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Human reliability analysis methods

İnsan güvenilirlik analizi metotları

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Abstract

Human error is one of the most important factors contributing to occupational accidents. Human Reliability Analysis (HRA) methods have been used successfully in many fields to determine the probability of errors contributing to such accidents, estimate the impact of their consequences, and develop error reduction strategies. In this study, it has described some HRA methods and their implementations in several fields, including maritime, aviation, railway, space, health, nuclear, petrochemical, and construction sectors. Examples are drawn from articles dealing with HRA issues listed in the Web of Science Core Collection database between 2012 and 2022. The relatively small number of HRA studies conducted in Türkiye are found mainly in maritime applications. This review is intended to encourage the widespread use of HRA methods in all industries.

Keywords: Human reliability analysis, Human error, Occupational safety and health, Human error probability, Human reliability

Öz

İş kazalarına neden olan en önemli etkenlerden biri insan hatasıdır. İnsan Güvenilirlik Analizi (HRA) metotları, bu tür kazalara neden olan hataların olasılığını belirlemek, sonuçlarının etkisini tahmin etmek ve hata azaltma stratejileri geliştirmek için birçok alanda başarıyla kullanılmaktadır. Bu çalışmada, denizcilik, havacılık, demiryolu, uzay, sağlık, nükleer, petrokimya ve inşaat sektörleri dahil olmak üzere çeşitli alanlardaki bir dizi HRA metotları ve uygulamaları açıklanmıştır. Örnekler, Web of Science Core Collection veritabanında 2012-2022 yılları arasında listelenen HRA konularını ele alan makalelerden alınmıştır. Türkiye'de HRA ile ilişkili yapılan az sayıda çalışmanın denizcilik uygulamalarında olduğu görülmüştür. Bu inceleme yazısı, HRA metotlarının tüm endüstrilerde yaygın olarak kullanılmasını amaçlamaktadır.

Anahtar Kelimeler: İnsan güvenilirlik analizi, İnsan hatası, İş sağlığı ve güvenliği, İnsan hata olasılığı, İnsan güvenilirliği

1 Introduction

Consider the series of disasters that made news in the last quarter of the 20th century:

- the Three-Mile Island nuclear power plant accident in the USA in 1979;
- the Bhopal Disaster, which caused the release of methyl isocyanate gas in India in 1984;
- the Chernobyl nuclear power plant accident in Ukraine in 1986 [1],[2]
- the Piper Alpha explosion and fire accident in the North Sea in 1988;
- the Kegworth air disaster in England in 1990;
- the Southall train accident in England in 1997 [3]

In every case, the accident has been attributed to human error. Human error may be described as the set of human acts which have serious and harmful consequences [4],[5]. Industrial accident statistics indicate that 60% - 90% of accidents are caused by human error [6],[7]. Specifically, research by Di Pasquale et al. [8] identifies human error as the primary cause of accidents in more than half of reported incidents. Rates were 65% in the automobile industry, 70% - 80% in the aviation industry, 90% in air traffic control, 80% - 85% in maritime shipping, 60% - 90% in the chemical industry, 50% - 70% in nuclear power plant operation and 85% in road transportation. Despite the reduction in overall accident rates achieved by technological improvements (especially automation), human error remains a serious problem.

Human error can occur during the design, manufacture, installation, operation, and maintenance of a product or system [9]. Human errors become more frequent and serious as the complexity of systems increases. They are also influenced by the context of the activity and must be discussed in the context of particular organizations [10]. Human reliability is defined as the ability of a worker to perform activities required for an overall task correctly in a prescribed time and to avoid any action that may disrupt the functioning of the system [9],[10]. Determination of human reliability is accepted as a guide to the prevention of accidents caused by human errors [11]. The extent to which human errors contribute to the risks is a parameter that determines the reliability of the risk assessments [12]. Human Reliability Analysis (HRA), is the

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name given to methods for risk assessment that consider all accident scenarios to identify causes of human errors together with their consequences [13] and make a probabilistic prediction of the overall safety of a system [11].

In this study, the concepts, methods, applications, and significance of HRA as deployed in a range of industrial sectors are summarized. This study aims to encourage researchers and experts who make accident analyses and assessments to extend the range of HRA applications in the Turkish industry and other countries.

1.1 Human Reliability Analysis (HRA) Methods

In this section, it has surveyed a range of established HRA methods. Table 1. contains a chronological summary of HRA methods and displays some details of those HRA methods. It has identified three generations of methods: the first generation extends from 1975 to 1990; the second from 1990 to 2005; and the third follows 2005 to the present day. In brief, first generation methods emphasize human error probabilities for specific subtasks in an overall operation. Second generation methods describe Performance Shaping Factors (PSFs) (including workers' cognitive processes), and third generation methods include recognition of interactions among these factors [14],[15].

Table 1: HRA methods by generation.

Methods	Developed by	Industrial Activity
AIPA (Accident Investigation and Progression Analysis)	Raabe, 1974	Nuclear
TESEO (Technica Empirica Stima Errori Operatori)	Bello and Colombari, 1980	Petrochemical/ Nuclear
OATS (Operator Action Tree System)	Wreathall, 1982	Nuclear
PC (Paired Comparisons)	Hunns,1982	General
THERP (Technique for Human Error Rate Prediction)	Swain and Guttmann, 1983	Nuclear
APJ (Absolute Probability Judgement)	Seaver and Sitwell, 1983	General
SLIM (Success Likelihood Index Method)	Embrey, 1983	Nuclear
HCR (Human Cognitive Reliability)	Hannaman et al. 1984	Nuclear
SHARP (Systematic Human Action Reliability Procedure)	Hannaman and Spurgin 1984	General
MAPPS (Maintenance Personnel Performance Simulations)	Knee et al., 1985	Nuclear
STAHR (Socio-Technical Assessment of Human Reliability)	Philips et al., 1985	Nuclear/ Maritime
HEART (Human Error Assessment and Reduction Technique)	Williams, 1985	General
SHERPA (Systematic Human Error Reduction and Prediction Approach)	Embrey, 1986	Nuclear
ASEP (Accident Sequence Evaluation Program)	Swain, 1987	Nuclear
JHEDI (Justified Human Error Data Information)	Kirwan, 1990	Nuclear
HRMS (Human Reliability Management System)	Kirwan, 1990	Nuclear
INTENT (not abbreviation)	Gertman et al., 1990	Nuclear
COGENT (Cognitive Event Tree)	Gertman, 1992	General
COSIMO (Cognitive Simulation Model)	Cacciabue et al., 1992	Nuclear
DREAMS (Dynamic Reliability Technique for Error Assessment in Man- Machine System)	Cacciabue et al., 1993	Nuclear
CREAM (Cognitive Reliability and Error Analysis Method)	Hollnagel, 1993	Nuclear
ATHEANA (A Technique for Human Error Analysis)	Cooper et al., 1996	Nuclear
CODA (Conclusions from Occurrences by Descriptions of Actions)	Reer, 1997	Nuclear
CAHR (Connectionism Assessment of Human Reliability)	Sträter, 1997	General
MERMOS (Méthode d'Evaluation de la Réalisation des Missions Operateur pour la Sureté)	Le Bot et al., 1997	Nuclear
SPAR-H (Standardized Plant Analysis Risk-Human Reliability Analysis)	Nuclear Regulatory Commission (NRC), 1999	Nuclear
HFACS (Human Factors Analysis and Classsification System)	Wiegmann and Shappell, 2000	Aviation
CESA (Commission Errors Search and Assessment)	Reer et al., 2004	Nuclear
NARA (Nuclear Action Reliability Assessment)	Kirwan et al., 2005	Nuclear
CARA (Controller Action Reliability Assessment)	Kirwan and Gibson, 2007	Aviation
RARA (Railway Action Reliability Assessment)	Gibson et al., 2013	Railway

First generation HRA methods focus on Human Error Probability (HEP) [14]. They subdivide a complex task into simple parts and then consider the potential impacts on HEP of modifying features of each step. First-generation techniques focus on "local" PSFs such as time pressure, equipment design, stress, and working time. These methods can include consideration of the effects of ergonomics and employees' education and experience, but they do not incorporate adequately PSFs representing the effects of the environment on human performance [16],[8],[17]. According to Catelani et al. [15], these methods generally assess and score the performance of employees as successful or unsuccessful. First-generation techniques, though superseded by more sophisticated methods, are still used in many industrial applications.

Second generation techniques have been developed to determine the relationship between the environment and HEP [17]. These methods consider the causes of errors as well as their frequency. PSFs emphasized in second-generation methods generally include the internal and external factors affecting employees' work performance such as workload, stress, sociological problems, psychological problems, disease, noise, and temperature. The second generation techniques also focus on the cognitive aspects of employees tasks [8],[15]. Cognitive effects refer to employees' information preprocessing, problem-solving, decision-making, and consequent action. The second generation analysis includes interdependencies of PSFs. These factors interact not only with each other but also with the temperament of employees; this defines an analytical category called a psychological factor [18]. The extension from first-generation analysis is illustrated by Hollnagel [19] who discusses HRA methods in two ways: dominant task approaches that address possible deviations in tasks and approaches that focus on cognitive processes.

Third generation methods, introduced as early as 2005, deal with the dynamic (evolving) relationships and dependencies among factors affecting human performance [8],[15]. Third generation methods extend second generation HRA methods to allow for the dynamic development of human behavior [15].

2 Methods

Many distinct HRA methods have been developed to determine human reliability; the literature review of 81 articles identified 31 different HRA methods. Methods named HEART, CREAM, and THERP methods are the most commonly implemented. A few selected methods are briefly characterized here.

2.1 THERP

The Technique for Human Error Rate Prediction (THERP) is a first-generation HRA method developed by Swain and Guttmann in 1983. Its purpose is to predict human errors in the nuclear power plant industry quantitatively or qualitatively. The technique analyzes Human Error Probabilities (HEPs) by using a large human reliability database that includes available literature reviews, interviews, and observations with nuclear plant employees as well as plant data. The "incident tree" approach allows quantitative modeling of the dependency between actions and errors. Branches emanating from binary decision points are developed for each node in a task [20]. The resulting incident tree expresses the order in which the incidents occur and the probable errors that may occur at each node [21]. It shows the response of each HEP value to changes in PSFs, particularly to nuclear plant operation; the main purpose is to expose high-error stages of an overall process and to focus study on ways to minimize errors. In the study by Kirwan [22], the THERP method was compared with other first-generation methods Human Error Assessment and Reduction Technique (HEART), and Justified Human Error Data Information (JHEDI); these three techniques all provide a reasonable level of accuracy (codifying 72% of all HEP). The THERP method, the first widely used method in HRA, is now commonly used in other industries other than the nuclear industry [14].

2.2 SLIM

The Success Likelihood Index Method (SLIM) is a first-generation technique introduced by Embrey et al. in 1983 and developed under the sponsorship of the U.S. Nuclear Regulatory Commission [23]. Like other first generation methods, it is intended to evaluate the probability of success or failure of subtasks in a process; it may be described as an "expert system" formalizing expert judgment to predict HEP values [24],[25]. In SLIM implementation, PSFs are weighted according to their importance. The accurate scaling of PSF impact is a critical aspect of SLIM analysis [26]. The applicability and usability of the technique have been verified by an interactive computer program based on Multi-Attribute Utility Decomposition-MAUD [27].

2.3 HCR

The Human Cognitive Reliability (HCR) method, a first-generation HRA technique, is a psychological modeling approach developed by Hannaman in 1984 [28]. The method assumes that the probability of an employee's failure in performing a critical task under time pressure is a consequence of cognitive deficiencies [8]. HCR uses Rasmussen's formulation of decision-making based on rules, skill, and knowledge; the SRK model [20], to determine the probability of failure in a particular task [29]. The PSFs that affect the average time taken to perform the task are employee experience, employee stress level, and the employee/facility interface. Considering all these factors allows the creation of "response time" curves, enabling comparison with the time available to perform the task. This in turn allows prediction of the probability that an employee will fail to take the correct action in the time available. HCR has been tested by nuclear power plant simulations [30].

2.4 HEART

The Human Error Assessment and Reduction Technique (HEART) was described by Williams in 1986 [14]. The HEART technique is widely implemented in various industries such as the nuclear industry, aviation, railway, medicine, and chemistry [27], [14]. It is a first generation HRA method intended to evaluate the probability of errors in a system and to identify aspects of a task which can be revised to improve overall security levels. It can assess human error swiftly. The HEART technique includes a questionnaire dealing with common task types and Error-Producing Conditions (EPCs). According to the method, there are thirty-eight error-producing conditions and nine HEP values relevant to common task types. Human reliability is assessed depending on the task [14]. EPC values can refer to the experience of the employee or his teammates, their education, stress, age, ambient noise, and the hours they perform the task [27]. HEART is one of the few experimentally verified HRA methods. As mentioned above, a large-scale, comparative verification study including HEART and THERP and JHEDI was done by Kirwan et al. [22]. These three methods are similar in accuracy.

2.5 2.5 SHERPA

The Systematic Human Error Reduction and Prediction Approach (SHERPA) was developed by Embrey (1986) [31] and was originally implemented in the nuclear power generation industry [32]. As in other first generation methods, SHERPA resolves an overall process into subtasks and provides a classification system for identifying potential error modes. Field experience shows that it produces valid, useful, cost-effective, and controllable results. Although it displays an approach based on the expertise and decision of the analyst, it has been determined to have good validity and reliability [33].

2.6 CREAM

The Cognitive Reliability and Error Analysis Method (CREAM) was suggested by Eric Hollnagel in 1998 [16]. It is a second-generation HRA method; two versions are available, basic and expanded. Both have two important advances over first-generation methods: first, incorporation of a cognitive model to determine the importance of mental processes in human performance; and then, the ability to analyze both prospectively and retrospectively at each step. The prospective analysis identifies potential human errors, while retrospective analysis expresses the consequences of human errors that have already occurred [30].

CREAM has three main study areas: analysis of subtasks, reduction of opportunities for error, and enhancement of human performance. Characteristics of the task setting called Common Performance Conditions (CPCs) have been identified. There are nine CPCs identified for the system. These are:

- the efficiency of the organization,
- working conditions,
- human-machine interface efficiency and operational support,
- availability of procedures and plans,
- number of concurrent objectives,
- available time,
- time of day,
- the efficiency of training and experience, and finally
- the quality of team collaboration [14].

CREAM is intended to correct the limitations of first-generation human reliability analysis methods, but it suffers its own deficiences. Foremost are the lack of data on CPCs and uncertainty of their relationship with operator control mode [17]. CREAM is nonetheless widely implemented; in a study analyzing 271 articles published between the years 2009-2020, it is found that domain are focused on CREAM, The method is mainly implemented in energy and chemical industries, and in maritime and transportation sectors [13].

2.7 ATHEANA

A Technique for Human Error Analysis (ATHEANA) was developed by Cooper et al. [30] to obtain qualitative and quantitative HRA results for the nuclear energy industry. As a second generation technique, ATHEANA focuses on the cognitive aspects of decision-making, and considers both prospective and retrospective aspects of incidents. It aims to provide a strong psychological framework capable identifying and assessing PSFs [30]. The basic consideration in ATHEANA is to identify Error-Forcing Contexts (EFCs) in which human errors and unsafe acts are likely [34]. The method emphasizes that significant human errors occur as a result of conditions specific to the plant combined with performance shaping factors such as fatigue, stress, and noise these conditions [35]. ATHEANA uses PSFs defined by experts. Further, how PSFs affect the prediction of Human Error Probabilities (HEP) is assessed by experts in the ATHEANA method, as in many other HRA methods [36]. Its reliability for detailed Probabilistic Risk Assessment (PRA) continues to be questioned precisely because it relies on expert opinion [37].

2.8 SPAR-H

Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) is a second-generation HRA method developed by the US Nuclear Regulatory Commission (NRC) in the 1990s, taking its final form as SPAR-H in 1999. The SPAR-H technique assigns human activity to one of two common task categories: act, and identification [38],[39]. Acts are activities such as starting up equipment such as pumps or performing calibration or testing, while identifications consist in understanding system condiions by reliance on knowledge and experience, planning activities and determination of appropriate actions. SPAR-H is built on the information processing model of human performances, derived from the behavioral sciences literature and adapted to the operation of nuclear power plants. Eight PSFs are used in the quantification of human performance. These factors include available time, stress factors, training and experience, complexity, ergonomics (including human-machine interface design), standardized procedures, and finally working processes. Upon comparison with other HRA techniques, the SPAR-H technique fares well [39]. SPAR-H has clear practical advantages: it is easy to use and fast, and does not require its users to be expert . It is flexible and useful in conditions that do not require a more detailed analysis [10].

2.9 HFACS

The Human Factors Analysis and Classification System (HFACS) was introduced by Shappell and Wiegmann in 2000 as a tool for classification, model data collection, and analysis. HFACS is based on James Reason's [40] Swiss Cheese Model of accident causation [41]. The method recognizes four types of human failure, each affecting the next. These are (1) unsafe acts; (2) underlying causes of the unsafe act; (3) unsafe management; and (4) other organizational effects. Unsafe acts are divided into two categories: (a) errors and (b) violations, The underlying causes of an unsafe act are divided into three categories: (a) personnel factors; (b) an individual's condition; and (c) environmental factors. Unsafe management is divided into four categories: (a) poor management; (b) inappropriate business planning; (c) failure to correct a known problem; and (d) management violations. Organizational effects are divided into three categories: (a) resource management; (b) organizational environment; and (c) organizational process [42]. HFACS is useful across a range of industrial settings. A report by Hulme et al. [43] cites 73 articles on accident analysis appearing between 1990-2018; of these, the HFACS technique was used in 43 articles. Of these 43 applications, The method is applied widely; 15 deal with aviation, 10 with maritime operations, 7 with mining, 6 with rail operations, 2 with construction, 2 with nuclear power, and 1 with industrial.

2.10 RARA

The Railway Action Reliability Assessment (RARA) analysis was developed by the Railway Safety and Standards Board in the UK to obtain a human error probability assessment technique specific to the railway industry [15]. It is a third generation technique described by Gibson et al. in 2013 and is effectively a quantitative extension of the first generation HEART technique [44]. RARA is a rapid system, simple to implement with little required training. It produces useful numerical output for the analyst along with error reduction suggestions. As a third-generation method, it takes into account relationships among error performance conditions. Furthermore, because it is a technique measured with a subjective judgment, it is still incomplete in reliability and consistency [45].

3 Sources Consulted

In this study, the studies in the Web of Science (WoS) Core Collection database on the use of HRA techniques in maritime, aviation, railway, health, petrochemical, space, nuclear, and construction sectors were examined. The broad category of lifting operations was also investigated. WoS is preferred because it is an internationally recognized database of scientific publications with high-quality standards [46]. It also provides detailed data such as abstracts, references, citation counts, and author lists. It found 1843 publications in the entire database which refer to "human reliability" and 1040 publications over the period 2012-2022. The term "human reliability analysis" appears in 978 publications overall and 645 publications in the interval 2012-2022. Of the 978 articles in the selected time interval referring to "human reliability" 971 are in English, while of the 645 articles referring to "human reliability analysis" 644 articles are in English.

4 Literature review

In the set of articles citing "human reliability" in the entire WoS database, the USA, China, and the UK lead, with 318, 287, and 172 articles. In the interval 2012 – 2022, 1040 articles are listed; China has 239 publications, the USA has 153 publications and South Korea has 76 publications. The number of publications from Türkiye is 47. Of the 978 publications in the entire WoS database citing "human reliability analysis," the USA contributed 213, China 206, and South Korea 102 publications. Türkiye produced 29 studies mentioning this term. Of 645 publications citing "human reliability analysis" between 2012 and 2022, China produced 176 publications, the USA 116 and South Korea 71, Türkiye contributed 29 technical articles.

Table 2 and Figure 1 display the details of those 14 HRA articles conducted in Türkiye. The table includes the first 14 articles with high citations.

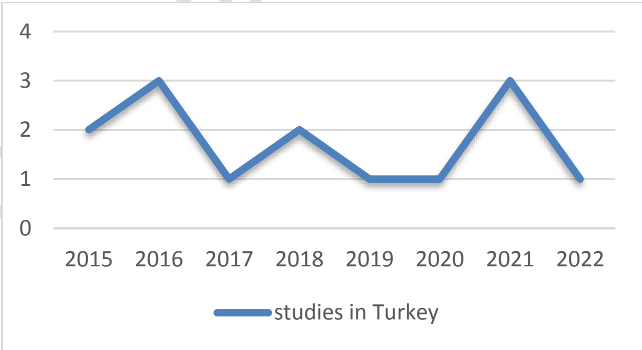

Figure 1. Number of publications by year.

As Table 2 shows, the most common use of HRA methods in Türkiye is in the maritime section. In the following sections it has looked more thoroughly into recent reports of specific methods and applications. Many of these incorporate advanced statistical analyses, such as "fuzzy logic" and Bayesian Network modeling. These new methods may find utility not only in the maritime sector but elsewhere in the Turkish industry as well.

4.1 Maritime

Yang, et al. [59] suggest a new CREAM technique combining Fuzzy Evidential Reasoning and Bayesian Inference Logic and applied it to a case of shutdown of a fuel pump of an oil tanker shutdown. The method computes human error probabilities instantly. A study by Wu et al. [60] described a modified CREAM technique intended to predict the probability of human error during a shipwreck and applied it to a ship capsizing accident. The analysis was consistent with empirical data, and showed that human performance reliability during LPG cargo handling is high. Zhou et al. [61] described a quantitative HRA model based on Fuzzy Logic Theory, Bayesian Network, and CREAM methods for the tanker shipping industry.

Table 2: Studies in Türkiye using HRA methods.

No	Author	Sector	Method	Field	Publisher
1	Akyuz & Celik [16]	Maritime	CREAM	Engineering	Journal of Loss Prevention in The Process Industries
2	Akyuz & Celik [47]	Maritime	HEART	Engineering	Safety Science
3	Akyuz & Celik [48]	Maritime	HEART	Engineering	Applied Ocean Research
4	Akyuz et al. [27]	Maritime	HEART-HFACS	Engineering	Safety Science
5	Akyuz & Celik [49]	Maritime	HEART	Engineering	Journal of Loss Prevention in The Process Industries
6	Akyuz [50]	Maritime	HFACS	Engineering	Safety Science
7	Akyuz & Celik [51]	Maritime	SLIM	Ecological Sciences	Human and Ecological Risk Assessment
8	Akyuz et al. [52]	Maritime	HEART (SOHRA)	Engineering	Safety Science
9	Kandemir et al. [53]	Maritime	HEART (SOHRA)	Engineering	Applied Ocean Research
10	Kandemir & Celik [54]	Maritime	HEART (SOHRA)	Engineering	Cognition Technology & Work
11	Bicen et al. [55]	Maritime	HEART (SOHRA)	Engineering	Journal of Engineering for the Maritime Environment
12	Kandemir & Celik [56]	Maritime	HEART (SOHRA)- HFACS	Engineering	Reliability Engineering & System Safety
13	Erdem & Akyuz [57]	Maritime	SLIM	Engineering	Ocean Engineering
14	Kaptan [58]	Maritime	HEART	Engineering	Journal of Engineering for the Maritime Environment

This model was applied to the case of a tanker with eighteen crew members, and found to be highly reliable. Islam, et al. [62] revised the HEART technique so to assess potential human errors in under varying sea, environmental and working conditions, and confirmed that extreme weather conditions, high workplace temperature, high noise and vibration, heavy workload, and stress increase the probability of human error and accidents. According to a study using the data from off-shore evacuation simulation, the BN-SLIM hybrid method performed better than other Bayesian Network-based HRA techniques (BN-CREAM, BN-SPARH, BN-SLIM) depending on their quantification [38].

4.2 Railway

It is accepted that human error is one of the main causes of railway accidents [63]. Wang et al., [44] devised a modified HEART method in which RARA and the Fuzzy Analytic Network Process (FANP) are integrated to assess the probability of human error in high-speed rail shipment tasks. Zhou and Lei [26] designed a hybrid SLIM method intended to improve the safety of the locomotive driving process. To verify its effectiveness, the method has been tested by Monte Carlo simulation. The encouraging results are in accord with the authors' experience in railway management. Kyriakidis et al. [45] defined a new methodology to assess the contribution of humans to risk in the railway industry named the Human Performance Railway Operational Index (HuPeROI) It combines SLIM and Analytic Network Process ANP techniques. It has been stated that the integrated method can be used efficiently in regional, high-speed, and underground railway operations. Sun et al. [63] suggested a modified CREAM method to be applied to evaluate the dispatcher's human reliability requirements. E-SHERPA, described by Catelani et al. [15] predicts the time-dependent probability of human error during a work shift. It incorporates a simulator that allows evaluation of the effect of variable rest breaks on human performance. The E-SHERPA method has been employed in maintenance studies of an automatic train protection system. This study highlights the important role of a well-trained operator, aware of the procedures necessary to maintain a low probability of error.

4.3 Aviation

Accidents in aviation may be considered a means to identify poor human-aircraft-environment interactions and organizational defects. Human error, strongly influenced by such flaws, is considered a critical proximate cause of accidents in the aviation industry [41]. Gong et al. [64] proposed an Accident Tree logical structure for accident modeling. They integrated the Accident Tree with the HFACS technique to improve its analysis and enhance its reliability. Guo & Sun [65] considered that the CREAM technique was not fully implemented in human reliability analysis in aviation, and presented a modified version integrating fuzzy logic theory into the CREAM framework. Their analysis suggests that cognitive failures in observing safety measures are the most significant. Hirose et al. [66] method was applied to a study of a real air accident in Colombia in 1995 and showed that a deviation in standard operating procedures in the cockpit had led to the fatal accident.

4.4 Space

More than 50% of disruptions and incidents in the space industry, as in the aviation industry, are attributed to human error [42]. In their study of human reliability during spaceflights, Chen, et al. [67] defined PSFs specific to space travel and devised an augmented version of the CREAM method incorporating Bayesian Network analysis to predict HEPs. The suggested method's accuracy has been proven in both mathematically modeled and practical contexts. In their study of human reliability in spaceflight Calhoun et al. [68] also used a version of CREAM with a set of PSFs specific to the setting. Further, they considered the three training styles used in NASA: skill-based training, mission-based training, and knowledge-based training. Skill-based education produced the most significant improvement in HEP.

4.5 Health

Although human reliability in health care is a new thread compared to other fields, it has drawn great interest in recent years [32]. In 2019 Evans et al. [69] investigated the underlying causes of human error in a private-sector healthcare organization with 1,100 employees in the United Kingdom. They distributed a questionnaire surveying information security core human error causes (IS-CHEC), adapted from the HEART technique. Of the 749 people receiving the questionnaire, 485 responded. The results suggested that the organization should focus on working environments and on employees' understanding of security information to reduce human errors most effectively. In another study, Sujan et al. [32] took into account the opportunities and difficulties of the implementation of HRA in healthcare services. On balance, it appears HRA can provide a useful framework for risk analysis and reduction in the health sector, but HRA techniques should be adapted and implemented according to the characteristics of the sector. Trucco et al. [70] proposed a modified version of the HEART technique adapted to one of the most common robotic surgeries, Radical Prostatectomy (prostate cancer surgery). Analysis revealed that team-related factors had the highest impact on surgeons' performance.

4.6 Petrochemical

Shirali et al. [17] point out that petrochemical industries encounter catastrophic risks owing to the hazardous materials used. Hence human reliability studies have particular importance in the petrochemical industry. The study by Shirali et al. adapts a CREAM technique incorporating Fuzzy Bayesian Network analysis, offering a simple method for calculating HEP in complex industries. It has been applied to a description of operations in the control room of petrochemical plants and recognizes fire in the storage unit as the most important emergency. Abbassinia et al. [1] have concluded that the Fuzzy Bayesian augmented CREAM approach is widely suitable for human error assessment and applicable to a range of emergencies. Petrillo et al. [71] developed a hybrid SHERPA method that considers both internal and external factors affecting an employee in its estimate of the probability of human error. They used their model to analyze real emergencies in a petrochemical plant, finding that operators' fatigue is particularly important. While the nominal human error probability is 6% in the operator's first hour of work, it is 31% in the sixteenth hour. Kumar et al. [6] developed a "Fuzzy HEART" model to estimate human error probabilities in their study of LPG (propane) refueling stations. Results include estimated failure rates for four subtasks: stopping the vehicle in the correct position (0.011114); connecting the nozzle (0.028463); filling the tank with fuel (0.01357) and disconnecting the nozzle (0.00856). In a direct comparison with CREAM, the Fuzzy HEART method gives results of similar quality.

4.7 Nuclear

Although the use of HRA analysis is long-standing in nuclear technology, new techniques have been developed in the last ten years. To illustrate, SPAR-H is a method developed to predict HEPs used in US nuclear power plants [38],[39]. Groth & Swiler [72] sought to remedy some shortcomings in this method by combining SPAR-H with the Bayesian Network (BN) technique. The study aims to show how the SPAR-H BN can be used by practitioners, and it also demonstrates how it can be modified to incorporate data and information from research to advance HRA practice. Zhao & Deng [73] extend the THERP technique by replacing the decision trees (DTs) and fuzzy expert system (FES) methods. They illustrated their method by application to the startup operation of a nuclear power plant. They found that failure in a particular subtask increases the probability of failure in the following subtask. This is expressed as a Conditional Human Error Probability (CHEP). It has been concluded that lower CHEP reduces overall failure rates. Preischel & Hellmich [74] extended the THERP technique by incorporating a Bayesian statistical method; for testing, they used operational data from German nuclear power plants. Their model can reproduce the number of errors in a task occurring in the past and on that basis estimate the probability of future human error (HEP). Liu & Li [75] studied the effects of performance shaping factors (PSF), their interrelationships, and their effects on HEP. They tested their model against the database obtained for SPAR-H and nuclear power plants. They conclude that there is a significant relationship between task complexity and HEP; for complex tasks, HEP values should decrease as operators gain experience. Ramezani et al. [76] developed the Cognitive Based THERP (CB-THERP) technique for HRA in nuclear power plants by incorporating the strengths of Deterministic Safety Analysis (DSA), THERP, and HCR. Their technique has been applied to the performance of the operators in the main control room of the nuclear power plant during an accidental loss of feedwater. The HEP values estimated in this model are reduced by a better Human-Machine Interface (HMI). Operators with a higher education level have smaller HEP. Pinto et al. [35] augmented the ATHEANA technique by incorporating fuzzy theory. Their model addresses possible malfunctions in the digital pressure controller system of the pressurized water reactor. The model describes the interaction of components such as sensors, actuators, software, process variables, and human acts. Results compare well with literature data.

4.8 Construction

Liao et al. [77] devised a method combining CREAM with Bayesian Network analysis, aiming to measure the probability of design errors causing unsafe behavior in the construction industry. They describe the effect of design errors on human behavior is 195%. and emphasize the need for achieving better understanding of the importance of design in preventing unsafe behaviors. In other words, when there is design failure on the construction site, the probability of worker unsafe behavior will increase by 195% compared to its original probability, which is a noticeable influence. Fargnoli and Lombardi [78] proposed a new model called Preliminary Human Safety Assessment (PHSA), which is created by combining Hierarchical Task Analysis (HTA), Predictive Human Error Analysis (PHEA), SHERPA, and HEART. Its intent is to better understand the hazards and risks and to monitor the behavioral aspects in the safety environment and to suggest improvements. The PHSA model has been applied to use of concrete mixer trucks. In practice, most of the errors occurred when the employee did not follow established working procedures and disregarded safety information, and when the employee changed the state of the system. Time pressure and the influence of other workers at the construction site contribute significantly to unsafe behaviors; improving organizational factors and training can be effective in reducing errors. Wang et al. [79] applied Fuzzy CREAM in a study for a metro construction site, concluding that their method can effectively assess human error hazards. Qin & Stewart [80] sought to determine the occurrence and consequences of human error underlying construction defects; they employed a CREAM model combined with a Bayesian probabilistic technique to estimate construction defect rates in roof joints in residential construction. Integrating their model into the previously developed Fragility Method by Qin & Stewart to assess wind damage and determine the reliability of metal roofing and wooden roof trusses for Australian houses, they find that construction defects caused by design deficiencies (which arise from human error) increase the fragility of roofing.

4.9 Lifting Operation

Lifting operations, which involve machines that move large masses of materials, are subject to human error. Tu et al. [81] present a method combining SLIM and Bayesian methods and apply it to crane lifting. HEPs for various errors have been measured. Five useful PSFs have been identified: these are (1) operator experience, (2) operator training level, (3) equipment and tool condition, (4) environmental conditions, and (5) frequency and thoroughness of the inspection. In a study of crane lifting by Borgheipour et al. [82] using SHERPA and CREAM techniques, 148 operator errors and error probabilities were determined. Monitoring of the collision avoidance system has the lowest risk probability (0.0003), while monitoring of available protections has the highest, (0.056). Mandal et al. [31] used the HTA technique to measure the risks associated with human error in overhead and gantry crane ground operations. In this study, 21 human errors related to crane operations have been identified. Most of these errors are irreversible; they can result in malfunctions of crane components or accessories during operation. Then the load will be dropped. The probability of making these errors can be reduced by training and planned inspections of crane components.

5 Discussion

Human Reliability Analysis (HRA) is important in any field that requires high reliability. HRA techniques can determine, predict and form a basis for control of human errors that contribute to accidents. In the review, it has pointed out the various advantages and disadvantages of a spectrum of HRA techniques.

HRA techniques are divided into three generations. The first generation techniques focus on the effects of human errors on the environment and the operational context, while the second generation techniques analyze the cognitive errors of the people together with the effects of the first generation techniques. Second-generation techniques have been developed because the first-generation techniques involve expert decisions and the data used in the methods are limited. Third-generation techniques, on the other hand, provide data by using simulation methods; they are refined by considering and changing first and second-generation techniques or by combining many first and second-generation techniques.

HRA researchers continue to develop methods to deal with uncertainties caused by incomplete information and to apply established techniques for different sectors, modifying the performance shaping factors (PSFs) according to conditions specific to that sector. In some cases, it is not possible to assess the effects of human errors on the system due to the complex structures of the systems. Then researchers try to overcome these difficulties through probabilistic methods such as fuzzy logic and Bayesian Network analysis to simplify complex processes and allow for incomplete information by qualitative judgments. To illustrate, the fuzzy logic approach can reflect the way people think, and model verbal understanding and decision-making [6].

Human Reliability Analysis techniques started with studies in the nuclear industry. New techniques have been developed by combining these early models with other techniques. HRA techniques have been extended by applications in different fields. In the literature review is found many articles on use of HRA factors in maritime, aviation, railway, space, health, nuclear, petrochemical, and construction sectors of the economy. HRA aims to assess the possibilities of human error systematically and quantitatively. Focus has been on CREAM, HEART, and SLIM techniques in the maritime sector, CREAM in the aerospace sector, HEART in the health sector, THERP and SPAR-H in the nuclear field, and CREAM in the construction sector.

The literature search reveals that studies on HRA techniques are limited in Türkiye. Most of these studies deal with the maritime sector. Turkish studies in the maritime sector use

HEART and HFACS techniques among the other HRA techniques.

6 Conclusions

The occupational accidents in various sectors in Türkiye differ from year to year. However, there is an increase in the number of occupational accidents, the number of people who died in occupational accidents, or the accidents that result in temporary or permanent failure even if there is no death, although risk assessments are made as an obligation in the workplace. Table 3. displays the occupational accident statistics obtained from the SGK data between 2012 and 2020 [83]. Although occupational accident data are published annually in Türkiye, there are no statistics or research on human error-related accidents.

Table 3. 2012-2021 Türkiye's occupational accident statistics

Year	Occupational Accident (Person)	Accident deaths (Person)	Temporary incapacity (Days)	Permanent incapacity
2012	74.871	744	1.647.127	66.039
2013	191.389	1.360	2.357.505	52.825
2014	221.366	1.626	2.065.962	42.857
2015	241.547	1.252	2.992.070	103.833
2016	286.068	1.405	3.453.702	134.403
2017	359.653	1.633	3.996.873	252.916
2018	430.985	1.541	2.488.001	484.791
2019	422.463	1.147	3.627.934	123.623
2020	384.262	1.231	3.492.824	98.620
2021	511.084	1.382	4.650.312	95.360

To reduce occupational accidents it is necessary to to extend the practice of risk assessment and to research the root causes of accidents thoroughly. It is important to analyze near misses as well. In particular, the human factor contributing to the accidents should be well researched and analyzed, with the aim to enhance human reliability in the workplace and to reduce the rate of accidents due to human error. It is suggested that developing HRA techniques and adapting them to occupational health and safety practices in many sectors of the economy will be helpful in reducing human errors underlying accidents. This review is intended to be a comprehensive guide to currently available but rarely applied HRA methods and encouragement of future studies of human reliability in Turkish and all countries businesses.

7 Author contribution statements

In this study, Author 1 took part in the formation of the idea, making the design, literature research, process, and writing phase, Author 2 contributed to providing control and supervision, examining the content, and Author 3 contributed to checking the spelling and checking the article in terms of content.

8 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person / institution in the article prepared.

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