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Human and organizational factors influencing structural safety: A review

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ABSTRACT

A broad review of the existing literature concerning Human and Organizational Factors (HOFs) and human errors influencing structural safety is presented in this study. Publications on this research topic were collected from the Scopus database. Two research focal points of this topic, namely modelling and evaluating the human error effects on structural reliability, and identifying causal factors for structural defects and failures, have been recognized and discussed with an in-depth literature review. The review of studies with a model focus summarizes the models and methods that have been developed to evaluate structural reliability considering human error effects. Besides, the review of publications on the factor subject outlines the most acknowledged HOFs that influence structural safety. Moreover, an additional spotlight was given to the studies from the offshore industry for the advanced development in HOFs and contributing the first complete Human Reliability Analysis (HRA) method for structural reliability analysis. In conclusion, this study provides a holistic overview of the knowledge developed in existing research on the topic of HOFs and human error influencing structural safety. Furthermore, current developments and challenges are reflected, and future research directions are explored for academics entering and working in this field. Additionally, the insights into HOFs generated from this review can assist engineers with better hazard identification and quality assurance in practice.

1. Introduction

While structural safety has long been viewed and treated with great importance, structural failures occur occasionally, despite the growth in knowledge and the advancement in technology in the construction industry. Recent accidents are the partial collapse of the surfside condominium in Miami, the United States and the collapse of a high-rise residential building in Lagos, Nigeria, causing 98 and 42 fatalities respectively. As can be seen from these accidents, structural failures can have severe consequences, economically, environmentally, and on the safety of individuals. Therefore, it is important to study the causes of structural failures and build up safety barriers accordingly to safeguard the reliability and serviceability of structures. It is observed that structural failures can originate from technical or human errors. However, findings from the Bragg Report [1] have already pointed out that "In hardly any case did we find that failure was the result of a problem beyond the scope of current technology". In fact, human error is widely acknowledged as the predominant cause of structural failures and near-miss cases [2–15], instead of technical issues. Therefore, it is essential that sufficient attention is paid to the human error issue in structural safety.

Human error has long been a research topic in the safety science community. There are, in general, two approaches towards human error: the person approach and the system approach [16]. The person approach focuses on the errors of individuals who perform the task and considers human errors as unsafe acts and violations that are attributed to personal traits such as forgetfulness, carelessness and lack of motivation. This approach is referred to by Dekker as "The Bad Apple Theory", or "the old view" of human error [17]. In the old view, human error is recognized as the cause of accidents and failures. Whereas in the system approach, human error is viewed as a symptom of (unrevealed) trouble that is embedded deeper inside the system, rather than a cause for problems [17]. The system approach considers humans as an inseparable part of the socio-technical system, wherein human error is the outcome that arises from the coherent system environment created by local factors like tools and workplace conditions, as well as upstream factors such as organizational structure and task design. This system environment contains latent conditions that can turn into error-provoking conditions at a certain time and space, which will lead to error occurrence [16]. The system approach is consistent with "the new view" of human error described by Dekker [17].

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While the research and the practice of the system approach to treat human errors have been further developed in several safety-critical industries such as aviation, nuclear and chemical processing, it remains under-developed in the Architecture, Engineering and Construction (AEC) industry, where the old view still dominates when it comes to human errors in structural failure investigations. In the AEC industry, structural safety research and failure investigations mostly stop at the spotting of "human error" (e.g., "design error", "construction error", "maintenance error", etc.) without digging further into the latent conditions in the project that trigger people at work to make that decision and to take that action, which matched with their reasoning and made perfect sense at that time, under their perceived situation. Because of this, it is not surprising that many studies find human errors to be responsible for 60%–90% of structural failures [11,18–20]. As a consequence, engineers and construction workers have very often been blamed for the failure, which in return offers no actual beneficial input to understand the failure situation and hinders the learning process to improve structural safety in practice. Thus, it is important to identify the working conditions and those upstream factors inside the system to understand how these latent conditions lead to the decisions made and shape the actions performed in the project. Based on that, these conditions can then be properly adjusted to safeguard the safety and reliability of the system.

Fortunately, some pioneering researchers in the structural safety field began to realize this problem and have made attempts to identify the latent factors that contribute to the failure of structures. For example, Schneider [7] provided a foresight that answers to the question of how to manage structural safety should be sought from management science, operations research and psychology. Likewise, Atkinson [21] argues that it is application errors instead of technical factors that are supposed to be held responsible for structural defects. Thus, attention should be diverted away from technical matters and redirected to the underlying psychological, social, and managerial factors that influence human performance, which can facilitate the occurrence of errors that eventually cause structural defects. These underlying factors, which include the human performance-related factors such as physical and mental conditions of the personnel at a job, and organizational-related factors that concern the organizational process and management strategies, are defined as the Human and Organizational Factors (HOFs). HOFs can shape people's performance at work in an unwitting and subtle manner to create a situation that potentially gives rise to human errors. For instance, inappropriate project planning might lead to an increased level of task complexity, which escalates the mental load on perceiving and processing information, thus giving opportunities for errors. Another example is when there is an insufficient budget allocated for design checking, thereby allowing errors to pass on to the final constructed structure. Terwel [22] pointed out that HOFs are pivotal latent conditions to be taken into consideration when dealing with human errors resulting in structural failures. HOFs are promising in assisting academics and practitioners in gaining beneficial insights into how human errors come to be, and furthermore, how to prevent them.

As discussed above, it is time for the AEC industry to transform to "the new view". This paradigm shift entails embracing a system approach when addressing human errors in relation to structural safety. In light of the new view of human error, the prevailing "blame culture", which tends to allocate fault to individuals, should be discarded. It is essential to recognize that error is an intrinsic part of the engineering process [23]. Nevertheless, the focus should shift to designing the system, in this context, the construction project, in a manner that enables the timely identification of errors while preventing their escalation.

Crucially, the intangible facets of project management within the system also bear accountability for ensuring structural safety. Elements like communication and quality assurance measures must be acknowledged as integral components in this regard. Given that a construction project constitutes an intricate socio-technical system, comprising both the physical entities and the professionals responsible for its design and realization, the matter of structural safety has consequently evolved into a multidimensional challenge demanding a systems approach for enhanced comprehension and resolution.

As a consequence, it is proposed to gain a better understanding of the HOFs in the AEC industry. The first step towards this proposed construct is to get a comprehensive overview of what we already know and what we do not. That is to be aware of the knowledge that has been developed on this subject and to identify the knowledge gaps, consequently, to recognize the way forward. However, this overview is currently missing. Therefore, the aim of this study is to gain an overview of the knowledge development concerning HOFs and human errors influencing structural safety, using existing studies as input, especially the research that goes beyond human errors and sheds light on HOF-related latent conditions in the AEC industry.

With this review, the authors try to answer the following questions:

(1) How are human errors evaluated for their effects on structural reliability? What are the available models and methods?

(2) What are the identified HOFs that are acknowledged to influence structural safety in the AEC industry?

(3) What are the knowledge gaps and the potential future research directions concerning the research topic of HOFs and human errors influencing structural safety?

In the following part of this paper, Section 2 demonstrates the research data and applied methods. Section 3 reviews the literature focusing on models and methods for evaluating human error effects on structural reliability. Subsequently, Section 4 reviews the literature on factors and causes for structural defects and failures. Furthermore, several observations from this review study are discussed in Section 5, along with some concerns and proposals. In the end, Section 6 recommends future research paths and concludes this review study.

2. Methods and materials

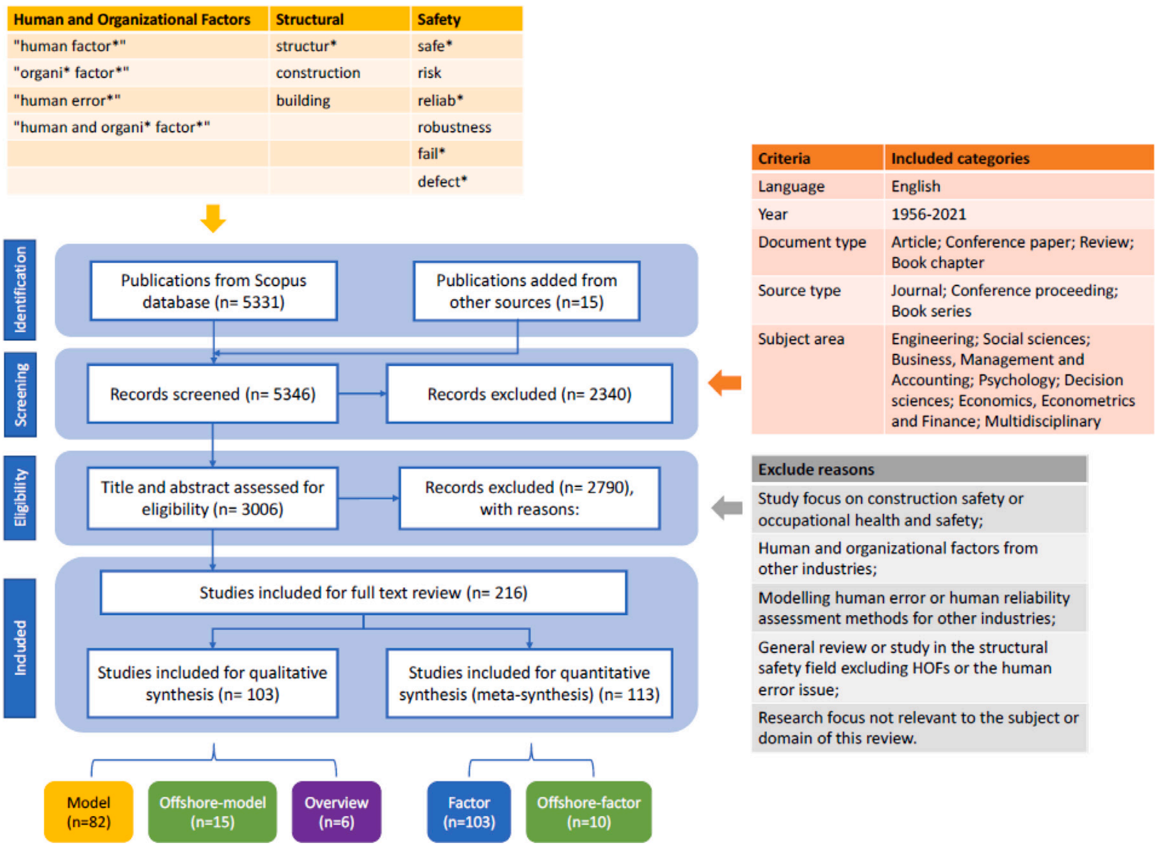
2.1. Data source and data collection process

The data used in this study were retrieved from the Scopus database on February 20, 2022. The data collection process roughly followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline [24]. Fig. 1 shows the flowchart that illustrates the data collecting and filtering process in four steps, which are *identification*, *screening*, *eligibility*, and *included*. Within this data refinement procedure, the number of documents excluded and the corresponding rejection reasons are provided for transparency.

The data collection started with inputting the combined terms "human and organizational factors" and "structural safety" as well as their synonym alternatives as the search words among publication titles, abstracts and keywords in Scopus, which yielded 5331 documents. The synonyms for each keyword (listed in Fig. 1) are searched with the "OR" operator, afterwards, all three keywords are combined and searched with "AND". After screening the publication title and abstract in accordance with the focus of this study, a majority of documents were ruled out, which resulted in 216 publication records that are considered relevant to this interdisciplinary topic. Moreover, based on the full-text review of these documents, 103 publications are gathered for qualitative synthesis and 113 publications for quantitative synthesis (meta-synthesis).

2.2. Literature group

To gain a better understanding of the various research directions explored on this interdisciplinary topic, a more detailed clustering of the collected literature was performed according to the subject of the study. The final included 216 publications were categorized into four groups based on their research focus: one group displays the research



Human and Organizational Factors	Structural	Safety
"human factor*"	structur*	safe*
"organi* factor*"	construction	risk
"human error*"	building	reliab*
"human and organi* factor*"		robustness
		fail*
		defect*

Criteria	Included categories
Language	English
Year	1956-2021
Document type	Article; Conference paper; Review; Book chapter
Source type	Journal; Conference proceeding; Book series
Subject area	Engineering; Social sciences; Business, Management and Accounting; Psychology; Decision sciences; Economics, Econometrics and Finance; Multidisciplinary

Exclude reasons
Study focus on construction safety or occupational health and safety;
Human and organizational factors from other industries;
Modelling human error or human reliability assessment methods for other industries;
General review or study in the structural safety field excluding HOFs or the human error issue;
Research focus not relevant to the subject or domain of this review.

Fig. 1. The data collection and selection process following the PRISMA flow.

into the causal factors for structural defects and failures in the AEC industry, named Factor, which consists of 103 publications; another group outlines the studies in which models and methods have been developed to evaluate the impacts of HOFs or human errors on structural reliability, named Model, which contains 82 publications; the third group of publications presents reviews on structural safety issues, progress and research needs considering human errors, named Overview, which comprises 6 papers; the last group are publications from the offshore engineering industry, named Offshore, which includes 25 papers. The publications from the offshore industry are further distinguished into studies on HOFs ($n = 10$) and studies on methods to assess the effects of HOFs ($n = 15$). This grouping is shown in Fig. 1. A spotlight is given to studies in the offshore industry since it is the first to introduce the term and concept of HOFs into the construction world and has performed extensive research specifically focused on the HOFs' influence on offshore structures.

Additionally, Fig. 2 illustrates the research output distribution of different research focuses over time. Generally, this research topic gained more attention during the 1980s and 1990s but was largely neglected during the 2000s. It can be observed that the publications in the Factor group outnumber those in the Model group, especially in recent years. This indicates a subtle shift of research interest in this topic from modelling human error effects to identifying causal factors in structural defects and failures. Possible explanations for this phenomenon are pondered in Section 5.2. Another observation is that the research from the offshore engineering field was mainly present in the period from 1995 to 2002.

2.3. Literature review

For the purpose of this study, an extensive, detailed literature review has been performed to answer the research questions. It overviews the studied topic and answers broad questions such as the research themes, the knowledge development history, and the state-of-the-art. Moreover, this literature review adopts a meta-synthesis method to dive into the detailed findings of existing studies concerning HOFs or human errors influencing structural safety. Unlike meta-analysis, meta-synthesis is "the non-statistical technique used to integrate, evaluate and interpret the findings of multiple qualitative research studies. Such studies may be combined to identify their common core elements and themes" [25]. Readers interested in the research landscape of this topic are referred to a bibliometric review, see [26].

3. Models and methods for assessing the human error effects on structural reliability

As pointed out by Kupfer and Rackwitz [27], "human error is, in fact, an important subject of an overall theory of structural reliability". Therefore, it is important to carefully evaluate the effects of potential human errors and take this into consideration when performing structural reliability analysis. In reality, this is rarely practised by structural engineers. The common practice is to apply the *partial safety factor*, which is a multiplier to adjust the load and load combination effects to a certain degree to ensure a uniform reliability level across structural components to provide the designed structures with an acceptable safety margin. The partial safety factors are employed to cover the inherent stochastic variability and uncertainties relating to the structural geometry and materials, the actions and action effects, as well as load and resistance modelling. However, uncertainties caused by human error are not included in the partial safety factor method during structural design [28]. Moreover, human errors exist in the whole life cycle of the structure, including design, construction, and service life. However, the error-induced uncertainties in the structural construction process and usage life are not addressed in structural reliability analysis. Ellingwood [29] pointed out that ignoring such failure possibilities is likely to lead to an overly optimistic view of the safety of the

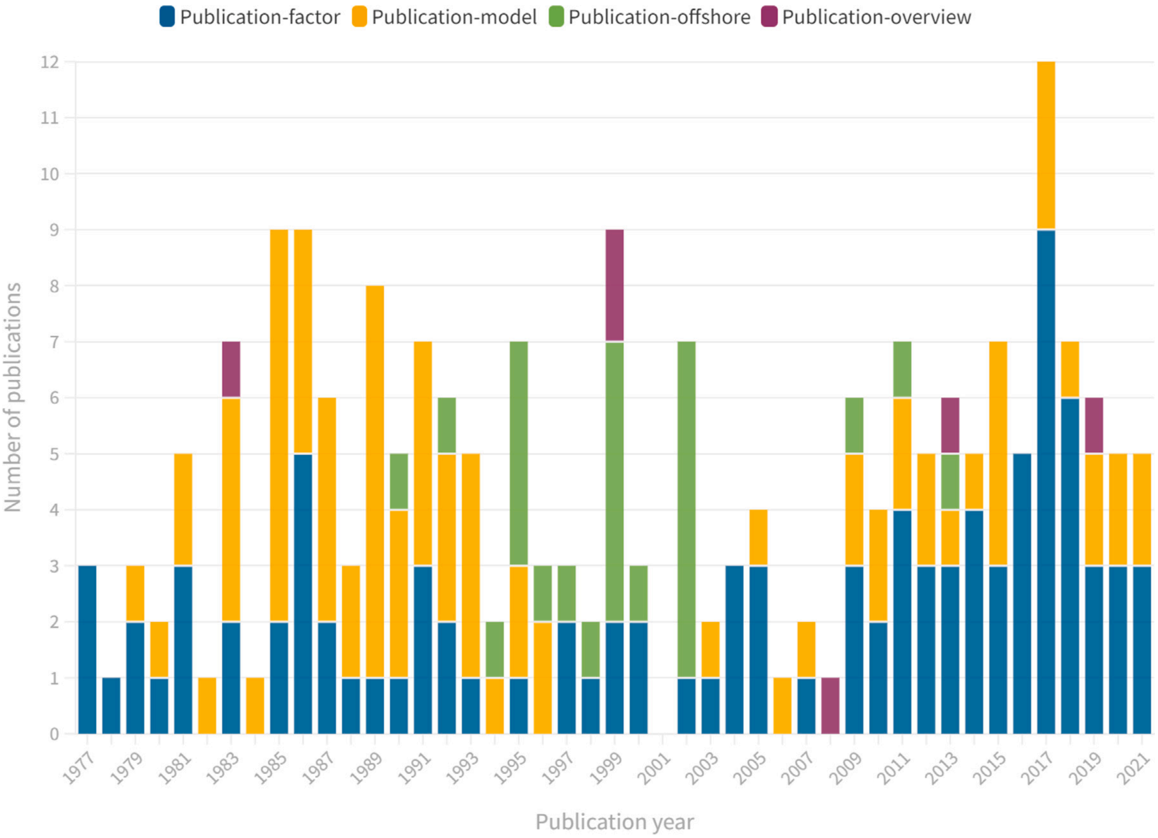


Fig. 2. Publication output from each literature group over time (books are not included).

structure. Even though the error effects can be covered to some extent by a high enough safety margin in a conservative structural design, the partial safety factor holds no control over the error occurrence rate or magnitude [4]. Therefore, Allen [30] noted that even though the safety factors help but are "essentially ineffective against most failures due to human error". Hence, the partial safety factors alone cannot fully address the human error issue. As a consequence, models and methods that take precise interest in evaluating structural reliability considering the human error effects, are in need. Such models and methods that have been developed in existing studies in the Model literature group are reviewed in Section 3.1. Special attention is given to the HOFs evaluation studies from the Offshore literature group (Offshore-model) for their significant contribution to assessing the HOFs' influence on the reliability of the offshore structures, which is a further development than the studies that evaluate the human error effects on structural reliability in the Model group. This is presented in Section 3.2.

3.1. Methods of the Model literature group

There are in total 82 publications in the Model literature group. However, due to the lack of full records or access restrictions, the authors only have access to 61 full texts of the collected literature. In the following part of this subsection, the papers in this group are reviewed in detail.

3.1.1. Mathematical and probabilistic methods

One of the fundamental contributions to modelling the human error effects on structural reliability is from Rackwitz [31], where errors were modelled as additional random effects introduced to the existing structural reliability model. However, Bosshard [32] questioned the effectiveness of Rackwitz's model by arguing that errors affect not only the structural parameters but also the structural behaviour models. Sharing a similar vision, Nowak [4] pointed out four ways to incorporate error effects into the probabilistic models of structures. Depending on the type of error considered, its effect can be modelled by (1) modifying the distribution function of structural parameters; (2) adding new parameters; (3) altering the limit state function; and (4) introducing new limit state functions. Another key study by Kupfer and Rackwitz [27] proposed a general mathematical human error model that can cover different error types, including the error of commission and the error of omission. In this model, the situation that involves a combination of different error types is not considered. Besides this, a human error occurrence rate model that follows a negative binomial distribution and an error detection model that is described by the checking time using an exponential distribution are summarized in this paper. In the end, the authors suggested that the solution for the human error issue can be found in optimal control effort allocation. Following their step, many studies have developed mathematical representations to describe the human error effects. For example, Lind [8] viewed human error as discrete events and proposed a discrete error model using load and resistance as variables. Similar to the error detection model from [27], he also suggested an error elimination model considering the inspection effort. Most importantly, Lind [8] brought up an error combination model that depicts a more realistic scenario in which multiple errors exist simultaneously in a structure, which is a clear advance from the error model of Kupfer and Rackwitz [27]. Apart from this, Frangopol [10] presented mathematical models to combine human errors with probabilistic structural risk assessment models by treating human errors as conservative (positive) or un-conservative (negative) changes to the probability distributions of load and resistance. In these models, errors that affect only the mean value or the standard deviation of the variable distribution (additive errors) and those that influence both the mean value and the standard deviation of the variables (multiplicative errors) are distinguished. Also, errors that affect only load or resistance and errors affecting both were considered. In addition, a sensitivity analysis of the reliability index to various human errors and their combinations was conducted to evaluate the human error influence on structural failure risk. Furthermore, El-Shahhat et al. [33] aimed to address the human error issue in a comprehensive manner by taking the perspective of multiple stakeholders. In this study, three approaches are presented to deal with human errors in design and construction, namely a mathematical model for researchers to investigate the human error effects on structural reliability when statistical data is available, an error scenario analysis method to assist engineers in evaluating failure probabilities and therefore improve corresponding quality assurance programs, and a framework to provide project managers with strategies that aim at minimizing human error occurrence from a management point of view. More recently, Bayburin [34] put forward a mathematical model that is capable of calculating the work quality and the influence of defects utilizing a defect rate parameter and a tolerance interval. It is worth mentioning that Stewart and Melchers [35] reviewed mathematical models for three widely applied error control measures in design, which cover *self-checking*, *independent detailed design checking* and *overview checking*. For each checking method, they examined the existing models with their survey data and proposed modifications to these models accordingly. A review of early mathematical models developed for human errors in structural engineering was presented in a research report, see [36].

Probabilistic approaches have been widely applied in the developed methods. This is due to the fact that dealing with human error, when viewed as a source of structural failure risk, is ultimately dealing with uncertainty. Under this context, Nessim and Jordaan [37] proposed two error occurrence models, including adopting the binomial distribution for errors in discrete tasks and the Poisson process for errors in the continuous production interval. Besides, an error detection model in which checking was modelled as a sequence of Bernoulli trials was also presented. In a consecutive study, Nessim and Jordaan [38] treated the uncertainties from human error in a similar manner as other uncertainties in the structural system. Thus, they could use a probabilistic decision tree and utility theory to assist the decision-making for optimal error control. On the contrary, Torng and Thacker [39] argued that the uncertainties carried by the physical structural variables in calculating structural reliability are inherent variabilities of a physical process, therefore not reducible; while the uncertainties brought by human errors can be controlled or reduced, therefore should be treated differently. Human errors can directly influence the calculated structural reliability and make the result a random variable itself. Based on this view, they constructed a confidence bound using a nested probabilistic analysis procedure and added it to the calculated reliability. In this way, the human error effects are included in the reliability result. After showing the differences in the calculated structural reliability between the different variable assumptions and interpretations, Elishakoff made a strong suggestion that “the error associated with reliability calculations should become a part of any serious implementation of probabilistic design for structural components or large-scale structures” [40,41]. Furthermore, Vrouwenvelder et al. [42] pointed out that the error occurrence probability and the error effect on resistance, defined as the error factor, are two pieces of necessary information for modelling human error in structural reliability. In addition, they proposed that the error factor can be modelled as a random variable that follows a normal or lognormal distribution. Baiburin [43] applied a probabilistic event tree considering defects and errors during the structural design and construction process to estimate the final safety condition of the structure. Moreover, Galvão et al. in their continuous work [44–47], explored the human error impacts on bridge structures. With a case study, a probabilistic analysis of the structural system resistance plus a sensitivity analysis were first performed to obtain the critical structural variables that pose significant impacts on the load-bearing capacity of the under-studied bridge structure. Then the effect of three design errors and two construction errors were modelled deterministically as several adjusting multipliers to these critical structural parameters according to different damage magnitudes of these errors. The overall error effects are finally reflected in the decrease in the calculated robustness of the bridge structure.

3.1.2. *Methods employing Bayesian theory and Fuzzy theory*

In addition to the aforementioned general mathematical and probabilistic methods, Bayesian theory and Fuzzy theory have also been employed in the modelling of human error influence on structural reliability. For example, Nessim and Jordaan [37] used Bayes’ theorem to update the error occurrence distribution model after checking. In a follow-up study, they proposed a Bayesian decision tree approach for error control decision-making considering checking efficiency [38]. Moreover, a Bayesian network was developed to assess the structural failure consequence induced by local damage whose causalities include human errors [42].

In terms of the fuzzy theory, Blockley [48] distilled conditions of structural failures into parameters, which were subjectively evaluated for their predictive confidence and criticality. Fuzzy set theory was then used to analyse these parameters for structural failure prediction. Moreover, Andersson [49] developed an indication of risk method for the civil engineering domain using the fuzzy set. The occurrence probabilities, which are stated linguistically and therefore become fuzzy possibilities, are assigned to each event by experts to the constructed fault tree. In this way, human errors could be assessed when evaluating failure risk for civil structures. Furthermore, Dembicki and Chi [50] integrated the fuzzy set and fuzzy logic into an approximate inference method to account for subjective information in the safety assessment of existing structures. Similar to the method of [49], Pan [51] presented a method applying a fault tree analysis, which is characterised by events involving physical components, whose failure probability could be obtained or calculated; and human-involved vague events whose failure possibility could not be precisely determined, such as a flawed design step or an inappropriate implementation in construction. To determine the failure probability of such vague events, subjective expert judgement was utilized and translated into fuzzy sets to facilitate a fuzzy fault tree to evaluate the overall reliability of the structure system.

3.1.3. *Human reliability methods and simulation models*

Human Reliability Analysis (HRA) is a set of methods to evaluate human influences on system reliability by estimating Human Error Probability (HEP) and assessing system degradation caused by human errors [52]. HRA aims to assess risks attributed to human error by identifying, modelling, and quantifying errors. A complete guide on practicing HRA is presented by Kirwan [53]. In a series of research works by R.E. Melchers and M.G. Stewart, an HRA method integrated into a simulation model has been developed to evaluate the human error effects on structural reliability in structural design and construction.

The HRA idea was initiated by Melchers in [54], in which a survey was carried out among 423 engineering students to obtain the human error rates of three basic design tasks (referred to as microtasks) namely “table look-up”, “numerical calculations”, and “ranking of numbers”. Afterwards, the overall structural failure probability was calculated with a binary structured event tree method based on the obtained human error rates for each task. In subsequent work, Melchers [55] attempted to validate the HRA method in [54] with a case study of macrotasks in a typical one-storey steel frame structure design process. A macrotask contains a set of sequential interrelated microtasks. The validation was done by comparing the macrotask outcome calculated from the HRA method and the empirical data gathered via a mailed survey. It was concluded that the HRA method is reasonably capable of simulating the human error effects on macrotasks in structural design and the resulting credibility depends largely on the process modelling as well as the availability and accuracy of the microtask error data. An additional finding from the collected microtask human error rate data is that they do not support modelling error occurrence using the Poisson process, as employed by [27,37]. Melchers argued that the human error rate is “clearly related to task complexity” [55]. Furthermore, Stewart and Melchers [56] developed a simulation model for load design macrotask using Monte Carlo simulation, with the microtask error rate obtained from surveys in earlier studies [54,57,58]. Microtasks of table look-up, wind reduction factor determination and one-step calculation were simulated in a sequential manner as the design macrotask considering both the error of omission and the error of commission. Thus, the human error effects were demonstrated by comparing the "error-free" design process simulation results (bending moment) with that from the "error-included" macrotask. In the end, the model was verified by both statistical hypothesis testing and comparison of probability distributions between the simulated results and the collected macrotask survey data.

Up to this point, an initial model that is capable of evaluating the human error effects on structural reliability for structural design tasks has been developed. This model incorporates two primary parts: an HRA method and a simulation model. The HRA method employs mathematical models to provide the human error rate estimation for each microtask step. These error rates are critical inputs for the simulation model. The simulation model is designed to simulate the member design process as a sequence of microtasks based on an event tree structure using Monte Carlo simulation. The output of this simulation model is the design result considering potential human error influence. With several more studies, Stewart further improved this initial model by enhancing both parts.

With a survey of 25 microtasks of similar complexity in structural design, Stewart [59] obtained an "average error rate" of 0.0163 for design microtasks. This result in general supports the findings in [54]. More importantly, he examined three mathematical models including a binomial distribution, a beta-binomial distribution, and a p-dependent binomial distribution for human error occurrence prediction with the survey data. It was concluded that the beta-binomial distribution makes the best fit for the survey data and thus was suggested for human error rate estimation in the HRA method for structural design tasks. In terms of the model part, Stewart strengthened the simulation model by incorporating a "self-correction" process into the model [19]. This better portrays the design work reality since it reflects the self-checking that is frequently performed by design engineers. A significant advancement was made to the HRA method part in [60], where a microtask human performance model was proposed. This model encompasses two important parameters namely the *human error rate* and the *error magnitude* (indicating the error size compared to the correct value), which are both modelled using a lognormal distribution with parametric information extracted from survey data. In addition, the upgraded model was applied to investigate the human error influence on construction tasks of a reinforced concrete beam, considering the effects of engineering inspection. Based on a similar case, Stewart employed this model to further study the engineering inspection effects by specifying three scenarios in which the detected errors are corrected or not corrected after two consecutive inspections [20]. Subsequently, this model was applied to simulate the entire structural design and construction process [12]. Besides, error control measures including design checking, construction inspection and the interaction between designer and contractor for error detection were investigated. It was found that construction errors are the major cause of the loss of structural safety and that while design checking is an effective error control measure, engineering inspection remains insufficient to deal with human errors in construction. Moreover, this model was adopted by [61] to study the human error influence on the reliability of a multi-storey reinforced concrete building during its construction. The construction process of a whole building structure was simulated, and more human error types were identified and assessed with the human performance model. A comprehensive introduction to human error in engineering systems and the available human reliability data are presented in [62].

Apart from the pioneering work and major contributions from Melchers and Stewart, De Haan [63] developed an HRA model to assess the human error influence on structural reliability. The HRA model is adapted from the Cognitive Reliability and Error Analysis Method (CREAM) [64] with seven identified cognitive activities from the structural design process, such as *consult*, *derive*, and *calculate*. These cognitive activities were further broken down to their demanded cognitive functions whose failure probabilities are known from CREAM. This adjustment makes the proposed HRA model suitable to assess the HEP of typical structural design tasks considering the task performance contexts, which are referred to as Common Performance Conditions (CPCs). These CPCs are in fact HOFs that can influence personnel task performance and contribute to a situation that gives rise to error. This method was then combined with the simulation model from [19,60] to evaluate structural reliability affected by HOFs in structural design. Even though the HRA method from Melchers and Stewart could provide HEP estimation for tasks in the structural engineering field, it stopped at the human error layer without addressing the task contexts and latent factors behind the human error surface, as acknowledged by Stewart in [12] that it was beyond the research scope to identify the exact Performance Shaping Factors (PSFs) that affect the HEP. Similar to HOFs and CPCs, PSFs refer to the personal, situational, and organizational factors that influence human performance, which are commonly used in HRA methods for HEP evaluation. Therefore, adapting the CPCs from the CREAM has made de Haan's model a complete HRA method for structural engineering. If we view the HRA method progressively developed by Melchers and Stewart as the first-generation HRA method in the AEC industry, then de Haan's HRA method should be considered the second-generation HRA due to the fact that it not only moves further beyond human error to include HOFs in the assessment but also considers cognition in evaluating task performance.

Arguing about the inadequate applicability of existing HRA methods to the risk analysis for construction projects, Xenidis and Giannaris proposed to develop an HRA method for the construction industry [65]. As a starting step towards such an HRA method, a model was developed to map the relations between the human failure event and the corresponding PSFs as well as the interdependences among the PSFs in a network. However, without providing a method to draw the HEP from this PSF network, this model cannot be regarded as a complete quantitative HRA method. More recently, Ren et al. [66] integrated the Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method from the nuclear industry into an agent-based model to evaluate the impacts of HOFs on structural reliability. Recognizing the building project as a socio-technical system, the whole structural member design and construction process was simulated considering the interactions between HOFs. This is a further development on the human error issue in structural safety adopting the system view.

3.1.4. Checking models

Design checking, especially peer review, together with construction inspection, serve as effective strategies to deal with human errors within structural design and construction. The primary goal of design checking is to identify any errors, inconsistencies, omissions, or potential issues within the design to ensure the accuracy, safety, and quality of the structural design. The checking process often involves verifying calculations, ensuring that the design complies with relevant codes and standards, and confirming that the design meets the project's requirements and objectives. According to Eurocode, there are three levels of design checking and construction inspection, depending on the structural Reliability Class and the project requirements [67]. These checks include *self-checking*, *normal supervision*, and *third-party checking*. These practices stand as indispensable elements of quality assurance measures for structural safety. Peer review (the "four-eye principle") is typically performed by qualified and experienced engineers who are completely independent of creating the original design. This separation of roles helps provide an additional layer of scrutiny and impartial evaluation of the design. The reviewer aims to catch inaccuracies or omissions that might have been missed by the design team during self-checking due to familiarity or oversight. Beyond human error treatment, peer review can identify potential design flaws or alternative approaches that might not have been considered in the original design, such as potential optimizations, improved constructability, and innovative solutions.

As an essential human error treatment, design checking has been modelled in many studies. These studies sought to determine the effectiveness of design checking and the optimum checking strategy. For instance, Rackwitz [31] constructed the checking procedure as a number of repeated independent checks in a mathematical model. Taking the checking cost into consideration using Rackwitz's model, Nowak [4] found out that the optimal number of checks lands on one or two. Assisted by the developed member design simulation model, Stewart and Melchers examined the effectiveness of error control measures in structural design. They proposed two design checking models: a simple linear mathematical model that considers the variable of checking efficiency; and a simulation model based on the member design task model [68]. The authors concluded from the simple model that it is most effective to enhance structural reliability when the checking efficiency value ranges from 0.6 to 0.9. Moreover, from the simulation checking model emerges the finding that one to three times design checking, mostly twice, is sufficient to increase the structural reliability from an "error-included" design to an "error-free" design. This conclusion agrees with that of Nowak [4]. Using the proposed HRA method to simulate the design process of a beam structure, De Haan [63] concluded that incorporating both normal supervision and self-checking can decrease the structural failure probability by approximately 2.4 times compared to a checking process that involves only self-checking. Moreover, Ren et al. [66] simulated the design and construction of a slab floor structure and examined the impact of checks and human errors on the structural failure probability.

3.2. Methods of the offshore industry

Similarly, the majority of accidents and failures in the offshore industry are also attributed to human errors. However, the development and application of safety risk analysis methods that take into account human reliability are more advanced in the offshore field since it is a safety-critical industry. The offshore industry has contributed the first mature HRA method that goes beyond the human error symptom to assess the impacts of the underlying HOFs on the reliability of offshore structures. Thus, these models and methods are reviewed and discussed separately in this subsection.

In a period of 15 years, Prof. Bea and his colleagues have performed thorough research into addressing HOFs in relation to the assessment and management of the life-cycle reliability of offshore structures [69–79]. This stream of studies was initiated after the Piper Alpha disaster and was influenced by the socio-technical systems view on failure and safety, where accidents are believed to arise from the interactions among man, machine, environment, and the organization [80]. This new development in safety science seems to be the prerequisite for these offshore studies. At the starting point, the risk analysis was extended from human error to include the organizational factors, in which the structural component failure and operation errors are believed to root [69]. In this study, the effects of organizational errors on the offshore platform failure probability were evaluated with an event tree-structured method. The inputs of this method are expert estimations of the probabilities for different types of errors in the design, construction, and operation phases. After recognizing the significance of the organizational factors, a more comprehensive development revealing how errors are made was illustrated in a conceptual model [71,72]. This model depicts the relations and interactions among the human and organizational components, the environment, the procedures, and the system itself. It was pointed out that human errors can stream from each of these constituents as well as the interfaces between them. At this point, the HOF was introduced as a critical research focal point for the reliability issue of offshore structures, but they have not yet been clearly defined. As a result, the identified HOFs – the error-producing factors, were mixed with the reliability influencing errors – the symptoms, and classified as Individual errors, Organization errors, as well as Hardware and Procedure errors. Using this HOFs and errors taxonomy, Bea [72] presented a method for system reliability analysis considering HOFs. In this method, the HOFs that contribute to an error scenario from each category are first spotted. Then the causal chain linking the error to its corresponding failure mechanism is identified. Thus, which HOFs and how they influence structural reliability are depicted. Based on this qualitative analysis method, a quantitative analysis of each failure mechanism is formulated in a probabilistic manner.

A preliminary HRA method for evaluating HOFs in offshore structural design was proposed in [70]. The proposed four-step approach for HOFs assessment includes understanding the entire system as well as the involved processes and situations, evaluating the system and the processes at their current state and after a reconfiguration. The reconfiguration is to adjust the PSFs in the identified critical processes to reduce the occurrence probabilities of human and organizational errors and thus improve system reliability and quality. The PSFs and nominal HEP values used in the assessment are adopted from HRA methods in the nuclear industry [52,81]. As a result, this suggested HRA method offers a comprehensive analysis of the whole system which accounts for aspects of human, organization, hardware, procedure and environment. Confirming the significant role of HOFs in the safety of offshore structures with observations from a few hundred marine structure accidents [82], Bea [73] emphasised the importance of integrating HOFs in risk analysis and management. Thus in this study, he formulated probabilistic Quantitative Risk Analysis (QRA) expressions for the life-cycle reliability assessment of offshore structures, integrating HOFs as well as the effects of quality control and assurance measures.

Based on these foundational research works, a sophisticated method for integrating HOFs in offshore structure reliability evaluation has been developed progressively [74,76–79]. This method provides life-cycle reliability evaluation for offshore structures in a system context and can be applied in reactive, proactive, or interactive Risk Assessment and Management (RAM). Two instruments of this method, namely the Quality Management Assessment System (QMAS) (initially called SMAS, Safety Management Assessment System) and the System Risk Analysis System (SYRAS), have been developed. Both instruments embody a computer program and an application protocol. The QMAS is a qualitative approach that assists the assessors with analysing the offshore structure system of its critical processes and various HOFs-related reliability and quality-critical aspects such as the operator, the organization, the system environment, and the procedure. Its applicability has been validated by a field test [76]. The SYRAS is a quantitative assessment process to evaluate the reliability of offshore structures by taking into account both natural hazards and HOFs-induced risks. SYRAS is a probabilistic risk analysis approach that incorporates fault tree and event tree in the analysis. These two approaches together are more than an HRA method. While the QMAS contains the qualitative HRA part which identifies and evaluates the Factors of Concern (FOC), the SYRAS covers the quantitative part of an HRA. Using an approach that is similar to the Success Likelihood Index Method (SLIM), SYRAS quantifies the impacts of the PSFs and calculates the HEPs for the understudied critical processes. These HEPs are then included in the evaluation of structural failure probability or the loss of structural reliability assessment. In addition, a link that connects QMAS and SYRAS has been developed [77]. This QMAS-SYRAS link constructs the qualitative analysis results from QMAS – the identified and evaluated FOC – into associated PSFs. It translates the grades of the FOC into the influence level of PSFs and inputs the quantified PSFs into SYRAS for human and system reliability analysis. Furthermore, this overall method has been applied and calibrated with offshore structure cases [77,79]. This method enables offshore engineers and managers to assess structural system reliability qualitatively and quantitatively, facilitating informed decisions on risk mitigation and management.

This is one of the state-of-the-art methods for HOF assessment associated with structural reliability. Its significance lies in (1) emphasising the focus on HOFs instead of human error; (2) taking on a system perspective; (3) performing a comprehensive analysis of the system by taking into account both the “hard” and “soft” components and the interface between the components; (4) conducting a thorough analysis of the industry-specific HOFs on different factor levels, which provides a high degree of details for the understudied factors; (5) having been made into a computer program to facilitate the application; (6) having been applied in field studies and calibrated. However, there are limitations to this method. Although the HRA component of this method - which is the primary focus - is strong, the procedure for incorporating the HRA results into structural reliability analysis - which uses the conventional fault tree and event tree analysis - is less innovative. Moreover, due to the thorough and detailed analysis process, this method is rather complicated to apply in practice. Given its close dependence on assessor expertise and insights, the evaluation necessitates a careful selection and thorough training of assessors. Besides, a large number of factors and attributes need to be assessed during the application process, which creates a high mental demand. Additionally, it takes five days for the assessment to complete [76]. Therefore, this is not a quick and easy method to be widely applied constantly, even though this is the recommended way of application by the method developers.

Overall, this QMAS-SYRAS method can be considered the first complete second-generation HRA method for structural engineering. Its significance cannot be ignored. Therefore, the above-reviewed methods in the offshore industry are an important source of reference for the rest of the AEC industry.

4. HOFs in structural safety

There are three “ages of safety” [80]. The focus of safety issues evolved from concentrating on technical failures to human failures in the first two ages, and now to the third age where these two foci are combined in a socio-technical systems view. Since a construction project can be considered a complex system that encompasses the physical structure and the stakeholders that design and construct it, the structural safety issue has thus become a system problem that can only be better understood by adopting systems thinking [83–85]. Besides the “hard” physical technical part within the system, human performance-related factors together with the managerial and organizational aspects are inseparable “soft” parts of the system, which play critical roles in the success and safety of the constructed structure [85]. These “soft” aspects are defined in the Introduction as HOFs, that can give rise to human errors, which are great sources of risk to the safety and reliability of the structure. Therefore, much attention, which is currently missing, should be paid to these latent factors behind human errors. This section tries to gather the knowledge of identified HOFs from existing studies. This is achieved via a review of the literature concerning HOFs from both the Factor and the Offshore-factor literature group.

4.1. Learning HOFs from structural failures

Many researchers have attempted to gain insights into failure causes by reviewing past structural failures so that lessons could be learned [2,6,86–92]. Human error is widely regarded as the principal cause of structural failures by these studies. However, some scholars penetrated further beyond human errors and explored the sources of errors in structural engineering, such as [3,5,11,21,28,93–104]. These outlined error sources are closely relevant to HOFs for structural safety in the AEC industry.

In the structural safety field, the seminal contribution that began to inquire into HOFs in structural and construction engineering was made by Sir Alfred Pugsley in [105]. In this study, he identified several causal parameters by examining a number of major structural failures. These parameters concern political, financial, professional, and industrial conditions that are outside of the technical domain but are critical to the safety of the structures. These causal condition-related parameters were summarised under the coined term “engineering climatology”. Furthermore, these parameters were applied in a qualitative analysis method to make predictions for the proneness of a structure to failures [106]. Following Pugsley’s foresight, Blockley further classified eight types of basic structural failures and presented a checklist that consists of parameters which could be used to measure the unsafe “situations” around these failures [48]. These parameters include the engineering climate parameters proposed by Pugsley [105,106] as well as design and construction errors.

Valuable insights were derived from examining four significant cases of metal bridge failures by Sibly and Walker [3]. Their findings reveal that many failures can be attributed to the unintentional introduction of a new type of structural behaviour to the original design and the designers’ uncritical reliance on existing practices. Consequently, it becomes essential to review the foundational principles of the design frequently considering all available information based on the current project situation. After reviewing 800 structural failures in Europe, Hauser came to the conclusion that besides the unfavourable environmental influences, the failures were mostly initiated by detrimental but avoidable factors introduced in design or construction [93]. These factors can be ignorance, insufficient knowledge or underestimation of influences, which can lead to commonly seen structural analysis errors. These factors were referred to as “human unreliability” by Matousek [5]. He believed that human unreliability is the root cause of human errors and proposed a systemic approach to document failure and near-miss case data to gain insights so that errors can be prevented. Ellingwood summarised causes for errors from existing studies as ignorance, negligence and carelessness; insufficient knowledge; forgetfulness and mistakes; and reliance on others [11]. Moreover, Brown and Yin performed a comprehensive overview of several such studies that examine past structural failure cases and presented interesting comparisons between results from different studies [96]. After reviewing and evaluating past experiences on the causes of errors, Melchers et al. [107] highlighted the important role of organizational factors such as project organizational structure, contract, and legal liability in quality assurance. These identified sources for errors have shown great foresight into HOFs for structural safety. Similarly, Porteous summarised 10 types of what he referred to as “human error” but in fact HOFs from a literature survey [108]. Most importantly, Porteous highlighted that the main intention of identifying these “human error types” is to direct structural failure investigations to the actual causes instead of to participants so that blame is avoided. His idea is consistent with “the new view” of human error, which is rather novel at that time in the structural safety field.

4.2. HOFs frameworks

Additionally, some scholars have contributed to categorising the causal factors for structural failures from a HOFs point of view. For example, Hadipriono and Wang classified failure causes into Triggering causes, Enabling causes and Procedural causes [94,95]. While the Triggering causes are the external load and environmental effects that can directly initiate structural failures, the Enabling causes refer to error-produced deficiencies that reside within the structure and indirectly lead to failure. The Procedural causes are hidden factors which can give rise to the Triggering and Enabling causes, such as inadequate inspection and design change. These causes emerge from the interactions between participating parties within the construction project and thus can be viewed as HOFs. Besides identifying personnel-related structural failure causes such as insufficient knowledge and underestimation of influence, Eldukair and Ayyub pointed out sources for management errors including responsibility, communication and cooperation [97]. Furthermore, they categorised the causes of structural failures into Primary causes and Secondary causes. Whilst the most significant Primary cause for failure is poor erection procedure, the top Secondary cause lies in an overall environmental effect which encompasses the weather effect, political pressure, financial constraint and industrial pressure.

In addition to the general categorisation, hierarchical classification frameworks of HOFs have also been proposed by researchers [21,28,99–103,109,110]. Most of these conceptual models share a characteristic of categorising HOFs into three levels: Micro-level factors related to individuals; Meso-level factors streamed from project organization or management; and Macro-level factors associated with the global or external environment above the project's control. For example, Atkinson presented a model for errors in construction projects that consists of error-inducing factors [21,99,109]. These factors are categorised into the Primary level, the Managerial level, and the Global level, which correlate to individual, management, and industrial climate-related error contributing factors. Moreover, Andi and Minato proposed a mechanism for defective structural design, in which they followed the active failure and latent condition theory from Reason [16] and distinguished direct failures and influencing factors that cause the failure [100,101]. In this model, the direct failures involve design errors and violations, as well as the failure of design review as the defence. The influencing factors include organizational factors and workplace factors. However, human factors are neglected in this model. Furthermore, Lopez et al. [111] framed a design error classification on the personal, organizational and project levels based on identified factors from a thorough literature review. A more comprehensive framework covering factors on all three levels was proposed by Terwel and Jansen [103]. In this framework, human factors such as physical resilience and attitude are listed on the Micro-level, company or project-related factors such as communication and safety culture are included on the Meso-level, and external factors such as economic and legal factors are covered on the Macro-level. Apart from the HOFs identified on the project scale, task-specific PSFs that influence human performance at work have also been studied. Summarised from a literature review, Bletsios et al. [112] proposed a three-layer classification scheme for PSFs in construction. The identified 79 PSFs are first clustered into 15 subclasses such as *task* and *culture*, then categorised into three main groups namely Organizational, Situational, and Individual. Additionally, a four-hierarchy PSF taxonomy for shield tunnel construction tasks is presented by Li et al. [113]. This PSF taxonomy consists of 85 detailed PSFs at the bottom level, four major components namely Human, Technical system, Environment and Task at the top hierarchy, and two hierarchical sub-categories in between.

4.3. Emerging factors of concern

The latest development in automation and digitalisation in the AEC industry promoted an evolution in the way structures are designed and constructed. Some academics began to pay attention to the potential impacts of involving such technologies in daily practice and how the changed way of working can influence the safety of the final produced structure. Lopez et al. [111] pointed out that over-dependence on Computer-Aided Design (CAD) can lead to errors. Additionally, Love et al. [114] discussed how Building Information Modelling (BIM) can be better implemented to contribute to human error reduction when taking on the "new view" of human error. Based on Reason's taxonomy of human error types [16], Kandregula and Le [115] investigated the roots of human errors in 4D BIM construction scheduling through a survey study. London et al. [116] provided a more comprehensive defect causation model that takes into account digital innovations, especially mobile technologies, by expanding Atkinson's construction defects causation model [99] with error-leading conditions summarised from 10 semi-structured interviews. Designed to improve construction quality, this model is able to assess the impacts of digital technologies on multiple and interdependent causal conditions that can result in human error.

The application of BIM and other emerging computer-based structural design and analysis technologies may have fundamentally changed the nature of how errors are made and should be treated. For example, BIM has been utilized to automate quality inspection [117] and enable real-time quality control [118]. Previously, engineers manually carried out these tasks, resulting in a higher level of uncertainty in the quality of task performance when compared to this automated process. Nevertheless, Lopez et al. [111] pointed out that the inclusion of novel technologies can bring about alterations in the opportunities and pathways for errors, leading to potential failures. Additionally, they presented five vulnerabilities and challenges related to the issue of human error introduced by BIM. Essentially an integrated system for documenting project information, BIM can enhance information exchange among project participants. The vast amount of interrelated information is a source of an increased level of complexity. Hence, human errors are more likely to result from information overload rather than missing information. In peer review, even an experienced engineer will struggle to uncover problems for a complex structural model with numerous details since the errors are submerged in massive (irrelevant) information [119].

Additionally, with the transition from manual paperwork to computer-aided design and scheduling, the design of the program's user interface, including considerations of ergonomics and human–computer interaction, becomes increasingly relevant to error occurrence. The implementation of 3D structural visualisation and 4D construction process simulation alleviates the cognitive burden placed on engineers in terms of spatial imagination and time planning, thereby minimising the likelihood of errors in these areas. On the other hand, errors are more likely to be generated from over-reliance on computer programs. As pointed out by Knoll [119], it is not easy to verify what was generated from the modelling program matches what was intended.

4.4. HOFs overview

A detailed literature review has been conducted to survey the acknowledged HOFs in existing studies from both the Factor and the Offshore-factor literature group. The review results are presented as a circular dendrogram in Fig. 3.

It can be observed from Fig. 3 that the widely acknowledged factors are mostly from the Human factors and the Organizational factors category. The standout factors from the Human factors group are qualified personnel, knowledge, as well as education and training, which all belong to the professional competence sub-category. The importance of professional competence is confirmed by the new Building Safety Act in the UK [120]. Insufficient knowledge and understanding of design principles, structural behaviour, and construction techniques can produce erroneous designs (e.g., failure to identify the most critical load combinations) and actions (e.g., wrong installation order). Professional competence becomes especially vital when dealing with complex tasks that involve intensive cognitive activities, such as structural analysis. Besides, experience is also frequently mentioned as a critical factor in existing studies. Lack of exposure to various project scenarios can result in poor judgment in a new situation or underestimating potential risks.

The top factor in the Organizational factors group is communication from the information sub-category, followed by supervision in the quality assurance sub-category. Diverse mental models characterise individuals' perception and cognitive processing of information. Thus, effective communication is key to establishing a shared understanding of the faced situation and required actions. Poor communication can lead to misunderstandings and missed information in specifications, causing erroneous actions taken in construction. Inadequate supervision can allow errors to go unnoticed or unaddressed, leading to hazards propagating and showing later within the constructed structure. In addition, the availability and quality of procedures and standards are

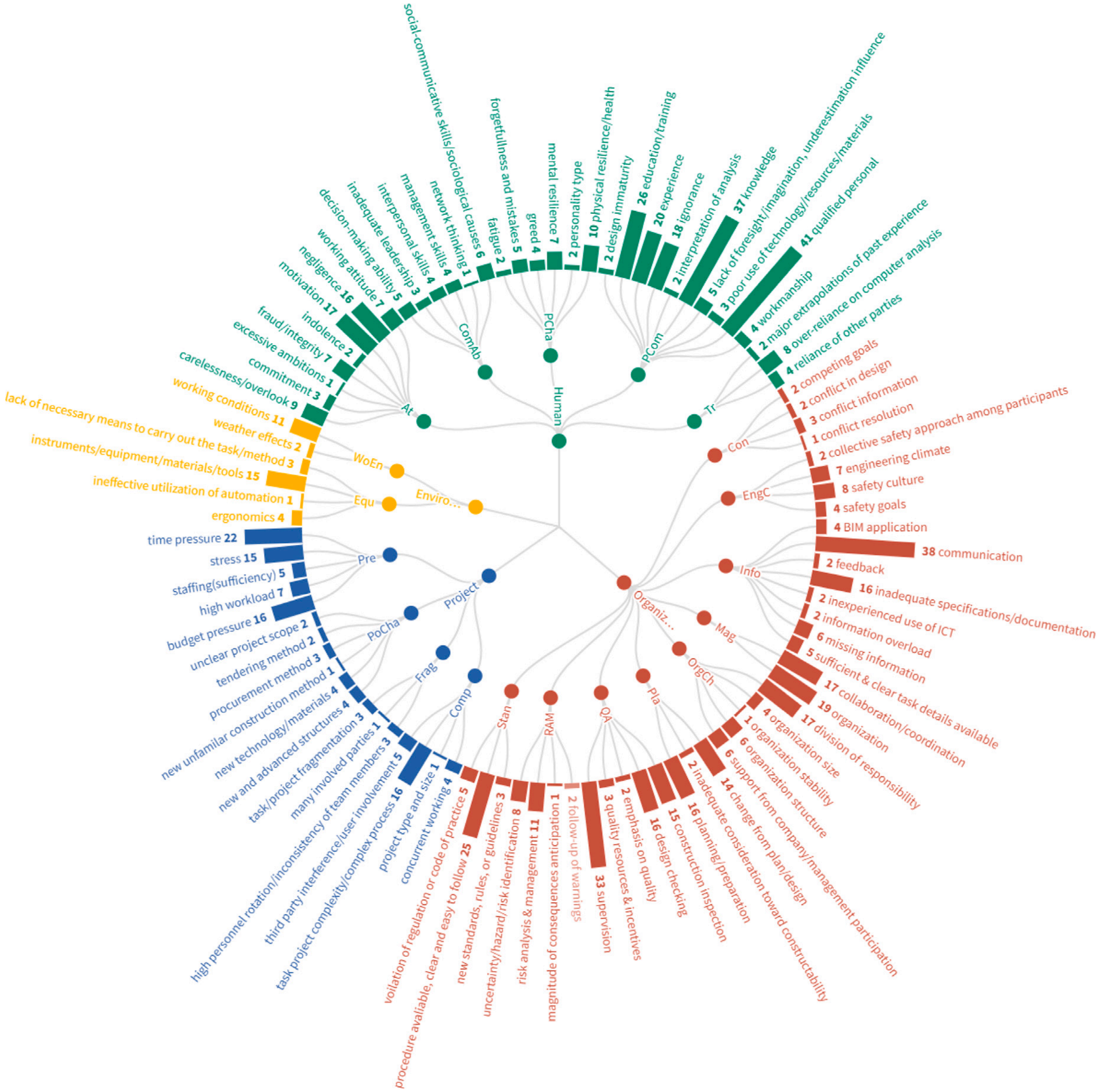


Fig. 3. Acknowledged HOFs from studies in the Factor and Offshore literature group. On the bottom hierarchy, the identified 96 HOFs are outlined along the outer circle. The number of studies in the collected literature that acknowledge this factor is shown in histograms alongside the factor label. On the top hierarchy, these identified HOFs are categorised into four groups, namely Human factors (in green), Organizational factors (in red), Project factors (in blue), and Environmental factors (in yellow). In addition to the four top hierarchical groups, these HOFs are classified into 20 sub-categories, as shown in the middle inner circle. Table 1 lists the full terms for the sub-category acronyms used in this figure.

also emphasised by many publications. Lack of clear procedures and standards can create ambiguity or misunderstanding, which can induce inconsistencies in design and implementation.

With regard to the Project factors, time pressure and budget pressure in the pressure sub-category are highlighted by most studies. Tight schedules and financial constraints can initiate rushed decision-making and compromises in design and construction. Cutting corners to meet deadlines or cost targets can foster errors due to inadequate peer review or poor-quality work that fails to meet the standards or requirements. Apart from those two, task and project complexity is repeatedly acknowledged as an important element that impacts structural safety. Complexity increases the mental load, posing professionals with high cognitive demands to comprehend and manage multiple considerations required in performing the task. Omission errors can arise from complexity. The Environment factors group recognize materials, equipment and working conditions as significant factors in most studies. These are recognized as necessary contextual conditions for successfully performing the task.

In summary, human errors can be attributed to a combination of factors across these categories. As specified in the conceptual model proposed by Bea [71], human errors arise under the influence of factors from each of these categories and the interface between them and the structure. Thus, isolating a single causal variable is an ineffective strategy since errors result from a complex array of interactions among the interconnected factors [121]. Therefore, the adoption of a system perspective and approach emerges as the most viable way to handle human errors.

Table 1
Acronyms and corresponding full terms used in Fig. 3.

Human	Pcom	Professional competence
	Tr	Trust
	At	Attitude
	Pcha	Personnel characteristics
	ComAb	Comprehensive abilities
Organization	Info	Information
	Con	Conflict
	Mag	Management
	OrgCh	Organizational characteristics
	QA	Quality assurance
	Stan	Standard
	Pla	Planning
	RAM	Risk analysis and management
	EngC	Engineering climate
Project	Comp	Complexity
	Pre	Pressure
	Frag	Fragmentation
	PoCha	Project characteristics
Environment	Equ	Equipment
	WoEn	Working environment

5. Discussion

5.1. Errors of omission

The most prevalent form of human error is omission [122], frequently found in structural failures [119] and responsible for approximately 38% of rework expenses in the AEC industry [123]. Reason [122] pointed out that omission errors arise from disruption in action control under a variety of cognitive processes. Certain task attributes, such as those with substantial information load, functionally isolated procedural steps, and recursive or repeated steps, tend to induce omissions [122]. Reason [122] identified the task situational factors (termed "Affordances") as the contributing factors for omission errors. Similarly, Love et al. [123] recognised silent latent conditions (termed "Pathogens") that reside within the construction project that foster omission errors.

Kupfer and Rackwitz's human error model defines omission error as the oversight of critical loads or failure modes [27]. Stewart and Melchers' model skips tasks in simulations upon encountering omission errors [56]. While many human error models reviewed in Section 3.1 change the distribution of relevant structural variables in the limit state function, this approach is ineffective in addressing omission errors. Unfortunately, there are limited models considering omission errors. The human error impacts on structural safety are not completely addressed unless omission errors are adequately modelled and studied.

To tackle omissions, Reason proposed a three-stage management program encompassing task analysis, omission error probability assessment, and the selection and application of appropriate reminders [122]. Errors of omission can be detected via peer review by experienced engineers, ideally before the construction starts [119]. Moreover, setting up good working procedures and quality design codes featuring detailed guidance and checklists can mitigate omissions. Understanding the underlying conditions in the task and their dynamics is vital for designing barriers that break the causal chain of omission errors. The qualitative analysis of omission errors' latent factors based on interview data by Love et al. [123] established a systemic causal model. This model provides valuable insights into omission errors; nonetheless, further research endeavours are needed.

5.2. Research attention evolvement: from models to factors

An interesting observation lies in the time difference between the two research foci. On one hand, the studies on modelling human error effects on structural reliability thrived during the 1980s and 1990s but declined remarkably after the 2000s; on the other hand, the studies inquiring into structural safety-related HOFs experienced noticeable growth. The possible explanations for this shift in research output and focus are pondered as follows.

Firstly, in the late 1970s, several impactful structural failures review and cause investigation studies were performed and published [2,6,86–90]. One conclusion in common from these studies is that human error is the leading cause held responsible for the majority of these failures. This finding introduced human error as a research focus in the structural safety field. Abundant research interests emerged afterwards trying to model the error effects on the reliability of structures in the structural safety research community. As a result, the following 1980s and 1990s witnessed a research boom on the human error issue.

In addition, the same period was marked by several high-profile accidents that drew attention to the importance of the human error issue in a broad engineering safety setting. These events include the Three Mile Island accident (1979), the Chernobyl nuclear disaster (1986), the *Challenger* Space Shuttle disaster (1986), and the Piper Alpha oil rig explosion (1988). The investigations into these incidents highlighted the critical role of human error, resulting in international and multidisciplinary research into human contribution to accidents and failures across a wide range of fields such as engineering, psychology and social studies [124]. In the safety science domain arose the widely accepted accident causation theories such as the *man-made disasters* [125] and the *normal accidents theory* [126] that promote a system view towards accident and human error. These new developments in general engineering safety research across various industries encouraged the research interest in human errors in the structural safety community. As researchers explored and expanded upon these new concepts, there was a surge in research activities during the 1980s and 1990s. Therefore, it can be considered a period of significant growth and development on the topic of human error influencing structural safety, accompanied by the emergence of abundant new theories, models and methods.

However, a decline in research activity is observed in subsequent years in the 2000s. This could be attributed to the achieved certain level of understanding and consensus on many fundamental aspects of the human error issue in structural safety over two decades of study. Specifically, the realisation that the human error issue should better be considered as a quality assurance problem since the effectiveness of including the human error-induced uncertainty in structural reliability analysis is questionable [127]. Besides, Ellingwood argued that human error cannot be addressed effectively by adjusted partial safety factors, thus it ought to be handled by non-technical approaches such as quality assurance [18]. This consensus led to the observed bounce back in causal factors research later in the 2010s.

Furthermore, the reduction of the error effect modelling research might be a result of the rising BIM research, which set off in the early 2000s [128] and soared over the years. BIM has been proven to benefit construction projects in terms of error reduction and quality control enhancement [129]. Thus, BIM partly won over the research community's attention on error-oriented quality control and diverted it to BIM-assisted quality assurance research.

Finally, it is found after some pioneering research attempts that human behaviour at worksites is difficult to model and predict. Hence fewer efforts have been made since. More importantly, there is a slim niche of researchers that are working on bridging the two distinct fields of structural reliability and human reliability together to handle the human error issue [26]. Thus, the overall research output on this topic is limited.

5.3. Notional reliability vs. Objective reliability

Quality assurance is an essential human error treatment [4,18,32]. However, good quality assurance practice means a wise allocation of control resources [4], which requires an informed decision made on the premise of a good understanding of the critical points prioritised by risks. This is especially the case for small-scale engineering firms whose resources are limited. Many scholars have noted that the calculated reliability derived from structural analysis tends to be higher than the observed structural reliability and this disparity is frequently attributed to the presence of human errors [4,83,130]. The notional reliability, which is calculated from design codes and intended to provide a baseline level of reliability, does not necessarily reflect the actual reliability performance of a structure in the real world. Since it does not cover all potential sources of uncertainty and variability thus shall be considered a component of the overall risk analysis for the structural system. As highlighted by Blockley [131]: "System uncertainty and the possibility of human error must be considered as part of any estimation of structural safety". Hence, the objective reliability should be assessed based on a comprehensive failure risk analysis including the consideration of HOFs and error-induced uncertainty to provide foresight on the as-built reliability. Therefore, it is necessary to possess a sound awareness of such risks to inform efforts for structural safety assurance. In light of this view, we argue for the necessity of HOFs and human error effects analysis research to provide better quality assurance guidance for practice.

5.4. Balancing safety and accountability: from a blame culture to a just culture

In May 2017, the under-constructed Eindhoven Airport parking building partially collapsed. An investigation conducted by the Dutch Safety Board revealed the direct cause as "failure to understand the consequences of the floor design", while reflection on deeper lessons learned pinpoint the existence of blame culture and reluctance to learn from incidents in the Dutch construction sector [132]. The blame culture has long existed in the AEC industry. In the aftermath of accidents and failures, the immediate reaction of stakeholders involved in a project is to pinpoint culpability, overshadowing analysis of what went wrong and how to improve it. Focus solely on assigning blame to professionals prohibits the learning process. Very often, each construction project or incident is viewed as unique. Thus lessons from one failure are considered not applicable to a different project, leaving similar underlying conditions repeatedly causing trouble. For instance, the direct failure cause of the Eindhoven case has been identified as the primary cause of structural failures by Walker [6] in 1981 and subsequently emphasised by Frühwald [133] for timber structures. As argued by Petroski [23], failure is an intrinsic part of engineering progress that drives engineering advances and innovations. The lessons learned from failures and mistakes contribute to learning and ultimately lead to successful outcomes.

Therefore, we propose transforming from a blame culture to a just culture in the AEC industry. The just culture is a facet of safety culture that balances individual accountability with a focus on learning and system improvement [134,135]. It emphasises understanding the system context and underlying factors contributing to errors [123,135], shifting from blame (control-based management) to learning (commitment-based management) [136]. Within the just culture paradigm, errors and incidents are perceived as collective learning opportunities [123,137]. The participants involved in an incident should be included in the discussion to maximise learning. As a result, a safe environment is created to encourage reporting errors and openly expressing concerns without fear of punishment [136]. Ultimately, a just culture strives to enhance safety through shared responsibility and continuous learning and improvement [135].

Adopting the HOF perspective towards the human error issue in structural safety seems to shift responsibility from the individual to the organization, thus making it impossible to hold individuals with unacceptable professional performance accountable. In fact, the just culture approach places responsibility on the shoulders of both the individual and the organization. It carefully differentiates the culpability associated with human error, intentional rule breaches, and reckless conduct, and establishes criteria to legitimise managerial involvement in disciplining organizational members. As pointed out by Dekker and Breakey [138], "its function is to fashion appropriate responses to evidence of errors and failures and to preserve the possibility of learning while holding people accountable for unacceptable behaviour".

Striking the right balance and designing an effective legal framework is crucial to ensure accountability and promote responsible corporate behaviour. A comprehensive discussion concerning structural failure and the law has been facilitated and presented in [139]. It aligns with Blockley's perspective [140], advocating for an interdisciplinary dialogue involving engineering, legal, insurance, and safety-risk experts to openly discuss and collectively seek solutions to this legal concern.

5.5. What should small structural engineering and construction firms do?

On the other hand, the proposed HOF and system approach towards human error can be too costly for a small engineering firm with limited resources. Nevertheless, there exist several paths small companies can take to achieve a similar level of structural safety as large corporations, such as:

1. Employ chartered engineers with proven professional competence.
2. Emphasise checking and maximise peer review within available resources.
3. Perform regular safety risk analysis and get insured according to the risk level.
4. Stay updated with relevant industrial regulations and standards and integrate them into company procedures.
5. Outsource expertise for critical safety-related tasks beyond the knowledge level of the company.
6. Engage with industry associations or partner with larger companies to gain access to resources, training, and best practices that small firms cannot develop in-house.
7. Foster an engineering climate under which engineers need to consistently prioritise safety, keeping in mind that structural safety is an essential responsibility and a fundamental principle that must guide every facet of engineering work throughout the entire engineering process. [141]
8. Cultivate a just culture to promote open communication and continuous learning. Hold a review session after each project to discuss what went well and what could be improved. It seems more achievable for a small engineering firm to create a just culture than a large company with a complex organizational structure.

By adopting a proactive approach and integrating structural safety measures into the company's procedures and culture, small engineering firms can mitigate the risks associated with human error. In the long run, investing in quality assurance measures can prevent costly litigation or project overruns. Most importantly, it is essential to continuously assess the effectiveness of implemented strategies and adjust them as needed to ensure ongoing improvement.

6. Recommendations and conclusion

Given the findings of this review study, some current research gaps and challenges are drawn, and possible future research directions are recommended as follows.

1. Insufficient research has been devoted to errors of omission in the AEC industry. Challenges exist in understanding latent factors that contribute to omissions, assessing the occurrence

probability of omission errors, modelling their effects on structural safety, and designing effective mitigation strategies.
2. Up-to-date HEP data for individual design and construction tasks are absent. Since the HEP values for individual tasks are critical inputs for structural reliability analysis models accounting for human error effects, it is essential to construct credible HEP data collection for the AEC industry so that the model outputs can be enhanced. Moreover, a tailored HRA method for the AEC industry is in demand to evaluate task HEP by systematically assessing the contributing HOFs.
3. Comprehensive failure risk assessment incorporating HOFs' impacts to analyse a realistic constructed object on a more detailed level, assisted with sophisticated structural analysis software, is desired. This can provide insights into error-prone structural elements and tasks to inform structural safety management proactively.
4. The growing application of emerging technologies like BIM, artificial intelligence, and construction automation is changing AEC practices. These innovations are partly aimed at decreasing the unfavourable influence of "unreliable humans" to assure better quality. However, they also bring new challenges [111]. Even though there have been a few studies that inquire into these innovations in the AEC industry [115,116,142,143], their impacts on task performance, error occurrence, and structural safety needs further investigation.
5. A systematic, interdisciplinary approach is in demand to progress on the human error issue in structural safety. The socio-technical systems theory and its methods like agent-based modelling seem promising for addressing this subject matter.
6. Despite insights derived from numerous structural failures, it is evident that previously recognised failure sources continue to play a role, indicating inadequate learning and transfer of the derived insights into practical quality assurance protocols. Therefore, it is recommended to promote a just culture in the AEC industry and to increase the research regarding how to better integrate the HOF's impact analysis results into concrete and practical risk-informed decision-making, proactive safety management programs, and quality assurance measures for practice.

Human errors and failures are inherent in the engineering process, yielding valuable lessons that drive engineering advancement. Active and continuous learning of underlying conditions behind errors and failures can mitigate recurrent issues. Therefore, the outcomes generated from such a comprehensive review are beneficial for academics and practitioners in the AEC industry for a better understanding of HOFs to improve structural safety. Furthermore, this review aims to motivate future research on HOFs influencing structural safety in a multidisciplinary and systematic fashion.

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.

Data availability

Data will be made available on request.

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