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ORIGINAL ARTICLE

PSPHERE: person specific human error estimation

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Abstract
Human error has always been a source of threat for any human–machine interaction system. Incidents like Bhopal gas tragedy, Three Mile Island and Chernobyl are examples of havoc caused due to human errors. With an aim to understand human error, human reliability analysis methods have been introduced. These methods use performance shaping factors (PSFs) to model human behavior. In-depth analyses of PSFs reveal that human factor is one of the important influencing factors affecting human behavior. However, most of the existing approaches depend on fixed or expert opinion values for estimating human error probability thus paying less attention to dynamic nature of human behavior. Every human is different and also their behavior changes along the course of time. Based on this philosophy, the work proposes a Person-Specific Human Error Estimation methodology called P-SPHERE to estimate human error probability. The architectural framework of the proposed method consists of environment, human, task, and organization factors. Using these factors, the framework evaluates human error probability by exploiting the advances of the dynamic human behavior using real values and the existing human reliability analysis methods. Considering the effect of type of task performed, time spent on task, work environment, time of work, work context, and the cognitive aspect of behavior, human error probability is evaluated. A case study has been taken to demonstrate the evaluation process with respect to railway industry. By incorporating human specific factor values, the proposed approach transforms the HEP estimation procedure into a person-specific approach, thereby overcoming the shortcomings of traditional HRA methods in addressing the uncertainty of the complex working environment.

Keywords Human error probability · Human reliability analysis · Performance shaping factor · Human factors

1 Introduction

Human reliability as the name suggests is the method for assessing the human contribution to an erroneous event which may lead to havoc. In spite of the enormous growth and development in system reliability, the overall system well-being continues to remain questioned due to unpredictable human behavior. This arises the need to assess human reliability as human errors are inevitable. It can be observed that ill-suited human activity are sources of possible errors which thereby brings safety issues in most of the working context. Furthermore, majority of the current mishaps occurred is a result of many small events of human errors that may not seem relevant individually, but their combined impact can lead to havoc and unrecoverable situations.

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The effect of catastrophes in different application scenarios which has occurred in recent times due to human errors is listed in Table 1. The historical data indeed are alarming and a threat to the safe world.

Human errors arise due to diverse factors including internal factors (such as, workload, stress, experience, etc.) and external factors (such as, training, task settings, ease of data access, etc.). These factors determine the performance of the human in the working environment and are popularly known as performance shaping factors (PSFs). In human reliability analysis (HRA) methods, the PSFs act as human error quantifying parameters. During evaluation, these PSFs are systemically analyzed to identify possible sources of human error.

Since humans are one of the major contributors to system failure, evaluation of human error probability (HEP) can help to improve the safety level in working environment. In contrast to the traditional approach of HEP estimation where pre-defined error rates associated with specific PSFs are used to determine HEP for a given task or situation, the evaluation

Table 1 Some of the major human error catastrophe

Year	Location	Accident	Cause	Consequence
2010	Gulf of Mexico	Deepwater Horizon drilling rig explosion	Six operations, tests, or equipment functions went wrong	It resulted in the sinking of the Deepwater Horizon and deaths of 11 workers
2011	Fukushima, Japan	Fukuschima Daiichi nuclear disaster	Deactivation of several safety systems to test a cooling system	Severe earthquake followed by a tsunami
2013	San Francisco, USA	Asiana Flight 214 crash	Crew's failure to monitor and maintain the plane's airspeed	Crashed while landing on runway killing 3 people and others severely injured
2016	Medellin, Colombia	LaMia flight 2933 crash	Crew negligence to identify low fuel	Aircraft plunged from the sky leaving only six survivors
2017	Ferozabad, India	Kalindi express train collision	The driver apparently overshot the signal	Collision with the freight train
2019	Hyderabad, India	Collision of two trains	Head-on collision due to signal overshot	Six coaches of the of the Hundry Express have been damaged thereby injuring 12 people

process must take into consideration the dynamically changing phenomenon of human behavior. Elaborately, it can be said that every human is different and behavior of a human at different hours is different. Considering the above fact, dynamic evaluation of HEP can provide insights for: (1)identifying the potential causes that can result in the undesired consequences, (2) numerically quantify the probability of the undesired consequences arise due to the potential causes, (3) indicating the variability of error probabilities, and (4) selection of suitable personnel for task assignment.

To capture human errors, it is necessary to precisely calculate their failure probabilities in a systematic manner. The effort for establishing methods for calculating error probability age back to 70s. Several methodologies are proposed and published by U.S Nuclear Regulatory Commission (USNRC) and other industries and Government Organizations [1]. These methods aim at better ability to account for the factors and conditions that can lead humans to take unsafe actions and thereby provide better estimates of the likelihood of human error. The earliest known HRA approaches, such as THERP (The Technique for Human Error-Rate Prediction) [2], Accident Sequence Evaluation Programme (ASEP) [3,4], Human Cognition Reliability (HCR) [4–6], and Human Error Assessment and Reduction Technique (HEART) [7] considered errors of commission for understanding the reasons for human mistakes [8]. However, it has been shown that there are systematic influences on decision-making and behavior of a human that cannot be categorized simply as omissions or commissions [9]. Based on this fact, advanced cognitive models such as Cognitive Reliability and Error Analysis Method (CREAM) [6], A Technique for Human Event Analysis (ATHEANA) [10], Méthode d'Evaluation de la Réalisation des Missions Opérateurs pour la Sûreté (MERMOS) [11], Connectionism Assessment of Human Reliability (CAHR) [12], and the Standardized Plant Analysis Risk-Human Reliability Analysis method (SPAR-H) [13] were developed. These methods focused on the cognitive aspects of humans, the causes of errors rather than their frequency, the study of the interaction of the factors that increase the probability of error, and the inter-dependencies of the PSFs. Despite having remarkable improvements, there remains the requirement of better human cognition model, such that the method is independent of the domain of applications. Recent developments in the HRA methodologies such as Nuclear Action Reliability Assessment (NARA) [14,15], Phoenix [16], A Simulator for Human Error Probability Analysis (SHERPA) [17] focused on HRA building of generic models based on empirical studies and uses the significant features. Besides, the emphasis was on simulation tools for better estimation of error probabilities.

In most of the existing methodologies [6,7,10], dependence on expert judgement for PSF selection is still predominant. Moreover, expert opinion is required to estimate the probability for each involved PSF [18]. In the work environment, there are various factors which contribute to the occurrence of human error. Nevertheless, the contribution value for each of these factors through simulation is not possible. For such factors, usage of expert judgement becomes mandatory. Furthermore, for the human factor, it would be wise if contributing values are directly collected from each human operator. Such an approach would minimize the approximation, which occurs because of expert opinions.

In spite of exploring various alternatives for predicting error probabilities, many limitations and problems still remain persistent due to complex human behavior which leads to difficulty in predicting and simulating human behavior. Some of the major limitations include lack of suitable human behavior model, resource intensive, and time-consuming, high dependency on expert judgement and context specificity leads to lack of generalization capability [17,19].

Generally, HEP methods identify a set of factors relating to performance and then manipulate those factors to arrive at a failure rate. Most of the existing approaches utilize expert opinion for classification and quantification of PSFs. Two issues apparent in the expert-based approaches are

1. The assignment of a PSF level requires making subjective judgements. These judgements are commonly multivariate, drawing on other direct or indirect measures synthesized through cognitive processes that may not be transparent even to the person making the judgement. Without clear criteria for making such judgements, one person's judgement may vary considerably from that another or even from his or her own judgement on another occasion [20].
2. Several of the direct PSFs feature Boolean levels of assignment. While this categorization facilitates the ready assessment of PSFs in many HRA methods, it fails to capture the continuous quantum essential to magnitude measurement [20].

To overcome the limitations of the existing expert-based approach, the proposed work evaluates HEP by considering the performance as well as the behavioral data of every individual in a controlled environment. Despite some limitations, data collected in a controlled environment using a well-designed experiment provide a relatively close estimate of the actual performance of an individual. Along with this, the work evaluates HEP by considering the impact of organization, task, and the working environment by considering them as the PSFs. All these factors are assigned different weights according to the concerned industry to make the approach applicable in a generalized manner. The human specific factors will make the estimation dynamic as well as independent to each other. Thus, to achieve this, the work should incorporate the following requirements:

– Analyze the possible causes for human error occurrences and understand the nature of the performance factors to reduce errors.
– Estimate the person-specific error probabilities which is more reasonable to apply for overall HEP evaluation.
– Gather knowledge for selecting suitable personnel for task assignment using the information of person-specific error probabilities.
– Easily scale into other applications for error estimation with less effort.

Various objective to accomplish this work are as follows:

1. Identify the PSFs present in various accident scenarios and their categorization depending on the factors influencing them.
2. Evaluate and define different levels of each PSF.
3. Multiplier evaluation for the considered PSFs.
4. Evaluating the weights of different PSF category depending on the applicable industry.
5. Approach to estimate human error probability.

The rest of the paper is organized as follows: Sect. 2 discusses the relevant literature covering the evolution of the human reliability analysis process. Following this; Sect. 3 illustrates the proposed approach. Section 4 discusses the identification of PSFs affecting performance and the different labels considered for each PSF category. Section 5 discusses the proposed methodology for evaluating multipliers for the considered PSFs. The procedure followed for combining the multipliers under each category has been discussed in Sect. 6. Further this section discusses the elaboration of weightage calculation of the factors for its applicability in different work domains. Finally, a case study has been presented in Sect. 7 which provides a summary of the major steps and techniques required for its implementation. Section 8 provides suggestion regarding the data collection process for the HRA analyst. Finally, Sect. 9 concludes the paper.

2 Literature survey

In human–machine interaction, there is a major contribution of human actions in operating the systems in a systematic manner. However, human actions are a source of vulnerability which may bring havoc to the overall system performance. As a solution, human reliability assessment methods come up to examines the risk associated with human factors in the workplace. HRA follows the underlying principle of identification, modelling, and quantification for evaluating the probability of human errors. HRA have originated as a part of probabilistic risk assessment (PRA) in the US nuclear energy development programme [21]. Technique for Human Error Rate Prediction (THERP) is among the first HRA methods developed for HEP estimation [2]. The method uses the concept of simple event tree analysis for evaluating the probability of a human error. Following THERP, other HRA methods have developed such as Accident Sequence

Evaluation Programme (ASEP) [3,4] and Human Cognition Reliability (HCR) [4,6]. Similar to THERP, these methods assume that natural deficiencies of human result in task failure. To perform a quick and simple evaluation, Human Error Assessment and Reduction Technique (HEART) was designed for quantifying the risk of human error [4,22–24]. The methods discussed above are popularly known as first generation methods. Methods of this generation focuses on success or failure of human actions while paying less attention to the cognitive aspects of human behavior. Besides, in this generation, human operator is treated as another component in the system. For estimation of human error probability (HEP), these methods take assistance from established tables, human reliability models and expert judgement. The characterization of human failure modes is usually very simple, such as in terms of error of omission and errors of commission.

However, this simplistic dichotomy does not take into consideration internal or external human factors which affects performance. These factors include the effects of workload, stress, sociological issues, psychological issues, illness, etc. [1]. Furthermore, research has shown that there are systematic influences on decision making and behavior that cannot be categorized simply as omissions or commissions [9]. Based on this fact, advanced cognitive models have been developed, which represent the process of logic operator and synthesize the dependence on personal factors and are popularly known as second-generation methods. One of the popular methods following this principle is Cognitive Reliability and Error Analysis Method (CREAM) [6]. CREAM analyzes task in hierarchical manner and also assesses the work condition using common performance conditions (CPCs). Next, it derives HEP using four Contextual Control Modes (CoCoMs) which assumes human cognition as cyclical and cognitive processes to be dependent on context and working environment. While CREAM emphasis on analyzing the causes of human actions, i.e., human cognitive activities, A Technique for Human Event Analysis (ATHEANA) [10] focuses on identifying especially post-accident errors of commission resulting from error-forcing context (EFC) and plant conditions. The analysis of the method begins with identification of human failure events (HFEs) from the accident scenarios of PSA model. Next, identification of unsafe actions (UAs) in the HFEs are done. UAs indicate inappropriately taken or not taken human actions which resulted in degraded plant safety condition [25]. Following this step, EFCs are combined with the effect of PSFs and plant conditions that create a havoc situation in which human error is likely. The Standardized Plant Analysis Risk-Human Reliability Analysis method (SPAR-H) [13] is instead built on an explicit information processing model of human performance derived from the behavioral sciences literature [17]. SPAR-H begins with identification of human activity as action or diagnosis. Next, using the eight PSFs [26] the dependency of human error on subsequent errors is addressed. The method estimates HEP by multiplying a nominal error rate with PSFs. PSFs represent aspects of individual characteristics, the environment, the organization, or the task that decrements or improves human performance, thereby increasing or decreasing the likelihood of human error [27].

For the field of nuclear power plants, an advanced version of HEART methodology, A Nuclear Action Reliability Assessment (NARA) [14,15], has been developed which is known as the third generation method. The method consists of two basic elements: Generic Task Types (GTTs) and Error Producing Conditions (EPCs). This method follows the procedure of classifying the task according to GTTs which is followed by assignment of nominal HEP to the task [4]. Next, to calculate the task HEP, the EPCs contributing to the system degradation are identified and the assessed proportion of affect (APOA) for each EPC is evaluated.

Recently, in HRA approaches, attempts are made to improve its estimation by including more relevant PSFs [19,28–30] or by incorporating values of PSF multiplier from empirical data [28,31]. PSFs such as sleep duration and fatigue are considered as important parameters for inclusion in HRA models [19,28,30]. It has been argued that these two parameters take an active role in enhancing human error probabilities which necessitates their inclusion in HRA models. Furthermore, efforts are made to alternate the traditional approach of assigning expert opinion human error probability values with more realistic empirical data [28]. Kim et al. proposed a remarkable work which followed statistical approach to estimate human error probabilities [32]. Moreover, substitution of expert option HEPs with quantitative approach has been proposed in [31] for fitness for duty and work processes PSFs. The summary of various HRA approaches is tabulated in Table 2.

Analysis of human error towards an event has always been the prime focus for the human error probability estimation. Also, the focal point of these studies was primarily centred around major industry domains. Lately, reliability estimation has shifted its domain from the age-long industry concern to the medical and healthcare domains. Herein, the major emphasis is on the analysis of human factors in relation to the environment and the equipment in use. For instance, Paragliola et al. have conducted a risk assessment study for nuclear medical department, wherein measures has been taken to avoid unintended entry of patients in dangerous and undesirable states [34]. Another interesting study carried out in [35] has explored the feasibility of assisted living software for elderly people in carrying out day-to-day activities. The authors have estimated the overall reliability of the system in terms of human factors and their effects on reliability requirements. An innovative risk assessment methodology has been proposed by Coronato et al. [36] for the medical

Table 2 Summary of human reliability estimation methods

Work	Human reliability assessment method	Application	Remarks
Swain et al. [2]	Technique for Human Error Rate Prediction (THERP)	Nuclear Power Plant	Evaluation of error probability using event tree analysis
Swain et al. [33]	Accident Sequence Evaluation Programme (ASEP)	Nuclear Power Plant	Usage of simple time-reliability table to assess the diagnosis component
Hollnagel [6]	Cognitive Reliability and Error Analysis Method (CREAM)	Nuclear with wider application	Calculation of reliability is based on Common Performance Conditions and Contextual Control Model (COCOM) functions
Gertman et al. [13]	The Standardized Plant Analysis Risk-Human Reliability Analysis method (SPAR-H)	Nuclear with wider application	Identifies tasks as action or diagnosis followed by identification of failure events using eight PSFs and finally modifying the base error probability
William [7,23]	Human Error Assessment and Reduction Technique (HEART)	Generic	Uses Generic Task Types (GTTs) and Error Producing Conditions (EPCs) for calculating reliability
Cooper et al. [10]	A Technique for Human Event Analysis (ATHEANA)	Nuclear with wider application	Based on quantification of the Error-Forcing Contexts (EFCs) and the probability of each unsafe action
Kirwan [14,15]	A Nuclear Action Reliability Assessment (NARA)	Nuclear Power Plant	Uses GTTs and EPCs to quantify operator reliability
Pasquale et al. [17]	A Simulator for Human Error Probability Analysis (SHERPA)	Generic	Takes the advantages of the simulation tools and the traditional HRA methods to predict the error probability
Ekanem et al. [16]	The Prediction of Human Operator Error using Numerical Index eXtrapolation (PHOENIX)	Generic	Selection of task type and the related PSFs to calculate error probability by multiplying the selected task type with the PSF value

information systems. The methodology focuses on quantitative measurement of risk involved in using medical devices by means of dynamic probabilistic risk analysis approach. The proposed approach assesses risk based on real-time data collection which thereby helps in improving the safety feature of the devices throughout their usage. Designing of intelligent environments (IE) for the benefit of people often lacks to take the users' involvement into account. This arises question regarding the reliability of such environments designed for the people. Based on this concern, the author in [37] has conducted an extensive study to understand the IEs' research community, aiming at highlighting to which extent users are taken into account, or are involved, into the reported research works. The study discussed so far give insight about the other recent trending activities in the field of reliability apart from the conventional human error estimation. From these studies, it is evident that reliability estimation is a diversified field and understanding of human factors is very much essential in the development of sustainable and reliable user environment.

Although several methods exist for the purpose of human error quantification, however, there still remains a scope for further research due to the following reasons: (a) lack of consideration of dependencies and inter-dependencies between the PSFs, (b) dependency on expert opinion for assigning PSF values, (c) mostly domain specific which makes the approaches unsuitable for other applicable domains, and (d) superficial consideration of human behavior into the models.

3 Proposed approach

Manual actions/interventions by any human in an event sequence are distinct in nature and thereby leads to either success or failure of the event. Based on this notion, the proposed approach is focused on the concept that every individual is different and so is their behavior towards the assigned task. Variation in human behavior is due to various performance shaping factors (PSFs) [38] such as: temperature, time pressure, stress, work procedure, work shift, task complexity, etc. These factors are considered in the proposed approach by grouping them into four categories: (i) Environmental factors, (ii) Human factors, (iii) Task oriented factors, and (iv) Organizational factors (refer Table 3). The factor categorization is done by considering the impact of different factors on the working of an individual. Furthermore, the proposed approach introduces a new methodology through which person-dependent PSFs values will be considered for the evaluation of human error probability towards an event.

Human performance is known to be affected by various factors. To effectively calibrate the human error probability, in the proposed approach, the factors are considered under different categories which appears in the workplace. This way, it would be efficient to evaluate and understand the capability of an individual to work under different working conditions.

For instance, in many scenarios, it has been observed that an individual is accountable to work towards the goal despite the changing circumstances and upcoming environmental disturbances. In the best case, the individual will carry out the task in the pre-defined manner. However, in certain cases, complexity might increase and the individual has to take fruitful decision on the spot.

Figuring out what to do in a particular situation requires knowledge of the structure of the work, familiarity with the task and the environment. In the proposed approach, importance has been given upon such factors (namely, training and experience) for including their effect into the evaluation process. With proper training and experience, it is possible to inculcate an individual with the unforeseen situations and the techniques to cope up with the uncertain conditions. However, for the least trained and minimally experienced individual, taking the correct course of action is similar to a shot in the dark and the outcome depends mostly on fortune or intuition.

Therefore, it becomes necessary that the best personnel is selected for these critical tasks. Also, it is worthwhile spending time working with people to understand their mental capacity to deal with any situation. Furthermore, the approach taken towards the situation can prove to be beneficial in identifying people who can be allotted for a critical task. Moreover, the command of leadership quality is a highly important factor that impacts the performance of an individual as well as the group. The proposed approach puts emphasis on such parameters for constructive estimation of human error probability.

In the proposed approach, human error probability is evaluated in three hierarchical levels. The first level concerns the cognitive factors of human beings to evaluate fitness for the duty. In the next level of evaluation, various factors are combined to get the overall score of each factor category. Finally, based on the importance of each factor for specific organization, the weights are computed. After this, the weights of each factor are combined to get overall human error contribution.

The estimation of human error probability begins with evaluation of different levels of each human-dependent factors. The different factors used in the proposed model along with their sub-levels are discussed in the preceding sections. Furthermore, the approach for evaluating the levels is also elaborated.

4 Identification of PSFs affecting performance

Most currently applicable HRA methods utilize PSFs to highlight human error contributors and to adjust basic HEPs that assume nominal conditions. Thus, the impact of PSFs has been treated independently. However, studies in the fields of psychology and human factors revealed that the interrelationships between PSFs need to be studied to reflect their effects on operator errors better [39,40]. For this, an extensive literature review was conducted to come up with the possible PSFs affecting individual performance. However, many of the identified PSFs have common characteristics and definition. This motivates us to combine the overlapping PSFs and provide a precise definition of each of these PSFs. The categorization of each of these PSFs into four groups is shown in Fig. 1.

The PSF categorization performed in this work not only groups the factors but also indicate sub-factors of a PSF. This way, it becomes efficient to mark the variation of different PSFs. It can be observed that the factors of each category affect differently in various organizational settings. Furthermore, for every individual, the PSF considered under different factor category does not vary similarly. Some of these factors may differ while performing the task, and others may remain the same. Similarly, some of the factors may affect every individual differently, while others may stay the same for a particular organizational setting which is highlighted in Table 3.

4.1 Evaluate and define different levels of each PSF

While performing the task, there may be variation in the strength of the PSFs (also known as level) due to a change in human behavior, work pressure, organizational settings, task demands, etc. This variation among the level of the PSFs either boosts or degrades human performance. Therefore, to estimate HEP, the level of the PSF must be well defined. This

Table 3 Relevant PSFs affecting human performance

Factors category	Factors influencing human performance	Remarks
Environmental factors (EF)	Work process (WP)	Almost remains fixed over the course of work
	Work shift (WS)	
	Environmental stressors (ES)	
Human factors (HF)	Fitness for duty (FD)	Varies considerably during the course of work and also from person to person
	(i) Mental workload (MW)	
	(ii) Vigilance (VI)	
	(iii) Sleep duration (SD)	
	(iv) Up time (UT)	
	(v) Stress (ST)	
	Experience (EX)	Varies from person to person
	Time pressure (TP)	
	Skill (SK)	
	Perceived task difficulty (PT)	
Task-oriented factors (TOF)	Complexity (CO)	Almost remains fixed over the course of work
	Type of task (TT)	
	Available time (AT)	
	Task frequency (TF)	
Organizational factors (OF)	Ergonomics (ER)	Almost remains fixed over the course of work
	Leadership (LD)	
	Human–machine interaction (HM)	
	Procedures (PR)	
	Training (TR)	

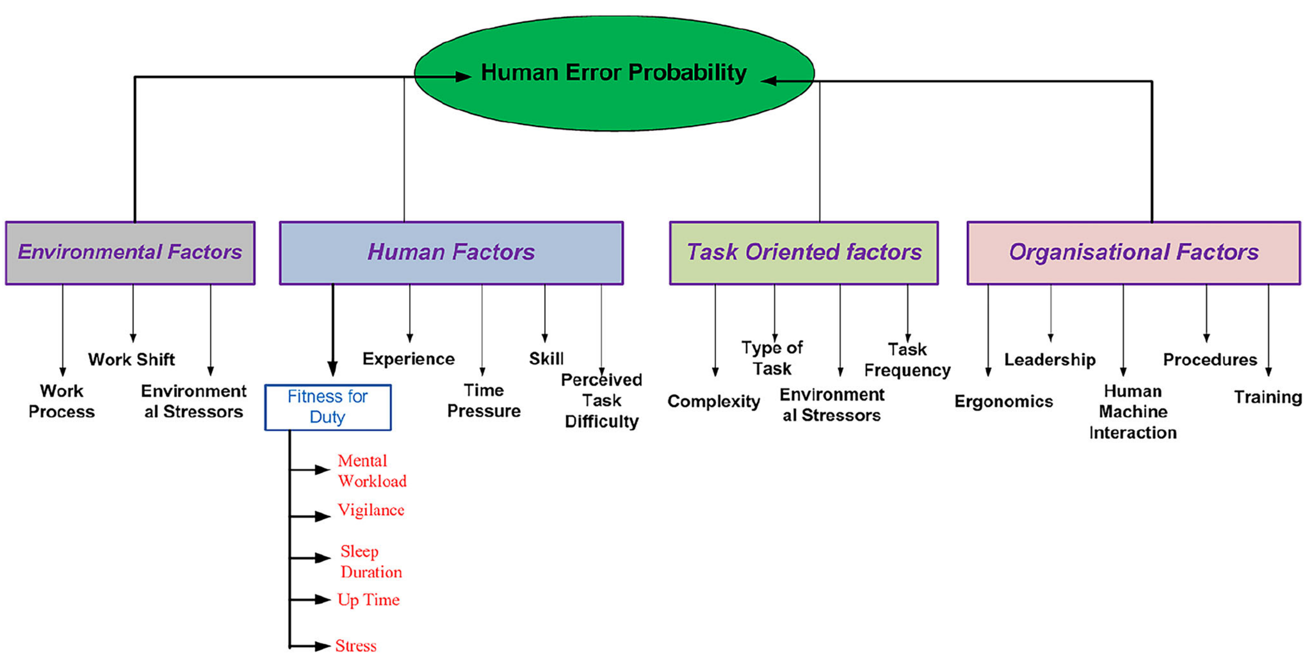

Fig. 1 Factors considered for HEP estimation

section provides a detailed discussion about the definition and levels of the considered PSFs and their sub-PSFs.

4.2 Environmental factors

Environmental factors are the external factors that influence human performance. These factors describe the reasonable working conditions for an operator. According to Davis [41], the performance of an individual degrades with poor working conditions. The authors have shown the correlation between the factors using personal causal models to understand their effect on the performance. Besides, operators concentration degrades with poor working conditions which lead to an increase in the number of errors and thus degrades the overall performance [42]. To understand the effect, the authors have done in-depth literature survey and thus narratively proven the effect of environment factors on the human performance. The environmental factors affecting human performance are described next.

- *Work process* Work process refers to the standard procedure of handling or performing the task. It includes different aspects of doing the task, which provides for work planning, safety culture, communication, and policies. Furthermore, it also consists of all managerial, administrative, or organizational factors that affect the individual's performance. Work process indicates how work is drafted, communicated, and accomplished. If planning and communication are weak, then the work requirements remain unclear for the individual. Furthermore, the importance of the PSF and its quantitative measurement need is described in [31]. In this work, the authors have proposed a quantitative evaluation framework where they have utilized error cause information from HERA (Human Event Reliability Analysis) and HuRAM + (Human-related event Root cause Analysis Method plus) databases to calculate the error occurrence intervals and their moving average to quantitatively estimate the considered factors. The levels used for the PSF work process, along with their definition, are tabulated in Table 4.
- *Work shift* Work shift represents the approach of the organization to utilize 24 h of the clock every day. In this approach, work may take place on a schedule outside the traditional '9 a.m.–5 p.m.' norm per day. In this approach, the employees are working in three shifts as tabulated in Table 5. Work shift has been linked to many human health disorders, as well as performance and safety on the job. Working in an unfavorable shift can slow down the reaction time, and also impair the operator's quick decision or response capability [30,43]. The authors in [43] have demonstrated the effect of time of day on the workers using the Federal Railroad Administration (FRA) database of injury reports. From this report of fatal and nonfatal injuries, the study has correlated the effect of day of time with the accident rate. Besides, concentration gets reduced focus and ability to stay on task. Studies show slower reaction times and the likelihood of more errors occur during night hours.
- *Environmental stressors:* Environmental stressors refer to the conditions and circumstances arising from the undesirable work environment. The factors responsible for environmental stressors may include high temperature, noise, poor ventilation, or radiation, which affects the mental or physical performance of an individual [44–47]. These stressors can negatively impact the functioning of an individual which poses a threat to the operation of the system. As observed from the literature [48], the impact of environmental stressors over performance is curvilinear. In other words, a certain amount of stress helps to enhance the performance of the individual, which in the context of the current work is considered nominal. In contrast, high and extreme levels of stress will negatively affect human performance. To demonstrate the effect of inadequate Indoor Environmental Quality (IEQ) on work performance and well-being, the authors in [47] have conducted online surveys in a sample of 114 office workers over a period of 8 months. The results from these survey indicate that environmental stress reduces not only the cognitive capacity for work, but also affects the rate of work. The levels of environmental stressors found along with their definition are given in Table 6.

4.3 Human factors

There are many human factors which affect the performance of an individual during the task. To minimize the risk and enhance the efficiency of the organization, it becomes reasonable to identify and manage human factors. By understanding, factors affecting human performance organizations can improve human reliability, reduce error, and mitigate its consequences. The human factors considered in this work are discussed next.

- *Fitness for duty:* Fitness for duty examines the individuals to determine if they can fulfill the physical and mental demands of the job requirement. Such a test analyzes the individual's suitability to deal with the task requirement and not the ability of an individual in general. The need for quantitative measurement of this PSF is described in [31]. For the considered factor, the authors have proposed a quantitative evaluation framework where they have utilized error cause information from HERA (Human Event Reliability Analysis) and HuRAM + (Human-related event Root cause Analysis Method plus) databases to calculate the error-occurrence intervals and their moving

Table 4 Levels and definition for the PSF work process

Factor influencing human performance	Levels	Definition
Work process	Poor	Disruptive work culture having minimum coordination among individuals
	Nominal	How individuals approach the work and get things done does not lead to performance enhancement. That is, the individuals have good work conduct but do not have proactive communication among themselves
	Good	The organization is well structured for coordination among individuals that encourages contributions from everyone leading to enhanced performance

Table 5 Levels and definition for the PSF work shift

Factors influencing human performance	Levels	Definition
Work shift	Morning	The task shifts begins before 10 a.m.
	Evening	The shift begins post lunch
	Night	The shift begins post supper

Table 6 Levels and definition for the PSF environmental stressors

Factors influencing human performance	Levels	Definition
Environmental stressors	Extreme	The individual is exposed to harsh environmental conditions which include natural disasters, electromagnetic radiation, pollution, extreme temperature, or noise which may have serious consequences
	High	The work environment is affected due to illumination, location and causes strain on the body and mind. The response of the body is a short-term fight or minor irritations
	Nominal	The work environment supports favorable performance of an individual

average. Fitness for duty is categorized into four different classes, as summarized in Table 7. Fitness of an individual needs to be analyzed based on several factors which are discussed next.

1. Mental workload: Mental workload results from the aggregation of many different demands and so is difficult to define it uniquely. According to the authors in [49,50], the mental workload is defined as the capability of an individual to deal with task requirements. Besides, Casali et al. [51] observed that mental workload could either be inferred from an individual's behavior or can be measured from psychological and physiological processes. On this direction, the authors in [52] have followed an EEG-based approach for measuring continuous mental workload of an individual involved in task. Furthermore, the literature indicates that the optimum performance occurs at intermediate levels of workload, that is, extremely low and high levels of mental demand can lead to poor performances because of under-load and over-load conditions. Also, it has been identified as one of the essential PSF factors for HRA in [53,54]. The various levels of the mental workload PSF are summarized in Table 8.
2. Vigilance: Vigilance, also known as sustained attention, is defined as the ability to maintain concentrated attention over prolonged periods. For efficient performance in applications involving persons in repetitive, monotonous, and long-term tasks, it is essential to maintain vigilance above a particular level [55–58]. Thus, for safety in work, systems demand continuous monitoring of operators' vigilance level and make appropriate interventions when declining vigilance is detected [59]. In general, individuals' performance deteriorated as a function of time while performing the task. This decrement in vigilance is attributed to the conservative shift in decision criterion. For instance, the authors in citeSamSa19 have investigated vigilance changes using physiological parameters to appropriately identify the vigilance levels while engaged in continuous monitoring task. The levels used for the vigilance PSF are shown in Table 9.

Table 7 Levels and definition for the PSF fitness for duty

Factors influencing human performance	Levels	Definition
Fitness for duty	Unfit for duty	The individual is unable to carry out the required tasks, due to unacceptable mental workload, drop in vigilance level or extreme fatigue
	Temporarily unfit with continuous rest	The individual is currently unable to carry out the task and needs some rest due to prolonged working schedule
	Fit with regular breaks	The individual can carry out the task but is affected with mild physical and mental deterioration
	Fit	The individual can carry out tasks; no known performance degradation is observed

Table 8 Levels and definition for the PSF mental workload

Factors influencing human performance	Levels	Definition
Mental workload	High	The individual experiences extreme difficulty in performing the task. This is due to high task demand caused due to an increase in error rate, high response time, resulting in low performance
	Nominal	The individual is motivated enough to perform the task with high productivity and minimum error rate
	Low	The individual experiences minimum difficulty in performing the task. This is due to minimum effort required in task interaction and task demands

Table 9 Levels and definition for the PSF vigilance

Factors influencing human performance	Levels	Definition
Vigilance	High	The individual is in a state of high alertness which is accompanied by high sensitivity towards detecting or observing activity which includes constant subconscious anticipation of danger or critical events
	Nominal	The individual is active in performing the task. This represents that the individual's behavior is assertive in terms of the number of lapses, missed events and reaction time
	Low	The individual is in a state of diminished alertness level, which is accompanied by impairment in continuous detection or observation capability

3. Sleep duration: Sleep is an integral part of our daily routine, and without proper sleep, it is not easy to concentrate and respond quickly [60]. Sleep deprivation is one of the major causes of human errors. Despite the importance of sleep in governing human performance, its impact is not explicitly included in the current HRA approaches. A study in the USA estimated the loss of more than $50 billion annually because of accidents happening due to lack of sleep. This cost can go up to $150 billion when productivity losses are considered [61,62]. In both these studies, the authors have done an extensive survey of the incidents where sleep deprivation has caused havoc. Also, focus has been put on the neuro-cognitive consequences with respect to sleep deprivation. Thus, a fruitful amount of sleep is compulsory to perform the task effectively. The levels used for the vigilance PSF are shown in Table 10.
4. Up time: Up time is the measure of the duration for which an individual is working. The effect of continuous work can manifest individual in many ways, that are marked by tiredness, feeling of being overworked, lack of motivation, and drop in performance level. Also, there is a severe lack of concentration which is followed by poor task services and decision capability. The levels used for the up time PSF are shown in Table 11.

Table 10 Levels and definition for the PSF sleep duration

Factors influencing human performance	Levels	Definition
Sleep duration	Poor	The individual is having sleep duration less than 6 h or more than 10 h
	Nominal	The individual is having sleep duration between 6 to 7 h
	Good	The individual is having sleep duration between 7 to 9 h

Table 11 Levels and definition for the PSF up time

Factors influencing human performance	Levels	Definition
Up time	Prolonged	The individual is involved in some task continuously without any break
	Nominal	The individual has worked before but had taken break
	Short	The individual has either not worked before or is in rest from long time

5. Stress: Stress affects the ability of any individual to remember things they already know, to process the new information they are learning, and to apply them both to analytical task conditions. Stress contributes to decreased task performance, high error rate, and poor quality of work [63,64]. To understand the effect of stress with respect to human errors, the authors in [64] have conducted a survey and found a high correlation between the stress and the human error component with Cronbach's alpha=0.806. Given the potential negative impact of stress on performance, and the divergent way in which people respond, it needs to be considered as an important factor for identifying an individual's fitness for the job. In this proposed work, the levels used for the stress PSF are shown in Table 12.

– *Experience*: Experience defines the familiarity with a skill or field of knowledge acquired through the involvement or exposure, which has resulted in superior understanding or mastery. It also considers the years of work exposure of the individual, accomplishment of formal training on the type of task by the operator and the awareness of the individual in dealing with critical or hazardous steps involved in the task. While assessing this PSF, the past resurrection record is recalled to understand the familiarity of the scenario in either training or an operational setting [65]. The importance of this PSF has been outlined in [66]. In this work, the authors have done meta-analysis of relevant studies to understand the effect of experience on the performance. The levels used for the experience PSF are shown in Table 13.
– *Time pressure*: Time pressure is a type of psychological stress that occurs when a person has less time available (real or perceived) than is necessary to complete a task or obtain a result. Previous research indicates that people respond to time pressure through increased physiological activity and by adapting their task strategy to mitigate the task demands [67,68]. Performance in such jobs is likely to be affected by the stress arising from the need to cope with limited time. In terms of performance, a minimum amount of time pressure is found to be fruitful in providing better performance which otherwise degrades in cases of low and high time pressure. The authors in [67] have reached to this conclusion by conducting an extensive literature review. The levels used for the time pressure PSF are shown in Table 14.
– *Skill*: Skill is the ability to carry out a task with determined results often within a given amount of time. To perform a task with perfection, an individual may need specialised expertise, training, knowledge, and potential at the job. Typically, every task is associated with individual elementary requirements needs to be performed in a specific environment which requires a certain degree of skill. Furthermore, a job with substantial complexity requires precise ability and comprehension to complete it successfully [69]. The levels used for the skill PSF are shown in Table 15.
– *Perceived Task Difficulty*:Perceived task difficulty is the outcome of assumed confidence of an individual regarding his/her capability. This parameter will analyze the self-perceptions of the ability of an individual and henceforth does not evaluate the task difficulty levels. Perceived task difficulty significantly predicts the performance of

Table 12 Levels and definition for the PSF stress

Factors influencing human performance	Levels	Definition
Stress	High	The individual suffers from absenteeism, nervousness, indecisiveness or complete breakdown resulting in bad judgement and poor performance
	Nominal	The individual is sufficiently aroused to give a high quality performance, while not being over-stressed and unhappy
	Low	The individual may suffer due to boredom, lack of concentration and lack of motivation

Table 13 Levels and definition for the PSF experience

Factors influencing human performance	Levels	Definition
Experience	Naive	The individual is not having any prior exposure to the task being assigned. This indicates that the individual is only having formal knowledge about the task
	Low	The individual is having experience in terms of training for the task being assigned
	Nominal	The individual has knowledge to deal with commonly occurring decisive situations in the task
	High	The individual is having expertise in handling rarely occurring critical task demands

Table 14 Levels and definition for the PSF time pressure

Factors influencing human performance	Levels	Definition
Time pressure	High	The perceived time is scarce. Individuals normally experience high time pressure when 85% of the available time is required to execute the tasks which severely affects decision-making capability. Furthermore, the quality of the work degrades drastically
	Medium	The individual experiences moderate time pressure which brings inconsistency in the task performance
	Nominal	The time pressure perceived helps to perform the task in a convenient way and supports creative thinking
	Low	The perceived time pressure is very low and induces boredom in the individual

Table 15 Levels and definition for the PSF skill

Factors influencing human performance	Levels	Definition
Skill	Unskilled	The individuals exhibiting a marked lack of skill or competence
	Basic skill	The individual is having a certain level of technical expertise which is essential for fitting into the job
	Nominal	The individual is able to solve most of the problems depending on the knowledge gained about the task and the system
	Expert	The individual have clear vision of what their goal is, what to do about it, and what should happen as a result

an individual for the given task. For instance, the performance for any task regarded as difficult is always found to be lower than the one perceived to be easy [70–72]. To understand the perceptions of task difficulty, the authors have conducted a survey on seventy-nine 8th graders and suggested that perception of task difficulty is an important variable that affects the interests in learning tasks. As stated in [73–75], a learner will be strategic only on tasks perceived to be moderately difficult; that is, the tasks which are moderately difficult the performance of the individual will be better. The levels used for the skill perceived task difficulty are shown in Table 16.

4.4 Task-oriented factors

Task affects a person explicitly depending on the demands posed in terms of timely action, required accuracy, parallel processing, etc. These factors are considered in this study to evaluate human performance and are discussed next.

- *Complexity*: Structure and type of the task add to its complexity which can impose attentional and other information processing demands on the performer [76]. The complexity of the task is concerned with the operator's perceptions of the demands of the task. It is dependent on differences between operators in the cognitive factors (e.g., aptitude, working memory) and effective variables (e.g., anxiety, confidence) that distinguish them from one another. Task complexity is related to the tasks cognitive dimensions and can be utilized in task design. It can be noted that the moderate complexity of the task will be effective in task performance. The importance of this PSF in HRA methodology is described in [27,77]. Furthermore, the authors in [77] have proposed an empirical approach known as TAsk COMplexity (TACOM) measure as an indicator of the task complexity issues relevant to HRA. The levels used for task complexity are shown in Table 17.
- *Type of task*: The type of work describes the essential nature of the task, that is, it primarily discusses the constituents of the task. Tasks can be of various genres such as decision-making, simple instruction following, monitoring, noting down of readings at regular intervals, etc. Performance of a person is affected due to imbibing of change in the type of task rather than routine task [69]. Also, different task genre has different levels of difficulty associated with it and hence needs to be given attention during the assessment of human reliability. The different genres considered for the proposed work are given in Table 18.
- *Available time*: It indicates the remaining time to complete the task. In the context of task performance, this time is usually the time required to complete the task [17]. The approach considers available time relative to the time needed to complete the task [78]. While defining different levels of available time, the work considers the fact that the amount of time required to complete the task is highly dependent on the individual itself. Hence, the nominal time is assessed in terms of how the average operator is estimated to perform the task. The levels used for task complexity are shown in Table 19.
- *Task frequency:* Task frequency explains how often an individual is repeating a task before the assignment of the upcoming task [79]. It also describes the time interval between two successive task events (same tasks). Replication of the task for several times helps to gain deeper insights about the task, thereby reducing the likelihood of potential errors. To understand the correlation between the cognitive status of an individual with the repetitive tasks, the authors in [79] have conducted electrodermal activity (EDA) test and compared it with the Occupational Repetitive Action (OCRA) index values. The various levels associated with this PSF are discussed in Table 20.

4.5 Organizational factors

Organizational factors affect human performance, depending on how well an operator can perform his/her job. Better the organizational factors are managed lesser is the likelihood of human error. The key to achieving better performance in any system is the seamless interaction between humans and the organization. However, the implementation of an approach that integrates human and organizational factors continues to run into numerous problems. Some of the critical organizational factors affecting human performance are considered in the current work and are discussed next.

- *Ergonomics*: It describes the strategy of arranging the equipment in the workplace, such that the controls, displays, and other information are easy to access for the operators using them. Furthermore, ergonomics aims to provide maximum productivity cost-effectively. The importance of this PSF for HRA is described in [80,81]. In [81], the authors have demonstrated an approach to systematically couple Human Error and Functional Failure Reasoning (HEFFR) framework with Digital Human Modeling (DHM) to perform ergonomic analysis in addition to identifying potential human errors, component failures, and their propagation paths during early design stages. The proposed model is highly beneficial for designers to visualize the human product interaction and identify the set of actions the user needs to perform to interact with the system. The various levels associated with this PSF are discussed in Table 21.

Table 16 Levels and definition for the PSF perceived task difficulty

Factors influencing human performance	Levels	Definition
Perceived task difficulty	High	The individual experiences extreme difficulty in performing the task. This may arise due to the objective nature of the task as well as the current capability of the individual
	Nominal	The individual experience moderate to low difficulty in carrying out the task. The task neither motivates nor degrades the performance
	Low	The individual finds the task attractive, which boosts the goal fulfillment

Table 17 Levels and definition for the PSF complexity

Factors influencing human performance	Levels	Definition
Complexity	High	The nature of the task is ambiguous and difficult to interpret
	Moderate	The task is hard to understand and involves various parameters which needs to be simultaneously analyzed to get the job done correctly
	Nominal	The task is easy to understand and perform
	Low	The task is very much simplified and easy to perform which positively impacts the individuals performance

Table 18 Levels and definition for the PSF task of type

Factors influencing human performance	Levels	Definition
Task type	Totally unfamiliar task	The task is new having no prior experience or exposure. Guidance is obtained through task manual protocol
	Familiar task requiring high precision	Knowledge about the task has been accomplished as a result of practice sessions; however, the task fulfillment demands high accuracy
	Highly practiced task with low level of precision	The task is acquainted well; and demands low level of accuracy
	Practiced task with time to correct	Familiarity with the task is good and the user has time to recover any wrong action taken

Table 19 Levels and definition for the PSF available time

Factors influencing human performance	Levels	Definition
Available time	Completely inadequate	Time available to perform the task is insufficient
	Inadequate	The time available to perform the task is exactly the minimum time required to perform the task
	Adequate	There is a small time margin, that is the time available to perform the task is slightly greater than the time required to perform the task
	Ample	The time margin is very high and the individual gets enough time to complete the task easily

Table 20 Levels and definition for the PSF task frequency

Factors influencing human performance	Levels	Definition
Task frequency	High	The individual needs to perform the task recursively with minimal time gap between them
	Nominal	The task repeats recursively with larger time gap thus giving significant inter task time to the individual
	Low	The task is rarely repeated and that too with large time interval

Table 21 Levels and definition for the PSF ergonomics

Factors influencing human performance	Levels	Definition
Ergonomics	Poor	The accessibility to the tools or machines or interfaces required to complete the task is limited. In such a work environment, the performance of the individual is prone to errors
	Moderate	The accessibility to the tools or machines or interfaces required to complete the task is available with some delay. This affects performance due to interruptions in the task
	Nominal	The design of the work environment is adequate to support correct performance but does not enhance performance
	Good	The design of the work environment enhances human performance for the task, as much as possible. This represents that the individual can carry out the task in such a way that minimizes the opportunity of errors

– *Leadership*: It is the potential with which an executive influences the behavior of operators at work for accomplishing the task. With good leadership, the members of a team can bind together to work towards a common goal [82–85]. To establish this, the authors in [82] have investigated the relationship between participative leadership and job performance within the internship setting. The data obtained from the conducted survey (309 intern-supervisor dyads) reveal that participative leadership has a positive relationship with job performance. Furthermore, when it comes to what is going on in the organization, leaders are either making it happen (good or bad), allowing it to happen (good or bad), or preventing it from happening (good or bad). Ultimately, the top leader is responsible for anything happening in the organization (good or bad). The different levels of this PSF are summarized in Table 22.
– *Human–machine interaction*: It refers to the interactions between humans and machines in the workplace. For smooth human–machine interactions, a comprehensive and user-friendly platform is required, which is provided through an interface. The interface is a blend circuitry of hardware and software that allows an operator to enter inputs to the system which is then translated as signals for the machines. The importance of this PSF for HRA is described in [80]. The various levels associated with this PSF are discussed in Table 23.
– *Procedures*: It is the terminology used in the industry perspective to describe the series of steps followed to accomplish a goal. Furthermore, it also explains a specific plan of action for carrying out a task. Besides, it advises the employees about the way to deal with a situation [65,69,86]. Procedures are designed to influence and determine all major decisions and actions, and all activities take place within the boundaries set by them. Procedures are the specific methods employed to express policies in effect in day-to-day operations of the organization. To estimate the work safety behavior, the authors in [86] have conducted online survey questionnaire and gathered the data for analyzing the importance of organizational climate together with individual characteristics. The various levels associated with this PSF are discussed in Table 24.
– *Training*: It is the type of activity which is planned, systematic and results in an enhanced level of skill, knowledge, and competency that are necessary to perform work effectively [87]. The primary purpose of training is to acquire and improve knowledge, skills, and attitude towards work-related tasks. It is one of the most critical potential motivators which can lead to both short-term and long-term benefits for individuals and organizations [66]. In this work, the authors have done meta-analysis of relevant studies to understand the effect of experience and training on the performance. The var-

Table 22 Levels and definition for the PSF leadership

Factors influencing human performance	Levels	Definition
Leadership	Democratic	In this scenario, the members of the group take a more participative role in the decision-making process
	Autocratic	Such leadership occurs when a leader dictates policies and procedures, decides what goals are to be achieved, and directs and controls all activities without any meaningful participation by the subordinates
	Laissez-Faire	This is a type of leadership style in which leaders are hands-off and allow group members to make the decisions. It has been found that this is generally the leadership style that leads to the lowest productivity among group members
	Transformational	It is a leadership style where a leader works with teams to identify needed change, creating a vision to guide the change through inspiration, and executing the change in tandem with committed members of the group

Table 23 Levels and definition for the PSF human machine interaction

Factors influencing human performance	Levels	Definition
Human machine interaction	Poor	In this situation the individual is unsuccessful in carrying out the task due to misleading information
	Nominal	The interface provided to carry out the task is although informative but not easy to use
	Comprehensive	The design of the interface is user friendly which supports ease in task performance

ious levels associated with this PSF are discussed in Table 25.

5 Multiplier evaluation for the considered PSFs

This section describes the procedure followed for deriving the multiplier values for the considered PSFs. The proposed approach considers that every individual's behavior and performance is independent of each other; therefore, the multiplier should be evaluated separately for every individual using his/her performance data. The PSF multiplier evaluation is based on two propositions: the first case considers those PSFs, which can change from one level to another during task performance. In contrast, the second case comprises of those PSFs which remains in the same level for a longer duration (refer Table 3). For evaluating PSF multiplier, user data are collected in a simulated working environment. These collected data are utilized to estimate the probability of making the transition from one level to another for state-changing PSFs and the probability of making an error in each state for both states changing and constant state PSFs. Once these values are obtained, the multiplier for each PSF level is evaluated as the probability of making an error while in a particular PSF level. The overview of the proposed approach is schematically shown in Fig. 2.

The proposed approach uses the principle of continuous-time Markov chain (CTMC) to derive the multiplier values of the PSFs. The CTMC model is more specifically applicable to random processes such as physical and biological worlds where time runs continuously. These random processes have discrete state space, but can change their values at any instant of time rather than at fixed intervals; for instance, radioactive

Table 24 Levels and definition for the PSF procedures

Factors influencing human performance	Levels	Definition
Procedures	Undefined	The procedure required to perform the task is not available. In this situation the individual has high probability of making errors
	Minimal	A primitive layout of the work flow is available
	Incomplete	Procedures are defined to perform task but does not define many critical events which may occur.These events may be rare but have highly negative impact on the task completion
	Nominal	The procedure is well defined and easy to follow

Table 25 Levels and definition for the PSF training

Factors influencing human performance	Levels	Definition
Training	Novice	The individual does not have the level of knowledge and understanding required to perform the task adequately task
	Basic	An adequate amount of formal instructions are received, which enable individuals to have an understanding of the task
	Nominal	The individual has received the necessary training and is well prepared to do the task
	Accomplished	The individual has undergone both preliminary and advanced phases of training for performing the task

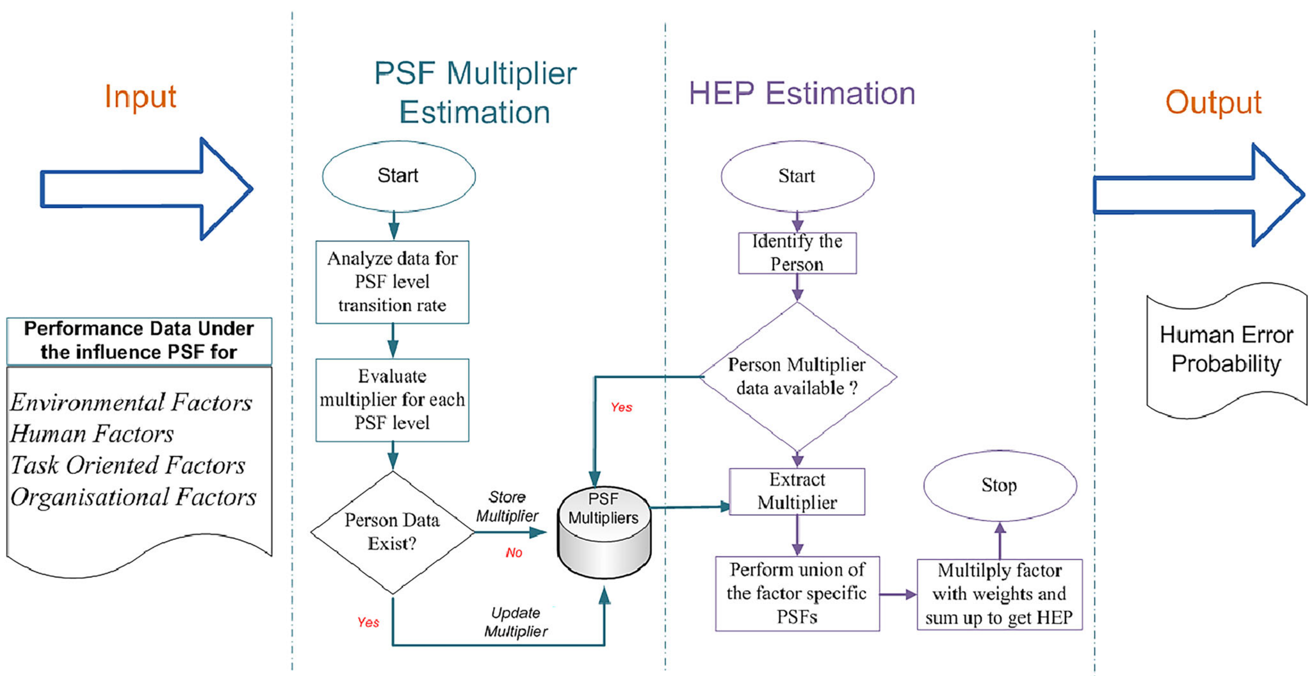

Fig. 2 Overview of the proposed HEP estimation approach

atoms decaying, the number of molecules in a chemical reaction, populations with birth/death/immigration/emigration, the number of emails in an inbox, number of human errors, etc. These processes are piecewise constant, with jumps that occur at continuous times. Also, in this model, the distribution of the chain at some time in the future only depends on the current state of the chain, and not its history. That is, the chain can jump between states at any time, not just at integer times. In particular, suppose that at time t, we know that $X(t) = i$. To make any prediction about the future, it should not matter how long the process has been in state i. Thus, the time that the process spends in each state must have a "memoryless" property.

More specifically, let us consider a random process $X(t)$, $t \in [0, \infty)$. Also, assume that there is a countable state space $S \subset 0, 1, 2, \ldots$. Now, if $X(0) = i$, then $X(t)$ stays in state i for a random amount of time, say T1, where T1 is a continuous random variable. At time T1, the process jumps to a new state j and will spend a random amount of time T2 in that state, and so on. And the probability of going from state i to state j is given by p_{ij}.

The rationale for considering the CTMC model in the proposed approach is that human nature is highly dynamic in nature and the state of a person can make transition from any state to the other at any instant of time. Furthermore, the human behavior is highly correlated to the present state rather than the past states that the person might have gone through. With this analogy, the proposed work has utilized the CTMC model for understanding the human behavior and utilize it for the evaluation of the human error probability.

It is a model which considers that in the span of work, the system will transition from one state to another. Here, states are the different possible scenarios which may occur during work span. These transitions will occur based on some probabilistic rules. The markov approach has essential characteristics which specifies that the next state attained of behavior of the system in future is influenced only by its current state, and not by any prior activity. That is, the next state of the system is dependent only on the current state and not on the path through which the system reached the current state. This key characteristic is the rational behind utilizing the continuous-time Markov chain approach as the person's future state (at any given time) depends only on the present state and not on the past states [88].

5.1 Multiplier evaluation for state-changing PSFs

As mentioned earlier, state-changing PSFs are the ones whose level changes during task performance. For this set of PSFs, the multipliers are evaluated in two steps.

1. The probability of being in one of the levels is evaluated.
2. The likelihood of making an error while at a particular level is evaluated.

During task performance, the PSFs can shift from one level to the other depending on the individual performing the task. These levels can be broadly divided into three categories: nominal state, positively affecting state, and negatively affecting the state. For some PSFs, positively or negatively affecting levels may be further categorized into more than one levels. The assumptions considered for this category of PSFs are described next.

1. Transition is possible from any state to itself or its neighboring state. With this assumption, we state that the behavior of every individual is random and can move from any state to the other at any instance of time.
2. The probability of error in any state is independent of the probability of error in any other state. With this assumption, we want to emphasize on the fact that human behavior is variable and therefore, while moving from one particular state to the other state, the behavior of committing errors will be independent of the other state.
3. After the state transition, the likelihood of error will again start from zero. In this assumption, we want to convey that whenever there is any transition from any state to the other, the chances of committing error in that particular state will again begin from zero. Since, from assumption 2, it has been considered that the number of errors made in any of the state is independent of the number of errors the individual makes in any other state.

In the proposed work, the state is represented as st at any time, t and the different states are: (1) nominal state (st = NO): it is the working state in which the individual performs in designated working condition, and this state is considered as the base state, (2) positively affecting state (st = PF): in this state, an individual performs the task in the favorable condition which helps in improving performance, (3) negatively affecting state (st = NF): in this state, an individual performs the task in unfavorable condition than the designated one which thereby may show degradation in performance. During task performance, at a given time, t, the possible transition between the considered states is shown in Fig. 3a.

An individual can commit errors in any of these states, and the likelihood of the error is computed separately. For the errors, the proposed approach considers two states. The first state is called the *error-free* state (st = NE), where an individual does not commit any error. In contrast, the second state is called the *error-occurrence* state (st = EO) where an individual commits a certain error in terms of delay in action, taking the wrong decision or performing an incomplete task.

5.2 Multiplier evaluation for constant state PSFs

For the PSFs falling under this category, the proposed work assumes that PSF has a fixed level for an individual during the entire duration of task performance. The multiplier for these PSFs is evaluated based on the probability of committing an error while in a particular PSF level. The multiplier evaluation process comprises of continuous-time Markov chain with two states. The person is assumed to be in the first state called the *error-free* state (st = NE) in the beginning and can move to the neighboring state called the *error-occurrence* state (st = EO) at any point of time. The transition state is shown in Fig. 3b.

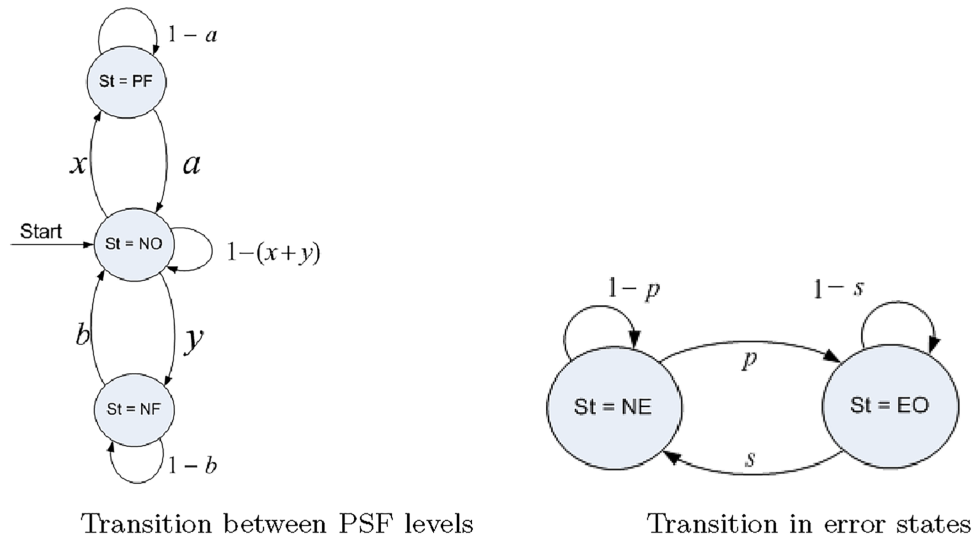

Fig. 3 Transition from one state to another

5.3 Computation of transition rate

To evaluate the multiplier for the state-changing PSFs and constant state PSFs, it is required that the transitions occurring between PSF levels and error states are known. As mentioned earlier, for the state-changing PSFs, the evaluation of both PSF level transition and error state transition is required for the evaluation of the multiplier (refer Fig. 3a, b). On the other hand, for the constant state PSFs, the evaluation of only error state transition is required for the evaluation of the multiplier (refer Fig. 3b). Thus, the probability of being in a particular state is considered as one.

The proposed approach focuses on the evaluation of multiplier based on person-specific performance data and the PSF level changes. That is, the number of errors committed and the PSF level changes occurred during the task performance. Using the aforesaid information, the transition rate is evaluated using the method discussed in [89]. According to this method, the PSF state transitions are considered as continuous Markov chain having the following properties, each time it enters a state (level) i:

1. A PSF remains in state i for (say, T_i) amount of time before making a transition into a different state with rate, say α_i.
2. The PSF leaves state, i and enters next state, j with probability P_{ij}, where $\sum_{j=0, j\neq i}^{r} P_{ij} = 1$

The mean sojourn time in state i is therefore

$$E(T_i) = \frac{1}{\alpha_i}. \tag{1}$$

Let a_{ij} be defined by $a_{ij} = \alpha_i.P_{ij}, \forall i \neq j$.

Here, α_i is the rate at which the PSF leaves state i and P_{ij} is the probability that the PSF goes to state j and a_{ij} denotes the transition rate from state i to state j, that is, when a person is in state i, there is a transition to state j with the rate a_{ij}.

Since, $\sum_{j\neq i} P_{ij} = 1$, so

$$\alpha_i = \sum_{j=0, j\neq i}^{r} a_{ij}. \tag{2}$$

Thus, the transition probability of each state is evaluated by following the trajectories of the state changes. Figure 4 shows an example of a possible state transition. Elaborately, a PSF may remain in state S_6 for T_1 amount of time before making a transition to S_0 where it remains for T_2 amount of time and then makes another transition to S_4 for T_3 of time and so on. Using this information, the probability of state transition is evaluated and is explained with an example in Table 26.

After computing the transition probability of each state, the steady-state probabilities, $P = [P_0, P_1, \ldots, P_r]$, must therefore satisfy the matrix equation

$$\left[P_0, P_1, \ldots, P_r\right]. \begin{bmatrix} a_{00} & a_{01} & \ldots\ldots & a_{0r} \\ a_{10} & a_{11} & \ldots\ldots & a_{1r} \\ .. & .. & \ldots\ldots & a_{..} \\ .. & .. & \ldots\ldots & .. \\ a_{r0} & a_{r1} & \ldots\ldots & a_{rr} \end{bmatrix} = \left[0, 0, ..., 0\right], \tag{3}$$

which may be abbreviated to

$$P \cdot A = 0,$$

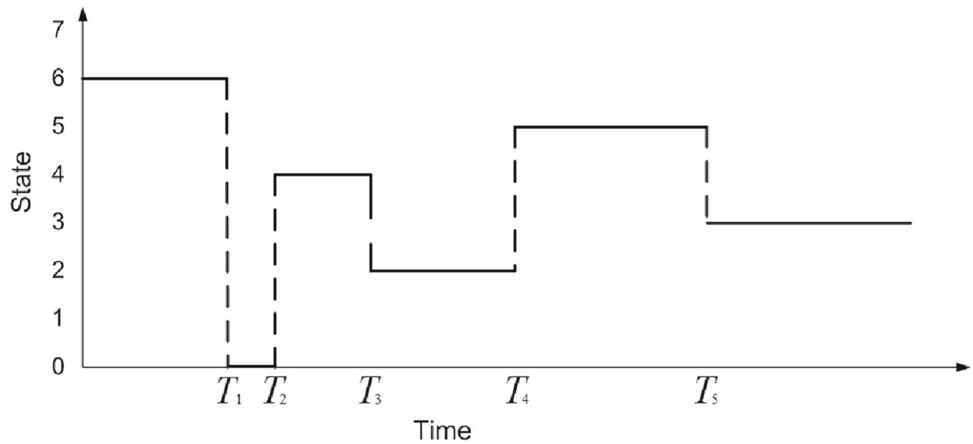

Fig. 4 Trajectories of the state changes during the course of work

Table 26 Computation of state transition probability example

State	Low			Medium			High		
Transition	L-L	L-M	L-H	M-L	M-M	M-H	H-L	H-M	H-H
No. of transition occurrences	11	3	0	0	28	1	0	0	5
Transition probability	11/14	3/14	0/14	0/29	28/29	1/29	0/5	0/5	5/5

where as before

$$\sum_{j=0}^{r} P_j = 1.$$

The computed steady-state probabilities ($P = [P_0, P_1, \ldots, P_r]$) represent the probability of being in any of the PSF states or error states. Once computed, the multiplier is evaluated by multiplying the state probability with the error occurrence probability.

6 Human error probability calculation

After defining the PSFs and estimating their multiplier, the HEP is evaluated as a combination of all the factors. The proposed approach combines the obtained sub-factor multipliers by taking the union of the values to cover up the error space occurring due to one or more PSFs. The step-wise approach followed for evaluating HEP are as follows:

1. Evaluate multipliers for each of the considered PSF using the Markov approach discussed in Sect. 5.
2. Once the multiplier is evaluated, the next step is to evaluate the multiplier for 'PSF dependent sub-factors'. This helps to combine error contributions from different factors under the same PSF.
3. Union of all the multiplier is performed to get the error contribution from the factors of different category.
4. Finally, the evaluated weights of each *Factor* (as discussed in Sect. 6.1) are multiplied and summed up to get the overall error probability of the person.

Note that, the considered factors (except 'Fitness for duty') are mutually exclusive and independent of each other. Considering this, the probability of contribution by the 'Environmental Factor' can be stated as unionization of 'Work process', 'Work shift', and 'Environmental stressors' as mathematically represented in Eq. (4):

$$\begin{aligned} P(\mathrm{EF}) &= P(\mathrm{WP} \cup \mathrm{WS} \cup \mathrm{ES}) = P(\mathrm{WP}) + P(\mathrm{WS}) \\ &+ P(\mathrm{ES}) - P(\mathrm{WP} \cap \mathrm{WS}) - P(\mathrm{WP} \cap \mathrm{ES}) \\ &- P(\mathrm{WS} \cap \mathrm{ES}) + P(\mathrm{WP} \cap \mathrm{WS} \cap \mathrm{ES}). \end{aligned} \tag{4}$$

Similarly, for other factors, namely, Human Factors, Task-oriented Factors, and Organizational Factors, the overall probability of contribution can be represented by Eqs. (5), (6), and (7), respectively.

Here, it is worthy to mention that the PSF- *Fitness for duty* is a 'PSF dependent sub-factor' whose values are based on five different dependent factors. Thus, the union of these factors is performed by taking the conditional probability law under consideration. Once the dependent sub-factor is evaluated, the overall contribution of all the PSFs is computed by performing the union operation.

In the PSF fitness for duty, among the given factors, the occurrence of stress is evaluated by considering the probability of occurrence of other states. Here, only the sub-factor stress is computed in this manner, since for other dependent factors, there is a direct approach to compute their state occurrence probabilities. Here, it is worthy to mention that vigilance and mental workload can be computed as mentioned in [52,90,91]; whereas the sleep duration and up time can be measured by subjective questionnaires. Once these factors are evaluated, the conditional probability approach is applied to compute the stress factor of an individual.

To integrate the evaluated features in the CTMC, the proposed approach evaluates the probability of moving from one state to another. Furthermore, the probability of making error in each state is combined with the probability of staying in a particular state to compute the error making probability of an individual under the influence of the particular factor

$$\begin{aligned}
\mathrm{P}(HF) &= \mathrm{P}(\mathrm{FD} \cup \mathrm{LD} \cup \mathrm{TP} \cup \mathrm{SK} \cup \mathrm{PT}) \\
&= \mathrm{P}(\mathrm{FD}) + \mathrm{P}(\mathrm{EX}) + \mathrm{P}(\mathrm{TP}) + \mathrm{P}(\mathrm{SK}) \\
&\quad + \mathrm{P}(\mathrm{PT}) - \mathrm{P}(\mathrm{FD} \cap \mathrm{EX}) - \mathrm{P}(\mathrm{FD} \cap \mathrm{TP}) \\
&\quad - \mathrm{P}(\mathrm{FD} \cap \mathrm{SK}) - \mathrm{P}(\mathrm{FD} \cap \mathrm{PT}) \\
&\quad - \mathrm{P}(\mathrm{EX} \cap \mathrm{TP}) - \mathrm{P}(\mathrm{EX} \cap \mathrm{SK}) \\
&\quad - \mathrm{P}(\mathrm{EX} \cap \mathrm{PT}) - \mathrm{P}(\mathrm{TP} \cap \mathrm{SK}) - \mathrm{P}(\mathrm{TP} \cap \mathrm{PT}) \\
&\quad - \mathrm{P}(\mathrm{SK} \cap \mathrm{PT}) + \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{TP}) \\
&\quad + \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{SK}) + \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{PT}) \\
&\quad + \mathrm{P}(\mathrm{FD} \cap \mathrm{TP} \cap \mathrm{SK}) + \mathrm{P}(\mathrm{FD} \cap \mathrm{TP} \cap \mathrm{PT}) \\
&\quad + \mathrm{P}(\mathrm{FD} \cap \mathrm{SK} \cap \mathrm{PT}) + \mathrm{P}(\mathrm{EX} \cap \mathrm{TP} \cap \mathrm{SK}) \\
&\quad + \mathrm{P}(\mathrm{EX} \cap \mathrm{TP} \cap \mathrm{PT}) + \mathrm{P}(\mathrm{EX} \cap \mathrm{SK} \cap \mathrm{PT}) \\
&\quad + \mathrm{P}(\mathrm{TP} \cap \mathrm{SK} \cap \mathrm{PT}) - \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{TP} \cap \mathrm{SK}) \\
&\quad - \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{TP} \cap \mathrm{PT}) \\
&\quad - \mathrm{P}(\mathrm{FD} \cap \mathrm{TP} \cap \mathrm{SK} \cap \mathrm{PT}) \\
&\quad - \mathrm{P}(\mathrm{EX} \cap \mathrm{TP} \cap \mathrm{SK} \cap \mathrm{PT}) \\
&\quad + \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{TP} \cap \mathrm{SK} \cap \mathrm{PT}) \qquad (5)
\end{aligned}$$

$$\begin{aligned}
\mathrm{P}(\mathrm{TOF}) &= \mathrm{P}(\mathrm{CO} \cup \mathrm{TT} \cup \mathrm{AT} \cup \mathrm{TF} = \mathrm{P}(\mathrm{CO}) + \mathrm{P}(\mathrm{TT}) \\
&\quad + \mathrm{P}(\mathrm{AT}) + \mathrm{P}(\mathrm{TF}) \\
&\quad - \mathrm{P}(\mathrm{CO} \cap \mathrm{TT}) - \mathrm{P}(\mathrm{CO} \cap \mathrm{AT}) \\
&\quad - \mathrm{P}(\mathrm{CO} \cap \mathrm{TF}) - \mathrm{P}(\mathrm{TT} \cap \mathrm{AT}) \\
&\quad - \mathrm{P}(\mathrm{TT} \cap \mathrm{TF}) - \mathrm{P}(\mathrm{AT} \cap \mathrm{TF}) \\
&\quad + \mathrm{P}(\mathrm{CO} \cap \mathrm{TT} \cap \mathrm{AT}) \\
&\quad + \mathrm{P}(\mathrm{CO} \cap \mathrm{TT} \cap \mathrm{TF}) \\
&\quad + \mathrm{P}(\mathrm{CO} \cap \mathrm{AT} \cap \mathrm{TF}) + \mathrm{P}(\mathrm{TT} \cap \mathrm{AT} \cap \mathrm{TF}) \\
&\quad - \mathrm{P}(\mathrm{CO} \cap \mathrm{TT} \cap \mathrm{AT} \cap \mathrm{TF}) \qquad (6)
\end{aligned}$$

$$\begin{aligned}
\mathrm{P}(\mathrm{OF}) &= \mathrm{P}(\mathrm{ER} \cup \mathrm{LD} \cup \mathrm{HM} \cup \mathrm{PR} \cup \mathrm{T}R) \\
&= \mathrm{P}(\mathrm{ER}) + \mathrm{P}(\mathrm{LD}) \\
&\quad + \mathrm{P}(\mathrm{HM}) + \mathrm{P}(\mathrm{PR}) + \mathrm{P}(\mathrm{TR}) \\
&\quad - \mathrm{P}(\mathrm{ER} \cap \mathrm{LD}) - \mathrm{P}(\mathrm{ER} \cap \mathrm{HM}) \\
&\quad - \mathrm{P}(\mathrm{ER} \cap \mathrm{PR}) \\
&\quad - \mathrm{P}(\mathrm{ER} \cap \mathrm{TR}) - \mathrm{P}(\mathrm{LD} \cap \mathrm{HM}) \\
&\quad - \mathrm{P}(\mathrm{LD} \cap \mathrm{PR}) - \mathrm{P}(\mathrm{LD} \cap \mathrm{TR}) \\
&\quad - \mathrm{P}(\mathrm{HM} \cap \mathrm{PR}) - \mathrm{P}(\mathrm{HM} \cap \mathrm{TR}) \\
&\quad - \mathrm{P}(\mathrm{PR} \cap \mathrm{TR}) + \mathrm{P}(\mathrm{ER} \cap \mathrm{LD} \cap \mathrm{HM}) \\
&\quad + \mathrm{P}(\mathrm{ER} \cap \mathrm{LD} \cap \mathrm{PR}) + \mathrm{P}(\mathrm{ER} \cap \mathrm{LD} \cap \mathrm{TR}) \\
&\quad + \mathrm{P}(\mathrm{ER} \cap \mathrm{HM} \cap \mathrm{PR}) \\
&\quad + \mathrm{P}(\mathrm{ER} \cap \mathrm{HM} \cap \mathrm{TR}) + \mathrm{P}(\mathrm{ER} \cap \mathrm{PR} \cap \mathrm{TR}) \\
&\quad + \mathrm{P}(\mathrm{LD} \cap \mathrm{HM} \cap \mathrm{PR}) \\
&\quad + \mathrm{P}(\mathrm{LD} \cap \mathrm{HM} \cap \mathrm{TR}) + \mathrm{P}(\mathrm{LD} \cap \mathrm{PR} \cap \mathrm{TR}) \\
&\quad + \mathrm{P}(\mathrm{HM} \cap \mathrm{PR} \cap \mathrm{TR}) \\
&\quad - \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{TP} \cap \mathrm{SK}) \\
&\quad - \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{TP} \cap \mathrm{PT}) \\
&\quad - \mathrm{P}(\mathrm{FD} \cap \mathrm{TP} \cap \mathrm{SK} \cap \mathrm{PT}) \\
&\quad - \mathrm{P}(\mathrm{EX} \cap \mathrm{TP} \cap \mathrm{SK} \cap \mathrm{PT}) \\
&\quad + \mathrm{P}(\mathrm{FD} \cap \mathrm{EX} \cap \mathrm{TP} \cap \mathrm{SK} \cap \mathrm{PT}). \qquad (7)
\end{aligned}$$

Next, these values are multiplied with the estimated weight and summed up to get the overall HEP as given in Eq. (8):

$$\begin{aligned}
HEP &= W_1 \times EF + W_2 \times HF \\
&\quad + W_3 \times TOF + W_4 \times OF \\
&\quad \text{such that, } W_1 + W_2 + W_3 + W_4 = 1,
\end{aligned} \qquad (8)$$

where W_1, W_2, W_3 and W_4 represent the weights, EF is the Environmental Factor, HF is the Human Factor, TOF is the Task-oriented Factor, and OF is the Organizational Factor.

6.1 Weightage calculation of the factors

In general, it is assumed that each factor has an equal impact on every individual. However, this assumption does not justify the calculation of HEP, since different work organizations have different work culture, environment, and task distribution. To consider the varying impact of different factors over human performance depending on the industry type or organization, the proposed approach assigns weightage to the performance governing factors. The step-wise procedure for weight calculation is described in the following sub-sections.

6.1.1 Estimation of human error in various sectors

The probability of human error is dependent on factors which include operating conditions, working place arrangements, level of training, the intensity of work, degree of fatigue, etc., and it varies from industry to industry. Thus, the importance of different factors varies for every type of organization. As a solution to the issues mentioned above, the proposed approach has computed weightage of the factors based on the kind of industry rather than a generalized index of consensus. The ranking of different performance affecting factors according to industry type is summarized in Table 27.

Table 27 Error-occurrence contribution (in %) according to different industries

Contribution to error occurrence according to different industries	Environmental factor	Human factor	Task-oriented factor	Organizational factor
[92] (%) contribution	4	57	24	15
Rank	4	1	2	3
[93] (%) contribution	7.2	48.2	15.2	29.4
Rank	4	1	3	2
[94] (%) contribution	16	43	1	40
Rank	3	1	4	2
[95] (%) contribution	6.4	49.6	1.6	42.4
Rank	3	1	4	2
[96] (%) contribution	6.0	66.0	10.1	18.0
Rank	4	1	3	2

6.1.2 Estimation of weight

Weight assignment to different factors has been done by following the Ordered Weighted Averaging (OWA) approach proposed by Fullér et al. [97]. It is used to prioritize the factors for HEP evaluation as per the industry requirement. A step-wise approach to evaluate weight using OWA approach is as follows:

1. The approach initially computes the minimum possible weight (W_1) which satisfies Eq. (9):

$$W_1[(n-1)\alpha + 1 - nW_1]^n = ((n-1)\alpha)^{n-1}[n-1]\alpha - n)W_1 + 1], \tag{9}$$

   where n is the number of parameters, and α is a constant which lies between 0 and 1.
2. After computing the minimum weight, the maximum weight to be assigned is evaluated using Eq. (10):

$$W_n = \frac{((n-1)\alpha - n)W_1 + 1}{(n-1)\alpha + 1 - nW_1}. \tag{10}$$

3. Finally, the other weight values are defined in terms of the minimum and maximum weights using Eq. (11):

$$W_j = \sqrt[n-1]{W_1^{n-j} W_n^{j-1}}; \quad 1 \le j \le n. \tag{11}$$

The computation of weights for each of the factor category is done by prioritizing the importance of the factors in accordance to the different industries. As the contribution of the different factors have different impact for different industries, so this step becomes essential for estimating human error probability in the proposed approach. For evaluating the importance of each factor, literature survey is carried out and the importance of each factor is considered from the most relevant works, as shown in Table 27. Once the contribution of each of the factors is known, they are ranked in accordance to their importance for human error probability estimation. Next, the weight calculation approach, Ordered Weighted Averaging (OWA) proposed by Fuller et al. [97] have been utilized to estimate the weight contribution by each of the factors. In this approach, the value of α is varied between 0 and 1 and the weights are evaluated. For each value of α, a different set of weights will be obtained. Out of these set, the weights which represent the maximum resemblance with the importance of each factor category in particular industry is considered as the final weight value. The calculated weight for different industries according to performance influencing factors is summarized in Table 28.

To illustrate the approach, let us take the aviation industry into consideration. For this particular industry, the prioritization of the important factors is taken from the reference [92]. According to this literature, the maximum importance is given to the human factors and minimum importance is given to environmental factors with the contribution percentage of 57 and 4, respectively. With the knowledge gained from this work, the ranking of each factor category is done on the scale of 1–5, with '1' holding the highest importance of contribution and '5' the lowest contributing factor. After this, the next step utilizes the OWA method for computing the weight of each factor category. The calculation begins with the computation of minimum weight. Here, the value of parameter α is taken in an interval of 0–1 with an increment of 0.01 in each iteration to find the best values. From this, the minimum weight value W_1 is calculated. Among the set of minimum weight values, the value which is close to the minimum contribution percentage (in this case, the value is 4) is selected. Now, the α values which are generating these weights are considered and the maximum weights are computed with respect to these α values. Once the set of maximum weights is obtained, then the weights which are close to the maximum contribution percentage are chosen. Next, based on the obtained values, the other weights are calculated, and in a

Table 28 Weight calculation for different industries according to performance influencing factors

Industries	Computed weight			
	Environmental factor	Human factor	Task-oriented factor	Organizational factor
Aviation [92]	0.0543	0.5674	0.2596	0.1187
Aviation [93]	0.0806	0.4994	0.1481	0.2719
Maritime [94]	0.1126	0.5818	0.0496	0.256
Railway [95]	0.0877	0.6425	0.0324	0.2374
Cement [96]	0.02161	0.691856	0.06862	0.21790

similar way, the values which are close to the given contribution percentage are taken as weight contribution of each factor. Finally, as per the ranking of the factors maximum to minimum weights are assigned to each of the considered factors.

7 Case study

In this section, a case study is presented to show how the proposed P-SPHERE approach can be implemented. In the considered case study, the participants perform a set of tasks under different working conditions. Next, using the information gathered from the experimental setup, the evaluation of PSF multiplier is carried out for every individual. This evaluated PSF multiplier is stored in the database for the future assessment of HEP at the time of task assignment. That is, before task assignment, the current state information of the individual is collected, and based on the recorded PSF multiplier, the current HEP of the individual is computed.

7.1 Design of experiment and data collection

For HEP evaluation, the proposed approach considers PSF levels based on the performance of the individuals. For this, data are collected from 15 healthy volunteers (25 $\pm$ 5 years old), after an explanation of the study, from Indian Institute of Technology Kharagpur. The participants performed two different tasks, namely, Mackworth clock test [98] and *n*-back task [99] from which the information about different PSFs is collected, and the performance data are recorded to estimate the error occurrences. Details of the two experiments are as follows.

7.1.1 Vigilance experiment

The experiment was performed by each participant in an isolated room, which was maintained at normal room temperature with adequate light conditions. The stimuli were presented on a 20-inch large monitor kept at a distance of about 65 cm from the participant. Before the experiment began, the participants were relaxed for 10 min to make them accustomed to the experimental environment. To better understand the state of an individual, subjective questionnaire was filled by the participant in terms of the Visual Analogue Scale (VAS) to indicate their present mood and Global Vigor and Affect (GVA) form which is used for subjective analysis of affective state (feelings, mood) and level of vigor (alertness, vigilance). Next, for each participant, an instruction and demonstration session were arranged. This was followed by 5-min practice session to make them inure with the experiment and also remove the novelty effect. After the practice session, baseline EEG data recording was done, in which participants were asked to sit idle for 5 min with restricted movement of body organs. Next, the participants went through the 20 min Mackworth Clock Test [98] which represented the Phase I experiment. During the test, the participant has to respond to the correct observation of stimuli within a specified time duration. After the completion of Phase I experiment, the difficulty of the experiment was analyzed by asking the participant to fill the NASA-TLX questionnaire. Subjective rating of the present mood was also recorded using the VAS questionnaire to understand the before and after effect of the experiment. Just after this, the Phase-II part of the experiment began which again started with the recoding of 5 min baseline data to seek the changes in the mental stress/load of the participants. This was followed by the 10 min clock test and ended with filling of NASA-TLX, VAS questionnaires. The entire experiment duration was 65 min. In a day between 7:00 AM and 10:00 AM, only a single participant's datum was recorded as per their availability.

7.1.2 Mental-workload experiment

For the mental workload experiment, the environmental conditions were kept constant like the vigilance experiment. Here, in this setup, two dedicated computers were used for the purpose of experimentation. One of the computers was used for recording the data, while the other one was used for presentation of stimuli. Additionally, an event marker was used for marking the start and end of each difficulty level task in the experiment. The participants were seated at a distance of 70 cm from the computer which had a display size of 20 inches. Also, upon arrival, the participants were given relaxation period of 10 min.

In the next 5 min, the VAS form was filled by each participant which indicated their current alertness and mental state. Furthermore, another questionnaire gathered information about the food habits, sleep hours, vision, working hours, and medical history of the participants. This was followed by an instruction and demonstration session for describing the entire experimental procedure. A sample practice session of 10 min was given to each participant to adapt with the experiment. After this, a 5 min baseline EEG data recording was carried out in which the participants had to sit idle with minimum body movement.

The induction of mental workload was done with the help of n-back task (Working Memory Test Battery [100]) which consists of complex span tasks based on the principle of item storage with concurrent processing of a separate cognitive processing tasks. Such tasks have the potential for capturing the conceptual requirements of simultaneous processing and memory operations which are essential in working memory functioning. The workload was varied in three (low, medium, and high) levels for each of the participant. Also, the pause duration between each of the presented stimuli was varied among the difficulty levels to induce the substantial effect of workload. The value of 'n' in the experiment was varied between 3 and 5, that is, 3-back task was considered as low task difficulty, 4-back as medium task difficulty, and 5-back as high task difficulty. Furthermore, in the first task, the inter-element pause duration was kept at 600 ms, and this duration was reduced successively by 100 ms for every upcoming task. Six different tasks namely Arrow span, Matrix span, Operation span, Reading span, Rotation span, and Symmetry span were performed by each of the participant in the workload experimentation. During the experiment, each participant has to respond by entering the correct answers and also their response duration was recorded. After completion of the session, the participant gave their subjective assessment of mental effort required in NASA-TLX questionnaire and current mood status in VAS questionnaire. Also, the individual judgement of task difficulty was noted for each participant on the scale of 10. The entire experiment duration was 75 min. As per the availability, the experiment was conducted between 7:00 AM and 10:00 AM in the morning.

For other information such as sleep duration, medication, experience, work shift, time pressure, perceived task difficulty, skill, stress, and up time relevant questionnaires have been utilized. The details about the environmental stressors were obtained from the experimental setup condition. The particulars about task-oriented factors were gathered from the design of experiment information. For organizational factors (ergonomics and human–machine interaction), the infrastructure information of the laboratory in which the experiment was conducted was used. The instruction brochure of the experiment provided the information regarding the factor procedures; while the training period given to the participants was used as training information. Next, for the factor leadership, the leadership quality information was used from the nature of the instructor experimenting. Thus, the data of different factors for PSF multiplier evaluation are collected using one of the four approaches, namely, EEG-based data, task-specific data, subjective rating, and existing literature. Details of the whereabouts of data collection for different factors are summarized in Table 29.

Table 29 Approach followed for data collection of different factor

Measurement approach	Factors
EEG device	Mental workload (MW)
	Vigilance (VI)
Task specific data	Time pressure (TP)
	Task frequency(TF)
	Type of task (TT)
	Available time (AT)
	Task complexity (TC)
Subjective data (collected during experiment)	Work shift (WS)
	Skill (SK)
	Perceived task difficulty (PT)
	Sleep duration (SD)
	Up time (UT)
	Stress (ST)
Existing literature	Ergonomics (ER)
	Leadership (LD)
	Human–machine interaction (HM)
	Procedures (PR)
	Training (TR)
	Work process (WP)
	Environmental stressors (ES)

7.2 PSF level multiplier evaluation

The PSFs for HEP evaluation will fall in one of the three categories, namely, (a) the PSF whose levels remain fixed throughout work and remain same for almost every person, (b) the PSF whose level remains fixed throughout work but varies from person to person, and (c) the PSF whose level changes over the course of work. In the first two categories, the PSF level remains same, and the transition occurs only from making 'no error' to 'committing some error'; however, for the remaining one, the transition occurs between the PSF levels as well as error occurrence. Thus, the evaluation of multiplier is done in two different manners.

Table 30 Mental workload transition data

State, i	Destination state j		
	Low	Medium	High
Low	10	3	0
Medium	0	31	1
High	0	0	1

Table 31 Mental workload error-occurrence data at each state

Mental workload state					
Low		Medium		High	
A–A	*A–B*	*A–A*	*A–B*	*A–A*	*A–B*
4	2	25	3	1	1
B–A	*B–B*	*B–A*	*B–B*	*B–A*	*B–B*
2	2	2	1	1	0

A no error occurrence, *B* error occurrence

7.2.1 Variable PSF level with transition during error occurrence

An excellent example of this category of PSFs is the factors involved under the 'Fitness for duty' in the 'Human Factors' category. Under this category, it has been identified that mental workload and vigilance are the most critical parameters affecting human performance [58]. In this work, multipliers for these parameters are evaluated using data collected using EEG device.

Here, the detailed procedure for mental workload multiplier evaluation is demonstrated. Following a similar approach, the calculation of remaining PSF multiplier is summarized in tabular format. The evaluation of multiplier is done in two parts: in the first part, the probability of being in any of the states (refer Sect. 5) is evaluated followed by calculation of error-occurrence probability in a particular level. After obtaining the probabilities, the values are combined to obtain the multiplier.

Steps to obtain mental workload multiplier are as follows:

For illustration, the data from one potential participant is considered. Next, the mental workload state transitions are analyzed from the recorded EEG data. Furthermore, the error occurrences in each state have been computed. The mental workload state transitions and the error occurrence for the participant are tabulated in Tables 30 and 31, respectively.

- **Step 1** Based on the state transition data of each participant (refer Table 30), the transition probability from state i to state j is evaluated using Eq. (12). The tabulation of the data is summarized in Table 32.

$$T_{ij} = \frac{\text{Total transition from state } i \text{ to state } j}{\text{Total transition from state} i} \tag{12}$$

Table 32 Participant specific mental workload state transition probability evaluation

State, i	Destination state j		
	Low	Medium	High
Low	0.769231	0.2307692	0
Medium	0	0.96875	0.03125
High	0	0	1

Table 33 Participant specific mental workload state probability

State	Probability
P_{Low}	0.433333
P_{Medium}	0.24086
P_{High}	0.325806

Table 34 Error state transition probability

Mental workload state					
Low		Medium		High	
A–A	*A–B*	*A–A*	*A–B*	*A–A*	*A–B*
0.666667	0.333333	0.8928571	0.107143	0.5	0.5
B–A	*B–B*	*B–A*	*B–B*	*B–A*	*B–B*
0.5	0.5	0.666667	0.333333	1	0

A no error occurrence, *B* error occurrence

Table 35 Participant specific error probability at each mental workload state

Error state	State probability		
	Low	Medium	High
P_A	0.6	0.756757	0
P_B	0.4	0.243243	1

- **Step 2** After computing the transition rates for different states, the probability of being in one of the states is calculated using the Markov approach discussed in Sect. 5 and is shown in Table 33.
- **Step 3** After obtaining the state probability values, the transition probability from state i to state j is evaluated using Eq. (12) based on the error state transition data of each participant (refer Table 31). The computed error transition probability from state i to state j is given in Table 34.
- **Step 4** Next, the error-occurrence probability is evaluated using the Markov approach discussed in Sect. 5 and is summarized in Table 35.

Finally, the multiplier for each PSF is evaluated by multiplying the probability of being in a state with the probability of error occurrence in that state. For instance, the multiplier value for the participant at 'Low' mental workload is $0.433333 \times 0.6 = 0.259999$.

Similar to the approach followed for mental workload multiplier evaluation, the multipliers for other PSF parameters, i.e., vigilance, stress, and up time (except sleep duration, since it will remain fixed for the entire task duration) are evaluated from the participant data. The tabulation of the final probabilities of being in one of the states as well as the probability of error occurrence in any state is summarized in Table 36.

7.2.2 Fixed PSF level with transition during error occurrence

In this category, the nature of PSFs is such that their level remains fixed during work and almost remain the same for every person. Good examples of such kind of PSFs are under the category of 'Environmental Factors', 'Task-oriented Factors', and 'Organisational Factors' (refer Table 3). Besides these PSFs, there are some PSFs whose level remains fixed during work, but is person-dependent; that is, they vary from person to person. The PSFs− experience, time pressure, skill, perceived task difficulty, and sleep duration under the 'Human Factors' category are examples of PSFs showing such behavior. For the above-mentioned PSFs, the calculation of the probability of being in a state is not required, and the only necessary estimate is the probability of error occurrence in a particular state.

7.3 HEP estimation

HEP is calculated for evaluating the person suitability for task assignment. In this stage, the PSF multiplier information stored in the database during the training period is used to estimate the current suitability of the person for task allocation. To illustrate the HEP estimation procedure, a snapshot of individual data during task performance has been utilized, which is shown in Table 37.

The step-wise elaboration of PSF computation under each category is described next.

– **Human factor** For the overall error contribution of PSFs under this category, first, the 'Fitness for duty' is evaluated using Eq. (5).
  Multiplier for Fitness for duty is

$$\begin{aligned} \mathrm{FD}_{\mathrm{Mult}} &= P(\mathrm{MW} \cup \mathrm{VI} \cup \mathrm{SD} \cup \mathrm{UT} \cup \mathrm{ST}) \\ &= P(0.058 \cup 0.051 \cup 0.043 \cup 0.125 \cup 0.005) \\ &= 0.256675206. \end{aligned} \tag{13}$$

  Next, by combining the value of 'Fitness for duty' with the other PSFs, the overall error contribution due to 'Human Factor' is evaluated

Table 36 Participant specific error probability at each mental workload state

Vigilance		Probability of		Up time		Probability of		Stress		Probability of	
State		Being in state	Making error	State		Being in state	Making error	State		Being in state	Making error
Low	*Error*	*0.0887*	1	Prolonged	*Error*	0.1365	0.6543	Poor	*Error*	0.4844	0.4091
	No Error		0		*No Error*		0.3457		*No Error*		0.5909
Medium	*Error*	0.1938	0.34444	Nominal	*Error*	0.2754	0.3333	Nominal	*Error*	0.3946	0.11429
	No Error		0.6556		*No Error*		0.6666		*No Error*		0.68571
High	*Error*	0.7175	0.07143	Short	*Error*	0.5881	0.09287	Good	*Error*	0.1211	0
	No Error		0.928571		*No Error*		0.9071		*No Error*		1

$$\begin{aligned} HF_{Mult} &= P(FD \cup EX \cup TP \cup SK \cup PT) \\ &= P(0.256 \cup 0.071 \cup 0.187 \cup 0.172 \cup 0.0307) \\ &= 0.550094459. \end{aligned} \tag{14}$$

- **Environmental factor** For evaluating the overall error contribution of PSFs under this category, the equation defined in Eq. (5) is utilized

$$\begin{aligned} EF_{Mult} &= P(WP \cup WS \cup ES) \\ &= P(0.0105 \cup 0.0184 \cup 0.0072) \\ &= 0.035815777. \end{aligned} \tag{15}$$

- **Task-oriented factor** Using Eq. (4), the overall error contribution of PSFs under this category is evaluated

$$\begin{aligned} TOF_{Mult} &= P(CO \cup TT \cup AT \cup TF) \\ &= P(0.012 \cup 0.026 \cup 0.009 \cup 0.003) \\ &= 0.049860855. \end{aligned} \tag{16}$$

- **Organizational factor** The overall error contribution is evaluated using Eq. (7):

$$\begin{aligned} OF_{Mult} &= P(ER \cup LD \cup HM \cup PR \cup TR) \\ &= P(0.008 \cup 0.216 \cup 0.043 \cup 0.018 \cup 0.015) \\ &= 0.28136654. \end{aligned} \tag{17}$$

Finally, the overall HEP by considering the weightage for the Railway industry is calculated using Eq. (8). The overall error calculation is

$$\begin{aligned} HEP &= W_1 \times EF + W_2 \times HF + W_3 \times TOF \\ &\quad + W_4 \times OF \\ &= (0.0877 \times 0.035) + (0.6425 \times 0.550) \\ &\quad + (0.0324 \times 0.049) + (0.2374 \times 0.281) \\ &= 0.424988642. \end{aligned} \tag{18}$$

8 Discussion

This paper proposes a novel technique for HEP estimation using human-dependent parameters. The proposed methodology works on the basic principle that every human is different, and so is their behavior to the work environment. Moreover, the behavior of the same person varies at different work diurnals. Therefore, for evaluating HEP, the dynamic nature of human behavior must be taken into account. To achieve this, various objectives has been formed which are successively fulfilled to design the overall HEP estimation process.

The first objective talks about identification of PSFs present in various accident scenarios and their categorization depending on the factors influencing them. To fulfill this objective, an extensive literature survey has been performed to identify the factors affecting human performance. Furthermore, all the identified factors have been classified as environmental, human, organization, and task-oriented factors. The second objective emphasizes on the evaluation and definition of different levels of the considered PSFs. Here, the considered PSFs have been analyzed to identify their possible constructive and detrimental effects on the human performance. Based on this, the levels for each of the PSF has been defined. The level categorization is done by considering both positive as well as negative impact on the individual performance. Next, this paper focuses on multiplier evaluation for the considered PSFs. For this, different levels of the considered factors have been evaluated. A Continuous Chain Markov model have been utilized to identify the different possible states a person can remain while at task. Using this model, once a person is in one of the levels of a particular factor, the probability of error in that particular state is evaluated. The probability of error occurrence for every individual is considered to evaluate the multiplier for each factor in every level. After this, to generalize the proposed HEP evaluation approach and also to make it more applicable to every industry domain, the weights of different PSF category have been evaluated based on the industry type. Here, it is worthy to mention that, in general, it is assumed that each factor has an equal impact on every individual. However, this assumption does not justify the calculation of HEP, since different work organizations have different work culture, environment, and task distribution. To consider the varying impact of different factors over human performance depending on the industry type or organization, the proposed approach assigns weightage to the performance governing factors using OWA approach. Finally, all the values calculated under different PSF category are merged together to obtain the overall human error probability.

To elaborate the implementation of the proposed approach, a short case study has been considered. The illustrated case study considers experimental environment for the calculation of the PSF multiplier followed by HEP evaluation. However, for application of the proposed methodology in real scenarios, data from actual work environment under the influence of PSFs are to be collected. For instance, for the PSF 'work shift' under the category of 'Environmental Factors', the error data have to be collected separately for different work shifts. Similarly, for 'environmental stressors', separate data have to be collected for all possible environment stress conditions in which the person is working. Apart from these, the 'work process' is application domain-dependent PSF, and

Table 37 Participant data snapshot utilized for human error probability calculation

Factors category	Factors influencing human performance	Current PSF level	PSF level probability	PSF error probability	PSF multiplier
Environmental factors	Work process	Good	–	0.010526	0.010526
	Work shift	Morning	–	0.0184615	0.0184615
	Environmental stressors	Nominal	–	0.0072308	0.0072308
Human factors	Fitness for duty				0.256675
	(i) Mental workload	Medium	0.24086	0.243243	0.05858750898
	(ii) Vigilance	High	0.7175	0.071429	0.05125
	(iii) Sleep duration	Nominal	–	0.04348	0.04348
	(iv) Up time	Nominal	0.375	0.333333	0.125
	(v) Stress	Nominal	0.3946	0.014286	0.005637
	Experience	Low	–	0.071429	0.071429
	Time pressure	Nominal	–	0.1875	0.1875
	Skill	Basic	–	0.172308	0.172308
	Perceived task difficulty	Nominal	–	0.0307692	0.0307692
	Complexity	Nominal	–	0.0123457	0.0123457
Task-oriented factors	Type of task	Familiar task requiring high precision	–	0.026	0.026
	Available time	Adequate	–	0.009001	0.009001
	Task frequency	Nominal	–	0.003333	0.003333
	Ergonomics	Good	–	0.00813	0.00813
	Leadership	Democratic	–	0.21619	0.21619
Organizational factors	Human machine interaction	Comprehensive	–	0.043478	0.043478
	Procedures	Nominal	–	0.018868	0.018868
	Training	Nominal	–	0.015038	0.015038

thus, depending on the domain, it may be considered fixed or variable. Hence, the error data have been collected as per the requirement.

The PSFs under the category of ‘Human Factors’ are crucial elements for the occurrences of havoc at work. Thus, to understand actual human behavior, in the proposed approach, assistance has been taken from the EEG device for capturing physiological data. While applying this methodology, a similar approach can be used for data collection. Furthermore, support from appropriate questionnaires can be taken for collection of PSFs level data, such as sleep duration, up time, experience, skill, stress, perceived task difficulty, and time pressure. However, for the error data collection, it is required that the conditions are varied for variable natured PSFs (mental workload, vigilance, up time, and stress). For the better track of the error occurrences, attempts should be made to upgrade the user interface, such that automatic capturing of committed errors or lapses is possible.

For the PSFs under the category of ‘Task-oriented Factors’, the information about the PSF level can be gathered using the task protocol manual and the error data can be collected by varying the parameters of the PSFs. On the other hand, for the PSFs under the category of ‘Organisational Factors’, the ISO standard maintained by the organization can be used for gaining knowledge about PSF level. Further for the error data, the error occurrence under the influence of varying PSF level can be used.

After calculation of PSF multipliers, the overall HEP is calculated by taking into account all the PSF category multipliers. Here, it is to noted that, during the combination process, the weightage values of the different factor categories are to be considered strictly according to the application domain (refer Sect. 6.1). In the case study, weightage has been taken from the Railway industry for illustrating the final calculation process and is found to be 0.42498. This suggests that there is a probability of 0.42 chances of making error during task assignment.

The effectiveness of the proposed approach lies in the fact that it considers human behavior as complex and often varied between individual. Every individual has different behavior even in same working conditions. Considering this, the approach evaluates human error probability based on individual data. Also, the data gathered for any individual are taken, such that it directly or indirectly affects the human performance. These data are collected in one of the two ways, that is, using EEG device or using subjective questionnaires. For the overall human error probability estimation, the proposed work has a major advantage that the brain data collected through EEG are able to unearth the actual potential of an individual without doing any rough estimations and the subjective questionnaires helps to collect individual information.

Although the inclusion of physiological measures such as EEG enhances the overall HEP estimation process, however, the proposed approach requires certain data such as sleep duration information from the subjective questionnaires. Thus, the effectiveness of these subjective questionnaires is dependent on the accuracy of the information provided by the participant. In this way, the overall error probability estimation accuracy varies with the correctness of the data furnished by each individual.

The proposed methodology is distinct and highly applicable to the different industry domains. In this work, a CTMC model has been considered for understanding the stochastic human states at working conditions. Unlike the existing literature where only errors are considered as a benchmark for estimating human error probability, the proposed approach evaluates error of an individual along with variation in different parameters. This is because errors are just one of a range of behavioral products of a number of individual and organizational precursors; they are not a class of behaviors that are entirely distinct from other behaviors and thus should not be considered in isolation. The evaluation of error probability at any state using the CTMC model is useful in capturing the dynamic behavior of human and thus helps in making the approach realistic. Furthermore, the consideration of weights depending on the industry type helps in providing wider applicability to the proposed HEP approach.

9 Conclusion

Human errors are sources of vulnerability in any work environment. Several minor and major errors combine gradually to give rise to havoc. Vulnerable human behavior must be estimated well in advance to minimize the probability of error occurrence during the task. The proposed methodology, P-SPHERE, aims at incorporating real human behavior into the HEP estimation process for better evaluation of person-specific HEP. The fundamental principle of the proposed method is that every individual is different, and so is their chances for committing errors. Using the proposed methodology, one can quickly analyze variation in HEP depending on the contextual changes at the work environment, work schedule or human behavior. Thus, making a person-specific estimation of HEP possible and usable during the task allocation process. Besides, the proposed approach is generic, since it can be used for any application domain at any work environment. Furthermore, the method can be used as a useful tool for estimating the best working environment, work schedule, or environment under which optimal performance could be reached.

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