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Research article

Looking beyond the screen: A systematic review of safety in control rooms

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A R T I C L E I N F O

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A B S T R A C T

As a complex socio-technical system, the Control Room (CR) is central to many industries, such as process, aviation, transportation, and mining. CRs' complexity impacts the safety, operational, engineering, regulatory, and financial performance of the system. In this study, a search strategy was defined and applied to three reputable databases: Scopus, Web of Science, and PubMed. The search results underwent a two-stage screening process based on inclusion and exclusion criteria. The inclusion criteria were investigating the safety in the CR, full-text availability, and writing in English. The exclusion criteria were unrelated to the safety in the CR, non-English Language, and non-original studies. A total of 59 studies were included in the analysis. The included articles were systematically reviewed from the Human Reliability Assessment (HRA) and Human Factors Engineering (HFE) perspectives. Since these records covered various subjects related to human reliability and human factor aspects, a categorization step was added to the study process. In this step, all included studies were categorized based on their subjects. A total of 7 categories were identified, including reliability (17 documents), safety performance (13 documents), decision-support systems (7 documents), fire safety (2 documents), communication/teamwork (11 documents), situation awareness (4 documents), and others (5 documents). Finally, the included studies in each category were analyzed and discussed. The results of this study help identify different aspects of safety in the control room and plan to improve their safety weaknesses, which ultimately leads to an increase in the efficiency of employees and various industries.

1. Introduction

The Control Room (CR) serves as the central control unit of a system, playing a vital role in monitoring and managing complex operations. There are two primary types of CR including: Analog CR and Digital CR. An Analog CR employs analog devices such as gauges, meters, and physical controls to measure and represent data. In this type of CR, data is expressed as continuous and fluctuating physical quantities, typically displayed through analog gauges or indicators. Due to the nature of analog systems, regular manual calibration and maintenance of physical devices are often required [1]. On the other side, Digital CR utilizes computer-based systems, digital displays, and advanced software applications to acquire, process, visualize, and control data. They transforms data into discrete numerical values, simplifying its manipulation, analysis, and presentation on digital screens or dashboards [2]. Both types of CRs are

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currently employed in various industries, with some facilities adopting hybrid CRs where outdated equipment in analog has been partially replaced with digital systems [1]. Control centers, including CRs, serve the purpose of isolating operators from the objects they control in complex systems. Operators do not have direct physical contact with the objects themselves but rely on display systems to access vital information about the status and changes of specific parameters. These display systems enable operators to gain a comprehensive view of the system at any given time, allowing them to perceive the complete picture and make informed decisions [3]. The function of a CR system varies depending on the specific operation it controls, yet its performance consistently influences the overall performance of the controlled system. While advancements in CR technologies have addressed numerous issues in safety-critical organizations, they have also been associated with disastrous events [4]. The main CR (MCR), serving as the center of control and coordination, represents a complex socio-technical system responsible for managing plant operations. The MCR encompasses various elements, encompassing the physical aspect of the CR, the personnel involved, the operating procedures followed by operators, the machine interfaces facilitating human interaction, and the organization of individuals in normal, abnormal, accidental, and emergency scenarios [5,6]. A socio-technical system aims to achieve goal-directed behaviors and ensure successful overall performance by combining the efforts of humans and technology [7]. In the context of CRs, safety refers to the implementation of measures and protocols aimed at ensuring the protection of personnel, equipment, and the surrounding environment from potential risks and hazards. It involves creating and maintaining a secure and reliable operational environment that minimizes the likelihood of accidents, disruptions, failures, or any detrimental events that could compromise the smooth functioning or integrity of the CR systems [8,9]. Significant incidents in history have exposed the critical consequences stemming from CR problems. One notable example is the catastrophic nuclear accident at the Chernobyl Nuclear Power Plant in Ukraine (1986). It was triggered by the failure of a safety test, leading to a sudden power surge, a series of explosions, and the release of radioactive materials. During the events, CR operators made critical errors [10]. Another tragic incident is the Three Mile Island Accident (1979) in Pennsylvania, USA. Equipment malfunctions and human errors in the CR precipitated the loss of coolant and subsequent overheating of the reactor [11]. CR errors, equipment malfunctions, and a combination of technical and human factors were identified as contributing factors in these catastrophic events. Consequently, extensive studies have been conducted to assess critical safety parameters that influence CR performance, overall plant efficiency, and socio-technical elements in CRs across different facilities. This study aims to provide a systematic review and analysis of safety-related articles focused on CRs. Considering the indispensable role of safety in CRs across diverse industries and facilities, it raises important questions regarding the various safety aspects involved, existing studies on these aspects, and the current state of safety in CRs.

2. Methods

As a complex socio-technical system, the CR is central to many industries. Considering the importance of safety in CRs, the following questions arise: what are the various aspects of safety in CR? How have researchers focused on these aspects? Also, what is the current status of safety in CRs? The systematic review addressed the mentioned questions following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). This guideline employs a methodical approach to define keywords, select databases, determine article inclusions/exclusions, and establish research timelines that facilitate the tasks for subsequent researchers [12–14].

We adopted a comprehensive approach in this systematic review by integrating Human Reliability Assessment (HRA) and Human Factors Engineering (HFE) perspectives. This approach allows us to provide a holistic understanding of safety in CRs.

In the first step, we carefully assembled a team comprising four members, each bringing distinct and valuable expertise to the project. The team consisted of two safety specialists, M.J. and R.J., and two human factors specialists, A.Ch. and S.A.Ch. By bringing together this diverse team, we ensured a multi-dimensional approach to our research, incorporating perspectives from both safety and human factors domains. The research team designed the study and formulated the search strategy as 'TITLE-ABS-KEY (safety) AND TITLE-ABS-KEY' ("Control Room") to achieve a high sensitivity and find all related articles. In addition, in this step, they also established a clear and focused research direction, allowing for efficient data collection and analysis in subsequent stages of the study.

In the second step, this search strategy was applied to three validated databases, Scopus, PubMed, and Web of Science, on

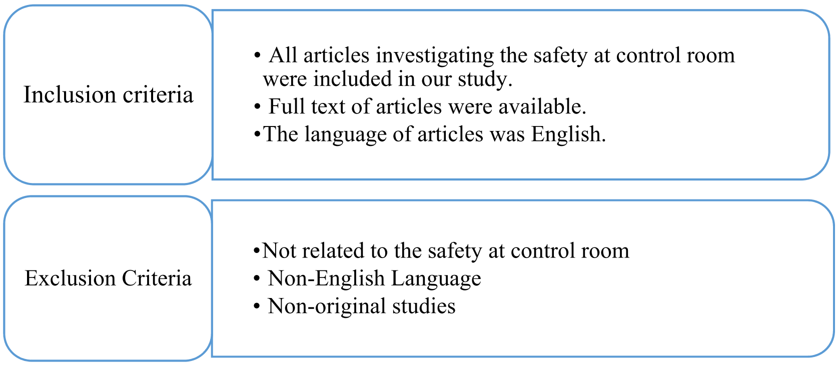

Fig. 1. The inclusion and exclusion criteria.

December 17, 2022 with the filters of "English" language and "Article"(Web of Science), "Document" (Scopus) and "Books and Documents" (Pub Med). These databases cover various academic disciplines and include scholarly literature from various sources. They have established reputations for indexing high-quality, peer-reviewed scholarly content, ensuring that the studies included in systematic reviews meet rigorous standards. In addition, they offer advanced search features and filters, allowing researchers to conduct precise and tailored searches to retrieve relevant studies for their systematic reviews.

In the next step, the two authors independently screened the search results in two stages based on predefined inclusion and exclusion criteria (Fig. 1). Initially, the documents were screened based on their title and abstract, and those deemed irrelevant were excluded. In the second screening, the remaining articles were assessed based on their full text, and the relevant documents were included in the study. Regarding articles with disagreement, two researchers discussed with each other, and ultimately, a decision was made about their inclusion or exclusion from the study. The step offers several benefits, it enhances the reliability and validity of the study by minimizing the risk of biased selection. Furthermore, this dual-stage screening process helps to identify relevant research more effectively. Ultimately, it leads to a more focused and rigorous analysis of the selected articles in the subsequent stages of the study. In the final step, the data and results from the selected documents were extracted by two authors. For this purpose, each author extracted half of the study's information, which the other author reviewed and confirmed. Independently extracted data and cross-verified each other's work ensures the accuracy and completeness of the data collection process, reducing the likelihood of errors or omissions. This collaborative approach also enhances the overall reliability of the study's findings by providing a consensus-based validation of the extracted information.

Since safety in the CR encompasses various aspects and the included studies cover different subjects, the authors categorized them based on their respective subjects and considering two observed perspectives including HRA and HFE. To accomplish this, each author rechecked each article's title and abstracts individually. The team members then discussed and proposed categories during a joint meeting. The final categories were determined after consultation and exchanging opinions among the authors. There were no limitations on including studies from different industries, so all studies on CRs with various applications, such as process and aviation industries, were considered.

Regarding the quality of the articles, the authors filled out the quality assessment checklist provided by The Joanna Briggs Institute (JBI) for all the included studies. The JBI offers a range of appraisal tools, including questionnaires, for evaluating the validity and applicability of studies. The questionnaires typically include structured questions and criteria that users can use to assess various aspects of a study, such as study design, methodology, data collection, and reporting. The specific questionnaire used depends on the type of study being evaluated. For instance, JBI offers separate appraisal tools for analytical cross-sectional studies, qualitative research, quasi-experimental studies, and more. Each questionnaire is tailored to the unique characteristics and requirements of the study type [15]. As each article was presented within its relevant category, a separate discussion section was written for each category.

3. Results

After applying the search strategy in the Scopus, PubMed, and Web of Science databases, 1900 documents were identified. Fig. 2 shows the PRISMA diagram illustrating the systematic search process. Among these, 237 records were found to be duplicates and were

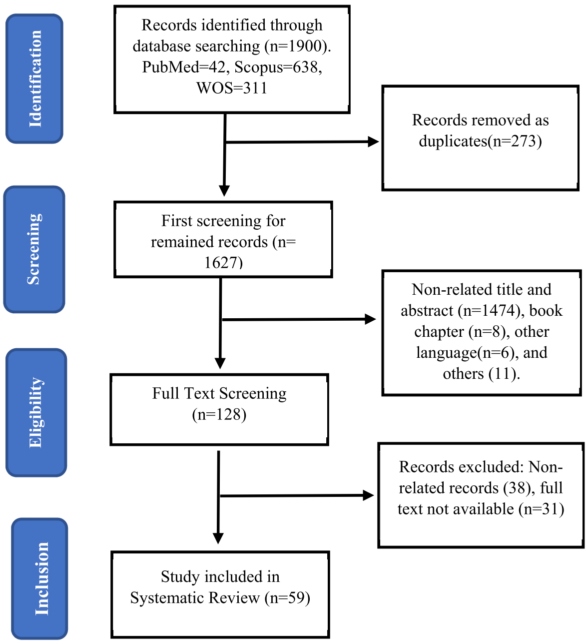

Fig. 2. The Prisma diagram of the study.

removed from the search results. Following the first screening based on title and abstract, 128 documents remained. After a full-text screening, 38 documents were excluded because they did not pass the inclusion criteria, and 31 articles were unavailable. Despite sending full-text requests to the authors through the Research Gate platform and email, we could not obtain them. Additionally, due to the economic challenges resulting from our country's sanctions, we could not afford the purchase of articles. Consequently, 59 records were included in the review. Then these 59 records were assessed based on the JBI tools and all of them were qualified to include in this review. All included studies are presented in the supplementary material (appendix A). Eight categories were identified after categorizing the included studies: reliability, safety performance, decision-support systems, fire safety, communication/teamwork, situation awareness, and Others (Fig. 2). This section will explain the articles included in each category and considering HRA and HFE perspective. It is important to note that all of these articles were in English.

3.1. Descriptive results

To present the trend of articles more comprehensibly, Fig. 3 illustrates the number of articles published in each decade. The first article was published in 1989, and a distinct spike in the publication was shown between 2011 and 2020. It can be due to the growing awareness of the importance of safety in and advancements in technology and research in this field. Additionally, several high-profile incidents during this period have drawn attention to the importance of safety in CRs [16,17]. It is essential to acknowledge that there was no time limitation filter on including articles in this study. Most research in this field was conducted in Nuclear Power Plants (NPPs) and chemical plants (Fig. 4).

Fig. 5 shows the frequency distribution of the articles based on subjects related to the safety of CRs. Most publications were allocated to reliability and safety performance, while fire safety had the fewest articles. All of included articles and subject categorization were considering HRA and HFE. In the following sections, the articles related to each category will be explained in detail.

3.2. Reliability

As reliability plays a critical role in creating safe situations, especially in safety-critical systems, many researchers have paid attention to this subject. Generally, reliability is divided into two subcategories: human reliability and equipment reliability. In the current study, we will describe the articles related to three subjects highlighted in the included studies: reliability assessment method development, equipment reliability, and human reliability.

3.2.1. Reliability assessment method development

The findings emphasize the development of diverse techniques and frameworks for reliability assessment in CRs. These advancements encompass data collection, qualitative and quantitative analysis, Markov modeling, forecasting, efficiency prediction, and the integration of various models and methodologies.

Firstly, regarding Techniques for HRA data collection, Starter and Bubb proposed a technique that addresses qualitative analysis (finding root causes) and quantitative assessment of HRA data based on a detailed information flow analysis. They stated that this method is flexible and reliable for ensuring consistency in event evaluation [18]. Secondly, as the monitoring process in the digital MCR plays a critical role in NPP safety, Jun Jiang et al. proposed a reliability Markov Model to minimize human factor events in the monitoring process. Their approach, using logical partition theory and dynamic processes, effectively estimates the probability of the subsequent monitoring object and, as a result, can significantly reduce accidents in the monitoring process [19]. Furthermore, a framework for reliability analysis of detailed action plans was the purpose of a study by Vaez and Nourai, they developed an

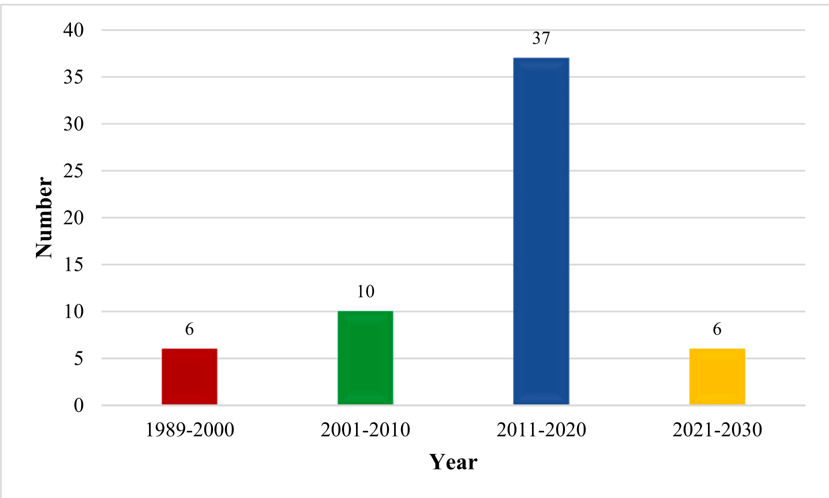

Fig. 3. Trend of studies on safety in CRs over time.

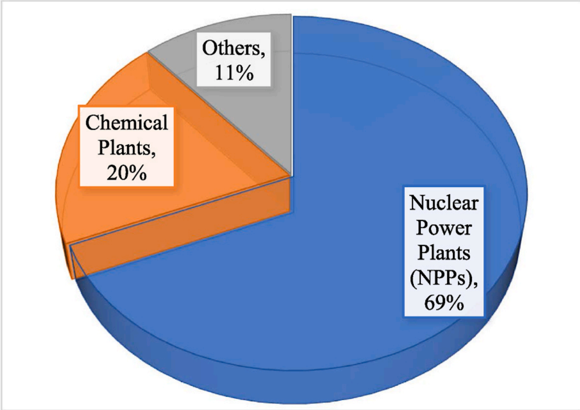

Fig. 4. The trend of studies on safety in CRs by industry.

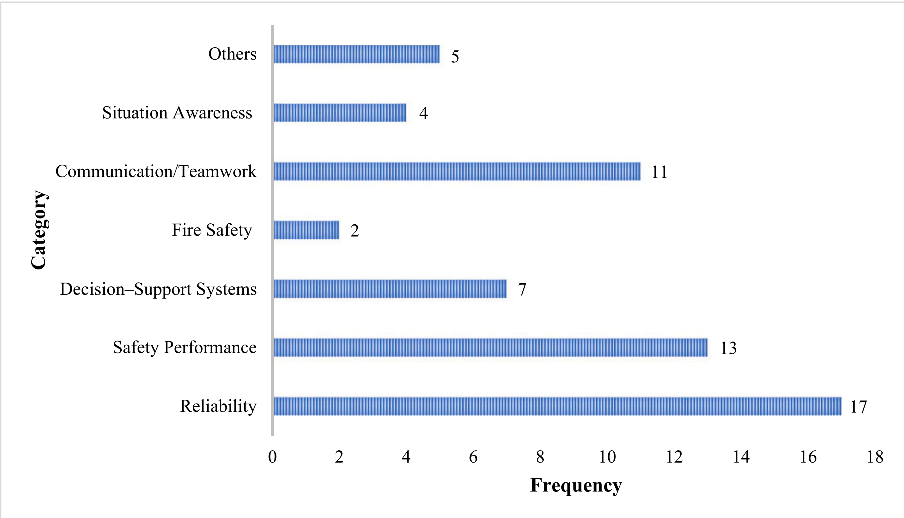

Fig. 5. Frequency of articles per each category.

integrating framework for reliability analysis of detailed action plans (RANDAP). Their framework provides quantitative information for emergency planners and enables a comparison of emergency operating procedures based on their probability of success [20].

Situation Assessment as a cognitive activity enables CR operators to evaluate the current condition to determine if it is normal or to identify the underlying causes of abnormalities. Therefore, they need to improve their situation assessment reliability level continuously. In this regard, Zou et al. proposed a reliability forecasting model for situation assessment, integrating time series forecasting with a dynamic network model. Their model, assessed using realistic scenarios, aids in HRA and enhances the training and performance of CR operators [21].

Moreover, for the efficiency prediction of CR operators, Zarei et al. utilized human reliability analysis and Dynamic Decision-Making Style (DDMS) to predict the efficiency of CR operators. They used self-administered and driver questionnaires for human reliability influencing factors and DDMS data collection. They employed an intelligent adaptive neuro-fuzzy inference system and ranked operators based on their efficiency scores [22]. Ramos et al. developed Phoenix-PRO, a methodology for human reliability analysis in petroleum refining operations. Using various information sources and models, Phoenix-PRO enhances the safety of oil refineries and petrochemical plant operations. They incorporated past accident studies in oil refineries, conducted CR visits to an oil refinery, gathered expert opinions, and compared CRs and operations between NPPs and refiners. Phoenix-PRO utilized the hybrid causal logic model, with event sequence diagrams, fault trees, and bayesian belief networks as a basis [23]. Lastly, a study demonstrated how supporting HRA data collection using a Simplified Human Error Experimental Program (SHEEP) can support HRA data collection in simplified simulators. This approach involves identifying HRA items, conducting experimentation based on participant type and simulator complexity, and integrating the data into a full-scope database for deployment in HRA methods [24].

Researchers have made significant efforts to improve the reliability of CR operations. These advancements assist in understanding and minimizing human errors, enhancing safety measures, and optimizing the efficiency of CR operators. These findings can guide the development of strategies, training programs, and decision-making processes to ensure reliable and effective CR operations in various industries.

3.2.2. Equipment reliability

Changing the MCRs from analog to digital technology raises a fundamental question: Can HRA data be applied from analog MCRs to digital MCRs? Park and Kim conducted research to address this question. They compared the Human Error Probability (HEP) of analog and digital MCRs. They collected HEP values for basic tasks performed by operators in an analog full-scope simulator. They simulated various off-normal scenarios in the digital MCR with MCR operators. The data comparison revealed that HEPs in the digital MCR were generally lower than those in the analog MCR. Therefore, the authors cautioned against directly applying HEPs from analog to digital MCRs, suggesting that specific HRA data should be collected for digital systems [25]. Another critical issue in this context is the future needs of HRA. In this regard, Andreas Bye addressed this issue in his study. He focused on HRA concerning the impact of new technology on human performance and the relationship between crew roles, teamwork, and performance. Bye emphasized the importance of considering the combination of new technology and how the crew uses it to evaluate performance. Additionally, analyzing work processes within the context of implementing new technology is crucial for understanding its impact on performance [26].

These studies provide valuable insights into the transition from analog to digital MCRs. They highlight the potential limitations of relying on HRA data from analog systems when assessing equipment reliability in digital MCRs. To ensure accurate assessments, collecting specific HRA data tailored to digital systems is essential. Additionally, these studies underscore the importance of evaluating the impact of new technology on human performance in the context of how the crew utilizes it. Analyzing work processes during the implementation of new technology becomes crucial for a comprehensive understanding of its effects on performance.

3.2.3. Human reliability

From 17 articles in this subsection, eight studies were related to human error as described in this subsection.

Kecklund and Svenson found that operators during annual outages had a higher workload and a greater risk of making minor errors. They suggested reducing work demands, such as time pressure and memory demands, to decrease the frequency of minor errors. Tsan Jou et al. identified potential problems contributing to human performance issues in CRs, including multiple accidents, pressure levels, the number of operators, the working environment, and stress levels [27,28]. Al Harbi et al. investigated the effects of a separate touch screen on human errors during emergency operations in NPPs. They found that more errors occurred during touch screen tasks, accompanied by higher stress levels. Kim et al. conducted an empirical survey on the probability of failure to recover from human errors when using soft controls in CRs. They found that selecting the wrong screen had the lowest probability of recovery failure while omitting operation selection and delaying operation had the highest probability of recovery failure [29,30]. Since data on human error probability in real CRs of NPPs is scarce, Prasad and Gaikwad proposed a method for estimating HEP by conducting specific accident scenarios in simulators, emphasizing the importance of scenario-specific data for reliable reliability analysis [31].

In another research, Yang et al. analyzed operator errors of commission in an advanced CR and identified specific errors that could affect system failure probabilities. Li et al. introduced an organization-oriented technique of human error analysis to investigate human errors and trace organizational root causes in CRs. They developed a classification framework that includes human errors, Performance Factors, psychological error mechanisms, error recovery failures, and safety barriers [32,33].

Furthermore, Karthick et al. integrated the Fuzzy Analytic Hierarchy Process (FAHP) into the Human Factors Analysis and Classification System (HFACS) framework to identify critical human factors contributing to human errors in CRs. They identified attention, perception, memory, decision-making, training, and communication as critical factors contributing to human errors. Their results also showed that the HFACS-based FAHP methodology can determine the intrinsic human factors contributing to the performance of NPP's CR operators [34].

The interaction between equipment reliability and human reliability is an important aspect to consider in CR settings. Both components play an integral role in ensuring the overall reliability and safety of the system. In the context of equipment reliability, the study by Park and Kim compared the HEP in analog and digital MCRs and emphasized the need for specific HRA data tailored to digital systems to ensure accurate assessments of equipment reliability [25]. In one hand, it is crucial to evaluate how the introduction of new technology in CRs affects human operators and their interaction with the equipment. The studies conducted by Park and Kim, as well as Andreas Bye, highlight the significance of new technology on human performance and its impact on crew roles, teamwork, and overall performance [26]. On the other hand, the reliability of humans has a direct impact on the reliability of equipment. Human errors can significantly affect the proper functioning of CR equipment and systems. The studies cited in the human reliability section shed light on various factors that contribute to human performance issues, including workload, stress levels, interface design, and training [27–34]. Understanding the interplay between equipment reliability and human reliability is essential for optimizing CR performance and minimizing errors. By considering the impact of new technology on human operators, analyzing work processes, addressing workload issues, and enhancing training programs, it becomes possible to improve both equipment reliability and human reliability.

3.3. Safety performance

Another category we will describe here is safety performance, with 14 articles. Based on these articles subjected, we divided them in to two sub-categories including operator performance and safety performance.

3.3.1. Safety performance

Several studies have contributed to our understanding of safety performance in CRs. Norros and Nuutinen conducted a usability-based evaluation of an Information System and Alarm Panel (ISAP) in CRs. The ISAP supported the process control activity of operators and decreased their stress, but it had some adverse effects on shift supervisors and operators [35]. According to Meshkati's study, operators' performance in CRs was affected by human factors such as interface design, workload, lack of concentration, and performance obstacles. Workload encompasses the mental demands operators face during routine tasks and escalates during abnormal conditions like leaks or system malfunctions. In normal operations, tasks include information processing, communication, and data recording. During emergencies, workload spikes significantly as operators must diagnose leaks, manage communications, and continue regular control functions. Elevated workload during abnormalities can impact safety by potentially hindering operators' ability to promptly detect and effectively respond to emergencies, emphasizing the importance of managing workload for ensuring operational safety [36]. In another study by Smith et al., themes such as uncertainty and trust, training, and focusing on reforms were identified as contributors to resilience performance in London Underground CRs [37]. Moreover, Zhang et al. showed that general mental ability positively impacts performance criteria, including task performance, safety compliance, and safety participation, at both individual and team levels in CR operators [38]. In another study, for CR operators handling high-complexity tasks, trait mindfulness had a strong positive influence on their safety and task performance [39]. Furthermore, dispositional mindfulness positively influenced safety compliance and safety participation behaviors in Zhang et al.'s study [40]. In Simonsen and Osvalder's study, six overall themes, including situations, functions, tasks, structural elements, and characteristics, were identified as contributing to safe operation in CRs [41]. Park et al. reported that operator experience is the most influential performance shaping factor overall performance. At the same time, task complexity affects secondary tasks and situation awareness (SA) but does not significantly impact primary task performance [42]. Regarding organizational factors, Ding et al. found that functional organization had significantly positive effects on the performance of the procedure task, with shorter task completion time, lower subjective workload, and more preference [43]. Over ally, these studies provide valuable insights into the multifaceted nature of safety performance in control rooms, encompassing factors such as information systems, human factors, resilience, mental ability, mindfulness, operator experience, and organizational aspects.

3.3.2. Operator performance

In this category, some researchers proposed or developed models, frameworks, or guides for operators' performance in CRs. Hwang et al. developed a predictive model for work performance in NPPs that demonstrated high prediction capability [44]. Ikuma et al. provided a guide for performance assessment in CRs using standard human factors measurement tools. They found that speed and accuracy measures, workload ratings, and eye tracking were sensitive to different workload levels [45]. In 2015, Park et al. proposed a helpful conceptual framework to estimate the response time of NPP's CR operators during seismic events. This framework identified representative contexts and extracted response time data from literature and databases [46]. Omidi et al. employed a hybrid intelligence model in the oil industry to identify human factors affecting CR operators' safety performance. They found that safe work practices, human-computer interface, and staff competence are among the key dimensions that significantly influence the safety performance of CR operators [47].

These studies collectively contribute to the understanding of operator performance in CRs and can guide the development of effective strategies to enhance safety outcomes in NPP operations.

3.4. Decision support systems

Several studies have focused on developing decision-support systems to aid operators in CRs of NPPs and other process industries. These systems enhance operator performance, reduce workload, and improve decision-making processes in CRs of NPPs and process industries.

Developing and implementing decision support systems, such as Integrated Operator Decision Support (IODAS), have shown promising results in supporting operator decision-making in CRs. IODAS quickly diagnoses plant failures and provides operator guidelines with a fast response time [48]. Seung Jun Lee et al. demonstrated the positive effects of decision-support systems in reducing human errors and operator workload [49]. Lee and Seong developed the integrated decision Support system to aid cognitive activity of operators that provide comprehensive support to operators by integrating display systems, fault diagnostics, computerized procedures, and operation validation systems. They use cognitive activity involves mental processes like monitoring, assessing situations, planning responses, and executing actions for design a decision support system in NPP context. Understanding these processes is crucial for designing better support systems and reducing human errors in complex operational environments [50]. In another study, Lina et al. showed that the monitoring-aid system helps operators detect alarms early, reducing mental workload by using quality control charts and effectively applying operators' experience [51]. Using machine learning techniques, Tamascelli developed a predictive tool to focus operators' attention on critical alarms. This technique enhances the operator's decision-making process and improves overall system performance [52]. Moreover, the emergency guidance intelligent system proposed by Kang and Lee serves as an operator support framework. This framework provides guidance and diagnostic procedures during emergencies using a procedure logic module and risk evaluators, leading to quick performance and reduced operator workload [53]. Regarding alarm systems, Shahriari et al. identified significant problems with existing alarm systems, including lack of prioritization, system rigidity, and alarm flooding. They proposed a specification based on optimal information flow among the operating system, guidance system, and operator [54].

3.5. Fire safety

This review examined two studies related to fire safety in CRs. In the first study, Cannalire et al. proposed an alternative approach to CR design that utilized risk analysis results. Their quantitative framework enables the evaluation of safety benefits associated with varying degrees of structural strength or CR locations. This approach assists in determining cost-effective solutions and provides a map of individual risk levels within the plant and its surroundings, which helps operators make informed decisions regarding the optimal location selection for CRs [55]. In the second study, the authors emphasized the importance of conducting thorough risk analyses as a crucial step in selecting fire protection systems, particularly for electrical CRs (ECRs). They stated that by carefully considering available options and preparing for emergency responses, personnel can effectively select appropriate fire protection systems for ECRs. This leads to adequate protection against fire hazards, mitigation of potential risks, and safeguarding the facility and its personnel [56].

3.6. Communication/teamwork

Teamwork and communication skills are two critical requirements for CR operators. The seamless integration of communication and teamwork within control room operations is pivotal. When operators and team members effectively exchange information, collaborate, and support each other, CRs can achieve optimal performance, enhance safety, and respond efficiently to changing conditions or emergencies [57,58]. Therefore, many researchers have studied them among CR operators. This study synthesized the primary outcomes of 11 articles focusing on communication and teamwork in CRs.

Several researchers emphasize the importance of training programs for CR team members. Janssens et al. implemented a three-day training program to improve information exchange and diagnostic assumptions during incident events. Their results showed an enhanced potential for coping with new situations [59]. O'Connor et al. developed a taxonomy of nuclear team skills based on a review of company documentation, observations in the CR, and critical incident technique interviews. They highlighted the need for shared SA, team-focused decision-making, communication, coordination, and influence [60].

Regarding workload assessment and team performance, Hwang et al. developed a real-time warning model for teamwork performance based on physiological parameters, error rates, and mental workload. The results showed a significant positive correlation between the teamwork error rates and the event arrival time interval [61]. In another study, Lin et al. proposed the Team Workload Assessment (TWA) measure as a sensitive tool for assessing team workload. The TWA questionnaire focused on essential characteristics of teamwork, such as coordination, communication, support, leadership, and time-sharing. TWA is designed to enhance the performance of operators dealing with complex tasks, such as those in the Main Control Room (MCR) of an NPP. This approach allows a comprehensive evaluation of team workload specifically tailored to tasks involving collaborative efforts, aiming to improve operator performance in digitally complex environments like the MCR of an NPP [62]. Moreover, Kim et al. developed a systematic methodology for evaluating the team performance of CR operators. They also created an estimation model by identifying team performance factors and behavior markers [63].

Regarding communication protocols and team performance in CRs, Kim et al. developed a standard communication protocol for emergencies in NPPs that leads to more efficient and transparent communication between operators. The protocol also improves their grasp of safety-related parameters and imposes little additional workload [64]. In another survey, Park assessed the applicability of Social Network Analysis (SNA) in identifying communication characteristics of operating crews in CRs. The SNA proved to be a helpful tool for understanding communication patterns in this context [65].

In communication and information exchange, Katara et al. explored collaborative team communication between the bridge and the engine CR in a maritime context. The study identified themes such as goals of communication, situations of interest, communication media used, information shared, and problems experienced in collaborative team communication in the Bridge-Engine CR [66]. The relationship between communication quality and team performance was investigated, focusing on the types of inquiry and command. Communication quality affected team performance, with two-way communication playing a significant role in self-confirmation [67]. Moreover, the levels of cognitive load and their impact on the team were considered by Khawaja et al. They analyzed novel linguistic and grammatical features extracted from transcribed speech of people working in a collaborative environment for cognitive load measurement. They found that different linguistic patterns and grammatical features, such as sentence length, use of agreement and disagreement phrases, and use of personal pronouns, were related to varying levels of cognitive load [68].

Researchers have investigated the last area in this category, implicit intentions monitoring. Kim et al. developed quantitative indicators for monitoring the implicit intentions of operators in advanced NPP's CRs. The proposed system used brain wave data to monitor agreement and disagreement with supervisor decisions during operational tasks. The study outcomes showed that the proposed system can be implemented to support the real-time monitoring of operators' intentions in an advanced MCR during working hours [69].

In conclusion, enhanced team dynamics in the CR environment translate into tangible safety improvements by enabling effective collaboration, minimizing errors, optimizing workload management, improving communication, and monitoring operator intentions. These factors collectively contribute to a safer and more efficient CR operation, ultimately ensuring the well-being of operators and the overall safety of the CR environment.

3.7. Situation awareness (SA)

SA refers to the ability to perceive, comprehend, and evaluate the critical elements of one's environment. It involves being cognitively aware of the current conditions, understanding their implications, and accurately predicting future developments. Situational awareness is a crucial element in CRs as it empowers operators to make informed decisions, detect anomalies, and respond effectively to complex operational environments. By maintaining a high level of situational awareness, CR personnel can enhance efficiency, mitigate risks, and ensure the smooth functioning of critical systems [70–72].

The review included four articles with four different subjects in the SA category. Hogg et al. developed the SA CR Index (SACRI) to evaluate advanced alarm systems of CRs in NPPs. They conducted four simulator studies to evaluate the effectiveness of SACRI. Their results showed that SACRI is a valuable tool for assessing advanced alarm systems and identifying key process parameters crucial for maintaining operators' SA across various situations [73]. In another study, the impact of different procedures on mental workload and SA in the MCR was investigated by Yang et al. The impact of paper-based procedures (PBPs), electronic procedures, and computer-based procedures (CBPs) was compared for this aim. The results indicated that CBPs significantly reduced mental workload and enhanced SA. Additionally, compared to PBPs, CBPs resulted in fewer errors of omission [74].

Lee et al. developed a SA assessment method by analyzing verbal protocols from operators in an advanced MCR simulator equipped with new Human-System Interfaces (HSIs). The method measured scores for different levels of team SA and showed a strong correlation between team SA scores and task performance. Moreover, the research showed that the total team SA score of operating teams in advanced MCRs was significantly higher than those in conventional MCRs [75]. In the last study, Bhavsar et al. assessed CR operators' SA during a simulated ethanol production process. At the end of their study, they proposed two entropy-based measures, namely gaze transition entropy and dwell time entropy, that provided distinct insights into the cognitive behavior of operators during process abnormalities [76].

3.8. Other

In the Others category, subjects such as job requirements, ergonomics, operator behavior analysis, task complexity, and modeling techniques were investigated by researchers.

Schumacher et al. assessed job requirements for CR jobs in NPPs and found that high cognitive and social/interpersonal abilities are needed. Moreover, ability requirements increased with hierarchical job levels [77]. Regarding ergonomics and safety in control centers, Quintana et al. developed the "Ergonomic Aspects Guide HSE for the Design of Control Centers" as an integrated guide for the design and implementation of CRs. They used a two-phase process, including diagnostic and guideline development phases [78]. For qualitative analysis of operators' behavior in CRs, Yanhua Zou and Li Zhang presented the dynamic evolution of operators' behavior. First, they presented the dynamic of operators' behavior (monitoring and detection, situation assessment, response planning, and response implementation) as an algebraic expression. Then, they investigated the problem of the dynamic evolution of operators' behaviors using such an algebraic expression. Finally, they constructed the boolean network model for analyzing the operators' behaviors [79]. Liu and Li compared the task complexity of digital and conventional CRs. They designed the Complexity questionnaire, and complexity factors were quantified in terms of their frequency, complexity, and impact. Their study outcomes showed that in digital CRs, the complexity factors have a higher frequency and impact in abnormal/emergencies and typical situations than in conventional CRs [80]. Sharma et al. used an eye tracker to study operator behavior in a typical chemical plant CR. They found that although operators successfully controlled most tasks, the pattern in eye gaze behavior showed varying levels of attention and understanding of the underlying process dynamics [81]. In another research, Kim and Seong proposed a State Token Petri Net (STPN) modeling language for computerized procedure systems. They stated that when the Computerized Procedure System (CPS) has STPN as a modeling language for procedure writing and execution, the CPS can provide a structural analysis when the procedure is written. This systematically prevents procedure flow errors and ensures the completeness of the procedure flow [82].

4. Discussion

In this systematic literature review, we conducted an in-depth analysis of safety in CRs across different industries, considering HRA and HFE perspectives. We included 59 articles published between 1989 and 2023 addressing various safety aspects in these critical environments. Although most studies were conducted in NPPs, we also considered studies from other CRs to provide a broader perspective on safety.

The studies analyzed three main components of the system: humans, equipment, and the environment. Additionally, they investigated how human interaction with the environment and equipment affects operators' behavior, decision-making, reliability, and performance. Many of these studies aimed to develop methods, protocols, guidelines, frameworks, models, or assessment techniques to analyze safety-related aspects of CRs.

Data collection methods in the most studies included interviews, surveys, observations, past incidents, questionnaires, and expert opinions. Peers used physiological and cognitive methods. From the existing literature, several essential categories of safety aspects can be derived, as follows.

4.1. Reliability

In the field of reliability in CRs, various studies have been conducted to develop reliability frameworks and models. Two crucial issues have received attention in these studies: technology and human reliability.

Studies on humans, past accidents, experts' opinions, questionnaires, and other sources have been used to predict human performance and efficiency. Most frameworks and models aim to reduce human-related accidents in CRs [22,23]. Studies conducted on equipment reliability have attempted to predict HEP using simulators and developing various programs related to humans and technology [25]. To provide a correct understanding of human performance, studies in the future of reliability in CRs must consider a combination of technology, humans, and work processes [26].

Several environmental and working conditions can interfere with the emerge of human errors, including work demand, time pressure, and the number of operators [27,28]. Other factors that may contribute to human errors have been identified in several studies. For example, cognitive and decision-making factors such as memory, attention, memory demand, perception, and organizational factors such as communication and training are involved [34]. Identifying and assessing these factors is essential due to their impact on human errors and safety in CRs.

Another study has examined different frameworks, categories, and simulators to identify and diagnose the causes of human errors related to screens, interfaces, and digital equipment [33]. Factors related to the organization, people, and equipment that contribute to human errors significantly impact safety and accidents in CRs. Therefore, developing different methods that can consider all aspects of human factor engineering and HRA can be effective.

4.2. Safety performance

Studies show that factors influencing safety performance have been studied at four levels: the individual level, which includes staff competence, experience, and mindfulness [38,40,83]. The team level, which includes general mindfulness [38]. The organizational level, includes safe work practices and permit-to-work systems [84], and the equipment level, includes the usability of equipment interfaces and alarms [35,36]. Models, frameworks, and guides developed and used in these studies provide valuable tools and approaches for optimizing operators' performance in CRs and improving safety outcomes.

Overall, the findings from studies in this category emphasize the importance of considering human, performance-shaping, and organizational factors in enhancing safety performance in CRs. By addressing these factors, implementing appropriate measures, and utilizing models and frameworks, CR operators can improve their performance and contribute to overall system safety and efficiency. According to the studies conducted, it is crucial to consider human factors and safety performance at all levels mentioned above during the design and operation stages.

4.3. Decision support system

Several studies have aimed to help CR operators make the best decisions with minimal errors in emergencies. In this regard, decision support systems and frameworks have been developed. Reducing mental workload and stress levels for CR operators has also been considered a crucial issue [51,85]. Identifying and diagnosing alarms, taking immediate action, and detecting emergencies in the early stages all contribute to improving the safety of CRs [48,53,54,85]. The findings from these studies highlight the potential benefits of decision-support systems in improving overall system performance and operator effectiveness.

By incorporating advanced technologies such as machine learning and cognitive aids and addressing specific challenges such as alarm management and emergencies, decision-support systems can contribute to safer and more efficient CR operations. Further research and development in this field are necessary to improve decision-support systems and integrate them into CR environments.

4.4. Fire safety

Studies on fire safety in CRs provide essential insights into designing CRs and selecting appropriate fire protection systems. These studies emphasize the significance of risk analysis and its impact on decision-making processes to ensure the safety of CRs, personnel, and the surrounding environment.

In addressing this issue, the studies first evaluate the level of risk and then calculate the level of fire risk. The system must respond adequately to emergency fire, so designing and building the CR in the right location is paramount. The solutions provided by these studies have also led to the creation of guidelines and fire response systems [55,56].

4.5. Communication and teamwork

This section provides the importance of various approaches and factors that contribute to the enhancement of team dynamics and, ultimately, safety within these critical environments.

The information exchange process, communication among team members, and evaluation of team performance in CRs are important issues that have been considered regarding teamwork in CRs [59,66,67]. Effective communication and teamwork are crucial for making informed decisions and ensuring smooth operations in routine and emergencies.

Some studies underscore the significance of training programs for CR team members. Their findings demonstrated that implication of training programs enhance the team's potential to cope with new and challenging situations. They emphasize the crucial role of comprehensive training in equipping CR teams with the necessary skills and competencies to ensure effective teamwork and safety [59,60].

Various studies have attempted to develop different methods and models to assess, evaluate, and improve team members' communication, workload, and cognitive load when working in a team and increase teamwork performance. In emergency conditions, team members' communication can affect the entire system's success and performance. The team's high cognitive load, communication quality, coordination, and leadership support are essential [61,63,64,68].

Overall, the findings from these studies underscore the significance of training programs, workload assessment, effective communication protocols, collaborative communication, and implicit intentions monitoring in ensuring safety and optimizing team performance within CR environments. By considering and implementing these research-based insights, CR operators and organizations can proactively enhance communication, teamwork, and overall operational outcomes. Continued research is essential to further understand and optimize communication and teamwork practices in CR environments. Additionally, many of these studies have been conducted in simulation environments, and there is a need to apply them in the real environment of the CR.

4.6. Situation awareness

Maintaining SA in the CR is one of the most critical aspects of individual and team situations. Responding to emergencies and warning systems requires increased SA. For this reason, researchers studying SA in CRs have attempted to develop criteria and methods for measuring SA. The operator's behavior, verbal protocols, mental workload, and performance can be measured using these methods to understand and maintain SA [74,75].

The results from the systematic review highlight that heightened SA translates into tangible safety improvements within the CR environment. The development and evaluation of tools such as the SACRI [73], the implementation of computer-based procedures [74], the utilization of advanced HSIs and SA assessment techniques [75], and the analysis of operators' cognitive behavior during abnormal events [76] all contribute to bolstering CR operators' awareness, decision-making, response capabilities, and overall safety performance. These findings emphasize the significance of promoting SA as a critical factor in enhancing safety within CRs and ensuring the well-being of operators and the systems they manage. Continued research is crucial to develop further and refine approaches for assessing and maintaining SA in CR settings.

4.7. Others

We categorized some studies that investigated aspects affecting the safety of CRs in the Others category. These studies provide valuable insights into the task complexities that affect safety in emergency/abnormal situations [80], analyze the operator's behavior to understand their success and failure in various operations [81], and determine the job requirements of CRs [77]. By considering these factors, organizations can optimize CR design, enhance operator performance, and improve overall system safety.

These results can help identify different aspects of safety in the CRs. It is also possible to improve safety in CRs by identifying the weaknesses and strengths of these aspects. Future research must focus on other facilities, such as aviation and transportation systems, as studies have mainly concentrated on nuclear and chemical plant CRs. Future research should focus on operators' human performance, system/technological design, and human-machine interface. Furthermore, developing methods, models, and frameworks with integrated perspectives of HRA and HFE will become more popular.

5. Study limitations

The systematic literature review was likely limited because we only searched for papers published in scientific journals. It is possible that various research that developed methods, frameworks, and models were published in separate pieces, such as conference papers and reports. Another limitation of our study was that we only examined studies published in English and did not include studies published in other languages. We also excluded studies whose authors were unwilling to respond to our email requesting the full text of their article.

6. Implication of findings in practice and future studies

Based on the systematic review, the authors propose the following directions in practice and future studies:

Integrated Approach: Integration refers to the cohesive interconnection of different system components, including human factors, technology, and environmental factors. The integration in CRs settings brings various benefits. It enhances situational awareness, promotes collaboration between operators and technology, and facilitates risk identification and management. This integration improves cognitive workload reduction, and overall performance, leading to increased safety. It also contributes to risk reduction by enabling error prevention, effective risk mitigation, enhanced decision-making in high-risk situations, and ongoing risk monitoring and assessment. Theoretical frameworks such as Systems Theory and Socio-Technical and Systems Theory underscore the importance of integration for safety outcomes. These frameworks highlight the need to align social and technical elements, share information, and consider human capabilities and limitations in system design to enhance safety. Effective integration improves communication, coordination, and cooperation, ultimately enhancing safety.

Innovative Methodologies: Insights from integrated studies can lead to innovative methodologies, such as advanced modeling and decision-making frameworks, enhancing CR safety and performance.

Cross-Industry Collaboration: Encouraging collaboration across industries with CR environments can lead to valuable insights and shared best practices, universally improving CR safety and performance.

7. Conclusion

All the studies that met the inclusion criteria for the systematic review were categorized into seven categories related to safety in CRs through HRA and HFE perspectives, including reliability, safety performance, decision support systems, fire safety, communication and teamwork, situation awareness, and others.

Overall, studies have focused on aspects of socio-technical systems, such as equipment, humans, the environment, and their relationships. However, they need to pay more attention to all the components of the socio-technical system in an integrated way and evaluate them simultaneously, which is crucial for safety in CRs. This can stem from the conventional methods that isolate the examination of individual components, neglecting the intricate network of connections and dependencies meaningful in HFE. As a result, a holistic and interconnected perspective of HRA and HFE that encompasses the complex associations among equipment, humans, and the environment needs to be improved. This fragmented approach hinders progress in enhancing overall performance and safety.

Consequently, future studies must adopt an integrated approach that considers all the components of socio-technical systems collectively and facilitates simultaneous evaluation. By doing so, researchers can comprehensively understand the system dynamics, uncover potential interactions and interdependencies, and unveil emergent properties that may arise from the interplay between diverse components. The findings from such integrated studies should inform the development and implementation of innovative methodologies and approaches in HRA and HFE in CRs. Additionally, an integrated perspective should prioritize the safety needs and requirements within CRs across various industries.

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CRediT authorship contribution statement

Raziyeh Janizadeh: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Alireza Choobineh:** Writing – review & editing, Supervision, Conceptualization. **Soheyla Ahmadi Charkhabi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mehdi Jahangiri:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25118.

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