076	0.004
EPC_{25}	1.014	0.078	0.004
EPC_{26}	1.106	0.086	0.004
⋮	⋮	⋮	⋮
ST_{4_1}			
EPC_1	$\ddot{w}_b^{mc}$	$\dot{w}_b^{mc}$	w_b^{mc}
EPC_2	0.859	0.859	0.004
EPC_3	0.859	0.859	0.004
EPC_6	0.859	0.859	0.004
EPC_{12}	0.859	0.859	0.003
EPC_{13}	0.859	0.859	0.004
EPC_{14}	0.859	0.859	0.003
EPC_{15}	0.859	0.859	0.003
EPC_{20}	0.859	0.859	0.004
EPC_{25}	0.859	0.859	0.004
EPC_{26}	0.859	0.859	0.004
⋮	⋮	⋮	⋮
ST_{5_3}			
EPCs	$\ddot{w}_b^{mc}$	$\dot{w}_b^{mc}$	w_b^{mc}
EPC_1	1.182	0.116	0.010

(Continues)

TABLE 18 (Continued)

ST_{53}			
EPCs	$\ddot{w}_b^{mc}$	$\dot{w}_b^{mc}$	w_b^{mc}
EPC_2	1.042	0.102	0.009
EPC_3	1.116	0.110	0.010
EPC_{12}	1.034	0.102	0.009
EPC_{13}	0.874	0.086	0.008
EPC_{14}	0.867	0.085	0.008
EPC_{15}	0.968	0.095	0.009
EPC_{20}	0.983	0.097	0.009
EPC_{25}	1.014	0.100	0.009
EPC_{26}	1.106	0.109	0.010

Abbreviations: EPC, error producing condition; ST, subtask.

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

$$w'^{h}_{ij} = \frac{w''_{ij}}{\sum_{j=1}^{m} w''_{ij}}, \tag{10}$$

$$w^h_{ij} = w'_{ij} \times W_i^h,$$

$$w''^{mc}_{ij} = \sqrt{(D_s^h + R_s^h)^2 + (D_s^h - R_s^h)^2},$$

$$w'^{mc}_{ij} = \frac{w''_{ij}}{\sum_{j=1}^{m} w''_{ij}}, \tag{11}$$

$$w^{mc}_{ij} = w'_{ij} \times W_i^{mc},$$

where w''^{h}_{ij} and w''^{mc}_{ij} are the preweight value of each STs' weights for HREs and MREs, w'^{h}_{ij} is the initial weight of each ST for HREs and w'^{mc}_{ij} is the importance weight initial weight of each ST for MREs. The weights of STs for steam boiler daily process are shown in Table 16.

As seen from Table 16, ST_{1_1} is the most important (0.168) ST for HREs and MREs. ST_{4_2} and ST_{4_3} are the least important STs for HREs and MREs.

Step 10. Compute the weights of EPCs

To compute the weights of EPCs for HREs w_b^h and for MREs w_b^{mc}, Equations (12) and (13) are used.

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

$$\dot{w}_b^h = \frac{\ddot{w}_b^h}{\sum_{b=1}^{40} \ddot{w}_b^h}, \tag{12}$$

$$w_b^h = \dot{w}_b^h \times w_{ij}^h.$$

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

$$\dot{w}_b^{mc} = \frac{\ddot{w}_b^{mc}}{\sum_{b=1}^{40} \ddot{w}_b^{mc}}, \tag{13}$$

$$w_b^{mc} = \dot{w}_b^{mc} \times w_{ij}^{mc},$$

TABLE 19 HEP_{ij}^h and $GHEP_{ij}^h$ values for steam boiler daily control process

STs						
EPCs	GTT_z	**NHU**	EF_b^h	w_b^h	HEP_{ij}^h	$GHEP_{ij}^h$
ST_{1_1}						
EPC_2	GTT_5 E type GTT	0.02	11.00	0.027	1.390	0.028
EPC_{15}			3.00	0.025		
EPC_{31}			1.20	0.026		
EPC_{34}			1.05	0.022		
EPC_{36}			1.06	0.021		
EPC_{38}			1.16	0.024		
EPC_{40}			2.40	0.023		
⋮			⋮	⋮	⋮	
EPCs	GTT_z	**NHE**	EF_b^h	w_b^h	HEP_{ij}^h	$GHEP_{ij}^h$
ST_{5_1}						
EPC_2	GTT_5 E type GTT	0.02	11.00	0.018	1.443	0.029
EPC_4			9.00	0.013		
EPC_6			8.00	0.012		
EPC_{31}			2.40	0.015		
EPC_{34}			1.20	0.017		
EPC_{40}			1.10	0.014		
ST_{5_2}						
EPC_2	GTT_6 F type GTT	0.007	11.00	0.025	1.536	0.011
EPC_4			9.00	0.018		
EPC_{15}			3.00	0.022		
EPC_{40}			2.40	0.021		
ST_{5_3}						
EPC_2	GTT_6 F type GTT	0.007	11.00	0.011	1.363	0.010
EPC_3			10.00	0.008		
EPC_4			9.00	0.009		
EPC_{15}			3.00	0.010		
EPC_{36}			1.06	0.009		
EPC_{38}			1.16	0.010		
EPC_{40}			2.40	0.010		
EPC_{31}			1.20	0.011		
EPC_{34}			1.10	0.009		
EPC_{39}			4.00	0.008		

Abbreviations: EPC, error producing condition; GHEP, general human error probability; GTT, generic task type; HEP, human error probability; NHU, nominal human unreliability; ST, subtask.

where $\ddot{w}_b^h$ and $\ddot{w}_b^{mc}$ are the preweight values of each EPC for in order of HREs and MREs. $\dot{w}_b^h$ and $\dot{w}_b^{mc}$ are the initial weights of each EPC. w_b^h and w_b^{mc} are the importance weights of *b*th EPC for the *j*th ST in *i*th MT. The parts of the weights of EPCs for HREs are shown in Table 17.

Table 17 shows that EPC_2 is the most important (0.027) EPC for ST_{1_1}. EPC_2 is also the most important (0.018, 0.025, 0.011) for ST_{5_1}, ST_{5_2}, and ST_{5_3}. The parts of the weights of EPCs for MREs are shown in Table 18.

Table 18 shows that EPC_1, EPC_2, and EPC_{26} are the most important EPCs for ST_{5_3}.

Step 11. Compute HEP and general HEP for each ST for HREs and MREs

TABLE 20 HEP_{ij}^{mc} and $GHEP_{ij}^{mc}$ values for steam boiler working process

STs						
EPCs	**GTT_z**	**NHE**	**EF_b^{mc}**	**w_b^{mc}**	**HEP_{ij}^{mc}**	**$GHEP_{ij}^{mc}$**
ST_{3_1}						
EPC_1	GTT_5 E type GTT	0.02	17	0.004	1.219	0.024
EPC_2			11	0.004		
EPC_3			10	0.004		
EPC_6			8	0.003		
EPC_{12}			4	0.004		
EPC_{13}			4	0.003		
EPC_{14}			4	0.003		
EPC_{15}			3	0.003		
EPC_{20}			2	0.004		
EPC_{25}			1.6	0.004		
EPC_{26}			1.4	0.004		
EPC_{31}			1.2	0.004		
ST_{3_2}						
EPC_1	GTT_6 F type GTT	0.007	17	0.005	1.239	0.008
EPC_2			11	0.004		
EPC_3			10	0.005		
EPC_6			8	0.004		
EPC_{12}			4	0.004		
EPC_{13}			4	0.004		
EPC_{14}			4	0.004		
EPC_{15}			3	0.004		
EPC_{20}			2	0.004		
EPC_{25}			1.6	0.004		
EPC_{26}			1.4	0.005		
⋮			⋮	⋮	⋮	
ST_{4_1}						
EPC_1	GTT_6 F type GTT	0.007	17	0.004	1.205	0.008
EPC_2			11	0.004		
EPC_3			10	0.004		
EPC_6			8	0.003		
EPC_{12}			4	0.004		
EPC_{13}			4	0.003		
EPC_{14}			4	0.003		
EPC_{15}			3	0.004		
EPC_{20}			2	0.004		
EPC_{25}			1.6	0.004		
EPC_{26}			1.4	0.004		
EPC_{31}			1.2	0.004		
EPC_{36}			1.060	0.003		
⋮			⋮	⋮	⋮	
ST_{5_3}						
EPC_1	GTT_6 F type GTT	0.007	17	0.010	1.548	0.010
EPC_2			11	0.009		
EPC_3			10	0.010		
EPC_{12}			4	0.009		
EPC_{13}			4	0.008		
EPC_{14}			4	0.008		
EPC_{15}			3	0.009		
EPC_{20}			2	0.009		
EPC_{25}			1.6	0.009		
EPC_{26}			1.4	0.010		

Abbreviations: EPC, error producing condition; GHEP, general human error probability; GTT, generic task type; HEP, human error probability; ST, subtask.

To calculate HEP and general HEP (GHEP) for HERs and MREs Equations (14)-(17) are used.

$$HEP_{ij}^{h} = \prod_{b=1}^{40}((EF_b^h - 1) \times w_b^h) + 1). \tag{14}$$

$$GHEP_{ij}^{h} = HEP_{ij}^{h} \times NHU_z^h. \tag{15}$$

$$HEP_{ij}^{mc} = \prod_{b=1}^{40}((EF_b^{mc} - 1) \times w_b^{mc}) + 1). \tag{16}$$

$$GHEP_{ij}^{mc} = HEP_{ij}^{mc} \times NHU_z^{mc}, \tag{17}$$

where

HEP_{ij}^{h} and HEP_{ij}^{mc} are the HEP of *j*th ST in *i*th MT for HREs and MREs, receptively. EF_b^h and EF_b^{mc} are the effect of *b*th EPC on any ST for HREs and MREs. w_b^h and w_b^{mc} are the importance weight of *b*th EPC for HREs and MREs, receptively. $GHEP_{ij}^{h}$ and $GHEP_{ij}^{mc}$ are the GHEP of *j*th ST in *i*th MT for HREs and MREs, receptively.

NHU_z^h and NHU_z^h are the nominal human unreliability for *z*th GTT for in order of HREs and MREs. Table 19 shows the HEP_{ij}^{h} and $GHEP_{ij}^{h}$ values for steam boiler working process.

As seen in Table 19, ST_{5_1} has the highest GHEP value as 0.029. ST_{1_1} has the smallest GHEP value as 0.001. Table 20 shows the HEP_{ij}^{mc} and $GHEP_{ij}^{mc}$ values for steam boiler working process.

As seen in Table 20, ST_{3_1} has the highest GHEP value as 0.024. ST_{3_2} and ST_{4_1} have the smallest GHEP value as 0.008.

Step 12. Compute the total HEP for each MT for HREs and MREs.

Total HEP for each MT for HREs ($THEP_i^h$) and for MREs $THEP_i^{mc}$ are obtained as in Equations (18) and (19). Table 21 presents $THEP_i^h$ and $THEP_i^{mc}$ values for MTs in steam boiler working process.

$$THEP_i^h = \sum_{j=1}^{n} GHEP_{ij}^{h}. \tag{18}$$

$$THEP_i^{mc} = \sum_{j=1}^{n} GHEP_{ij}^{mc}. \tag{19}$$

TABLE 21 $THEP_i^h$ and $THEP_i^{mc}$ values for MTs

MTs	$THEP_i^h$	$THEP_i^{mc}$
MT_1	0.028	0.000
MT_2	0.048	0.000
MT_3	0.159	0.144
MT_4	0.369	0.064
MT_5	0.049	0.010
HEP_{wf}	0.653	0.218

As seen from Table 21, MT_4 has the highest THEP value as 0.369 and MT_1 has the smallest THEP value as 0.028 for HREs and MREs.

Step 13. Compute the HEP for workflow

HEP for work flow computed as in Equations (20) and (21) is denoted as HEP^h_{wf} and HEP^{mc}_{wf}.

$$HEP^h_{wf} = \sum_{i=1}^{m} THEP^h_i. \tag{20}$$

$$HEP^{mc}_{wf} = \sum_{i=1}^{m} THEP^{mc}_i. \tag{21}$$

Table 21 shows that HREs have 0.653 human error probabilities while MREs have 0.218 human error probabilities for the steam boiler daily control process.

Step 14. Compute the PEP

PEP is computed as in Equation (22) considering both HEP^h_{wf} and HEP^{mc}_{wf}.

$$PEP = (HEP^h_{wf} \times w_{HEP^h_{wf}}) + (HEP^{mc}_{wf} \times w_{HEP^{mc}_{wf}}), \tag{22}$$

where

$w_{HEP^h_{wf}}$, $w_{HEP^{mc}_{wf}}$ are the weight of HEP^h_{wf} and HEP^{mc}_{wf}, respectively. $w_{HEP^h_{wf}}$ value is computed using Equation (23) considering the frequency of HREs and the sum of frequencies of HREs and MREs in the related process. The same procedure is implemented for $w_{HEP^{mc}_{wf}}$

$$w_{HEP^h_{wf}} = \frac{F_{HREs}}{F_{HREs} + F_{MREs}}. \tag{23}$$

In steam boiler daily control process, there are 21 HREs and 6 MREs (totally 27 errors). Therefore; $w_{HEP^h_{wf}}$ is 0.778 (21/27) and $w_{HEP^{mc}_{wf}}$ is 0.222 (6/27). *PEP* value is 0.556. This means that steam boiler daily control process has 55.6% HEP considering HREs and MREs. The flowchart of the proposed approach is given in Figure 1.

FIGURE 1 The flowchart of the proposed approach [Color figure can be viewed at wileyonlinelibrary.com]

4 | RESULTS AND DISCUSSIONS

This study proposes an advanced HEA approach based on HEART and AV-DEMATEL integration. İt is aimed to reflect complex effect relations among MTs, STs, and EPCs and to consider HREs and MREs in the PEP. In addition, a flexible matching can be provided by the proposed approach in terms of GTTs and EPCs for STs. In this way, more than one experts involved in the HEA process. Finally, a new term "PEP" is suggested to compute process HEP considering both HREs and MREs. The proposed approach was implemented in a steam boiler daily control process of a medium voltage cell manufacturing company. Three experts divided this process into five MTs and 21 STs. In 21 STs, 15 STs have only HREs, and 6 STs have both HREs and MREs. Obtained results are debated in two different aspects as results for HREs and results for MREs.

In term of results for HREs and MREs, according to the proposed integrated effect relation matrix, MT_4 has the lowest $D_s - R_s$ value and this means that it is affected by the other MTs, STs, and EPCs more than them. MT_4 is named as burners and fuel system control. This MT is very important for steam boiler daily control process. If this MT is not performed truly, the steam boiler may explode. Burners play an integral role in oil and gas production. They generate the heat necessary for separating the oil, gas and water mixture and to keep the gases in their vapor phase during transportation through pipelines. For this reason, it is a logical result that this MT is affected more than the other MTs, STs, and EPCs. It can be also seen from the results, EPC_{39} and EPC_3 have the highest $D_s - R_s$ value for in order of HREs and MREs and these EPCs have more effect to cause a human error in steam boiler daily control process than the others. EPC_{39} is called as the distraction or task interruption according to HEART. This may causes the workers to forget the task they are supposed to do. EPC_3 is the A low signal-to-noise ratio. This may lead to workers not to perceive the error related to the steam boiler.

In term of $D_s + R_s$ values, MT_5 has the highest $D_s + R_s$ value and this MT has more relation than the others for the HREs and MREs. This is a security and warning system control task. There is a wide range of safety and monitoring equipment that can be fitted to boilers, designed to help protect the boiler from operating outside the set parameters and shut it down to prevent a dangerous situation. This may include equipment such as alarms, water-level controls, burner controls, and pressure-relief valves. For example, with the water-level controls, the first low-water-level alarm prevents the boiler operating when the water level is low, but allows the boiler to restart and resume operation once the water has risen to an appropriate level. The second low-water-level alarm is triggered at a lower level than the first and this shuts the boiler down completely and requires a manual restart. This result is an eligible result because the success of daily control activities of steam boiler working process depends on this MT. MT_5 has also the highest importance in steam boiler daily control process. In terms of HREs and MREs, MT_5 is the riskiest one in steam boiler daily control process. On the other hand, EPC_{37} and EPC_{36} have the lowest $D_s + R_s$ value for in order of HREs and MREs and this means that they have lesser relation with the other MTs, STs, and EPCs than them. EPC_{37} is defined as additional team members over and above those necessary to perform the task normally and satisfactorily. This EPC is not related to the daily control procedure of the steam boiler. It is only one of the potential human error causes in steam boiler. According to the expert group's observations this type of EPC is not encountered generally in this working area. The sufficient number of workers are employed for this process. EPC_{36} is called as task pacing caused by the intervention of others and is encountered generally in this working area. For these reasons, these results are also logical. In this working area, each worker has a separate task and the task is not allowed to be interrupted.

In the context of MT_5 for HREs and MREs, ST_{5_3} has the highest importance weight. ST_{5_3} is checking whether the boiler presotalt settings are correct or not. Presotalts are the elements that allow the pressure inside the boiler to be kept at a certain point and convert the pressure signal into an electrical signal. They enable the burner to switch off at the setpoint and to reactivate it after the set differential pressure. They feel the temperature and pressure values and ensure that the relevant element is activated. In addition, among EPCs in ST_{5_3}, EPC_2, EPC_3, EPC_{31} have the highest importance according to the expert group. EPC_2 is a shortage of time available for error detection and correction, EPC_3 is a low signal to noise ratio, and EPC_{31} is the low workforce morale. These are the main problems in all processes as in steam boiler daily control process. These are becoming more important for checking whether the boiler presosat settings are correct. If this ST does not perform truly because of these EPCs the steam boiler may explodes. Among these EPCs, EPC_2 has the highest importance. Shortage in time is very dangerous for this type of process because if any problem occurs in this process, this leads to emerge deaths.

MT_1 has the lowest weight in terms of HREs because this is an easy task to perform and it is the first task that should be done according to the work guidance prepared by the company. This task is defined as controlling the steam boiler water level indicator. Due to being the first task, the possibility of being forgotten or discontinued by the worker is lower. In the context of this MT there is only ST_{1_1} which is to see if boiler water level is within the desired range. This ST has the highest weight among the other STs. This is an eligible result because of this ST is the first action for the daily control process. If the boiler water level is not in the desired range, this causes the boiler to dehydrate and explode if the sensors do not work. On the other hand, ST_{4_2} and ST_{4_3} has the least importance weight in term of HREs. ST_{4_2} is defined as checking whether the burner fuel valve is open or not. ST_{4_3} is checking for whether the fuel circuits have leaks or not. On the other hand, MT_1 has the lowest weight in terms of MREs because there is no MRE for this MT defined by the expert group.

Finally, it is found that in the study the HEP value of workflow is 65.3% in term of HREs. It means that in this steam boiler daily control process, HREs can occur 65.3% probabilities. Due to this, human errors related to MT_4 (it has the highest THEP value) should be prevented. Especially, measurements related to ST_{4_1} and ST_{4_2} should be taken into account because this STs has the highest GHEP values among the others STs in the fourth MT. To prevent HREs for this ST_{41} and ST_{42}, first of all EPC_2 related measures should be considered because the most effective EPC among the other EPCs in ST_{41} and ST_{42} is EPC_2. EPC_2 is a shortage of time available for error detection. This is the main problem in steam boiler working process. On the other hand MT_1 has the smallest THEP value. This MT consist of only one ST and only two EPC as EPC_2 and EPC_{15} are effective on worker performance for this task. On the other hand, it is found that in the study the HEP value of workflow is 21.8% in term of MREs. Due to this, MREs for MT_3 (it has the highest THEP value) should be prevented. ST_{31} should be taken into account because this STs has the highest GHEP values among the others STs. Finally, according to the for ST_{31}, EPC_1, EPC_2, EPC_3, EPC_{12}, EPC_{20}, EPC_{25}, EPC_{26}, and EPC_{31} should be considered because these are the most effective EPCs to cause MREs. The THEP values of MT_1 and MT_2 are zero because EPCs are not defined in the these STs for MREs. Finally, according to the PEP value for steam boiler daily control process, this process has error probability as 55.6% when considering both HREs and MREs.

For future research, different error sources can be considered for HEA. Different MCDM approaches can be performed to reflect complex effect relations in the process. Fuzzy logic, intuitionistic fuzzy logic, and so forth can be involved in the assessment process. Different computations for case-specific effects of EPCs can be advanced. This also may reflect the real condition of the process, system or environment. The proposed approach can be implemented to the different working processes as application studies. EPCs can be divided into not only human and machine-related ones but also design-related errors, environment-related errors, and so forth. In addition, by adding a stochastic structure to the method, the effect of increasing the number of decision-makers to the results can be examined. In this way, more opinions can be aggregated and more accurate results can be obtained. Another future research option may be proposing time-based HEART. Markov chain can be used to evaluate HREs. Finally, the dependency among MTs, STs, and EPCs may be modeled with a conditional probability approach.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

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How to cite this article: Can GF, Delice EK. An advanced human error assessment approach: HEART and AV-DEMATEL. *Hum. Factors Man*. 2020;30:29–49. https://doi.org/10.1002/hfm.20819