Human and Organizational Factors Influencing Structural Safety
Analysing critical HOFs behind human errors in structural design and construction

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ANALYSING CRITICAL HOFS BEHIND HUMAN ERRORS IN STRUCTURAL DESIGN AND CONSTRUCTION

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In memory of my beloved mother

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CONTENTS

SUMMARY

THIS dissertation focuses on studying the impact of Human and Organizational Factors (HOFs) on structural safety within the Architectural, Engineering, and Construction (AEC) industry. It is widely acknowledged that human errors are the primary cause of the majority of structural failures. In addition, HOFs are pivotal task contexts that shape human performance at work and contribute to the occurrence of human errors. Therefore, this research aims to study the critical HOFs in the structural design and construction process and analyze their influence on structural safety from a socio-technical systems perspective.

The study attempts to provide an answer to the research question of how and to what extent structural safety is influenced by the critical HOFs in the structural design and construction process. This inquiry is supported by answering several sub-questions, including the identification of critical HOFs in structural design and construction tasks, quantifying their contribution to human error occurrence, and modelling their impacts on structural reliability. These answers are provided through four separate research works, including a comprehensive literature review, two survey studies performed in the Dutch construction sector, and a methodology development.

Following a general introduction in Chapter 1, Chapter 2 presents a thorough review of existing literature to identify the recognized HOFs that influence structural safety in published research, as well as the developed models and methods to assess human error impacts on the reliability of structures. This review offers a clear picture of the research efforts and knowledge developments on the subject matter. Based on the collected HOFs in existing studies, a hierarchical HOPE framework that presents the acknowledged HOFs from the human, organization, project, and environment perspectives is proposed in Chapter 3. In addition, the Generic Task Types (GTT) in structural design and construction are summarized based on a task analysis. More importantly, the critical HOFs influencing each GTT are identified through a survey study. Furthermore, the impacts of these critical HOFs on human error occurrence probability are measured via a Structured Expert Judgement (SEJ) study in Chapter 4. Finally, a methodology to model the dynamic and nonlinear influence of HOFs on structural reliability is proposed and illustrated through a case study in Chapter 5.

In conclusion, this dissertation highlights the critical role of HOFs in contributing to structural failures and offers methods to depict the causal relationship and assess HOFs' influence. It contributes to a quantitative approach towards enhanced structural reliability analysis by bridging human reliability to structural reliability to account for the human and organizational influences on structural safety. As a result, insights into the impactful HOFs and error-prone task combinations in the design and construction process can be provided, which can inform human error risk mitigation strategies in the AEC industry's practice to enhance structural safety.

SAMENVATTING

DIT proefschrift richt zich op het bestuderen van de impact van menselijke en organisatorische factoren (HOFs) op de constructieve veiligheid binnen de architectuur-, engineering- en uitvoeringsindustrie (AEC). Over het algemeen wordt erkend dat menselijke fouten de voornaamste oorzaak zijn van de meeste constructieve faalgevallen. Bovendien zijn HOFs cruciale invloedsfactoren die vorm geven aan de menselijke prestaties op het werk en dragen ze ook bij aan het optreden van menselijke fouten. Daarom heeft dit onderzoek tot doel om de kritische HOFs in het constructieve ontwerp- en uitvoeringsproces te bepalen en om hun invloed op de constructieve veiligheid te beoordelen vanuit een socio-technisch systeemperspectief.

De studie probeert een antwoord te geven op de onderzoeksvraag: hoe en in welke mate wordt de constructieve veiligheid beïnvloed door de kritische HOFs in het constructieve ontwerp- en bouwproces? Dit onderzoek wordt ondersteund door het beantwoorden van verschillende deelvragen die zijn gericht op: de identificatie van kritische HOF's bij constructieve ontwerp- en uitvoeringstaken, het kwantificeren van hun bijdrage aan het optreden van menselijke fouten en het modelleren van hun impact op de constructieve betrouwbaarheid. De antwoorden op deze deelvragen zijn gegeven in vier afzonderlijke deelonderzoeken, waaronder een uitgebreid literatuuronderzoek, twee enquêtestudies die zijn uitgevoerd in de Nederlandse bouwsector en een methodologieontwikkeling.

Na een algemene introductie in Hoofdstuk 1, presenteert Hoofdstuk 2 een grondig overzicht van de bestaande literatuur waarin de invloed van HOFs die in publicaties worden erkend ook voor constructieve veiligheid in kaart zijn gebracht, daarnaast wordt een overzicht gegeven van de modellen en methodieken die zijn ontwikkeld om de impact van menselijke fouten op de betrouwbaarheid van constructies te beoordelen. Dit overzicht geeft een helder beeld van de onderzoeksinspanningen en kennisontwikkelingen binnen dit onderwerp. Gebaseerd op de, uit de literatuur, verzamelde HOFs, wordt in Hoofdstuk 3 een hiërarchisch HOPE-raamwerk voorgesteld dat de erkende HOFs vanuit het perspectief van mens, organisatie, project en omgeving presenteert. Daarnaast worden, op basis van een taakanalyse, de generieke taakypen (GTTs) binnen het constructieve ontwerp- en bouwproces samengevat. Belangrijker nog, is dat de kritische HOFs in elke GTT worden geïdentificeerd door middel van een enquêteonderzoek. Bovendien worden in hoofdstuk 4 de effecten van deze kritische HOF's op de kans op menselijke fouten gemeten via een Structured Expert Judgment (SEJ)-onderzoek. Ten slotte wordt in Hoofdstuk 5 een methodologie voorgesteld om de dynamische en niet-lineaire invloed van HOFs op de constructieve betrouwbaarheid te modelleren samen met een demonstratie aan de hand van een case study van een eenvoudig ondersteunde vlakke plaatvloer.

In conclusie, benadrukt dit proefschrift de cruciale rol van HOFs bij constructieve faal-

gevallen en biedt het methodieken om de causale relaties en inzichten in foutgevoelige HOFs en taakcombinaties in het ontwerp- en bouwproces weer te geven. Het draagt bij aan een kwantitatieve aanpak voor een verbeterde constructieve betroubaarheidsanalyse door een brug te slaan tussen menselijke en constructieve betrouwbaarheid. Als resultaat verschaft dit proefschrift inzichten in de invloedrijke HOFs en de foutgevoelige taakcombinaties tijdens het ontwerp- en uitvoeringsproces, hetgeen gebruikt kan worden bij het uitzetten van strategieën ter voorkomen van menselijke fouten om zo de constructieve veiligheid binnen de AEC industrie te verbeteren.

1

INTRODUCTION

This chapter provides a general overview of the research subject and the research work. First, the research background is introduced. In the following sections, the evolvement path of the research focus from human error to human and organizational factors is depicted. Moreover, the research aim and the research questions are presented. In the end, the structure of this paper-based dissertation is outlined.

1.1. RESEARCH BACKGROUND

DESPITE significant advancements in construction technology and an increased understanding of structural safety, structural failures still occur occasionally, leading to devastating consequences impacting the finance and reputation of the business, and sometimes the health and safety of individuals. This highlights the critical need to investigate the causes of structural failures in order to enhance structural reliability and serviceability. Although both technical and human errors can lead to structural failures, a wide array of studies [1–8] have recognised human error as the primary causal factor, rather than technical deficiencies. This points to the importance of addressing the human error issue in structural safety. For a better introduction to this interdisciplinary topic spanning structural engineering and safety science, definitions of some basic terms and key concepts, as well as how they are involved and evolved in this research topic, are first provided in the following introduction.

1.1.1. STRUCTURAL SAFETY AND STRUCTURAL RELIABILITY

ACHIEVING and maintaining a safe state, or an expected quality state of the constructed structures is one of the primary goals in the Architecture, Engineering and Construction (AEC) industry. To meet this fundamental requirement, unacceptable structural failure, such as (partial) collapse, structural damage that can lead to the loss of structural integrity, severe material deterioration that reduces structural reliability, and insufficient functionality that decreases the serviceability of the structure [8], should be avoided. Therefore, structural safety is closely related to structural failure. In general, a structure is safe if structural failure is absent during its service lifetime. Eurocode [9] defines structural safety as “the capacity of a structure to resist all actions, as well as specified accidental phenomena, it will have to withstand during construction work and anticipated use”. In consistency with this structural integrity point of view, a structure is determined to be safe by Elms [10] if the structure “will not fail under foreseeable demands, leading to loss of life, injury and unacceptable economic loss, and if it is unlikely to fail under extraordinary demands or circumstances”.

Safety is closely related to the concept of risk. While safety cannot be directly measured, risk can. Risk is calculated by the product of the event occurrence likelihood and the quantified consequence of that event. Therefore structural safety can also be defined and assessed via risk. Elms [10] provides another definition of structural safety as “a structure is safe if the probability of failure during its design life is less than a specified low value”. In line with this risk perspective, structural safety is defined by Terwel [8] as “the absence of unacceptable risk associated with failure of (part of) a structure”.

As indicated in the latter two structural safety definitions, risk is a continuum in nature, however, safety contains a limiting threshold [11]. When the risk value is under the safety threshold, it is deemed to be safe, and the risk level becomes acceptable. This is due to the fact that risk can never be eliminated or tuned down to zero, but can be controlled to some extent within an acceptable range or even at best resembles an asymptote towards zero, with the help of abundant knowledge and reliable technology. The acceptable risk for structural engineering should lie within the probability range between 10^{-7} to 10^{-3} per year, with an estimated annual building collapse probability of smaller than 10^{-5} in the built environment [12]. From the individual risk viewpoint, the acceptable risk of individual fatality involved in a structural element failure of an existing structure is suggested to be 10^{-5} in the Netherlands [13]. Thus, structural failures can be regarded as low-probability high-consequence events [6]. The low probability of structural failure risk is largely attributed to the ample quality assurance measures, especially the well-developed probability-based structural design standards for structural reliability.

Reliability refers to the "ability of a component or construction to perform a required function under stated conditions for a stated period of time" [9]. Thus a structure member or a structural system is reliable means that it meets the safety requirements and fulfills the intended functionalities throughout its expected lifetime. As pointed out by Rosowsky [14], structural reliability stands for the safe performance probability for a particular structural limit state. Furthermore, the reliability of a structure accounts for its safety, serviceability and durability, which are designed by calculating the ultimate and serviceability limit states that consider different failure modes such as ductile failure (e.g., deflecting, cracking, vibrating) or brittle failure (i.e., collapse), and by considering the partial factor in the design to guarantee a sufficient safety margin.

Therefore, structural reliability, as a measurement of the relative safety of a structure or a structural element, is measurable [15]. In general, a structure is reliable when the structural resistance R is larger in value than the combined load effect S that acts on the structure. Based on this, the structural failure probability P_f can be computed, when the joint probability density function $f_{(R,S)}(r,s)$ for R and S is known, as:

$$P_f = P(Z = R - S \leq 0) = \iint_{R \leq S} f_{R,S}(r,s)\, dr\, ds \tag{1.1}$$

In fact, reliability (denoted as P_r) is the complement of the failure probability P_f [14], which can be calculated by:

$$P_r = 1 - P_f \tag{1.2}$$

Generally, in the structural design practice, optimal reliability is used to obtain the maximum acceptable failure probability of the structure under consideration so that the minimum safety requirements are met. To achieve this, a reliability index β and its corresponding (annual) target reliability should first be determined by taking into account the different functions (consequence classes), failure types and designed lifetime of the structure. Since the reliability indices differ between countries and among different application fields, for detailed numerical values and discussions of target reliability, readers are referred to [9, 16–19]. For a detailed structural system reliability theory and methods review, readers are referred to [20].

1.1.2. HUMAN ERROR

WRITTEN by the 18th century English poet Alexander Pope, "to err is human", the renowned poem line intends to highlight the value of forgiveness. Meanwhile, it reveals the fact that it is common for people to make errors and it is extremely difficult to eliminate all errors. Hollnagel [21] quoted this phrase and introduced the human error research subject by adding "To understand the reasons why humans err is science".

Human error emerged as a scientific concept in the 1940s. It first gained attention from behavioural psychology studies as a performance measurement that could be objectively observed before the Second World War [22]. Following the war, on the one hand, arose cognitive psychology, which underpinned human error research with the information processing theory. On the other hand, the Second World War boosted the discipline of ergonomics, which studies the interactions between humans and other elements in a technical system [23]. Ergonomics investigates human capabilities and limitations, as well as human-machine interactions to gain an understanding of the sources behind human errors, aiming at a better system design to promote safety and productivity at work. This extended the research of human error beyond the oversimplified, superficial explanations to the system level. Gained high public attention, the Three Mile Island accident in 1979 raised the visibility of human error, which resulted in the international and multidisciplinary investigation into human contribution to accidents and failures, across a wide range of fields such as engineering, psychology and social studies [24]. Alternative to the conventional deterministic view on human error, a dynamic view that considers human error as a part of performance variability [25] came into sight accompanied by the development of systems thinking and resilience engineering from 1980 onwards. Taking this fresh view on human error – acknowledging it as one form of a wide performance spectrum - researchers began to look around the error and examine the engineered environment and social context under which the erroneous action is taken.

As can be seen from the brief development history above, human error has long been a research subject in psychology, ergonomics and the safety research community. Despite the self-evident meaning of human error, it is in fact highly difficult to precisely define human error as a technical or scientific term. One reason for this is due to the lack of agreement on what are the definitive qualities of human performance that can be used as principles to count the actions as successful or erroneous. The other reason why it is challenging to define human error lies in the linguistic ambiguity in the use of the term "human error", as it can refer to 1) the cause of an incident; 2) the outcome of an incident; and 3) the incident itself [26]. Therefore, Woods et al. [24] argue that human error is just a label, a judgment by people made in hindsight. Senders and Moray [27] pointed out that the study of human error is actually the study of an ordinary psychological process, and whether or not an error has happened totally depends on the perspective of the judging person. At a system level, this argument is backed up by the statement of Read et al. [22] that the outcome of a running system is deemed as either operating properly or malfunctioning in the eyes of the stakeholders, however, the system itself only functions.

A challenging task as it is, scholars have made attempts to provide a proper definition of human error. Table 1.1 lists a sample of definitions from existing literature chronologically, including some from the perspective of structural engineering.

Table 1.1.: Definitions for human error.

Author	Definition	Reference
Rasmussen	"A more fruitful point of view is to consider human errors as instances of man-machine or man-task misfits."	[28]
Swain & Guttmann	"Any member of a set of human actions that exceed some limit of acceptability, i.e., an out-of-tolerance action, where the limits of human performance are defined by the system."	[29]
Nowak & Carr	"The two major categories of uncertainty which cause failure are variations within accepted practice and departures from accepted practice. This second category will be called human error."	[2]
Stewart & Melchers	"A human error in the structural design context may be defined as an event or process that departs from commonly accepted competent professional practice. It excludes such unforeseen events as 'acts of God', variation in material properties, etc."	[30]
Reason	"Error will be taken as a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency."	[31]
Pheasant	"An incorrect belief or an incorrect action."	[32]
Senders & Moray	"'human error' is a deviation from expected human performance…error means that something that has been done which was: not intended by the actor; not desired by a set of rules or an external observer; or that led the task or system outside its acceptable limits".	[27]
Bea	"Human error is a departure from acceptable or desirable practice on the part of an individual that can result in unacceptable or undesirable results. Human error refers to a basic event involving a lack of action or an inappropriate action taken by individuals that can lead to unanticipated and undesirable quality."	[33]
Hollnagel	"A 'human error' is the post hoc attribution of a cause to an observed outcome, where the cause refers to a human action or performance characteristic."	[26]
Kletz	"A failure to carry out a task in the way intended by the person performing it, in the way expected by another people or in a way that achieves the desired objective."	[34]
Love & Josephson	"Deviation from what is intended and caused by human actions".	[35]

continues on next page

Table 1.1.: Definitions for human error (*continued from previous page*).

Author	Definition	Reference
NASA	"Either an action that is not intended or desired by the human or a failure on the part of the human to perform a prescribed action within specified limits of accuracy, sequence, or time that fails to produce the expected result and has led or has the potential to lead to an unwanted consequence."	[36]
Daniellou, et al.	"An error is a situation where a planned sequence of actions fails to achieve its objectives. It is a deviation from an internal or external reference (objective, model, standard, rule, etc.), even though the person had no intention of deviating from this reference. An error is never deliberate."	[37]

Even though there is no unified definition for human error, we can arrive at the common ground from the review of definitions above that human error is an unintended departure from the desired performance, rather than an intentional violation of the expected action. The rest of the dissertation develops based on this view of human error.

As one appearance of the wide human performance variance, human error presents itself in various ways. Swain and Guttmann [30] divided human error into two general categories, namely error of omission (i.e., failing to perform a task or an action) and error of commission (i.e., incorrectly performing a task or an action). Taking cognition into consideration, Rasmussen [38] distinguished human performance into three different levels: skill-based, rule-based and knowledge-based. Human errors can stem from each of these levels, which require different scales of cognitive functions. They vary from automated, free from conscious control essentials at the skill-based level, to the goal-oriented, know-how needs guided by existing rules and procedures at the rule-based level, until the functional reasoning demanded at the knowledge-based level. Consequently, the error occurrence frequency roughly decreases as the cognition demand of that activity grows, however, the potential consequence tends to be more severe [37]. Based on this Skill-Rule-Knowledge (SRK) performance level taxonomy, Reason [31] proposed a general human error classification scheme called the Generic Error Modelling System (GEMS). This model integrates the cognition-based SRK performance levels with different error mechanisms so that an extended description of the human error types is provided. GEMS recognizes three basic error types, namely slip (i.e., attention failure), lapse (i.e., memory failure) and mistake. While slip and lapse both belong to the skill-based performance level, mistakes can be differentiated into rule-based mistakes and knowledge-based mistakes. Closely related to GEMS and Reason's Swiss Cheese Model [39], Shappell and Wiegmann [40] developed the Human Factors Analysis and Classification System (HFACS) framework for aviation to systematically locate the root causes relating to the human contribution to accidents. HFACS specifies potential human error sources on three distinct hierarchical levels of organizational influences, unsafe supervision and preconditions for unsafe acts from top to down in an organization, in addition to several human errors and violations listed at the bottom unsafe acts level. These four levels are adopted from the four safeguard layers (i.e., the cheese pieces) in the Swiss Cheese Model, and the presented underlying organizational factors and human errors are potential defects that could contribute to creating an opportunity trajectory for an accident. In addition, Hollnagel [26] grouped the manifestations of erroneous actions into four categories, which are action at the wrong time, action of the wrong type, action at the wrong object, and action in the wrong place, respectively. These error modes are then connected with the four basic cognitive functions (i.e., observation, interpretation, planning and execution) to evaluate the human error occurrence probability.

1.1.3. HUMAN ERRORS IN STRUCTURAL ENGINEERING

SINCE abundant evidence points at human error as the major cause for structural failures, a great amount of research efforts has been paid to study various errors that play significant roles in affecting structural safety. Very often in the AEC industry, human errors are categorized based on the phase when the error is produced or detected, by whom the error is made, or within which type of structure or structural elements the error is situated. For example, Holicky and Sykora [41] divided the observed causes from 249 structural damages in the Czech Republic into human errors and insufficient code provisions, and furthermore classified human errors by their occurrence phase into errors in design, errors during execution and errors during use. After studying 604 structural and construction failures from 1975 to 1986 in the US, Eldukair and Ayyub [42] concluded that construction errors, among errors in the plan, design and utilization phase, are the highest contributing causes for structural defects and failures. However, some researchers find errors in the design phase outweigh the ones in construction, such as [43]. Even though various research concludes differently concerning the error occurrence frequencies in different project phases, such as [4, 33, 44], an agreement lies in that most errors happen in the structural design and the construction phase, with roughly the same number of errors generated in each of these two phases. This is later supported by the results from the research of Terwel [45], which surveyed three structural failure databases in the Netherlands. Regarding the time of error detection, Fraczek [46] analyzed 275 error cases in concrete structures in North America and observed that most construction errors that lead to structural failures or distress are detected during construction; however, most design errors that turn into serviceability issues are detected during occupancy. As for the source of error made by the project participants, the structural designer and the site staff of the contractor contributed the greatest number of errors, followed by the resident engineer and the inspector [42]. A similar conclusion was gained through a review of 800 structural failure case investigations in Europe by Hauser [47], which revealed that structural engineers and contractors are involved in the largest proportion of errors made in a project. Whilst the contractors commit slightly more errors than the structural engineers, the financial consequences of the errors made by structural engineers are significantly higher. Allen [48, 49] surveyed 188 error cases of concrete structures in Canada and discovered that there are notably more error occurrences when a cast-in-place construction is applied in the project than the precast construction. Furthermore, the most commonly affected structural element is the slab, followed by connections; retaining, tank, basement wall; and beams. Eldukair and Ayyub [42] have also found in their large-scale structural failure survey that most errors reside within slabs and plates and are mostly seen in reinforced concrete structures. For more reviews of human errors in structural failure, readers are referred to [33, 44, 45, 50, 51].

When taking a more detailed look at the errors in structural engineering, Walker [52] pointed out that the error in defining the loads in design is the dominant error type (61%). Moreover, ignoring loads, ignoring structural behaviour, mistakes in calculations and drawings, and inadequate instructions are the primary errors contributing to building structural failures. Melchers et al. [53] divided gross human errors by the activities in a construction project into error of concept, error of calculation, error of design and error of construction. Nowak and Carr [2] presented a comprehensive discussion of various human error classification schemes in structural engineering. For example, errors can be categorized by their causes (e.g., who, why, how, when) and consequences (e.g., what structural components are involved, the failure cost), as well as occurrence mechanisms (i.e., error of concept, error of execution, and error of intention). Carper [54] extended the design, construction and operational errors to include the site selection and development errors of a construction project. At a detailed micro-task level, Stewart and Melchers [55] identified several error types that frequently occur in the structural design tasks, namely errors in code interpretation, errors in ranking numbers, errors in looking up parameter values in a table, and error of one-step or several-step calculations. On a more general level in the planning and structural design process, errors can be made in tasks of the conceptual design, structural analysis, drawing and specification, work planning and preparation [56]. In addition, Terwel [8] listed commonly observed errors in design (i.e., incorrect modelling or calculation, incorrect dimensioning on drawings, conflict drawing and calculation, absence of drawing and/or calculation, other design errors) and construction (i.e., insufficient quality of applied materials. incorrect elements assembling at the building site, insufficient amount of material used, erroneous measurements at the building site, and other execution errors). Furthermore, the design and construction errors that pose a high risk to reinforced concrete bridges have been identified via a survey, which resulted in a collection of 20 specific errors in structural analysis and design, and the structural detailing process, plus 29 detailed errors in the material quality control and execution process [57]. However, these identified errors are mostly technical errors which lack input from the structural safety management perspective. On the contrary, Bea [33] believes that human errors in structural engineering can be generated from elements like individual, organization, system, procedure, environment, and the interfaces between humans and each of the other four. Therefore, he proposed the Human and Organizational Error (HOE) scheme that includes a human error classification framework and an organizational error classification framework. In fact, most of the “errors” in the framework are rather an underlying behavioral or managerial cause that can lead to the occurrence of error than the error itself, such as selection and training in human error and culture in organization error. Thus, this new HOE concept he coined opened a new chapter of more comprehensive human error research in the structural engineering field. Other than a single focus on technical errors, it joined the structural safety study to the emerging trend of a system thinking approach in the wider human error research domain.

1.1.4. LIMITATIONS AND NEW DEVELOPMENT OF THE HUMAN ERROR APPROACH

HUMAN error is the most widely accepted root cause for accidents and failures, regardless of the industry [21]. However, it is an inadequate explanation for these adverse events [37]. The reason lies in three folds. First of all, it is people who design and build systems and are involved in every activity creating and running the system. This offers an excuse for the blame culture to stand. In the end, any trouble could be attributed to human error. Therefore, only looking for human errors when an accident or failure occurs produces a dangerous tunnel vision and hinders the learning process for the organization to develop, meanwhile offering no constructive insights regarding how these errors come to be. Secondly, as a matter of fact, we as humans, constantly make errors. However, accidents and failures do not take place every time an error is made. This is due to two aspects: not every error comes with a consequence; the system is designed to withstand some errors. In most circumstances, safety barriers, such as technical redundancy and control measures, are built into the system as defences to offset the error effects and block the causal chain. Hence, when a system does fail as a consequence of human errors, it is time to inquire into why the designed barriers could not protect the system as intended. And accept the fact that sometimes it is unavoidable for people to commit errors under certain circumstances. Lastly, human errors cannot be isolated from the broader system context [39]. Failures will happen regardless of who is involved. Replacing personnel generally cannot make the system safer when the system design, the management strategy, the working procedure and the working environment have not been improved. Intriguingly, what has been observed is that under the same working conditions, different people fall into the same behaviour pattern and commit similar errors. Therefore, the failure investigation focus should be on the causes and contexts that result in the deviated (erroneous) performance, instead of locating the person who made the error.

There are, in general, two approaches toward human error: the person approach and the system approach [39]. The person approach focuses on the errors of individuals who perform the task. This approach considers human errors as unsafe acts and violations which are attributed to personal traits such as forgetfulness, carelessness and lacking motivation. This approach is referred to by Dekker [58] as “The Bad Apple Theory”, or “the old view” of human error. In the old view, human error is recognized as the cause of accidents and failures. The system is considered inherently safe whilst the humans operating or working within the system are considered unreliable by nature. As a result, unreliable humans pose a major threat to system safety and therefore should be controlled or excluded. On the contrary, the system approach considers human as an inseparable part of the socio-technical system. Given that, human error is the outcome that arises from the coherent system environment created by local factors like tools and workplace environment, 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 [39]. For example, inappropriate project planning may cause time stress and consequently trigger people to make errors when there is no sufficient time to finish the task with the requirements being fully met. This approach was touched and phrased as the “blunt end” in the "sharp end-blunt end" interactions model proposed [24]. In this model, the "blunt end" encompasses factors at several social and organizational levels, including morals and social norms, government, regulators, companies, management, and the workplace. Besides this model, the system human error approach is consistence with "the new view" of human error described by [59], in which human error is viewed as a symptom of (unrevealed) trouble, instead of a cause of trouble, that embedded deeper inside the system. In contrast with the old view, the new view sees the system as inherently unsafe or tends to fail. It is the professionals working in the system that create safety and maintain the reliability of the system. These two approaches are referred to as the individual blame logic and the organizational function logic in [60], where a comparison of these two views concerning their aim, cause, and context is presented.

While the research and the practice of the system approach to treat the human error issue have been advanced in several safety-critical industries such as aviation, nuclear and chemical processing, it remains under-developed in the AEC industry, where the old view still dominates when it comes to human errors in structural failure investigation. 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") 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. As a result, it is not surprising that many studies find human errors to be responsible for 60% – 90% of structural failures [4, 61]. Consequently, engineers and construction workers have very often been blamed for the failure, which neither benefits understanding the failure context nor improving safety practices. Thus, it is important to identify the working conditions and those upstream factors inside the system and 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.

1.1.5. FROM HUMAN ERROR TO HUMAN AND ORGANIZATIONAL FACTORS

THE above-mentioned working context and underlying factors, which include the human performance related factors such as physical and mental conditions of the personnel at work, and organization related factors that concern the organizational process and management strategies, can shape the performance of people at work and potentially lead to the occurrence of human errors and accidents, are defined as the Human and Organizational Factors (HOFs). HOFs are the latent conditions in the construction project system that play an important role in structural safety. HOFs arise as the development of accident causation theories, such as the widely accepted Man-made disasters from Turner [62] and the Normal accidents theory by Perrow [63]. The HOFs concept, which is a successor of the Human Factors and Ergonomics (HFE) in the safety domain, represents the rising of the system approach and promotes the new view towards human error.

It has been a long way before safety research arrived at the HOFs theory. The development of HOFs depends largely on knowledge accumulation concerning accidents and failures as well as the evolvement of safety theories. The accident causation models have evolved from sequential accident models to epidemiological accident models, and nowadays to systemic accident models [25]. The sequential accident models view accidents as a result of a chain of events that occur in a sequential order, such as the Domino Theory proposed by Heinrich [64]. The epidemiological accident models recognize accidents as caused by a group of networked manifest and latent factors like pathogens, that co-exist in a certain time and location [65]. According to Reason [39], active failures and latent conditions are two kinds of causes that are responsible for the defects on the safety barriers, which in combination lead to adverse events and accidents. While the active failures are the unsafe acts made by the frontline employees, which can be perceived as human errors, including slips, lapses, mistakes and violations; the latent conditions are the characteristics and decisions made within the system that will translate into error-provoking conditions and create weaknesses in the safety defences. The systemic accident models regard accidents as emergent phenomena generated from the dynamic interactions between components within the system. The system here refers to the whole socio-technical system which accounts for both the technical and the social aspects, such as a construction project, which consists of the physical structure and the participating stakeholders. As pointed out by Leveson [66], a new accident model, based on systems theory that considers not only the technical and social facets but also the system components interacting relationships, is in need. This vision, which matches with the HOE scheme from Bea [33] and the under-developing HOFs concept, is a promising new area for a more comprehensive understanding of safety.

The changing view on how accidents and failures came to be has also been reflected in the approaches taken towards safety in industrial practice. The focus was first fully on improving the technical design and engineering for accident prevention. After the Seveso and Three Mile Island accidents in the late 70's, it has been realized that dealing only with the technical part cannot improve the safety performance in the industries. Therefore, the Safety Management System (SMS), which serves as a supplement to the efforts toward enhancing safety besides the technical improvement, was introduced. SMS provides the industry with a systematic, structured means to achieve the desired safety from a managerial perspective, including necessary safety policy and objectives, safety risk management, safety assurance and safety promotion measures. More recently, the HOFs that are embedded in everyday tasks, which influence task performance and system operation, are gaining more attention. How to adjust and integrate HOFs into activities for better error control and safety performance improvement became an essential topic of interest for both academia and the industry.

HOFs is a multidisciplinary study area, which has not been recognized as an independent academic discipline yet, according to Andrew Hopkins in the RAND interview [67]. Even though there are a large number of studies covering HOF related concepts and factors across different industries, a gap exists concerning a clear definition and a systematic knowledge body for HOFs as a scientific domain. In general, HOFs is a study that encompasses the socio-technical systems theory, cognitive psychology, management science, organizational theory and more [67]. Meshkati [68] points out that the human, organizational and technological factors in a system and the way how they fit and interact with each other are key to understanding system accidents. Accidents and failures may be directly triggered by human errors and related human factors, as a result of the pre-conditions created by organizational factors in the system. Therefore, the research on human factors should be expanded to involve the organizational and environmental related factors such as decision making, safety culture, management procedures, organizational structure, resource allocation and environmental pressure.

HOFs can be viewed as separate and discrete variables that cause an event [69]. Some widely recognized HOFs across industries include training, decision-making, communication, preparation for the unexpected, and organizational interdependencies. The HOF approach to safety not only investigates the "trouble-making" factors that harm system safety but also identifies positive safety-contributing conditions in a system. Hence HOFs can provide knowledge and a better understanding of the conditions under which human activities take place with a good safety and quality orientation [37]. Therefore, HOFs, as the underlying factors in a system which provide incubation conditions for human error occurrence and unsafe situations, can offer powerful solutions to handle these problems at the same time.

In the structural engineering domain, the appeal to be facilitated with the system theory mindset and to wear the HOFs lens to observe structural failure hazards as well as to manage structural safety issues in research and practice is growing. Blockley [70] provided the foresight that civil engineering failures are as much of a human and organizational phenomenon as a technical failure. Hence, he believes that social science can assist engineers in identifying and predicting factors contributing to failures. Afterwards, Blockley [71] categorized the technical aspects that involve the physical parts as the "hard system" (e.g., beam and column), which is objective and measurable; and the managerial aspects that include people and social relations as the "soft system" (e.g., action and organization), which is subjective and need to be judged. He believes that structural unsafe issues can arise from any, both, or the interface between the hard and soft systems. For this reason, he promoted systems thinking to integrate these two systems so that engineers are equipped with the ability to identify issues across disciplinary boundaries and to make judgements from multiple perspectives. With that said, he argues that we can only understand major failures in the construction industry by adopting systems thinking. Close to the view of Blockley, Allen [72] proposed to research structural failures due to human error. It is pointed out that a multidisciplinary approach, which includes both the "soft" human science aspects and the "hard" physical science parts, is required. He recognized that there lack of understanding regarding the fundamental principles and factors involved in human errors that cause failures. Based on this judgement, he proposed to look for input elsewhere and learn from disciplines such as human behaviour and management studies. Later, Menzies [73] questioned the credibility of the structural reliability analysis that only considers the technical aspects while omitting the critical human factor considerations, which is often the cause for structural failures. Additionally, he criticized the incompleteness of the structural reliability theory for its inability to take human performance aspects (e.g., workmanship) into consideration in its mathematical models. He claims that system reliability analysis needs to replace the structural reliability analysis due to the fact that structures are complex systems and their reliability needs to be addressed through a comprehensive assessment considering human and organizational contributions. In this regard, he points out that practitioners in the construction industry need to be provided with better tools to manage risks and analyze reliability. Atkinson [74] 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 lead to the occurrence of errors that eventually cause structural defects. Similarly, Elms [11] states that to handle the current structural safety issues, it is important to be aware of the factors that lead to increased error proneness. Apart from this, he identified that "a fundamental change in viewpoint from a narrower technical focus to a broader systemic approach" is in need. Possessing the same pioneering insight, Melchers [75] specified that human error and human intervention have not been studied extensively in the structural reliability theory. However, their influence on structural safety must be further investigated. Therefore, he proposed to refine the structural load and resistance models to incorporate human error effects and to integrate human intervention strategies such as supervision and quality control. As pointed out by Terwel [76], HOFs are pivotal latent conditions to be taken into consideration when dealing with human errors resulting in structural failures. These HOFs can assist academics and practitioners in gaining beneficial insights into how human errors come to be, and furthermore, how to prevent them.

As can be seen from the discussions and proposals from scholars in the structural engineering field, HOFs are key to treating human error issues and making progress in improving structural safety in practice.

1.2. RESEARCH AIM AND SCOPE

In light of the new view of human error, it is time to gain a better understanding of the HOFs behind human errors in the AEC industry regarding their impacts on structural safety. Therefore, this research aims to contribute knowledge to improve structural safety from a social-technical systems point of view by studying HOFs. More specifically, to obtain knowledge concerning what are the critical HOFs, as well as how and to what extent they influence structural safety.

As discussed in section 1.1.3, errors in the structural design and construction process are responsible for the majority of structural failures. Therefore, the primary focus of this research is on these two stages of the construction project's life cycle. Consequently, the main research goal is to assess structural safety by taking the influence of HOFs in the structural design and construction process into consideration. As a result, the developed model can facilitate a more comprehensive structural reliability analysis accounting for human contributions. Moreover, the insights into HOFs can provide effective error control and informed risk mitigation measures to practice.

As a clarification note, this study is not concerned with the psychological basis of the identified HOFs.

1.3. RESEARCH QUESTIONS

To achieve this research goal, triggered research questions need to be answered. Based on the object of this project, the main research question is as below:

How to account for the human and organizational influence on structural safety? HOFs can contribute to the occurrence of human errors, and these errors in structural design and construction will compromise the safety of constructed structures and may lead to potential structural failures. Therefore, to answer the main research question, several sub-questions need to be addressed, as listed in the following.

RQ1 (Chapter 2) *What are the HOFs that have been identified in existing studies? And how are the impacts of human errors on structural reliability evaluated?*

This is the research starting point to lay the foundation for this study. A thorough literature review on the topic of HOFs and human errors influencing structural safety is needed in order to get an overview of the existing knowledge and the state-of-the-art development on this subject matter. What are the HOFs recognized to affect structural safety in existing studies? Moreover, how are the effects of human errors on structural safety modelled and evaluated? Further research is based on the insights gained in this review.

RQ2 (Chapter 3) *What are the critical HOFs in structural design and construction tasks that influence structural safety?*

The HOFs that are considered crucial for the occurrence of human error and structural safety throughout the structural design and construction process need to be determined based on the collection of HOFs identified in the literature review. Focusing solely on the critical HOFs and their impacts will make further assessments in a more practical fashion.

RQ3 (Chapter 4) *How much do the critical HOFs contribute to human error occurrence?*

HOFs indirectly affect structural safety through the human errors they lead to. It is absent knowledge regarding how influential the critical HOFs are on the human error occurrence likelihood for structural design and construction tasks in the AEC industry. This is critical information for human error estimation.

RQ4 (Chapter 5) *How and how much do the critical HOFs affect structural reliability?*

A model that can adequately depict the influence of the critical HOFs on structural safety is absent. Specifically, this model is expected to capture the dynamic and non-linear nature of HOFs' influence. Additionally, the change in structural reliability due to human error occurrence contributed by specific HOFs needs to be measured.

An overview of how these sub-questions are linked to the fundamental logic and key elements of this study is shown in Fig. 1.1.

1.4. DISSERTATION OUTLINE

THE structure of this paper-based dissertation is outlined in Fig. 1.2, in which the relationship between the research purpose and the chapters that realized it is presented. First, Chapter 1 gives a general introduction to the research background, aim, and questions of this dissertation. Secondly, Chapter 2 reviews the existing literature regarding

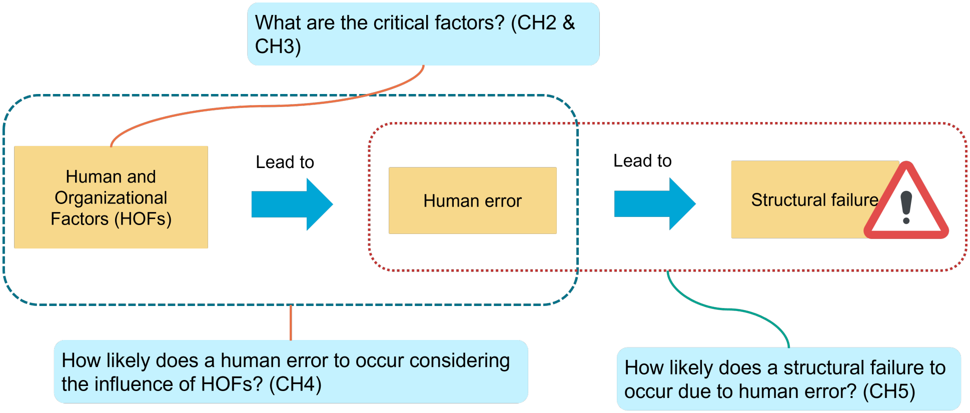


Figure 1.1.: The link between research questions and key research subjects.

HOFs and human errors influencing structural safety. Based on the HOFs collected from the literature review in Chapter 2, Chapter 3 identifies the critical HOFs in structural design and construction tasks. Subsequently, the impacts of these critical HOFs on human error occurrence are quantified for the AEC industry in Chapter 4. Furthermore, a model that can simulate the dynamic and nonlinear influence of the critical HOFs on the reliability of structures is proposed and illustrated with a case study in Chapter 5. In the end, Chapter 6 outlines the conclusions obtained from this study and discusses potential future works.

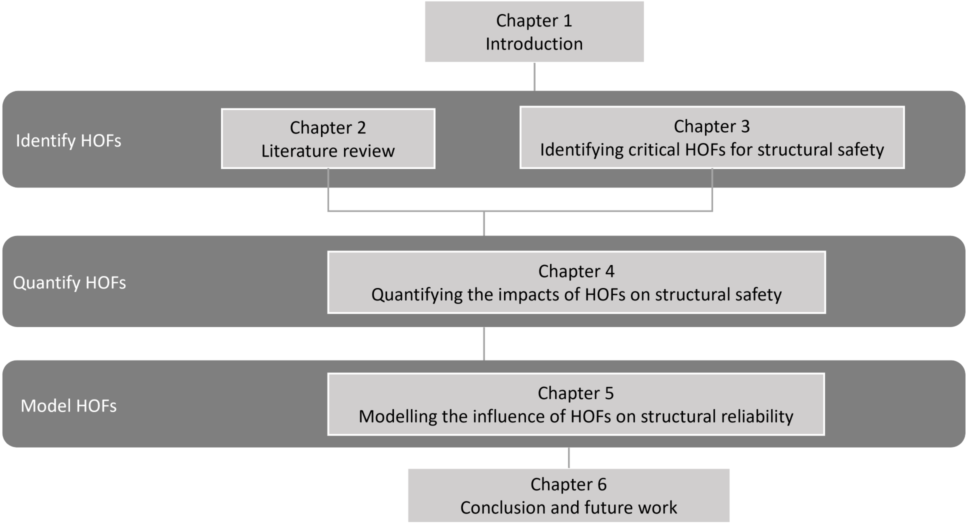


Figure 1.2.: Dissertation outline.

Despite the repetitive nature of research background information in the introductory section of each main content chapter, a paper-based dissertation allows readers to quickly grasp individual research works and key findings without the necessity of reviewing the entire dissertation. Consequently, this dissertation employs a paper-based format, with chapters 2 through 5 structured as individual research publications.

2

LITERATURE REVIEW

A broad review of the existing literature concerning Human and Organizational Factor (HOF) 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.

This chapter has been published in Structural Safety **107**, 289 (2024) [77].

2.1. 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 [78] 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 [1–4, 6, 7, 52, 79–85], 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 toward human error: the person approach and the system approach [39]. 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 [59]. 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 [59]. 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 [39]. The system approach is consistent with “the new view” of human error described by Dekker [59].

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 [4, 5, 12, 61]. 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 the structure in the end. For example, Schneider [85] provided a foresight that answers to the question of how to manage structural safety should be sought from management science, operation research and psychology. Likewise, Atkinson [74] 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 Factor (HOF). 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 [76] 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 [86]. 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 don't. 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?

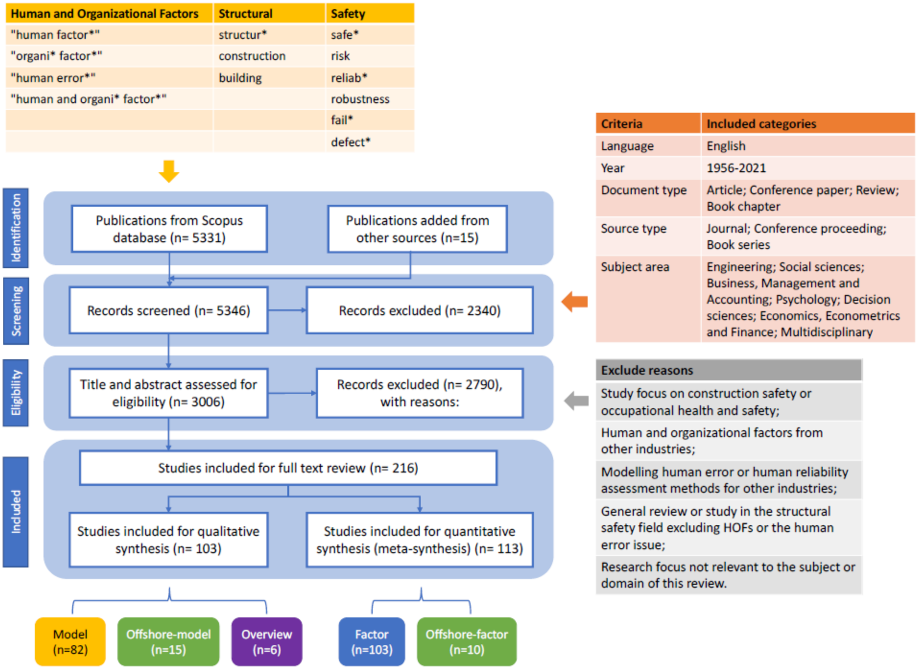
In the following part of this paper, Section 2.2 demonstrates the research data and applied methods. Section 2.3reviews the literature focusing on models and methods for evaluating human error effects on structural reliability. Subsequently, Section 2.4 reviews the literature on factors and causes for structural defects and failures. Furthermore, several observations from this review study are discussed in Section 2.5, along with some concerns and proposals. In the end, Section 2.6 recommends future research paths and concludes this review study.

2.2. METHODS AND MATERIALS

2.2.1. 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-Analysis (PRISMA) guideline [87]. Figure 2.1 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 Figure 2.1) 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).



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.

Figure 2.1.: The data collection and selection process following the PRISMA flow.

2.2.2. 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 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 Figure 2.1. 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, Figure 2.2 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 Subsection 2.5.2. Another observation is that the research from the offshore engineering field was mainly present in the period from 1995 to 2002.

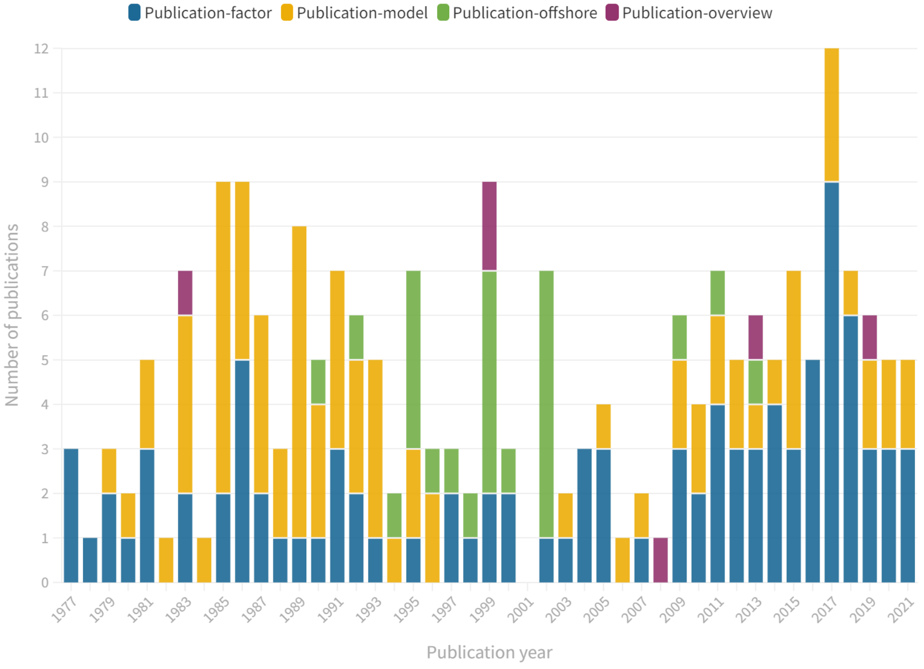


Figure 2.2.: Publication output from each literature group over time (books are not included).

2.2.3. 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." [88]. Readers interested in the research landscape of this topic are referred to a bibliometric review, see [89].

2.3. MODELS AND METHODS FOR ASSESSING THE HUMAN ERROR EFFECTS

As pointed out by Kupfer and Rackwitz [90], "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 [8]. 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 [91] pointed out that ignoring such failure possibilities is likely to lead to an overly optimistic view of the safety of the 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 [83]. Therefore, Allen [72] 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 Subsection 2.3.1. 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 Subsection 2.3.2.

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.

MATHEMATICAL AND PROBABILISTIC METHODS

ONE of the fundamental contributions to modelling the human error effects on structural reliability is from Rackwitz [92], where errors were modelled as additional random effects introduced to the existing structural reliability model. However, Bosshard [93] 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 [83] 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 [90] 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 [1] 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 [90], he also suggested an error elimination model considering the inspection effort. Most importantly, Lind [1] 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 [90]. Apart from this, Frangopol [3] 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 the error combinations 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. [94] 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 [95] put forward a mathematical model that is capable of calculating the work quality and the influence of defects utilizing a defect rate parameter and tolerance interval. It is worth mentioning that Stewart and Melchers [30] 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 [96].

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[97] 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 [98] 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 [99] 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” [100, 101]. Furthermore, Vrouwenvelder et al. [102] 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 [103] 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 [104–107], explored the human error impacts on bridge structures. With a case study, a probabilistic analysis of the structural system resistance plus a sensitivity analysis was 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.

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 [97] 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 [98]. Moreover, a Bayesian network was developed to assess the structural failure consequence induced by local damage whose causalities include human errors [102].

In terms of the fuzzy theory, Blockley [108] distilled conditions of structural failures into parameters, which were subjectively evaluated for their predictive confidence and criticality. Fuzzy set theory was then used to analyze these parameters for structural failure prediction. Moreover, Andersson [109] 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 [110] 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 [109], Pan [111] presented a method applying the fault tree analysis, which is characterized 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.

HUMAN RELIABILITY METHOD AND SIMULATION MODELS

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 [29]. 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 [112]. 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 [113], 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 [114] attempted to validate the HRA method in [113] with a case study of macrotasks in a typical one-story 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 [90] and [97]. Melchers argued that the human error rate is "clearly related to task complexity" [114]. Furthermore, Stewart and Melchers [115] developed a simulation model for load design macrotask using Monte-Carlo simulation, with the microtask error rate obtained from surveys in earlier studies [113, 116, 117]. Microtasks of table look-up, wind reduction factor determination and one-step calculation were simulated in a sequential manner in the design microtask 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 estimations 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 [118] obtained an "average error rate" of 0.0163 for design microtasks. This result in general supports the findings in [113]. 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 [61]. 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 [119], 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 [5]. Subsequently, this model was applied to simulate the entire structural design and construction process[80]. 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 [120] 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 [121].

Apart from the pioneering work and major contributions from Melchers and Stewart, De Haan [122] 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) [26] 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 Condition (CPC). 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 [61, 119] 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 [80] that it was beyond the research scope to identify the exact Performance Shaping Factor (PSF) 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 [123]. 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.

[124] 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.

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 [9]. 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 [92] 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 [83] 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 [55]. 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 [83]. Using the proposed HRA method to simulate the design process of a beam structure, De Haan [122] 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. [124] simulated the design and construction of a slab floor structure and examined the impact of checks and human errors on the structural failure probability.

2.3.2. 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 [125–135]. 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 [136]. 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 [125]. 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 [129, 130]. 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 [130] 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 [128]. 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 [29, 137]. 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 [33], Bea [131] emphasized 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 [126, 127, 132, 134, 135]. 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 analyzing the offshore structure system of its critical processes and various HOF-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 [134]. The SYRAS is a quantitative assessment process to evaluate the reliability of offshore structures by taking into account both natural hazards and HOF-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 [135]. 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 [127, 135]. 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) emphasizing 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 [134]. 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.

2.4. HOFS IN STRUCTURAL SAFETY

THERE are three "ages of safety" [136]. 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 system 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 [11, 71, 138]. 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 [71]. 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.

2.4.1. 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 [45, 46, 48, 49, 52, 79, 139–141]. 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 [4, 8, 42, 43, 47, 50, 74, 82, 84, 142–149]. 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 [150]. In this study, he identified several causal parameters by examining a number of major structural failures. These parameters concern political, financial, scientific, 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 summarized 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 [151]. 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 [108]. These parameters include the engineering climate parameters proposed by Pugsley [150, 151] as well as design and construction errors.

Valuable insights were derived from examining four significant cases of metal bridge failures by Sibly and Walker [82]. 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 [47]. 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 [84]. 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 summarized causes for errors from existing studies as ignorance, negligence and carelessness; insufficient knowledge; forgetfulness and mistakes; and reliance on others [4]. 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 [50]. After reviewing and evaluating past experiences on the causes of errors, Melchers et al. [53] 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 summarized 10 types of what he referred to as “human error” but in fact HOFs from a literature survey [152]. 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.

2.4.2. HOFS FRAMEWORKS

ADDITIONALLY, some scholars have contributed to categorising the causal factors for structural failures from a HOF point of view. For example, Hadipriono and Wang classified failure causes into Triggering causes, Enabling causes and Procedural causes [148, 149]. 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 [42]. Furthermore, they categorized 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 categorization, hierarchical classification frameworks of HOFs have also been proposed by researchers [8, 74, 142–146, 153, 154]. Most of these conceptual models share a characteristic of categorizing 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 [74, 142, 153]. These factors are categorized 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 [39] and distinguished direct failures and influencing factors that cause the failure [143, 144]. 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. [155] 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 [146]. 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. Besides the HOFs identified on the project scale, task-specific PSFs that influence human performance at work and are used in HRA have also been studied. Summarized from a literature review, Bletsios et al. [156] 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 categorized 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. [157]. 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.

2.4.3. EMERGING FACTORS OF CONCERN

THE latest development in automation and digitalization 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. [155] pointed out that over-dependence on Computer-Aided Design (CAD) can lead to errors. Additionally, Love et al. [158] 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 [39], Kandregula and Le [159] investigated the roots of human errors in 4D BIM construction scheduling through a survey study. London et al. [160] provided a more comprehensive defect causation model that takes into account digital innovations, especially mobile technologies, by expanding Atkinson’s construction defects causation model [142] with error-leading conditions summarized 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 [161] and enable real-time quality control [162]. 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. [155] 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 [163].

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 visualization and 4D construction process simulation alleviates the cognitive burden placed on engineers in terms of spatial imagination and time planning, thereby minimizing 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 [163], it is not easy to verify what was generated from the modelling program matches what was intended.

2.4.4. 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 Figure 2.3. 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 categorized 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 in Figure 2.3. Table 2.1 lists the full terms for the sub-category acronyms used in Figure 2.3.

It can be observed from Figure 2.3 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 [164]. 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 characterize 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 also emphasized 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 ele-

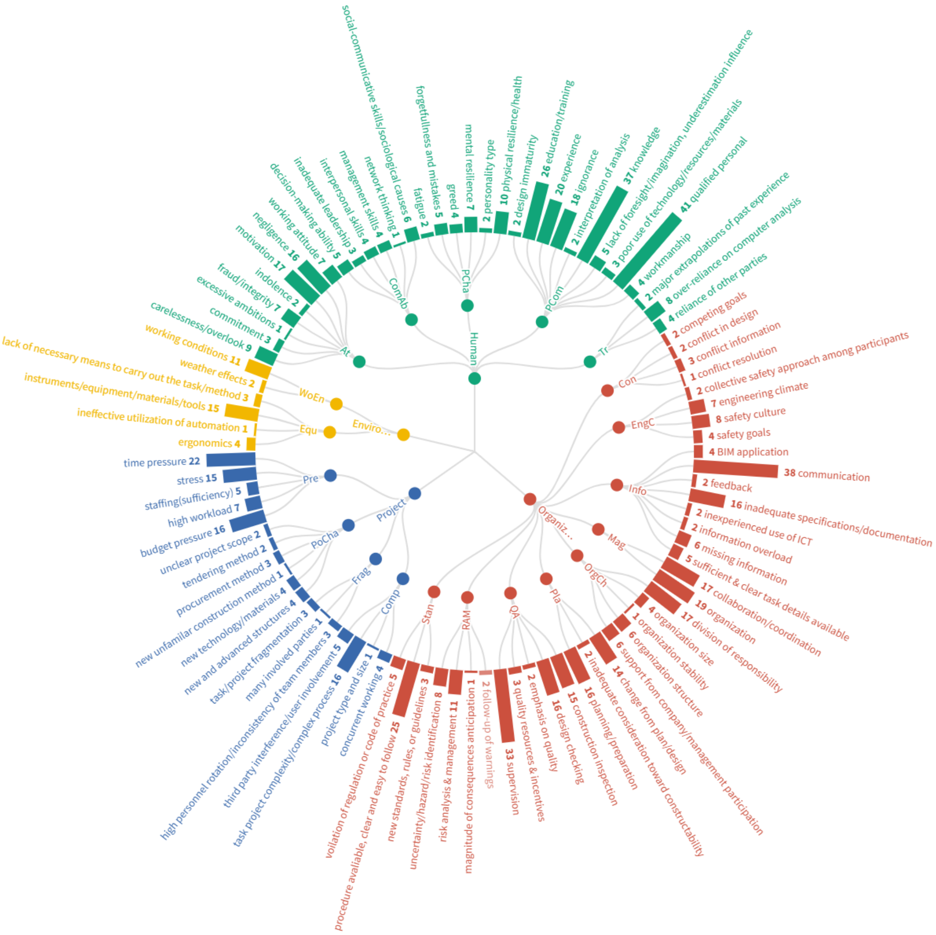


Figure 2.3.: Acknowledged HOFs from studies in the Factor and Offshore literature group.

ment 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 [129], 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 intercon-

Table 2.1.: Acronyms and corresponding full terms used in Figure 2.3.

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

nected factors [165]. Therefore, the adoption of a system perspective and approach emerges as the most viable way to handle human errors.

2.5. DISCUSSION

2.5.1. ERRORS OF OMISSION

THE most prevalent form of human error is omission [166], frequently found in structural failures [163] and responsible for approximately 38% of rework expenses in the AEC industry [167]. Reason [166] 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 [166]. Reason [166] identified the task situational factors (termed "Affordances") as the contributing factors for omission errors. Similarly, Love et al [167] recognize 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 [90]. Stewart and Melchers' model skips tasks in simulations upon encountering omission errors [115]. While many human error models reviewed in Subsection 2.3.1 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 proposes a three-stage management program encompassing task analysis, omission error probability assessment, and the selection and application of appropriate reminders [166]. Errors of omission can be detected via peer review by experienced engineers, ideally before the construction starts [163]. 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 the underlying factors of omission errors by Love et al. [167] based on interview data establishes a systemic causal model. This model provides valuable insights into omission errors; nonetheless, further research endeavours are needed.

2.5.2. 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 [46, 48, 49, 52, 79, 139, 140]. 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 and 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 boom in research 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, which resulted in the international and multidisciplinary investigation into human contribution to accidents and failures across a wide range of fields such as engineering, psychology and social studies [168]. In the safety science domain arise the widely accepted accident causation theories such as the *man-made disasters* [62] and the *normal accidents theory* [63] 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 activity 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 realization 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 [169]. 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 [12]. 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 [170] and soared over the years. BIM has been proven to benefit construction projects in terms of error reduction and quality control enhancement [171]. Thus, BIM partly won over the research attention from error-oriented quality control and diverted it to BIM-assisted quality assurance from the structural quality assurance community.

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 [89]. Thus, the overall research output on this topic is limited.

2.5.3. NOTIONAL RELIABILITY VS. OBJECTIVE RELIABILITY

QUALITY assurance is an essential human error treatment [12, 83, 93]. However, good quality assurance practice means a wise allocation of control resources [83], which requires an informed decision made on the premise of a good understanding of the critical points prioritized 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 [11, 83, 172]. 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 [173]: "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.

2.5.4. 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 a blame culture and reluctance to learn from incidents [174]. 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 [52] in 1981 and subsequently emphasized by Frühwald [175] for timber structures. As argued by Petroski [86], 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 [176, 177]. It emphasizes understanding the system context and underlying factors contributing to errors [167, 177], shifting from blame (control-based management) to learning (commitment-based management) [178]. Within the just culture paradigm, errors and incidents are perceived as collective learning opportunities [167, 179]. The participants involved in an incident should be included in the discussion to maximize learning. As a result, a safe environment is created to encourage reporting errors and openly expressing concerns without fear of punishment [178]. Ultimately, a just culture strives to enhance safety through shared responsibility and continuous learning and improvement [177].

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 legitimize managerial involvement in disciplining organizational members. As pointed out by Dekker and Breakey [180], "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 [181]. It aligns with Blockley's perspective [182], advocating for an interdisciplinary dialogue involving engineering, legal, insurance, and safety-risk experts to openly discuss and collectively seek solutions to this legal concern.

2.5.5. 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. Emphasize checking and maximize 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 prioritize safety, keeping in mind that safety is an essential responsibility and a fundamental principle that must guide every facet of engineering work throughout the entire engineering process. [183]
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.

2.6. 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 analyze 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, AI, 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 [155]. Even though there have been a few studies that inquire into these innovations in the AEC industry [159, 160, 184, 185], 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 recognized 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 systemic fashion.

3

IDENTIFYING CRITICAL HOFS FOR STRUCTURAL SAFETY

Human errors are widely acknowledged as the primary cause of structural failures in the construction industry. Research has found that such errors arise from the situation created by human factors and organizational factors embedded in the task context. However, these contextual factors have not been adequately addressed in the construction industry. Therefore, this study aims to identify the critical Human and Organizational Factor (HOF) that influence structural safety in frequently performed tasks in structural design and construction. Through a comprehensive literature review, a framework consisting of potential critical factors called the Human-Organization-Project-Environment (HOPE) framework, is presented. To identify the most critical HOFs that contribute to human error occurrences, a questionnaire survey to experts in the Dutch construction industry was conducted. Finally, the resulting framework was compared with three actual structural failures for validation. This study shows that the HOFs should be extended with project related factors (P) and working environment-related factors (E) due to the fact that these task contextual conditions play a significant role in shaping professionals' on-the-job performance. Furthermore, a survey identified 14 HOFs as critical in contributing to an error-prone situation in the structural design and construction tasks. The presented HOPE framework and the identified critical HOFs for structural safety can assist engineers with better hazard identification and quality assurance in practice.

This chapter is currently under review in American Journal of Industrial Medicine [186].

3.1. INTRODUCTION

THE construction industry is one of the most unsafe industries worldwide [187]. It witnessed the highest number of fatalities among all industries in the United States in 2021 [188], and consistently records the largest amount of work-related fatal injuries in the UK [189]. A large proportion of fatal injuries in the construction industry are caused by structural failures and collapsing objects [189]. For example, the collapse of a five-story apartment building in Cairo, Egypt on July 17th 2023 claimed 13 lives. Besides, a railway bridge collapsed under construction in Mizoram, India on August 23rd 2023, killing at least 26 construction workers. As can be seen, structural failures can result in enormous detrimental social and individual consequences, such as financial losses, reputation losses, and even injuries and fatalities. Therefore, the safety of structures is critical to the safety of structural users and construction workers. Achieving and maintaining a safe state, or an expected quality state of the constructed structure is one of the primary goals in the construction industry. To meet this fundamental requirement, unacceptable structural failures, such as (partial) collapse and structural damage that can lead to the loss of structural integrity [8], should be avoided.

3.1.1. CAUSES OF STRUCTURAL FAILURES

WHAT causes structural failures? Many studies and accident investigations exist on identifying the root causes of structural failures [42, 43, 47, 52, 54, 175]. Numerous studies have identified the primary cause of structural failures and near-miss cases as human errors rather than technical issues [4, 6–8, 52, 79, 80]. Therefore, human error is recognized as an essential issue to be tackled in order to achieve structural safety. As a result, a great amount of research efforts have been made to study various errors that play significant roles in affecting structural safety. For example, Walker pointed out that the error in defining the loads in design is the dominant error type (61%). Moreover, ignoring loads, ignoring structural behavior, mistakes in calculations and drawings, and inadequate instructions are recognized as the primary errors contributing to structural failures [52]. After studying 604 structural and construction failures from 1975 to 1986 in the US, Eldukair and Ayyub concluded that construction errors, among errors in the plan, design and utilization phase, are the highest contributing causes for structural defects and failures [42].

3.1.2. HUMAN AND ORGANIZATIONAL FACTORS

HOWEVER, the latest development in safety science no longer views human error as the root cause for accidents, but rather the symptom of troubles that are deeply embedded in or at the higher hierarchy of the system [59]. Human errors arise from these unfavorable system conditions and work contexts, specifically, how the system is designed and managed, and the way humans interact with the system [39]. These underlying factors can shape the performance of people at work and potentially lead to the occurrence of human errors and accidents. They include human performance-related factors such as physical and mental conditions of the personnel at the job, and organization-related factors that concern the organizational process and management strategies, which are termed the Human and Organizational Factor (HOF). Figure 3.1

illustrates the progressive development of industrial safety approaches. It is clear that the approaches towards industrial safety evolved from focusing on the technical aspects to improve safety to introducing the Safety Management System (SMS) to account for the management facet of the overall system safety, and the latest to take the human and organizational perspectives of the system into consideration. The HOF concept arose after the widely accepted Man-made disasters [62] and the Normal accidents theory [63] of accident causation, representing a system approach towards human error [39]. Consequently, a better solution towards the human error issue lies in the enhanced understanding of the HOFs.

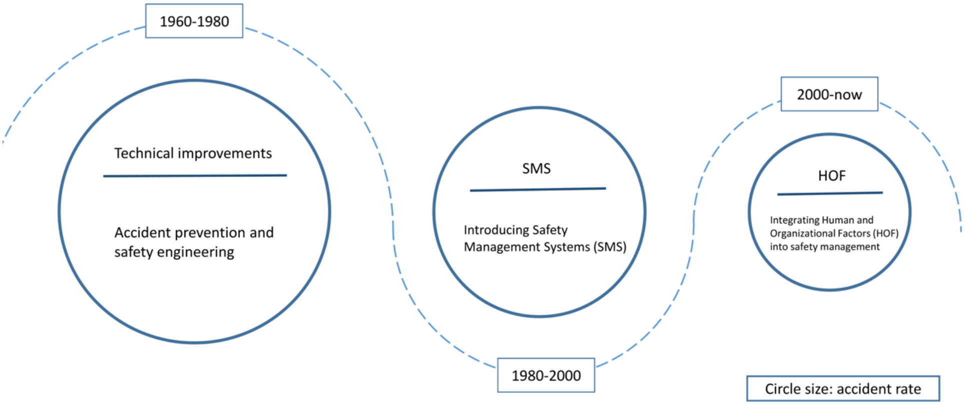


Figure 3.1.: The development of approaches towards industrial safety (adapted from Daniellou et al[37]).

In the construction domain, human errors are still frequently viewed as the root cause of structural failures. The underlying HOFs behind the errors are very often neglected. As a result, the factors that contribute to the error occurrence can repeatedly cause trouble. Blockley provided the foresight that civil engineering failures are as much of a human and organizational phenomenon as a technical failure [70]. Moreover, Elms specified that it is important to be aware of the factors that lead to increased error proneness when handling structural safety [11]. Therefore, HOFs are key to treating human errors and making progress in improving structural safety. As pointed out by Melchers, human error and human intervention have not been studied extensively in the structural reliability field [75]. The current research into the contributing HOFs in structural failures is far from adequate. Thus, a better understanding of the HOFs associated with structural safety is in demand.

As a starting point to fill in this gap, this study aims to contribute to the knowledge of HOFs by identifying critical task-specific HOFs that can lead to the occurrence of human error in the structural design and construction process. Consequently, the following research question is answered in this study.

What are the critical HOFs in structural design and construction tasks that influence structural safety?

3.2. Methods

To reach the above research goal, several methods were applied in this study and some results were obtained consequently. The overall research workflow of this study is outlined in Figure 3.2.

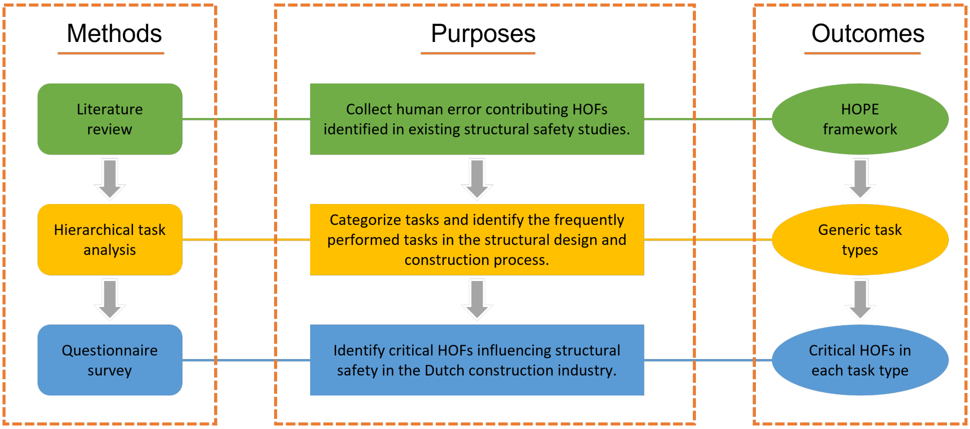


Figure 3.2.: The research workflow.

3.2.1. Literature review

Important factors that affect structural safety, which have been identified in existing studies were collected from a comprehensive literature review [77]. As a result, a hierarchical HOFs framework is proposed. Moreover, the definitions of each factor and the distinguished task types in structural design and construction, termed Generic Task Type (GTT), are provided. Furthermore, the critical factors of each GTT were identified through a survey to experts in the Dutch construction industry.

3.2.2. Questionnaire survey

To identify the most critical HOFs that contribute to human error occurrences and consequently influence structural safety in the Dutch construction industry, a questionnaire survey was designed and issued to experts in the Dutch construction sector. For practicability considerations, the sub-category HOFs were used in the survey study instead of the specific HOFs. The questionnaire is designed such that each question inquiries about the critical HOFs for a specific GTT. Using a 5-point Likert scale, the respondents were asked to rate each factor regarding how influential it is on the type of task under consideration (i.e., not-at-all influential, slightly influential, somewhat influential, very influential, extremely influential). An example question from this questionnaire can be seen in Appendix B, Figure B.1. The profiles of the responding experts are shown in Figure 3.3.

Figure 3.3.: Profiles of the survey responding experts.

3.2.3. ANALYTIC HIERARCHY PROCESS

The collected expert judgment data were subsequently analyzed using the Analytic Hierarchy Process (AHP) to elicit a rational consensus concerning the relative importance ranking of the HOFs for each GTT. AHP is a widely used method in solving Multi-Criterion Decision Making (MCDM) problems. It is a pair-wise comparison method which provides mathematical assessments to prioritize decision criteria and alternative options. Based on rational judgements, it assigns distinct weights to the alternatives with regard to their contribution to the decision goal. AHP can derive both group and individual preferences. Developed by Prof. Saaty [190, 191], AHP has been applied in a wide range of domains such as logistics, manufacturing, policy, and construction for various purposes such as planning, optimizing, risk analysis, and resource allocation [192]. In the construction field, AHP has been primarily applied for risk management, including risk identification and assessment, as well as risk-informed decision-making support [193]. For example, AHP is used to develop a framework for injury risk prioritization so that an adequate safety budget can be secured during the construction project planning phase [194]. In addition, AHP and the Failure Mode and Effect Analysis (FMEA) are combined with fuzzy logic to assess the criticality of potential risks in construction for better risk management [195].

3.3. RESULTS

3.3.1. THE HOPE FRAMEWORK

Based on an extensive literature review on the topic of HOFs influencing structural safety [77], a comprehensive set of HOFs have been identified and analyzed. Consequently, a framework that consists of the widely acknowledged HOFs is proposed for proactive structural safety management in the construction industry.

In this framework, the identified specific HOFs (see Fig. 2.3 in Chapter 2) are further analyzed and summarized into 17 middle hierarchy sub-category HOFs. Some less frequently recognized specific HOFs are excluded, such as excessive ambition in the Attitude sub-category. Additionally, a few correlated sub-categories are merged. For example, planning and management are combined into Task management. Beyond this, these sub-category HOFs are classified into four main categories on the top hierarchy, which are the Human factors, the Organizational factors, the Project factors, and the Environmental factors. The project-related factors and the working environment-related factors are also included in this framework along with the human and organization-related factors due to the fact that these task contextual conditions play a significant role in shaping professionals' on-the-job performance. As a result, a Human-Organization-Project-Environment (HOPE) framework is proposed. The final synthesized framework that embodies all three layers of factors is presented in Table 3.1.

Table 3.1.: The HOPE framework.

Main Category	Sub-category HOFs	Specific HOFs
Human factors	Professional competence	professional knowledge and skills
		professional insights/anticipation
		education
		training
		experience
	Trust	over-confident about traditional approaches and past experience
		overly confident in engineering software and computer analysis
		reliance on other parties
	Attitude	motivation
		commitment to the job
		negligence and carelessness
		violation of protocols, standards and regulations to save effort
	Well-being for duty	physical health condition
		mental health condition
		fatigue
	Comprehensive abilities	management skills
		social-communicative skills
		teamwork skills
		ability to learn
		decision-making ability
		network and critical thinking
Organizational factors	Information flow	communication quality information availability and quality
		information overload
	Task management	task planning and preparation
		task coordination and collaboration
		change management
		conflict management

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Table 3.1.: The HOPE framework (*Continued from previous page*).

Main Category	Sub-category HOFs	Specific HOFs
Organizational factors	Organizational characteristics	organization structure
		organization stability
		team size
		responsibility division
		support and provision from the parent company
	Quality assurance	supervision
		design checking
		construction inspection
		protocols/procedure/regulation availability and quality
	Risk analysis and management	risk identification
		risk analysis
		risk and safety management
		follow-up warnings
	Engineering climate	safety culture
		structural safety goals
Project factors	Complexity	task complexity project type and size
		concurrent working
		many parties involved
	Stress	time pressure
		budget pressure
		workload
	Fragmentation	high personnel rotation
		task fragmentation
	New and unfamiliarity	new or advanced structures
		new technology or construction materials
		new or unfamiliar construction methods
Environment factors	Equipment	correct equipment availability equipment condition
		ergonomics (Human-Machine-Interface)
	Working conditions	physical working environment
		interpersonal/team environment
		weather conditions
		time of the day

DEFINITIONS OF HOFS

THE HOFs are a similar concept as the Performance Shaping Factor (PSF) or Performance Influencing Factor (PIF), which are widely applied in the Human Reliability Analysis (HRA) domain. These factors are considered the contextual factors surrounding the task and influence the individual or team performance in completing the assigned task. HRA uses qualitative or quantitative methods to evaluate the human error occurrence potential by assessing the effects of PSFs or PIFs on task performance. Therefore, task-specific PSFs are key for Human Error Probability (HEP) estimation. It is essential that these HOFs are clearly defined under the construction industry context so that confusion is avoided when applying them in task success or failure outcome evaluation and prediction. Thus, the sub-category HOFs in the HOPE framework are defined in Table 3.2.

Table 3.2.: The definitions of HOFs.

ID	Factor	Definition	Aspects of consideration
F1	Professional competence	The degree of utilization of professional knowledge, skills, and good judgment related to one's profession, which reflects one's readiness to work in a specialized area or profession.	professional knowledge; professional skills; education; training; experience
F2	Trust	To have confidence over past experience or the work of teammates or other project participants; or blind belief in the results given by a computer programme. Here trust refers to overconfidence or blind trust behaviour which leads to careless examination or limited checking.	overly confidence over past experience; over-reliance on computer analysis/overly confidence in engineering software; blind trust/assuming errorless output from others; overconfident about traditional approaches
F3	Attitude	Attitude shows the task performer's commitment towards the task at hand, whether they are willing to make efforts to achieve the task goal successfully.	motivation; commitment; violations
F4	Well-being for duty	Whether or not the task performer is physically and mentally capable of accomplishing the task successfully. For instance, fatigue, drug effects and emotional instability might lead to errors while performing a task.	mental resilience; physical resilience; fatigue

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Table 3.2.: The definitions of HOFs (*Continued from previous page*).

ID	Factor	Definition	Aspects of consideration
F5	Comprehensive abilities	Comprehensive abilities refer to the capabilities an individual possesses in addition to professional competence. These abilities include self-management skills, teamwork and social-communicative skills, ability to learn, critical thinking, network thinking and keeping an overview of the whole structure/project in mind while conducting divided task steps, etc.	management skills; social-communicative skills; ability to learn; critical thinking; network thinking
F6	Information flow	Information flow refers to the exchange of desired information between individuals and parties in the design and construction process. This consists of quality information being created, safely stored and transferred to the targeted party on time so that a mutual understanding of the information is reached	communication; information availability and quality; information overload
F7	Task management	The planning, organizing, controlling and coordinating of the task process and the task performers to achieve the task goal.	teamwork; coordination; planning/preparation; change management
F8	Organizational characteristics	Organizational characteristics are aspects of organizations (e.g. structural engineering company, contractor, the whole project organization, etc.) that can be identified in relation to performance, such as the organization structure, team size, responsibility division, organization stability, etc.	support and provision from parent company; organization structure; team size; responsibility division; organization stability
F9	Quality assurance	Quality assurance is part of quality management focused on fulfilling quality requirements of the structure via supervision, regulation, checking and inspections.	supervision; design checking; construction inspection; protocols/procedure/regulation;

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Table 3.2.: The definitions of HOFs (*Continued from previous page*).

ID	Factor	Definition	Aspects of consideration
F10	Risk analysis and management	Risk analysis is the process of identifying potential hazards and evaluating the probability and consequence of corresponding failures and accidents. Risk management is to prioritize the risks and coordinate the available resources and measures to minimize the risk and prevent the occurrence of undesired events.	Hazard identification; risk analysis; risk management; Follow-up warnings
F11	Engineering climate	Engineering climate is the shared value, common attitude, collective goal and group behaviour shared towards structural safety and reliability by the majority of people within the workplace or project. It can be characterised as "the way we do things around here".	safety culture; safety goals
F12	Complexity	Complexity refers to how difficult the task is to perform in the given context. A complex task means it requires great mental efforts such as work related (short term) memory and knowledge to accomplish the task successfully.	task complexity; project type and size
F13	Stress	Stress refers to the mental or emotional tension caused by constrained or undesirable conditions and circumstances at work, which will impede the task performer in completing a task. Stress can result from time pressure, budget constraints, and high workload due to limited staffing, etc.	time pressure; budget pressure; workload
F14	Fragmentation	Fragmentation refers to the fact that the project is divided into small working packages that are assigned to highly specialised teams. This means that it requires great communication, coordination and management efforts to accomplish the project successfully.	frequent personnel change; lack of project overview and network thinking

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Table 3.2.: The definitions of HOFs (*Continued from previous page*).

ID	Factor	Definition	Aspects of consideration
F15	Equipment	The available equipment for conducting a task. The equipment includes hardware such as machines, tools; and software like structural modelling and analysis programs. The influence of equipment on human error can be considered from the availability of desired equipment and their conditions, as well as Human-Machine Interface (HMI, how the operator interact with the equipment to correctly perform the task).	equipment condition; ergonomics (HMI)
F16	Working conditions	Working conditions refer to the physical and interpersonal working environment at the workplace. It considers aspects such as weather conditions (rain, snow, wind, etc.), physical working environment (darkness, noise, dust, heat, small space, etc.) and interpersonal environment (peer pressure, competition, etc.).	working environment; interpersonal/team environment; weather effects

GENERIC TASK TYPES IN STRUCTURAL DESIGN AND CONSTRUCTION

It is found that most human errors occur during the structural design and construction process [8, 50, 80]. Thus this study focuses on the tasks in these two critical phases. Given that there are numerous detailed tasks involved in the structural design and construction process, some frequently performed typical tasks, summarized as the GTTs, were identified through a Hierarchical Task Analysis (HTA) in this study. An HTA outlines the primary tasks in a process and further breaks them down into detailed elementary actions. A GTT represents a typical type of task that shares similar system interactions, cognitive demands, and potential affecting factors [196]. GTTs should be clearly defined, mutually exclusive, and subject to the same sets of HOFs that post the same amount of impacts.

An HTA was performed to analyze tasks involved in a reinforced wide slab floor structure design and construction. As a result, 109 bottom hierarchy detailed tasks were obtained in this HTA. With a comparison to the decomposed tasks in another two studies[122, 197] and the critical cognitive activities in the Cognitive Reliability and Error Analysis Method (CREAM) [26], 14 frequently performed GTTs in the structural design and construction process have been abstracted. The definition of each GTT, the involved phase, and example tasks are outlined in Table 3.3.

3.3.2. SURVEY RESULTS

APPLICATION OF AHP

WE applied AHP to prioritize the criticality of the HOFs in each GTT. The established hierarchical structure is shown in Figure 3.4. It can be seen that for each GTT, there are 16 potential critical HOFs involved. However, there are only two levels in this hierarchy because the goal of our study is to identify the critical HOFs (as the criteria layer) without the HOFs management strategies (as the alternative option layer). Additionally, the questions in the questionnaire are designed for experts to rate the level of influence each factor has on the specified task type. In this way, the consistency ratio is always equal to 0 and thus the expert judgement consistency is guaranteed. Given the lowest level of influence (not-at-all influential) is numerically translated into 1, and the highest level of influence (extremely influential) can be numerically translated into 5, the current paired comparison ratings range from 1 to 5. Thus the ratings above 5 from the nine-point scale in AHP [191] were not used in the formulated comparison matrix in this study. Since the final aim is to obtain the relative importance of these factors, the incomplete adoption of the nine-point scale is believed to cause no concern to the final factors' relative importance ranking. To solve the current group decision problem, the geometric mean of all experts' ratings on one factor for one task type was first computed. It should be noted that the experts were equally weighted. Then these geometric mean results were used to formulate the pair-wise comparison matrices. These decision matrices were subsequently solved to calculate the maximum eigenvalue and the corresponding eigenvector. Consequently, the normalized weight of each factor for each task type, which can be interpreted as the criticality level of these HOFs for each GTT, was obtained.

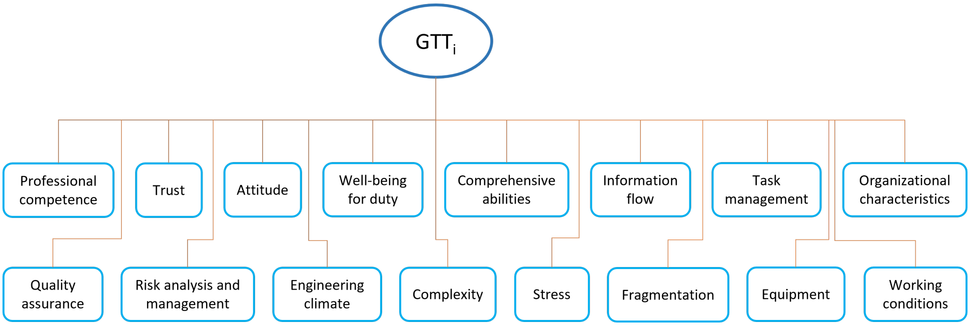

Figure 3.4.: The GTT-HOFs hierarchy.

Table 3.3.: Generic task types in the structural design and construction process.

Task type	Phase	Definition	Task example
Diagnosis based on knowledge/ experience/situation	design/construction	Examine the current situation and make a decision based on professional judgement.	Listing all load combinations
Derive value	design	To find out the desired parameter value from text, a table or a graph; or to obtain necessary information (e.g. material properties) from another party (e.g. architect, material supplier, etc.)	Looking up for the minimum reinforcement percentage from a table.
Consult code	design	To consult the Eurocode for the corresponding design requirements and calculation methods.	determining consequence class based on building function
Mechanical schematization	design	The process of analysing and visualising the supports and forces that apply to the structure using mechanical schemas.	Choosing the appropriate type of supports ; schematizing a load distribution on a structural element
Calculation	design	The process of producing a desired value using the known input value(s) and the mathematical relationships between the input and the desired value	Calculating self-weight; Calculating moment resistance
Comparison/ranking	design/construction	To examine or look for the differences between values or things. To place values or things in an order according to a certain criterion.	Checking minimum or maximum reinforcement percentages; comparing design variants
Interaction with design software	design	To digitally model, visualise or analyse the structure by inputting and adjusting parametric values using computational software.	Drawing floor plans and cross sections
Documenting the design and prepare specifications	design	To record the structural design in documents and write down the detailed requirements and instructions for the structural construction.	Writing a structural design report
Follow instructions and act	construction	Follow the given instructions (by site engineer or supervisor) to perform the task at hand accordingly.	Binding/welding mesh reinforcement; pouring concrete

Task type	Phase	Definition	Task example
Consult drawings and specifications	construction	To obtain and interpret information about how to perform the task in order to realise the design from the design drawings and specifications.	Reading specifications about the type and the amount of reinforcement should be applied
Measurement	construction	To survey the dimensions and features of a physical entity or a space.	Measuring the center-to-center distance between two adjacent reinforcement bars
Interaction with hardware equipment (tools/machine)	construction	Human cooperation with a machine or utilization of a tool.	Configuring a pre-stressing bench (in a factory)
Communication	design/construction	To share information with others via speaking, signals, documents or other forms of communication.	Supplying the structural design to contractor
Checking/inspection	design/construction	To carefully examine the designed or constructed structure in order to determine its accuracy, quality, or condition, or to detect the presence of errors or the lack of required elements.	check by supervisor; structure inspected by specialist before delivery

HOFS' WEIGHTS OVERVIEW

THE factor's normalized weight in each type of task has been calculated from the questionnaire survey data through AHP. The HOFs' weights range from 0.0397 to 0.0997. The arithmetic mean of these factors' weights is 0.0625. A matrix showing the normalized weights overview of each factor for each task type is presented as a heatmap in Figure 3.5.

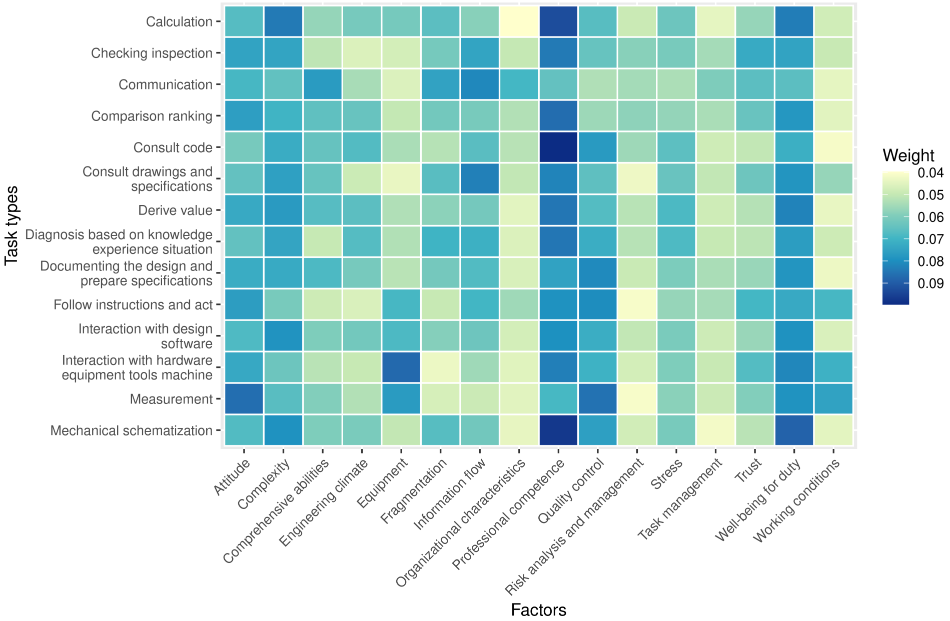

Figure 3.5.: HOFs' weights overview. In this figure, the HOFs are outlined on the x-axis and the GTTs are listed on the y-axis. Therefore, each grid in this heatmap represents one factor in one task type. The color of the grid indicates the factor's weight, which reflects the factor's level of influence on this type of task. The factor with a higher weight is displayed with a darker-colored grid.

It can be seen from Figure 3.5 that *professional competence* holds the highest weight among all HOFs, which indicates its significant influence on human performance in most of the GTTs. It is ranked by the experts as the most influential factor for 8 task types, among which it is considered especially critical for task types of *consulting code, mechanical schematization*, and *calculation*. Apart from *professional competence, well-being for duty* and *complexity* are also recognized as critical factors for the majority of GTTs. Both *well-being for duty* and *complexity* are more influential on *mechanical schematization* and *calculation* type of task. Moreover, *attitude* and *quality assurance* are also selected as critical considerations for many GTTs, especially for *measurement* tasks.

On the other hand, *task management, organizational characteristics, risk analysis and management*, and *working conditions* are rated with lower weights in most GTTs. The reason for this low influence grading might lie in that these factors have a rather general, sometimes abstract nature when evaluating their influence for a specific error condition. In addition, *risk analysis and management* is mostly in the project planning phase rather than the design and construction phase. *Organizational characteristics* is a factor located in the upper stream of the project system, so its impact on task performance is indirect and thus difficult for the experts to make a judgement of its direct contribution to human error occurrence in these GTTs. Intuitively, *task management* should be an important factor with regard to task performance. Its low weight might be the result of the belief that individual errors can better be handled by quality assurance measures rather than management strategies of specific tasks. Another observation is that *working conditions* is considered less influential for GTTs related to structural design but more impactful for construction tasks. The reason behind this finding might be that structural design tasks are indoor office work whose working conditions are more favorable and reliable; whilst construction tasks on site are often outdoor, the working conditions are complicated, and less favorable and controllable.

TASK-BASED HOFS

BASED on the calculated factor weights, considering the arithmetic mean of all factors' weights (0.0625), the factors with a weight above 0.06 (above average) are included as critical factors for a GTT. An overview of the critical HOFs for each GTT is outlined in Figure 3.6. It can be clearly seen that *professional competence*, *attitude*, *well-being for duty*, and *complexity* are identified as critical factors for all 14 GTTs. The other widely recognized influential HOFs are *quality assurance* and *information flow*, which are considered critical in 12 GTTs and 11 GTTs, respectively. However, *organizational characteristic* is only considered influential for the *communication* task type. Moreover, *working conditions* is considered influential on human performance in three GTTs in the construction process. It is worth mentioning that the normalized weights of the factors *task management* and *risk analysis and management* are always below 0.06. Thus these two factors are not included in any GTTs as critical influential factors. Consequently, the critical HOFs set is left with 14 factors.

Another observation lies in the more vulnerable or robust task types. It can be seen from Figure 3.6 that most of the GTTs contain 9 critical HOFs. With 10 influential HOFs, *documenting the design and preparing specifications* in the design process and *consult drawings and specifications* in the construction process are considered more vulnerable with regard to human error proneness since they contain more error-inducing conditions. On the other hand, there are 7 and 8 critical HOFs included in the *measurement* and *interaction with hardware equipment* (tools/machine) task types in the construction process, which make them more robust against human errors.

3.3.3. VALIDATION BY CROSS-COMPARISON AGAINST ACTUAL STRUCTURAL FAILURES

THE Dutch Safety Board (DSB) is an independent body that investigates incidents and safety issues in a broad range of industries in the Netherlands. Until now, it has published accident investigation reports on three high social impact structural failure incidents in the Netherlands, including the temporary structure collapse of Rotterdam

Diagnosis based on knowledge/ experience/ situation	Derive value	Consult code	Mechanical schematization	Calculation	Comparison/ ranking	Interaction with design software	Documenting the design and prepare specifications	Follow instructions and act	Consult drawings and specifications	Measurement	Interaction with hardware equipment (tools/machine)	Communication	Checking/ inspection
Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence	Professional competence
					Trust			Trust	Trust		Trust	Trust	Trust
Attitude	Attitude	Attitude	Attitude	Attitude	Attitude	Attitude	Attitude	Attitude	Attitude	Attitude	Attitude	Attitude	Attitude
Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty	Well-being for duty
	Comprehensive abilities	Comprehensive abilities			Comprehensive abilities		Comprehensive abilities		Comprehensive abilities			Comprehensive abilities	
Information flow	Information flow	Information flow	Information flow		Information flow	Information flow	Information flow	Information flow	Information flow			Information flow	Information flow
												Organizational characteristics	
Quality control	Quality control	Quality control	Quality control	Quality control		Quality control	Quality control	Quality control	Quality control	Quality control	Quality control		Quality control
Engineering climate	Engineering climate	Engineering climate	Engineering climate	Engineering climate	Engineering climate	Engineering climate	Engineering climate						
Complexity	Complexity	Complexity	Complexity	Complexity	Complexity	Complexity	Complexity	Complexity	Complexity	Complexity	Complexity	Complexity	Complexity
Stress	Stress	Stress	Stress	Stress		Stress	Stress		Stress				Stress
Fragmentation			Fragmentation	Fragmentation	Fragmentation		Fragmentation		Fragmentation			Fragmentation	Fragmentation
				Equipment		Equipment		Equipment		Equipment	Equipment		
								Working conditions		Working conditions	Working conditions		

Figure 3.6.: Critical HOFs in each task type.

B-tower in 2010 [198], the stadium roof collapse of FC Twente in 2011 [199], and the Eindhoven parking building floor collapse in 2017 [174]. A review of these reports confirmed the identified critical HOFs in this study and showcased the effectiveness of the proposed HOPE framework in guiding qualitative risk analysis for structural safety management.

ROTTERDAM B-TOWER

On 21 October 2010, the third floor of the Rotterdam B-Tower collapsed during the concrete casting process, resulting in severe injuries to five construction workers. Subsequent investigation of this accident identified the immediate cause as the instability of the temporary scaffolding support structure, which proved incapable of bearing the load of the poured concrete. Furthermore, four key underlying factors contributing to this failure were identified during the investigation. Firstly, the personnel responsible for scaffolding construction lacked adequate training and supervision, aligning with the factors of *professional competence* (training) and *quality assurance* (supervision) within the HOPE framework. Secondly, the scaffolding was inspected prior to the concrete pouring. However, the identified load-bearing capacity issue was not treated properly. This relates to the *risk analysis and management* (follow-up warnings) factor. Thirdly, the involvement of multiple parties and the lack of clearly allocated responsibilities among the parties contributed to the failure, implicating issues related to *fragmentation* and *organizational characteristics* (responsibility division) in the HOPE framework. Lastly, the DSB pointed to the absence of a collective safety approach and insufficient failure risk assessment concerning the supporting structure, which corresponds to the *engineering climate* and *risk analysis and management* factors within the HOPE framework.

FC TWENTE STADIUM

The extended roof structure of the FC Twente stadium collapsed on 7 July 2011, claiming two lives and leaving nine injured. The roof collapse was initiated by the failure of a roof beam. Due to time constraints, the roof construction process was changed from sequential to simultaneous, leading the beam to be overloaded before it was sufficiently stabilized. While the direct failure cause differs, this failure shares some similar underlying causes as the Rotterdam B-Tower case, such as a lack of a joint safety approach between parties, unclear responsibility allocation, and inadequate checking and supervision. Additionally, this case exposed other latent factors. The DSB pointed out that decisions associated with structural safety were not made at the appropriate organizational level. This is associated with the *organizational characteristics* factor in the HOPE framework. Moreover, the investigation disclosed that the parties collaborated based on mutual trust in each other's professional competence without verifying the required prerequisites before conducting the next steps. This trust is based on the past collaboration experience between the parties. This underlying factor is closely linked to the factor of *trust* (reliance on other parties, over-confident about past experience, blind trust without verification) in the HOPE framework. Even though *task management* is not recognized as a critical factor in this survey study, the FC Twente case revealed its importance in structural safety, especially change management as well as task coordination and collaboration, as listed in the HOPE framework.

EINDHOVEN AIRPORT PARKING BUILDING

On 27 May 2017, the Eindhoven Airport parking building partially collapsed. Fortunately, no causality or injury was caused. The DSB recognized the direct cause of this failure as the wrong design decision to rotate the floor slabs in their installation while failing to anticipate or assess the potential consequences of this design change. In the end, the longitudinal shear capacity between prefab and cast-in-situ concrete at the floor slab seams was insufficient. While investigating the underlying conditions that contributed to this failure, the DSB arrived at conclusions that are strikingly similar to the findings of the previous two structural failure investigations. The Eindhoven case was also subject to the lack of a clear responsibility distribution and collective attention towards structural safety. In addition, the DSB identified the existence of a detrimental blame culture in the Dutch construction sector. This is related to the *engineering climate* (safety culture) factor in the HOPE framework. The DSB proposed the elimination of this blame culture to foster a culture of learning from past incidents, thereby facilitating continuous improvement in structural safety. Furthermore, the factors of *fragmentation* and *organizational characteristics* (complex project organization structure) were spotted as contributing underlying conditions to this structural failure. Most importantly, the DSB highlighted the crucial role played by a strong focus on the lowest price in limiting the allocation of adequate resources and attention to risk. This is reflected in the *stress* (budget pressure) factor outlined in the HOPE framework.

3.4. DISCUSSION

The proposed HOPE framework can assist project managers and engineers in gaining an overall vision of the safety of the structure taking into consideration the subtle, often invisible, yet rather critical impacts from the “soft” human and organizational aspects of the project system. This deliberation is largely missing in engineering practice. Therefore, with the help of the HOPE framework, the potential human and managerial hazards that threaten structural safety can be identified proactively. Additionally, the HOPE framework can be used as a tool to deliver structural quality assurance support, with which better allocation of structural safety management resources can be achieved.

With the obtained results from this survey study, the critical HOFs that contribute to the occurrence of human errors in each GTT in the structural design and construction process have been identified through expert judgements for the Dutch construction industry. These results can assist professionals with more specific human error-oriented risk identification and management in practice. Additionally, quality assurance resources should be leaned towards the vulnerable task types when considering their error proneness. Furthermore, these results lay the groundwork for the future development of a tailored HRA method for the construction industry, which is currently absent. HRA has been an essential component of an overall Quantitative Risk Analysis (QRA) for a system in many safety-critical industries such as nuclear, aviation and chemical processing. Therefore, developing an HRA method for the construction industry can complete the long-ignored human contribution puzzle in the structural failure risk analysis. In the following subsection, the identified HOFs are cross-validated with additional sources of study findings.

3.4.1. COMPARE HOFS WITH PSFS

THE identified sub-category HOFs are further compared with the PSFs/PIFs in widely applied HRA methods and studies, including INTENT [200], HRMS [201], CREAM[26], SPAR-H [202], Good Practices for HRA [203], and the PIF hierarchy proposed by Groth and Mosleh [204]. The outcome of this comparison is presented in Table 3.4. The comparative analysis reveals that the majority of the identified sub-category HOFs are covered in these reviewed methods and studies through one or several specific HOFs as outlined in the HOPE framework. This alignment indicates a broad consensus regarding the underlying conditions contributing to human error occurrences across industries.

However, differences between the critical HOFs and PSFs reveal intriguing insights. Specifically, the factors of *trust*, *organizational characteristics*, and *fragmentation* are recognized as critical HOFs in the Dutch construction industry but are not encompassed within any of the reviewed HRA methods and studies. Consequently, these three HOFs can be regarded as unique error-inducing factors specific to the Dutch construction industry, a finding confirmed by the analysis presented in Section 3.3.3, where these factors were frequently identified as critical underlying contributors to structural failures in the Netherlands.

Moreover, the factors of task *management* and *risk analysis and management* do not attain the status of critical HOFs for the Dutch construction industry in this survey, despite their inclusion as latent factors contributing to human errors in many of the reviewed HRA methods and studies. It is important to clarify that their omission from the list of critical HOFs in this study should not be interpreted as implying their negligible influence on human error occurrences. Rather, this outcome suggests that these two factors are relatively less significant when compared to the other 14 HOFs under consideration.

3.4.2. THE APPLICATION OF THE CRITICAL HOFS AND THE HOPE FRAMEWORK

GIVEN the global scope of the reviewed literature, the synthesized HOPE framework is considered to be applicable to the broader construction industry worldwide. However, it is important to note that the critical HOFs, a more selective subset of factors from the HOPE framework and identified through a survey involving experts from the Dutch construction sector, exhibit a greater specificity to the circumstances within the Dutch construction industry. Consequently, these critical HOFs cannot be generalized to the construction industries of other nations without undergoing further investigation and adaptation.

When to consult the HOPE framework and when to focus on the critical HOFs? The choice hinges upon the specific objective of the analysis. When the analysis seeks to provide qualitative insights into various underlying conditions that lead to human errors or pinpoint potential structural failure risks, the comprehensive array of specific HOFs

Table 3.4.: Comparison of the identified HOFs with PSFs from existing HRA methods.

HOFs for Dutch construction	INTENT [200]	HRMS [201]	CREAM [26]	SPAR-H [202]	Good Practices for HRA [203]	PIF hierarchy [204]
Professional competence	Experience, training	Training/ Expertise/ Experience/ Competence	Adequacy of training and experience	Experience/ training	Training/ experience	Knowledge/ experience, skills, familiarity with situation
Trust						
Attitude	Motivation					Bias, morale/ motivation/attitude
Well-being for duty				Fitness for duty	Special fitness needs	Physical/ psychological abilities
Comprehensive abilities					Crew characteristics	Role awareness, attention
Information flow	Communication	Quality of information			Communication	Necessary information, communication
Organizational characteristics						
Quality assurance	Supervision, procedures	Procedures	Availability of procedures	Procedures	Suitability of relevant procedures and administrative controls	Training program, corrective action program, procedures, direct supervision
Engineering climate	Safety culture					Safety culture
Complexity		Task complexity	Number of simultaneous goals	Complexity	Complexity	Task complexity
Stress	Stress, workload	Time	Available time	Stress/stressors, available time	Time availability, workload/time pressure/stress, available staffing/resources	Staffing/scheduling, task/time load, stress

HOFs for Dutch construction	INTENT [200]	HRMS [201]	CREAM [26]	SPAR-H [202]	Good Practices for HRA [203]	PIF hierarchy [204]
Fragmentation						
Equipment	HMI	Quality of interface	Adequacy of MMI and operational support	Ergonomics/ HMI	Availability and clarity of instrumentation, ergonomic quality of Human-System Interface (HSI), accessibility and operability of the equipment, need for special tools	Tools, HIS, system response
Working conditions			Working conditions, time of day		Environment	Workplace adequacy, external environment,
Task management		Task organization	Adequacy of organization, availability of plans, crew collaboration quality	Work process	Team/crew dynamics	Team coordination/ cohesion
Risk analysis and management					Consideration of realistic accident sequence diversions and deviations	Perceived situation, perceived decision

outlined at the bottom hierarchy of the HOPE framework is better suited for this purpose. On the other hand, when the goal is to assess human error likelihood and the associated structural failure risks, then the critical HOFs offer practical risk assessment by focusing only on the factors with significant impacts [205].

3.5. CONCLUSION

A primary contribution of this study lies in the introduction of the HOPE framework, a comprehensive, hierarchical taxonomy of latent factors behind human errors. This framework serves as an insightful guide for practitioners in the construction industry, facilitating improved treatment of human errors and identification of structural failure risks. It encompasses considerations related to human factors, organizational factors, project factors, and environmental factors. Drawing upon this framework, a survey study was conducted to pinpoint critical HOFs that exert significant influence on human error occurrence in structural design and construction tasks. Findings from this survey yield an enhanced understanding of task-specific underlying conditions contributing to human errors within the Dutch construction sector. This knowledge can be instrumental in aiding professionals in implementing more effective quality assurance measures for structural safety. In addition, the critical HOFs identified for each GTT, as shown in Figure 3.6, lay the foundation for the future development of a quantitative HRA method tailored for the Dutch construction industry.

4

QUANTIFYING THE IMPACTS OF HOFS ON STRUCTURAL SAFETY

This study focuses on measuring the influence of critical Human and Organizational Factor (HOF) on human error occurrence in structural design and construction tasks within the context of the Dutch construction industry. The primary research question addressed in this chapter concerns the extent of HOFs' contribution to human error occurrence. To answer this question, the Classical Model for Structured Expert Judgement (CM-SEJ) is employed, enabling experts to provide their judgments on task Human Error Probability (HEP) influenced by different HOFs, which are subsequently aggregated mathematically. SEJ is chosen as a suitable approach due to the limited availability of applicable data in the construction sector. As a result, the impacts of HOFs are quantified as multipliers, representing the ratio between the observed or evaluated task HEP and its baseline value. These multipliers are then compared with corresponding multipliers from existing Human Reliability Analysis methods and studies. The findings reveal that fitness-for-duty, organizational characteristics and fragmentation exhibit the most pronounced negative effects, whereas complexity, attitude and fitness-for-duty demonstrate the most significant positive impacts on task performance. These results offer valuable insights that can be applied to enhance structural safety assurance practices.

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4.1. INTRODUCTION

WHILE structural safety has long been viewed and treated with great importance, it remains a fundamental and critical issue in the construction industry. This is attributed to the often severe consequences in the economic, environmental, and life losses given the occurrence of a structural collapse, even though the possibility of such an event is low. In this regard, continuous research has been performed to assist and guide the engineering practice in the construction industry to prevent structural failures and enhance structural safety. It is acknowledged by numerous studies that the leading cause for structural failures is unintended human error [4, 7, 81, 146], rather than technical problems. Furthermore, researchers have pointed out that human errors occurred in the structural design and construction process are most critical and have thus contributed to the largest number of structural defects and failures [4, 42, 45]. Therefore, it is pivotal to gain a better understanding of how human errors in these two phases come to be so that effective quality assurance measures and safety barriers can be strategically placed to prevent and reduce the occurrence of these errors.

As the understanding of human error grows, a new system approach towards human error has been brought to light [25, 39, 59]. In this new view, human error is no longer considered the cause of the system failure; instead, as a symptom of improper system design, organization, or other troublesome issues embedded inside the system. Considering that, the system should be designed in such a way that human errors do not propagate. Moreover, the system approach views humans as an inseparable part of the socio-technical system. Given that, human error is the outcome that arises from the coherent system environment created by local factors like tools and workplace environment, 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 specific time and space, which will result in errors [39]. For example, inappropriate project planning may cause time stress and consequently trigger people to make errors when there is no sufficient time to finish the task with the requirements being fully met.

As pointed out by Elms [11], in order to handle the current structural safety issues, it is important to be aware of the factors that lead to increased error proneness. Besides, a pioneering insight of “a fundamental change in viewpoint from a narrower technical focus to a broader systemic approach is in need” was concluded. The system context and the underlying factors, which include the human performance related factors such as physical and mental capabilities and limitations of the personnel at the job, and organizational related factors that concern the organizational process and management strategies, which can shape the performance of people at work and potentially lead to the occurrence of human errors and system failures, are defined as the Human and Organizational Factor (HOF). HOFs are the latent conditions in the building project system that play an important role in structural safety [76]. Unlike other safety-critical industries such as nuclear [207, 208], maritime [209], and chemical processing [210, 211], which have well adopted the system human error perspective and researched the error-provoking HOFs, the construction industry remains underdeveloped in this regard. As has been suggested by Melchers [75], human error and human intervention have not been studied extensively in the structural reliability theory within the structural safety field.

The approach that has been widely applied in safety-critical industries for human performance assessment in complex systems or processes is Human Reliability Analysis (HRA). It is a set of methods to evaluate human contributions to system reliability and risk by identifying potential human errors, estimating the likelihood of error occurrence, and assessing system degradation as a consequence of human errors [29]. Embodying a combination of qualitative and quantitative methods, HRA aims to provide a better understanding of the latent conditions and context behind errors. This way, designated proactive strategies can be developed to mitigate errors. Additionally, safety barriers can be placed at the root cause to prevent accidents and failures. As a result, the reliability performance of the systems is enhanced.

An important component of HRA methods is the Performance Shaping Factors (PSFs), which represent the system's personal, situational, and environmental characteristics that can affect human performance in a positive or negative manner [212]. HRA methods qualitatively or quantitatively consider the contribution of PSFs to the human error potential and human influence on the system. In a quantitative HRA, PSFs are quantified to measure their impacts on human performance in tasks to provide Human Error Probability (HEP) estimation. HOFs and PSFs are similar constructs given that they both depict the task context for human performance. Thus in this study, they are treated exchangeably. Several existing studies have identified HOFs that influence structural safety in the construction industry, such as [74, 89, 132, 146]. However, how likely a human error is to occur under the influence of HOFs remains absent knowledge. Therefore, a closer investigation into the effects of HOFs on the task's HEP, and furthermore on the safety of the constructed structures, is in demand for the construction industry.

Thus, this study aims to contribute to quantitatively measuring the impacts of the identified HOFs using collected expert data employing the Classical Model for Structured Expert Judgement (CM-SEJ). CM-SEJ [213] is a mathematical model that validates and aggregates individual uncertainty assessments. The research question to be answered by the current study is:

How much do HOFs contribute to the human error occurrence in structural design and construction tasks?

This is the second step towards the development of an HRA method that provides human performance assessment for structural safety in the construction industry. Following its development, this HRA method could be integrated into structural reliability analysis to provide a more comprehensive failure risk assessment by accounting for the human and organizational contributions in the structural design and construction activities to the reliability of the constructed structures. It will take the largely neglected "soft" personnel and managerial component's influence on structural reliability into account when addressing the current human error issue challenge within structural safety from a broader socio-technical systems perspective. As a first step, HOFs recognised to influence structural safety by existing studies are reviewed [77]. Subsequently, 14 HOFs from the review results have been identified as critical for the Dutch construction industry [186]. These critical HOFs (as shown in Figure 4.2) will be adopted in this study.

In the following part of this paper, Section 4.2 elaborates on how the impacts of HOFs are quantified by applying the SEJ method. Consequently, the expert judgement elicitation results are presented in Section 4.3. Furthermore, the quantified impacts of HOFs are calculated and shown in Section 4.4. In addition, the quantification results are compared with corresponding PSFs from existing HRA methods, as shown in Section 4.5. Section 4.6 justifies the validity of using expert judgement data and SEJ for the purpose of this study, and discusses the choices made for the study design. In the end, Section 4.7 concludes this study.

4.2. METHODOLOGY

4.2.1. MEASURING THE IMPACTS OF HOFS ON HEP

In a quantitative HRA method, the influence of a PSF on the HEP of a given task is manifested by the degree of alteration in the HEP value resulting from the presence of the PSF, in comparison to the HEP value observed in the absence of the PSF, while keeping all the other task-related variables constant. In the context of a given task, a PSF can exert a detrimental influence on human performance, leading to an elevation in the associated HEP. Such a negative impact can be observed when taking the PSF of *experience and training* accounted in the Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method as an illustrative example. If the personnel at the job possess a lower than required experience and training level, this can raise the likelihood of erroneous actions to as high as 10 times [214]. However, it is noteworthy that a PSF may also elicit a positive effect on the HEP. For example, in the SPAR-H method, highly experienced and intensively trained personnel tend to lower the probability of erroneous performance by a factor of two [215].

The HEP is the probability that an error will occur in a given task [29]. It is calculated as the proportion of the number of times an error has occurred in the total number of opportunities for an error to occur [216]. Another important concept in the HRA method is the Nominal Human Error Probability (NHEP), which is the probability that human error will occur without the influence of PSFs [29]. It is the baseline probability of human error occurrence in a task and the benchmark for evaluating the potential impact of PSFs on human performance. Thus in this study, the negative or positive effect of HOF is quantified as a multiplier that increases or decreases the HEP value of a given task based on its baseline NHEP.

Yet such task HEP and NHEP data are scarce [217, 218]. There are a few human error databases available in safety-critical industries [219, 220], especially in the nuclear industry [221–225]. However, such data are missing in the construction industry. Four data sources for evaluating the impacts of HOFs were discussed by Bea [128]. It was pointed out that expert judgment is an important quantitative information source. Besides, Bea [128] argued for expert judgement data having the "primary and rightful place in making quantitative evaluations", particularly when considering the deficiency of available data when evaluating a specific situation. Therefore, expert judgement data are collected using SEJ to quantitatively measure the impacts of HOFs on task HEP in the Dutch construction industry. In this study, the Absolute Probability Judgement (APJ) is performed to acquire a direct estimation of the HEP value of a given task under the influence of each individual HOF under consideration.

4.2.2. THE CLASSICAL MODEL FOR STRUCTURED EXPERT JUDGEMENT

DEVELOPED by Prof.Cooke [213, 226], the Classical Model or Cooke's method for SEJ is a well-known method for aggregating professional judgement from multiple experts for uncertain quantity assessment in situations where objective data are unavailable or incomplete. CM-SEJ provides a mathematically rigorous, performance-based approach for eliciting and combining subjective uncertainty judgements to reach rational consensus under empirical control. As a sensible and practical method to pool expert knowledge to inform decision-making, CM-SEJ has experienced broad applications in various fields such as risk assessment [227] for infrastructures [228] and medical device design [229]; environmental science and climate change [230–232]; policy analysis [233]; and more recently, COVID-19 studies [234].

In CM-SEJ, instead of describing the entire distribution by specifying parameters, experts are expected to estimate several percentiles (e.g., the 5th, 50th and 95th percentile) of the probability distribution for the variable under elicitation. Thus a minimal non-parametric distribution can be derived from their assessments [235]. For empirical validation, two types of questions are elicited: one is the *Calibration questions*, or *Seed questions*, whose true value is known, or will be known post hoc to the SEJ facilitator, but not known to the experts at the time of elicitation; *Target questions* queries the uncertainty quantification of the target variables. Experts' uncertainty assessments are evaluated by two metrics namely statistical accuracy and informativeness. Statistical accuracy indicates how well the true values are captured by experts' uncertainty assessments. Informativeness intuitively denotes how uncertain experts' assessments are. In the CM-SEJ, the statistical accuracy is measured by the calibration score that is calculated by comparing the empirical to the theoretical probability vector of the true values relative to experts' percentile assessments, using the Kullback-Leibler (KL) divergence measure. The informativeness is assessed by an information score computed from the expert's percentile assessments relative to a uniform background measure, using the KL divergence measure. The product of these two scores results in a combined score, that, in turn, leads to normalized weights used to aggregate experts' distributions. The ideal expert is both statistically accurate and informative, which leads to a high combined score and normalized weight. It is worth noting that in the CM-SEJ, the weight is dominated by the calibration score due to the fact that its variation across experts is more significant than that of the information score. Therefore, the input from a statistically highly accurate expert will heavily influence the aggregated result.

The outcome of the CM-SEJ is a weighted average across the elicited probability distribution of the target variable from all contributing experts, called the Decision Maker (DM). Based on the way the expert judgements are aggregated (performance-based or equal-weighted), there are three main types of DM, namely the GLobal weight decision maker (GL), the ITem weight decision maker (IT), and the EQual weight decision maker (EQ). While the GL averages the expert's information scores of all calibration questions, the IT allows for different weights for different questions for one expert based on the information score of each individual question. The EQ equally involves every expert's contribution to the result. Moreover, there exists an optimized DM for GL and IT, termed GLopt and ITopt, which possesses the highest combined score among GL and IT at any possible significance level (α). The significance level is a cut-off threshold to exclude experts whose calibration scores are smaller than the value of α. In CM-SEJ, the significance level is often set as 0.05 (i.e., GL0.05 and IT0.05), which coincides with the classical hypothesis testing p-value. For a comprehensive introduction to the CM-SEJ, the readers are referred to [226, 235, 236].

There are two existing data analysis tools for the CM-SEJ. The earlier software is Excalibur, which was developed by the Delft University of Technology in the 1990s [235]. The latest developed tool is Anduryl [237], an open-access Python application for data processing for the CM-SEJ. In this study, the data analysis is performed using the updated Anduryl version 1.2.1 [238].

4.2.3. DESIGNING AND PERFORMING THE SEJ

THE SEJ was performed by inquiring experts in the Dutch construction industry for the estimated HEP of given tasks. Prior to carrying out SEJ, the human research ethics of this study have been reviewed and approved by the Human Research Ethics Committee (HREC) at the Delft University of Technology. Afterwards, official invitation letters were issued out to 24 experts and 15 responded positively to participation in this study. The questionnaire and the SEJ procedure were tested by two dry runs with two experts. The response from one expert contained wrong data and therefore was discarded. Correct data were filled in and accepted from the other dry run. In the end, the expert judgement data from 14 experts were adopted in the CM-SEJ analysis. Background information of the 14 responding experts is shown in Figure 4.1.

Figure 4.1.: Background information of the 14 experts.

The SEJ was performed individually for each expert. There was no exchange among the experts. Due to the COVID-19 restrictions at the time of this study, all expert elicitation sessions were carried out via scheduled online meetings. Each SEJ session lasted for 1.5 hours, of which the first half an hour provided a project introduction and some background knowledge, as well as showed example questions with answers as training for experts. The SEJ was assisted with a designed online questionnaire for expert uncertainty elicitation. The questionnaire consisted of two sections. The first section contained 10 calibration questions whose answers are known to the researcher of this study from the literature, but not known to the experts. The second section presented the nine target questions that each query the impacts of one factor. An overview of these questions is presented in Table C.1 in Appendix C. The experts could not differentiate between calibration questions and target questions. In this way, the confidence level of an expert is expected to be maintained relatively consistently when providing judgments.

The 14 experts were separated evenly into two panels, with similar distributions of expert backgrounds in each panel. The experts estimated the $5th$, $95th$, and $50th$ percentile of the HEP value of a specified task under the negative or positive influence of a given factor in this order. The target HOFs were distributed to the two panels, with four overlapping factors judged by both panels, as illustrated in Figure 4.2. As a result, the number of questions answered by each expert was reduced from 24 to 19, which greatly eased the mental demand for the experts during the elicitation. In addition, the systematic difference in judgement between the two expert panels can be investigated through the four commonly elicited HOFs. Furthermore, this innovative design enables insights into the robustness of the overall method, which can be observed from the combined scores in Tables D.1, D.2 and D.3. Despite the variability in individual expert performance, as captured by the combined score, the DMs' performance remained stable throughout the two panels and for the commonly elicited HOFs.

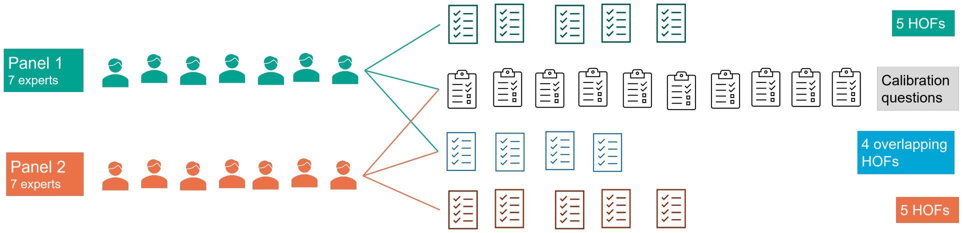
4.3. SEJ RESULTS

THE results of the SEJ study are presented in this section. The performance of experts' assessments is first shown in Subsection 4.3.1. Subsequently, the negative or positive impacts of HOFs on the HEP of a given task are elicited through the target questions and the results are presented and discussed in Subsection 4.3.2.

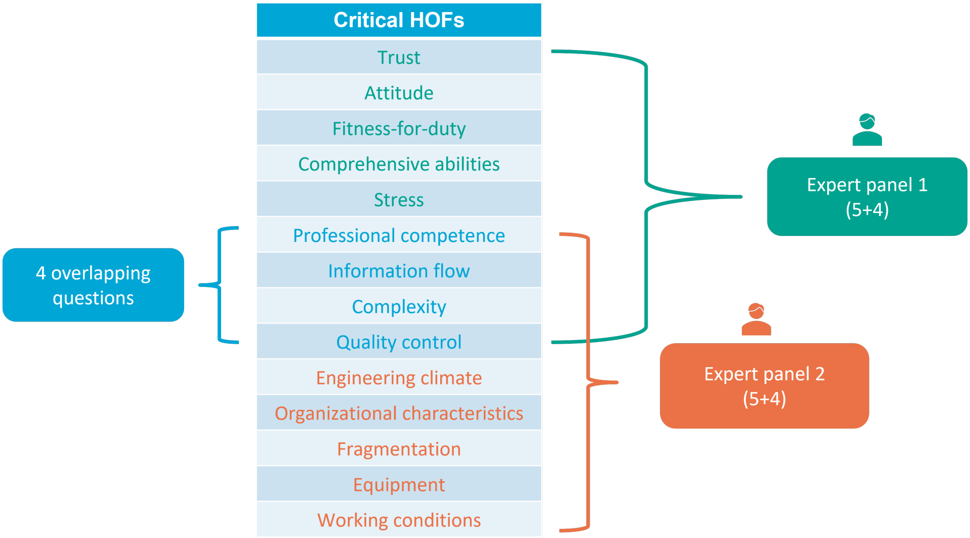
4.3.1. EXPERT PERFORMANCE REVEALED BY THE CALIBRATION QUESTIONS

EXPERTS' AND DECICISON MAKERS' PERFORMANCE SCORES

IN this study, seven types of DMs have been synthesized based on performance-based weight and equal weight, namely: the GL, the optimized GL (GLopt), the GL with a significance level of 0.05 (GL0.05); the IT, the optimized IT (ITopt), the IT with a significance level of 0.05 (IT0.05); and the EQ. The calibration score, information score, combined score, and normalized weight for each expert under the different DMs are calculated for the Panel 1 experts, the Panel 2 experts, and all experts of both panels (Panel 1&2). These results are listed in Table D.1, Table D.2, and Table D.3 respectively in Appendix D. It can be observed that while the calibration scores vary considerably across experts, the discrepancy in information scores among experts is limited to the same order of magnitude. Therefore, the synthesized DM is dominated by input from the expert with a high



(a) Questions assigned to experts.



(b) HOFs assigned to experts.

Figure 4.2.: SEJ design: questions and HOFs assigned to experts. (a) illustrates how the calibration questions and target questions are assigned to the expert panels. (b) shows how the 14 HOFs are distributed to experts for elicitation.

calibration score. In this case, since Expert 3 from Panel 1 (EXP1-3) holds the highest calibration score among all experts, the knowledge contributed by EXP1-3 greatly constitutes the DMs of Panel 1 and Panel 1&2. Similarly, the DMs of Panel 2 mainly comprise inputs from EXP2-2 and EXP2-7. Moreover, two types of information scores are calculated to monitor the expert's confidence level variation. One is computed based on the informativeness of the answers provided to the calibration questions, referred to as *Information score-realization*; the other type is calculated based on the answers to all questions, called *Information score-total*. Since the experts do not know whether they are responding to the calibration questions or the target questions, the difference between these two information scores is expected to be slim. Except for expert 2 from Panel 2 (EXP2-2), the values of these two types of information scores are similar, indicating a consistent confidence level of most experts in judging both the calibration variables and the target variables. EXP2-2 exhibits the lowest certainty in answers to the calibration questions, but a noticeably higher confidence level in providing judgements to target questions.

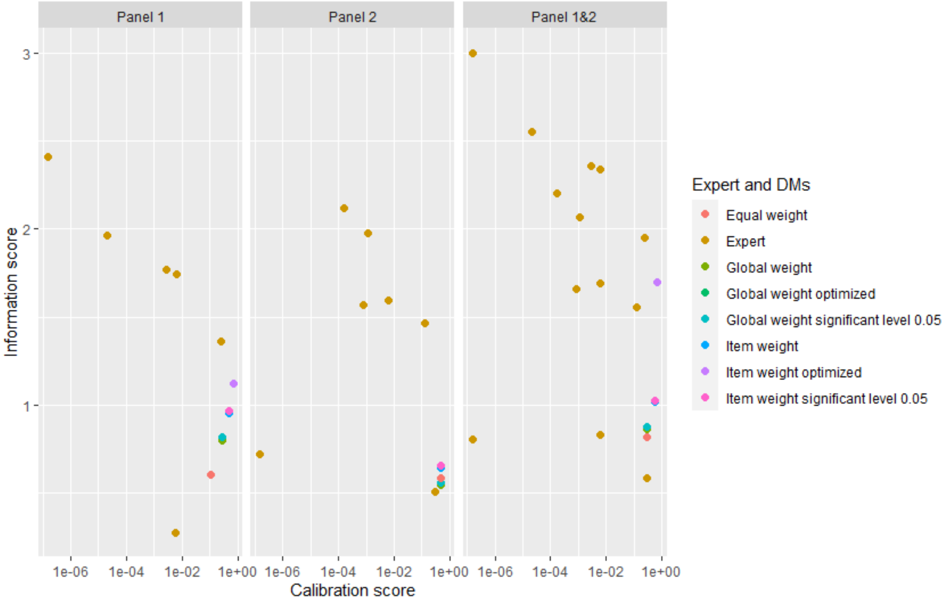


Figure 4.3.: The calibration score and information score of each expert and DM.

In addition, an overview of the calibration score and the information score of each expert and DM from each panel is shown in Figure 4.3. It is evident that there is significant variation in the uncertainty quantification performance of the experts within each panel, both in terms of statistical accuracy and informativeness. Meanwhile, the calibration scores of the DMs exhibit a low level of variance and consistently surpass the scores of individual experts, with the exception of EXP1-3, who attains the highest calibration score among all the experts and non-optimized DMs.

An important observation from these scores is that the ITopt consistently emerges as the best performing DM across all panels. This is supported mathematically, as the DM with the highest combined score is considered the optimal DM. Consequently, the optimized weight DM consistently achieves the highest combined score and is therefore deemed the best DM. Alongside the ITopt, the IT0.05 and IT also exhibit strong performance according to the scores. Generally, the item weight DM tends to outperform the global weight DM and equal weight DM. This can be attributed to the item weight DM's feature to highlight the increased informativeness while preserving the same level of statistical accuracy. Therefore, in the following discourse, the IT, ITopt and IT0.05 will be presented and discussed as the DM for all variables.

ELICITED HUMAN ERROR PROBABILITY VS. REALIZATION

THE "true value", also referred to as the realization of a calibration question is obtained from the survey studies conducted in the Australian construction industry between 1982 to 1993 [5, 55, 115]. It is compared with the elicited HEP estimates from this SEJ study for the same question as an empirical measurement for expert performance. The HEP results of the three item weight DMs from the three panels for the 10 calibration questions are depicted in Fig 4.4. The results indicated that except for the ITopt from Panel 1 and Panel 1&2 of questions *Q1-9* and *Q1-10*, all the other DMs of the three expert panels were able to capture the realization for every calibration question within the given 90% confidence interval. Except *Q1-4*, the medians of the DMs were found to be relatively close to the realization, indicating the high accuracy performance of the synthesized DMs. It is noteworthy that the experts in Panel 1 provided assessments which resulted in informative and low uncertainty intervals, whereas the experts in Panel 2 showed a lower level of agreement. Overall, when considering both statistical accuracy and informativeness, the best performance was observed in Panels 1&2, which includes responses from all 14 experts to the calibration questions. Furthermore, Figure D.7 in Appendix D shows the performance of each expert as well as the synthesized DMs in response to each calibration question.

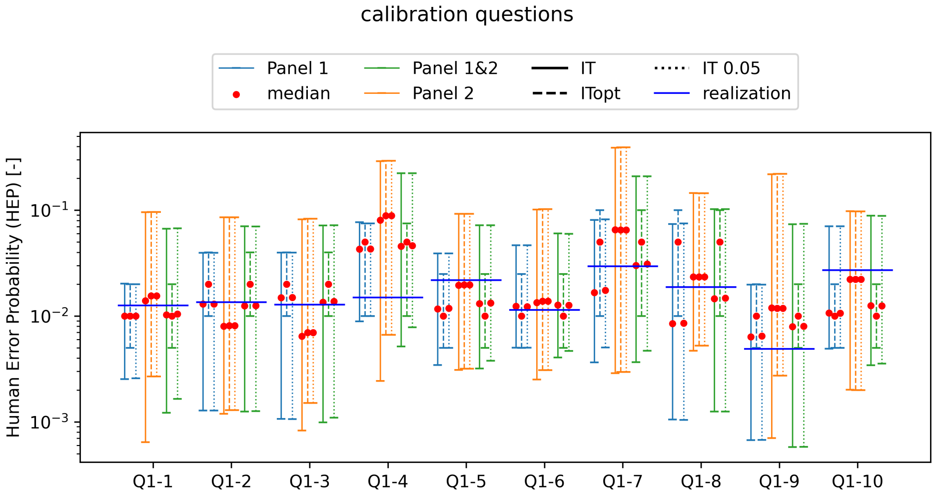


Figure 4.4.: Comparison between the elicited HEP and the realization of the calibration questions. The HEP estimates range from the 5th percentile (bottom) to the 95th percentile (top), with the median indicated as a red dot. The HEP estimates were sketched using the logarithmic scale.

4.3.2. HOFS' INFLUENCE REVEALED BY THE TARGET QUESTIONS

THIS subsection presents the outcomes of the target questions that measure the impact of critical HOFs on human performance. The target question evaluates the HEP under the influence of a specified factor, using the NHEP value as a reference point. As an initial estimation, considering the feasibility of this SEJ study, a HOF's influence on various tasks in structural design and construction, such as defining load combinations and placing rebars according to design specifications, is assumed to be the same. Thus the impacts of each HOF are measured against a specified checking task whose NHEP is known from [239] as 1.1×10^{-3}. In addition, the HOFs are presumed to have both negative and positive effects on human performance, resulting in an increase or decrease in the HEP from the baseline NHEP, respectively. For instance, when poor communication, a lack of necessary information, or information overload is present in the task, the *information flow* factor has a negative impact on task performance. Conversely, when timely, effective communication and clear, high-quality information are available, the *information flow* factor poses a positive impact on task performance. The specific meaning of the negative or positive impact of each factor on task performance can be found in the descriptions of the surveyed target questions (TQ) as listed in Table C.1. The target question results have been obtained by aggregating expert judgments based on the CM-SEJ using item-based weights.

NEGATIVE IMPACTS

WHEN a task is performed under the negative impact of a critical HOF, the probability of human error occurrence increases, compared to the NHEP. Figure 4.5 illustrates the three item weight DMs of the estimated HEP under the negative effect of the 10 HOFs that were judged by Panel 1 and Panel 2 experts separately. As can be seen from the median values in Figure 4.5, the HOFs that have a stronger negative impact on task HEP are *fitness-for-duty*, *organizational characteristics*, and *fragmentation*. In contrast, *working conditions* and *comprehensive abilities* are believed to have the least negative effect on task performance. It can be seen that except for the ITopt of factor *attitude*, the results are consistent among the three DMs in terms of median HEP estimates and the quantified uncertainty. The aggregated median HEP estimates of these 10 HOFs are all located within the range from 5×10^{-3} to 3×10^{-2}. The noticeably larger HEP for *attitude* under the ITopt is due to the inclusion of a single expert's input (EXP1-3) in the ITopt. In terms of the confidence intervals, these 10 HOFs vary considerably. In general, the HOFs assessed by Panel 2 experts exhibit wider ranges than HOFs assessed by Panel 1, except for the factor *attitude* which has the widest uncertainty span under IT and IT0.05. This may be attributed to that the experts find it challenging to judge people's attitudes or to relate an erroneous action to a bad working attitude. On the other hand, the lowest uncertainty can be observed from the factor *comprehensive abilities*, which the experts confidently consider posing a limited negative impact on task performance. While the $5th$ percentiles of the DMs for these 10 HOFs are comparable, the $95th$ percentile HEPs show greater variance.

The corresponding DMs for the negative effect of the four HOFs evaluated by all 14 experts are presented in Figure 4.6. It appears that the factor *complexity* has the highest negative impact among these four HOFs on task HEP when taking all experts' judgements into consideration (DMs of Panel 1&2). Moreover, in the absence of minimum acceptable *professional competence* ($95th$ percentile), errors are considered almost certainly will occur. Similar consistent results are noticeable among these four factors: the

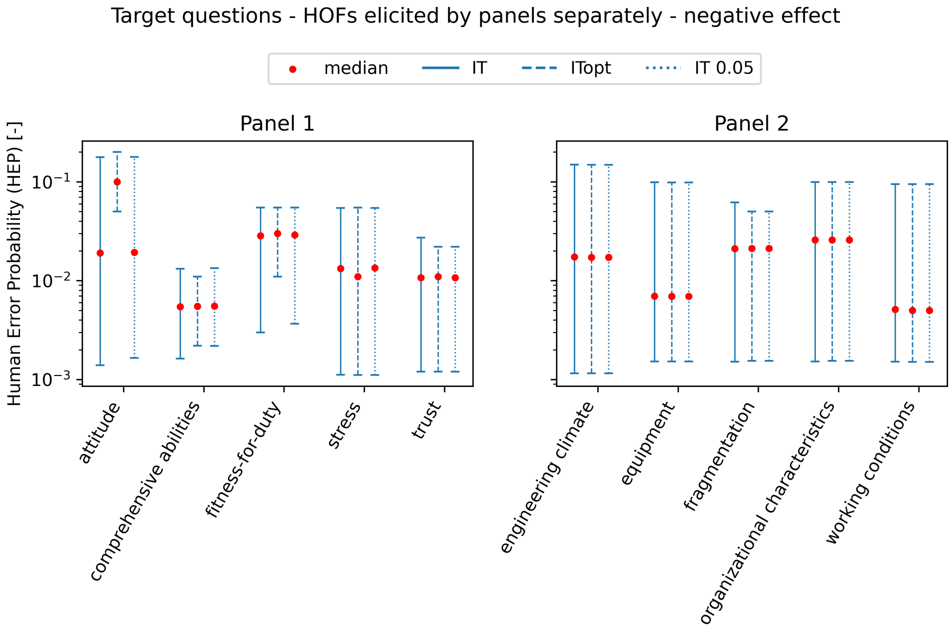


Figure 4.5.: Three DMs for the HEP estimation under the 10 HOFs' negative effects judged separately by expert Panel 1 and Panel 2. The 90% confidence interval of the IT, ITopt and IT0.05 are illustrated as vertical lines in log scale and the median value is denoted as a red dot.

median HEP estimates for these HOFs are close to 1×10^{-2}, except for the ITopt of factor *professional competence* elicited from Panel 1 and Panel 1&2. This high median HEP is largely contributed by EXP1-3 who holds the highest weight in these two panels and provided a large HEP estimation for *professional competence*. Consequently, there is a noticeable disagreement regarding the negative effects of *professional competence* between Panel 1 experts and Panel 2 experts.

POSITIVE IMPACTS

THE critical HOFs can also pose a positive impact on the task carrier to enhance performance, leading to a decreased task HEP from the NHEP. The positive effects of HOFs have been inquired through this SEJ study and the results are presented in Figure 4.7 and Figure 4.8 respectively.

In Figure 4.7, the median HEP estimates indicate that *attitude* and *fitness-for-duty* can influence the task HEP positively to a large extent, whilst the aggregated assessments of the five HOFs by Panel 2 indicate a mildly positive impact on task performance. What is worth mentioning is the absence in value for the ITopt of factor *stress*. This is due to the fact that the ITopt in Panel 1 only includes the input from EXP1-3, who considers *stress* to have no positive influence on task performance and purposely left this question

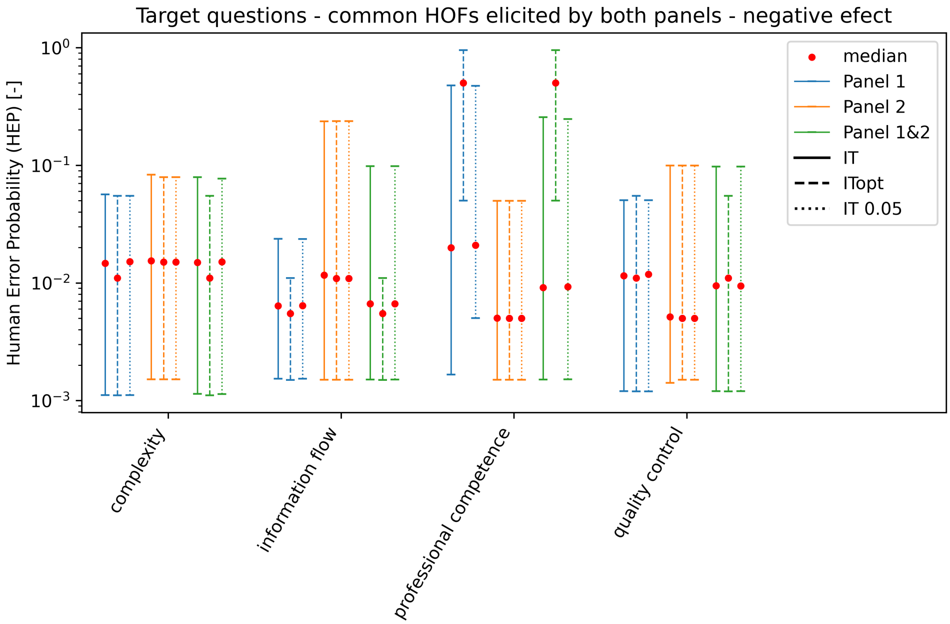


Figure 4.6.: Three DMs for the HEP estimation under the 4 common HOFs' negative effects judged by both expert panels. The 90% confidence interval of the IT, ITopt and IT0.05 are aggregated for each expert panel and illustrated in differently coloured log scale lines. The median of these DMs is denoted as a red dot.

out. Additionally, note that while the DMs of the factor *equipment* exhibit the largest uncertainty, the HOFs in Panel 1 show higher uncertainty when compared with the other factors in Panel 2. This indicates that the Panel 2 experts believe that providing ideal tools and equipment for a given task can potentially lead to the largest reduction in HEP (to the $5th$ percentile) under extreme conditions. Finally, it is observed from Figure 4.7 that there is less variation among the DMs' median HEP estimates for HOFs judged by Panel 2 than that of factors assessed by Panel 1. This results from the experts in Panel 2 receiving comparable weight allocation across various DMs.

The results for the positive effects of the four commonly elicited HOFs are demonstrated in Figure 4.8. It can be seen from the DMs' median HEPs in Figure 4.8 that *complexity* holds the highest positive impact on task performance, whilst the other three factors exhibit comparable positive effects. In addition, there appears to be a clear distinction in the median HEP estimates between the synthesized results from Panel 1 and Panel 2 for each factor. However, these medians all fall within the same order of magnitude at around 7×10^{-4}. Another observation is that the DMs' median estimates of Panel 1&2 are predominantly influenced by the inputs from the Panel 2 experts. Moreover, the 90% confidence interval of DMs from Panel 1 is evidently larger than that of Panel 2, showing less informativeness.

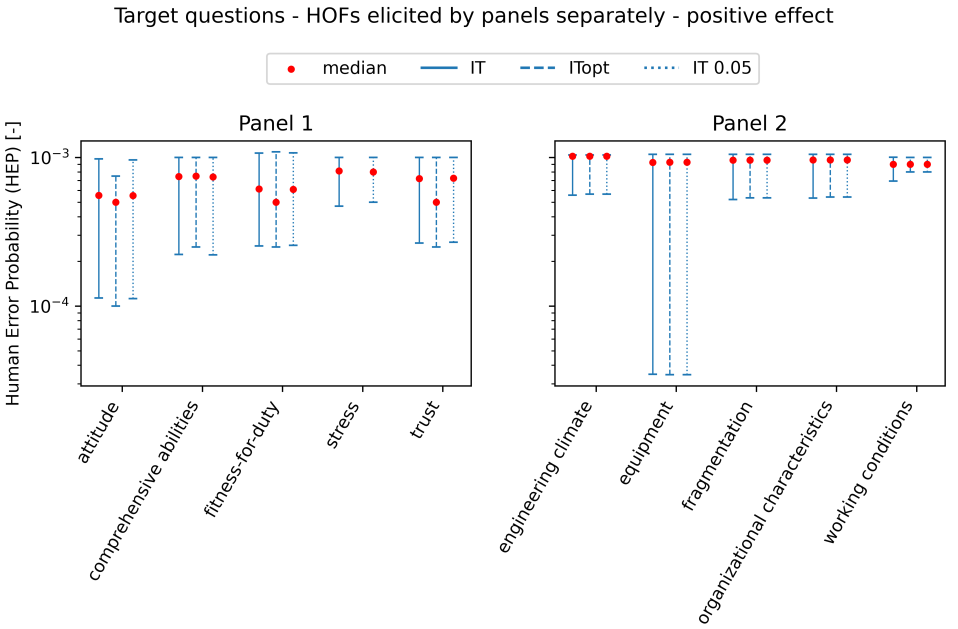


Figure 4.7.: Three DMs for the HEP estimation under the 10 HOFs' positive effects judged separately by expert Panel 1 and Panel 2. The DMs of these 10 HOFs are depicted in vertical log scale lines with the median value marked as a red dot. The intervals denote the 5th and 95th percentiles of DMs' distribution.

In general, the positive effects of critical HOFs on task HEP appear to be less significant compared to their negative effects. While under HOFs' negative impacts, the task HEP can rise up to 25 times the NHEP, it can only reduce to half of the NHEP under the HOFs' positive effects. Therefore, the results of this SEJ study suggest that great efforts are required to tackle the negative impacts of the HOFs on task performance.

Given the aforementioned findings and discussions, as well as the performance of different DMs, the outcomes obtained through the IT are accepted as the results for the CM-SEJ. Consequently, the Cumulative Distribution Function (CDF) for the experts' estimates and the aggregated IT under the negative or positive impact of each HOF are presented in Figure D.4, Figure D.5 and Figure D.6 in Appendix D. These results are further employed to quantify the impacts of each HOF in the following section.

4.4. QUANTIFIED HOFS FOR THE CONSTRUCTION INDUSTRY

BASED on the elicited HEP under the negative and positive effects of the 14 critical HOFs through APJ in this SEJ study and the NHEP of the given task, the negative or positive impacts of HOFs on human error occurrence can be measured via a multiplier quantifying the change in the HEP value relative to the baseline NHEP. Therefore, the multiplier (denoted as M) for each factor can be obtained from the following calculation:

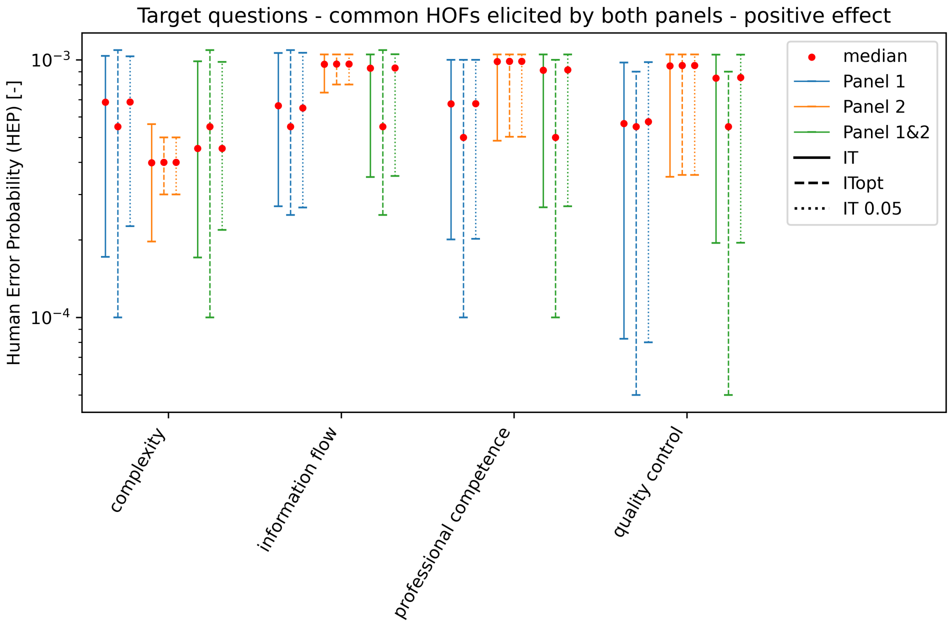


Figure 4.8.: Three DMs for the HEP estimation under the 4 common HOFs' positive effects judged by both expert panels. The 90% confidence interval of the IT, ITopt and IT0.05 are aggregated for each expert panel and illustrated in differently coloured log scale lines. The median of these DMs is denoted as a red dot.

$$M = \frac{HEP_{task}}{NHEP_{task}} \tag{4.1}$$

In this SEJ study, all HOFs impacts are measured against the same checking task, whose NHEP is 1.1×10^{-3} [239]. Thus, the multipliers for both the negative and the positive effect of each factor, denoted as M_{neg} and M_{pos}, can be derived from the synthesized DM (IT). As a result, the best estimates for M_{neg} and M_{pos}, along with their uncertainties are summarized in Table 4.1. These multipliers reveal that there are greater variations in both the best estimates (M median) and the uncertainty (90% confidence interval) for the M_{neg} than the M_{pos}. Moreover, it is interesting to note that *fitness-for-duty* is considered to have the highest negative effect with very low uncertainty, while the experts express strong confidence in the limited negative impact of *comprehensive abilities* on task performance. Furthermore, it is evident that *complexity* has the most substantial positive impact on task HEP, whereas *engineering climate* is regarded as providing minimal positive assistance in diminishing the task HEP.

In this way, the HOFs' impacts on human error occurrence are quantified for the construction industry based on the SEJ from Dutch experts. These multipliers provide essential parametric references for task HEP estimation considering the different influences of HOFs, which enables future human reliability assessment for the construction industry.

Table 4.1.: The Multipliers of HOFs according to the item weight decision maker (IT). This table shows the $5th$, $50th$ and $95th$ percentiles of the negative effect multiplier's (M_{neg}) distribution and the positive effect multiplier's (M_{neg}) distribution for each HOF.

HOFs	**Elicited by**	M_{neg}			M_{pos}		
		5th	50th	95th	5th	50th	95th
Professional competence	Panel 1&2	1.37	8.29	232.55	0.24	0.83	0.95
Information flow	Panel 1&2	1.37	6.05	89.24	0.32	0.84	0.95
Complexity	Panel 1&2	1.04	13.55	72.12	0.16	0.41	0.90
Quality control	Panel 1&2	1.09	8.59	88.61	0.18	0.77	0.95
Stress	Panel 1	1.01	12.05	49.53	0.43	0.74	0.91
Fitness-for-duty	Panel 1	2.73	25.92	49.98	0.23	0.56	0.97
Attitude	Panel 1	1.27	17.32	161.73	0.10	0.51	0.89
Trust	Panel 1	1.09	9.76	24.77	0.24	0.66	0.91
Comprehensive abilities	Panel 1	1.48	4.96	12.03	0.20	0.68	0.91
Engineering climate	Panel 2	1.05	15.80	135.91	0.51	0.93	0.95
Fragmentation	Panel 2	1.38	19.16	56.27	0.47	0.87	0.95
Organizational characteristics	Panel 2	1.38	23.50	90.43	0.49	0.87	0.95
Equipment	Panel 2	1.38	6.36	89.81	0.03	0.84	0.95
Working conditions	Panel 2	1.38	4.65	86.09	0.63	0.82	0.91

4.5. Comparison of the results

The elicited multipliers for HOFs were further compared with multipliers of corresponding PSFs from existing HRA methods and empirical studies. A total of six widely acknowledged HRA methods [26, 29, 137, 200, 202, 240] and six PSFs' effects and multipliers studies, which were based on record or simulator data and expert judgment [241–246], have been reviewed. The multiplier value intervals, ranging from positive effects ($M < 1$) to negative effects ($M > 1$), are summarized in Table 2. When a reviewed method or study does not consider the positive effects of the PSFs, the multiplier range begins from the nominal condition ($M = 1$). In addition, the last column of Table 2 lists the medians of the elicited multipliers for critical HOFs in the construction industry, as derived from this SEJ study. The range is formed from the median values of M_{pos} to that of M_{neg} for each factor from Table 1.

One observation from this review is a lack of agreement among the multipliers of the PSFs used in the 12 existing HRA methods and studies. The main point of difference lies in the M_{neg} of each PSF. As a result, it appears that no consensus has been reached regarding the impacts of PSFs in HRA studies. There are several possible explanations for this variation. One reason is that some of these methods are related to one another or have evolved from one another. Consequently, the multipliers tend to be similar in these related studies. For example, *Improved SPAR-H* [242] and *Petro-HRA* [240] exhibit similar multipliers because they are related to each other. However, most of these HRA methods and studies are independent of each other and thus have varied multipliers for PSFs. Another reason for the difference in PSFs' multipliers is the distinct industrial background within which the method was developed. For instance, the multipliers differ largely between *HEART* [137] and *Marine-specific EPC* [241] due to the different industries for which these PSFs are measured and applied, even though the *Marine-specific EPC* was developed based on *HEART*. In addition, the same PSF might be interpreted differently [247] or be perceived with a distinct level of impact among different industries. Moreover, the contexts of applicability are different for these methods and studies. The impacts of the PSFs on human performance are measured against diverse types of tasks that involve various forms and levels of cognition, different system conditions (e.g., emergency operations), and distinct error modes (error of omission or error of commission) in different methods. For example, *INTENT* [200] was developed for decision-based HEP assessment, whilst most of the other methods and studies target operational errors in tasks. Finally, the data sources for obtaining the multipliers are different. While some studies derive the multiplier values from actual human performance records or simulator data, such as the three Korean nuclear studies [243–245], the multipliers from many studies are elicited from expert knowledge judgement, such as the *Improved SPAR-H* [242] and the Chinese nuclear study [246].

In conclusion, the multiplier assigned to the same PSF tends to vary between different HRA methods. The same is true for the present study, where the multipliers of HOFs differ from those found in the reviewed methods and studies. However, certain consistency can be observed in the multiplier ranges of some HOFs elicited in this study and those of the existing HRA methods and studies. These similarities are especially notable in factors such as *professional competence*, *comprehensive abilities*, *quality control*, *complexity*, *stress*, and *equipment*. On the other hand, there are noticeable differences in the multipliers assigned to the factors of *attitude*, *fitness-for-duty*, *organizational characteristics*, and *fragmentation* in construction, when compared to the reviewed methods and studies.

The dissimilar multipliers for *attitude* and *organizational characteristics* in task HEP estimations may stem from their abstract nature and lack of concrete reference points, making it difficult for experts to relate tangible experiences to these two factors. Similarly, the factor of *trust* lacks a multiplier reference in the reviewed methods and studies. It seems that the estimated large negative effect of *fragmentation* reflects the true belief of the experts from the construction industry. *Fragmentation*, though not commonly recognized as a PSF in existing HRA methods, is acknowledged as a crucial factor for causing structural failures in the construction industry [146]. The observed high M_{neg} in the factor of *fitness-for-duty* could be attributed to experts' belief that physical and mental health significantly impact the occurrence of errors. Alternatively, experts may have confused the intention of this factor with the "suitability for task" of personnel, which coincide with *professional competence* and has a relatively high negative effect.

The comparison between the multiplier ranges of HOFs in this study with those of the reviewed methods and studies shows reasonably consistent results on the measured effects of the HOFs on human performance in the construction industry with the multipliers of the PSFs from existing HRA methods and studies. As a side result, this finding provides empirical evidence for the viability of using HRA methods or data from a different field for human reliability assessment in the construction industry.

Table 4.2.: Comparison of the HOFs' multipliers with PSFs' multipliers of existing HRA methods and studies.

	Professional competence	*Trust*	*Attitude*	*Fitness-for-duty*	*Comprehensive abilities*	*Information flow*	*Organizational characteristics*
HEART [137]	2-17	-	1.2-1.4	1.02-1.8	1-6	1.2-10	1-1.6
Marine EPC [241]	2.88-17	-	2.56-3	1.64-10.3	1-5.29	2.64-14.45	1-1.22
CREAM [26]	0.5-5	-	-		0.5-5	-	0.8-2
THERP [29]	1-2	-	-	-	-	-	-
SPAR-H [202]	0.5-10	-	-	1-5	-	0.5-5	-
Impr. SPAR-H [242]	0.1-50	-	-	-	0.5-50	-	-
INTENT [200]	7-12	-	6-9	-	-	5-13	-
Petro-HRA [240]	0.1-50	-	-	-	0.5-50	-	-
Kor. nucl.-I [243]	1-2.57	-	-	-	-	-	-
Kor. nucl.-II [244]	1-45.4	-	-	-	-	1-12.4	-
Kor. nucl.-III [245]	-	-	-	-	-	-	-
China nucl. [246]	0.5-10	-	-	1-4	1-5	1-5	-
this study	0.83-8.29	0.66-9.76	0.51-17.32	0.56-25.92	0.68-4.96	0.84-6.05	0.87-23.5

continued	*Quality control*	*Engineering climate*	*Complexity*	*Stress*	*Fragmentation*	*Equipment*	*Working conditions*
HEART [137]	1.4-5	2-2.5	1.05-6	1.3-11	1.03-1.06	1.4-1.6	1-1.15
Marine EPC [241]	2.74-12.55	2.15-3.62	2.63-14.45	1.59-14.01	3.85-4.14	4.35-5.69	1-9.9
CREAM [26]	0.5-5	-	-	0.5-5	1-5	0.5-5	0.8-2
THERP [29]	1-50	-	0.1-5	0.01-10[a]	-	1-50	
SPAR-H [202]	0.5-50	0.5-5	0.1-5	0.01-10 [a]	-	0.5-50	-
Impr. SPAR-H [242]	0.5-50	1-50	0.1-50	0.1-50[a]	-	0.5-50[a]	1-10[a]
INTENT [200]	6-13	5-23	-	6-13	-	6-14	-
Petro-HRA [240]	0.5-50	0.5-50	0.1-50	0.1-50[a]	-	0.5-50[a]	1-10[a]
Kor. nucl.-I [243]	0.58-5.53	-	-	0.34-1.24	-	0.39-1	-
Kor. nucl.-II [244]	1-6.3	-	1-36.7	1-24	-	-	-
Kor. nucl.-III [245]	3-15	-	1.5-10	2-7.5	-	-	-
China nucl. [246]	1-10	-	1-20	0.5-12	1-5	1-10	1-5
this study	0.77-8.59	0.93-15.8	0.41-13.55	0.74-12.05	0.87-19.16	0.84-6.36	0.82-4.65

[a] The multiplier value is ∞ under extreme condition level (e.g., extremely high negative effect, unfit, inadequate time), leading to the HEP value equal to 1.

[b] The value 0.89 in this range is excluded according to [241].

4.6. DISCUSSION

4.6.1. THE VALIDITY OF EXPERT JUDGEMENT DATA AS SCIENTIFIC DATA

THE ideal human reliability data should be derived from valid experience, records, or robust experiments [248]. However, such data are, in most cases, not available. The reasons for the difficulty of collecting and generating human error data have been detailed in [249]. The scarcity of relevant data for human reliability quantification for the task of interest remains the most significant issue in the human reliability analysis field, as pointed out by Swain [250]. This is particularly the case for the construction industry as a result of the lack of attention and development of HRA in this industry.

The primary source of uncertainty in all HRA methods is the less-than-adequate data, and it appears to be a challenge that cannot be readily overcome in the immediate future [251]. Even in situations where former data are available, it is questionable if and to what extent such data remain applicable in the context of the specific problem at hand [128, 248, 252]. Thus, in many circumstances, the only way to proceed with human reliability quantification lies in expert judgement, which is the data source for most, if not all, quantitative HRA methods [248].

Therefore, expert judgement data are used in this study due to the lack of proper HEP data in the construction industry. A structured protocol was chosen to elicit, objectively evaluate and aggregate expert data. Within the CM-SEJ, expert knowledge is treated as "subjective but scientific" [253]. Cooke [213] proposed four principles (*Scrutability/accountability, Empirical control, Neutrality, Fairness*) to be satisfied by a structured elicitation method. The elicited expert judgement data from an SEJ meet all these requirements and thus can be treated as scientific data [254].

4.6.2. THE CONCERNS AND PROVEN BENEFITS OF THE CLASSICAL METHOD FOR SEJ

THE CM-SEJ is employed to elicit and aggregate expert judgement with uncertainty using performance-based weight in the current study. The standout features of the CM-SEJ include empirical control with calibration variables and performance-based weighting for combining expert opinions. Certain critiques and concerns have been raised related to these features of the CM-SEJ. Regarding the effectiveness of calibration questions as empirical control, Hanea et al. [255] believed that it is necessary to assess expert performance in uncertainty quantification and the quality of their judgements in order to treat expert data as scientific data. However, critics question the consistency as a property in expert performance between judging the calibration variables and the target variables [254]. That is, can the expert's performance in answering the target questions be reflected by the performance in answering the calibration questions? Clemen [256] commented that "the decision makers should care about a method's performance on the seed variables only to the extent that it accurately reflects performance on the variables of interest". Hanea et al. [255] suggest from their observations that "prior performance predicts future performance". Furthermore, applying the *Random Expert Hypothesis* to simulate data from 49 SEJ studies, Cooke et al. [257] validated that the variations in expert performance reflect the expert's enduring characteristics rather than random influences during elicitation. This clears the concern that the expert's performance is purely arbitrary and is not a persistent property that propagates beyond the calibration questions.

Another important discussion concerns whether performance-based weighting is better than equal weighting in expert judgement aggregation. In fact, the performance-based weighting of the CM-SEJ is found to outperform equal weighting for most SEJ studies using in-sample data from the TU Delft database [254]. Bolger and Rowe [258] heated up this debate by arguing that when aggregating expert opinions, unequal weighting does not produce any obvious advantages over equal weighting. They reason that on the one hand, it is challenging to develop valid measurements for expert knowledge as the foundation for discriminated weights; on the other hand, the extra cost associated with CM-SEJ outweighs the gained benefits, if any. In response to these comments, Cooke [259] justified the strength of CM-SEJ by highlighting that while the mean tends to be of no significant difference, the performance-based weighting leads to improved informativeness in the aggregated result compared with equal weighting. Consequently, cross validation of the CM-SEJ using data collected from continuously performed SEJ studies in various domains has been carried out using both in-sample and out-of-sample validation. These cross validations concluded the performance superiority of the performance-based weight over equal weight [260, 261]. In terms of point prediction, it is found that the aggregated median using performance-based weight outperforms that using equal weight regarding forecast accuracy [257]. Moreover, Marti et al. [262] tested the *Random Expert Hypothesis* with data of 44 post-2006 SEJ studies and verified that the statistical accuracy of real experts is considerably better than simulated random experts. This finding supports the argument that expertise is a persistent property of an expert. Therefore, it is reasonable that experts exhibiting different performances in providing professional judgement should be discriminated against with unequal weights instead of being equally weighted regardless of their distinct performance.

Overall, the CM-SEJ has been validated over the years in terms of various performance measures. Besides, data from numerous studies revealed an overall superior performance of this method. According to Aspinall [263], the CM-SEJ is "the most effective when data are sparse, unreliable or unobtainable", which is the case for the current study. Additionally, the measured impacts of HOFs from this SEJ study have been compared with the PSF multipliers of existing HRA methods and studies, see Section 4.5. The results, in return, justified the soundness of the CM-SEJ as the chosen method for this research.

4.6.3. THE ART OF SELECTING EXPERTS AND CALIBRATION VARIABLES

THERE is no set definition of what constitutes an expert. However, the general expectation of an expert involves mastering abundant knowledge and experience in one's domain expertise. In expert elicitation studies, an expert can simply be "the person whose knowledge we wish to elicit", or more sophisticated, "persons to whom society and/or his peers attribute special knowledge about the matters being elicited" [264]. In this SEJ study, 11 out of 14 respondents have more than 10 years of working experience in the Dutch construction industry, as shown in Figure 4.1. The remaining three experts comprised a structural engineer holding a doctorate degree and two professionals whose master theses specifically researched the human error issue in the Dutch construction industry. Consequently, despite having less practical expertise, these three were regarded as experts for the purpose of this study due to their extensive expertise on this subject matter. In terms of the number of experts needed for an adequate answer to the target question, Aspinall [263] suggested 8-15 based on his experience, claiming that the results change in an insignificant way with an increased number of experts. Moreover, Quigley et al. [236] pointed out that the common practice with SEJ involves 5-20 experts. In this study, seven experts in each panel elicited five unique HOFs and together 14 experts elicited the four overlapping HOFs and calibration variables. Thus, the number of experts in this SEJ study meets the recommended practice.

The calibration variables are particularly critical to the CM-SEJ as they form the basis for calibrating the model that is used to aggregate experts' uncertainty assessments. It is essential for the calibration variables to share sufficient similarity with and exhibit a direct link to the target variables, so as to activate similar judgment heuristics [236]. Quigley et al. [236] emphasized that "finding good seed variables is an art". The calibration questions in this study query the HEP of several commonly practised tasks in the structural design and construction process. Whilst the target questions inquire about the HEP of one specific task under the (negative or positive) influence of different HOFs. The true values of the calibration variables are obtained from the available studies [5, 55, 115], which makes the calibration variables least desirable since they are both "adjacent" and "retrodiction" [235]. However, the ideal "domain-prediction" type of calibration variable rarely exists in the CM-SEJ practice [236]. Despite the potential doubts regarding the suitability of these data considering their age and region of origin, they still stand as the best possible calibration variables relevant to the current target questions the authors can find.

There is no definitive number of calibration variables for adequate application of the CM-SEJ. While Quigley et al. [236] stated 8-20 is the common practice, Hanea and Nane [235] proposed at least 15 when the target variables are less than 35. However, Eggstaff et al. [260] imply that a maximum number of calibration variables may exist beyond which the CM-SEJ no longer outperform the equal weight linear aggregation. There are 10 calibration variables and nine target variables for each expert panel in this study. Based on the studies used in the analysis by Eggstaff et al. [260], when 10 calibration variables are used in the CM-SEJ, the performance measure ratio of the performance-based weighting scheme to the equal weighting scheme was assessed to be 1.06. In addition, the combined score of the performance-based weight reached 1.9 times that of the equal weight when there is one more calibration variable than the target variable. The significance in the performance of the performance-based weighting can also be observed in Panel 1 and Pane 1&2 in the current study, see Figure 4.3. However, while the item weight DMs receive slightly higher combined scores, the performance of global weight DMs is inferior to that of EQ in Panel 2.

4.7. CONCLUSION

HUMAN error in structural design and construction plays a major role in structural safety. Recent developments in safety science propose to adopt a socio-technical system view towards the human error issue and research into the task contextual HOFs behind human errors. Therefore, this study measures the impacts of the identified critical HOFs in the Dutch construction industry on human error occurrence, employing the CM-SEJ. Unlike other human reliability quantification studies that predominantly focused on the negative impacts of the HOFs, this study also assessed their positive effects, which has largely been overlooked.

The results of the CM-SEJ reveal that *fitness-for-duty*, *organizational characteristics* and *fragmentation* are the primary factors associated with the highest negative effects on task performance. Conversely, the factors *complexity*, *attitude* and *fitness-for-duty* demonstrate considerable potential of positive influence to decrease the human error occurrence probability. These results offer valuable insights for industrial practice, highlighting the factors that demand extra attention and quality assurance resources for structural safety. Moreover, the quantified HOFs can serve as initial inputs for the future development of a quantitative HRA method tailored specifically for assessing human reliability for the construction industry. Due to the limitations of this SEJ study, the HOFs' impacts were measured based on a checking task, with an assumption of its relevance to broader structural design and construction tasks. Future research is required to validate this assumption. Moreover, the HOFs' influence ought to be assessed in a more complex setting, considering various task types and error modes. In addition, creating other forms of data sources than expert judgement, such as task record data and experiment data, for HEP estimation in the construction industry, is a worthwhile future endeavour to validate the results of this study.

5

MODELLING THE INFLUENCE OF HOFS ON STRUCTURAL RELIABILITY

Human and Organizational Factors (HOFs) are recognized to significantly impact the safety and reliability of structures. Yet how structural reliability is affected by these factors and how large their impacts are remains inadequately studied. A proof-of-concept methodology that is designated to reveal such relationships is proposed in this paper, bridging human reliability to structural reliability. First, a review of related studies and methods from cross-interdisciplinary domains is presented. Then, a simulation-based methodology capable of capturing the dynamics and nonlinear influences of HOFs on structural reliability is proposed. Furthermore, a case study of a simple cast in-situ slab floor structure is performed to illustrate the potential of the developed methodology. Preliminary results of the case study and a sensitivity analysis are subsequently presented. It is found that the failure probability distribution changes significantly due to the influence of HOFs and the error checking procedure. Moreover, the critical factor and task combinations to which structural reliability is sensitive can be identified. This innovative approach will prove useful in expanding our understanding of how HOFs influence the reliability of structures and contribute to better structural reliability evaluation by taking human contributions to the structure's life cycle into consideration.

This chapter has been submitted to Reliability Engineering & System Safety [265].

5.1. INTRODUCTION

STRUCTURAL reliability is defined as the capacity of a structure or a structural member to fulfil specified requirements [9]. This concept is critical within the Architecture, Engineering, and Construction (AEC) industry, given its role in preventing economic, social, and environmental damages, as well as human injuries or fatalities that can arise from structural failures. Thus much attention has been paid to prevent structural failures and to enhance structural reliability in practice. It is widely acknowledged in the structural safety field that a significant portion of these failures can be attributed to human errors introduced during the design and construction phases [3, 7, 80, 81]. An approximation of 70% – 90% of the structural failures result from human errors, among which 40% – 50% are due to structural design and construction errors [4, 42, 44, 113]. Evidently, human errors overshadow technical issues such as extreme loads or material deterioration as the cause of structural failures [45, 119]. Therefore, investigating structural reliability from a non-technical perspective offers a promising approach to enhancing structural safety

To err is human. It is important to acknowledge that human error is an inherent component of the engineering process and cannot be eliminated. Lessons learned from errors drive technological advances and innovation [86]. Nevertheless, not every error brings along failure, thanks to the built-in reliability, robustness and resilience of the structure system. These qualities are provided by efforts such as redundancy, safety barriers, risk-informed design, and quality assurance measures. Hence, when a structural failure occurs, it is better to investigate the failure of these quality and reliability-ensuring efforts inside the construction project and the structural system instead of the failure of the personnel. This suggestion is justified by the point that focusing solely on human errors as the cause of mishaps or failures breeds a damaging blame culture that is built on tunnel vision. This will impede the learning of the organization from this incident, meanwhile providing no constructive insights regarding how these errors come to be. It is suggested by many scholars to shift to a system approach towards human error, which means looking beyond the manifested error itself to find the latent factors and surrounding working context in the system that lead people to make that error. As argued by Reason [39], human errors cannot be isolated from the broader system context. Replacing personnel is ineffective in handling human error. Such attempts will not make the system safer while the system design, the management strategy, the working procedure, and the work environment have not been improved. Intriguingly, what has been observed is that under the same working conditions, different individuals exhibit the same behaviour patterns and make similar errors. Hollnagel [25] argued that errors are one variety of the human performance variation spectrum, resulting from latent conditions surrounding the task. Therefore, rather than focusing on identifying the error or the individuals who commit it, the failure inquiry should be directed to the factors and situations that lead to the deviated erroneous performance.

These underlying factors, defined as the Human and Organizational Factors (HOFs), can be the organizational characteristics of the system, as well as personnel capabilities and limitations when matching to the assigned task. HOFs are the latent conditions in the construction project that play an important role in task performance, and ultimately, the structural safety and reliability [76].

Some safety-critical industries such as nuclear, aviation, and chemical processing have well researched into the task contexts and latent factors that contribute to human error occurrence. These factors are called the Performance Shaping Factors (PSFs). These factors are used in Human Reliability Analysis (HRA) methods for human error potential evaluation. However, this is not the case for the AEC industry. Nevertheless, numerous studies and structural failure investigations have researched the structural failure causes, both technical and non-technical. Some of the non-technical causes can be considered as HOFs that influence structural safety, such as communication problem [42], lack of knowledge [141], fragmentation [146], underestimation of the impacts of a certain design [42], and not following-up warnings [174]. An overview of the HOFs acknowledged to affect structural safety in existing studies is presented by Ren et al. [77]. Despite existing research into the impacts of human error on structural reliability, such as [5, 55, 113], the comprehensive influence of HOFs behind these errors on the reliability of structures remains insufficiently explored.

The purpose of this research is to model the dynamic influence of HOFs on structural reliability through the development of an initial proof-of-concept methodology, such that objective structural reliability estimates can be approximated by taking the human contribution during the structural design and construction process into consideration. In this paper, previously published related works from two research domains are first reviewed to grasp the latest development on the subject matter, which is presented in Section 5.2. Afterwards, the proposed modelling methodology is elaborated in detail in Section 5.3. Moreover, a case study and its analysis results are presented in Section 5.4 to illustrate the potential of the proposed methodology. In addition, contributions and remarks on this model are discussed in Section 5.5. In the end, Section 5.6 concludes this study and recommends future work.

5.2. RELATED WORKS

5.2.1. HUMAN ERROR AFFECTING STRUCTURAL RELIABILITY

STRUCTURAL reliability is significantly affected by undetected, uncorrected human errors embedded in the structure, especially errors made during the structural design and construction process. The human error issue in structural safety gained much research attention in the 1980s and 1990s, following the human error research trend in the general engineering domain, after several high-profile industrial accidents [77]. As a result, many researchers have investigated the effects of human error on structural reliability through proposed models and methods. For example, Melchers [113] proposed a mathematical model with linear dependency of the structural failure probability on the human error probability. Frangopol [3] presented mathematical models to combine human error probabilities with probabilistic models for structural failure risk assessment.

Several types of models and methods have been developed to evaluate the effects of human error on structural reliability in the existing literature. In the early stage of research, several mathematical and probabilistic models and methods were proposed by academics from the structural engineering field. In these methods, human error effects on the reliability of the structures being studied are mostly modelled as a change or deviation in the load and resistance variable distributions from the original ones [1, 3, 83].

How the distribution changes depends on the error scenario. The final structural reliability is consequently calculated based on the error-shifted load and resistance. Another methodological idea is to incorporate some uncertainties caused by human errors into the calculated existing structural reliability [99]. However, these two method schemes are intrinsically the same, which is to introduce the error-induced uncertainties to the structural reliability calculation. Apart from this, Bayesian theorem [97] and Fuzzy theory [108, 110] have also been applied to assess the impacts of human error on structural reliability.

In addition, Vrouwenvelder et al. [102] pointed out that the Human Error Probability (HEP) is necessary information for modelling human error in structural engineering. At first, the HEP was roughly fitted to several well-known distributions based on limited observations, such as negative binomial distribution [90] and Poisson distribution [97]. Later arose the successive development of a human reliability method that provides HEP estimations for specific tasks in the structural design process based on massive survey data [118]. This human reliability method was combined with a simulation model to analyze the influenced structural reliability and to evaluate the effectiveness of quality control measures [5, 80, 119]. The proposed methodology in this paper incorporates this simulation model, which has been adapted to reflect recent developments.

More recently, two HRA methods integrated with simulation techniques were further explored to go beyond human error and model the HOFs' impacts on structural reliability [122, 124]. However, these two models employed existing HRA methods from other industries without verifying their applicability to the AEC industry. A thorough overview of the human error models and methods developed for structural reliability analysis can be found in [77].

5.2.2. HUMAN RELIABILITY ANALYSIS

HUMAN error is acknowledged as a complex factor that plays a direct or indirect role in initiating incidents within the chain of events leading to accidents or failure. Methods of HRA have been developed as a principal proactive approach to address this challenge. HRA provides qualitative or quantitative methods to systematically identify, analyze, and predict human errors across various activities that could potentially contribute to failures in complex systems and processes. At its core, these methods aim to identify human failure vulnerabilities in tasks and operations, understand the error shaping factors, quantify error occurrence likelihood, and thereby enable the implementation of strategies to mitigate risks, enhance safety, and improve overall system performance [266].

Originating in the 1960s as a method for analysing human errors in nuclear weapon operations within the military domain, HRA subsequently expanded its application to nuclear power plants with the development of the Technique for Human Error Rate Prediction (THERP) method [29]. Following the establishment of THERP, HRA methods witnessed rapid development and experienced a boom post-2000 [267]. Human reliability has since emerged as a pivotal component of risk analysis and safety management across safety-critical industries. Consequently, a diverse array of HRA methods has been developed and implemented in sectors such as nuclear [268], aviation [269], healthcare [270], offshore operations [271], and chemical processing [266].

The existing HRA methods are generally categorised into three generations. The first-generation HRA methods treat a human error in a similar manner as a physical component failure, emphasising the human action phenomenology and the HEP quantification [271, 272]. The first-generation HRA methods include, for example, THERP, Accident Sequence Evaluation Program (ASEP) [273], and Human Error Assessment and Reduction Technique (HEART) [137]. The second-generation HRA methods integrate human cognitive models as well as the operator's task and environment context into the overall analysis [271]. Examples of the second-generation HRA method include Cognitive Reliability and Error Analysis Method (CREAM) [26] and A Technique for Human Event Analysis (ATHEANA) [274]. The third-generation HRA methods feature a solid database foundation, such as the Nuclear Action Reliability Assessment (NARA) method [275]. Lately, Groth et al. [276] have drawn attention to the comprehensive, research-based, adaptable and flexible, and multi-purpose requirements that a method must satisfy in order to qualify as a third-generation HRA method.

Boring [277] argued that the emerging simulation-based dynamic HRA could be regarded as the third-generation HRA in the sense that simulation-based HRA marks a significant advancement beyond the static approaches of the first and second generation HRA methods by employing dynamic modelling techniques to replicate human decision-making and actions, thereby providing a more nuanced foundation for the assessment of human performance. This method employs virtual scenarios, environments, and humans to closely mimic real-world human interactions and performance, offering an overview of human reliability. According to Boring [277], the principal benefits of this approach include the cost-effective estimation of safety for novel equipment and configurations, the ability to identify and eliminate designs that do not meet criteria for safety, efficiency, and user-friendliness, and the capability to pinpoint specific areas requiring further investigation. The simulation-based dynamic HRA enhances human performance modelling and is thus promising with respect to the research aim of this paper.

These HRA methods are primarily developed for safety-critical industries, while they are currently absent in the AEC industry. Therefore, this study developed a simulation-based dynamic HRA accounting for performance-shaping HOFs in the structural design and construction tasks. It is further integrated into a simulation model to achieve better structural reliability assessment considering human contributions.

5.3. METHODOLOGY

THE ultimate research aim is to enable modelling of the dynamic influence of HOFs on structural reliability. Therefore, a proof-of-concept methodology is presented in this section, which can evaluate structural reliability considering the dynamic and non-linear influence of HOFs in the structural design and construction process for the AEC industry. A task-based simulation model is proposed, integrating several methods involving task analysis, HRA method, error effects simulation, checking procedure simulation, and structural reliability analysis. The framework of this methodology is outlined in Fig. 5.1.

As shown in the framework, this methodology involves five main steps:

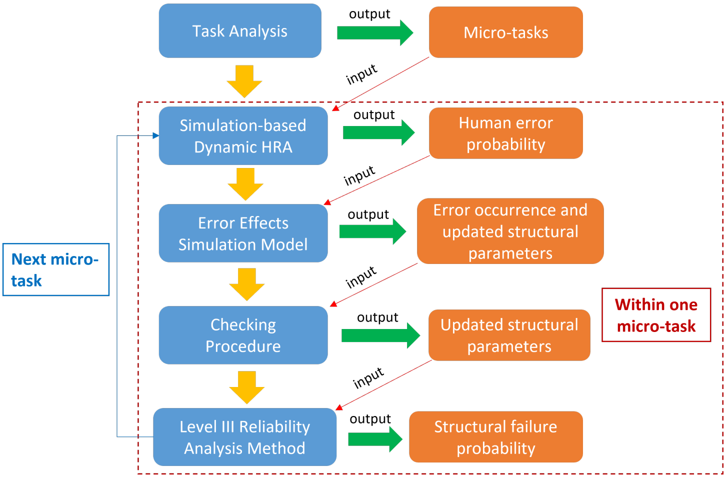


Figure 5.1.: The methodology framework.

Step 1: Task analysis. The primary goal of this step is to identify the detailed tasks involved on a micro level in the process being studied.

Step 2: Simulation-based dynamic HRA. This step aims to quantify the HEP of a micro-task.

Step 3: Error effects simulation. This step determines whether a human error occurs in a micro-task. If an error occurs, it will change the structural parameters affected by the micro-task.

Step 4: Checking procedure. A check is performed after the completion of each micro-task and has the potential to correct errors if they have occurred.

Step 5: Structural reliability analysis. A level-III reliability analysis is performed to calculate the structural failure probability.

Step 1 is at an overarching level that lays the foundation for the analysis, steps 2-5 simulate the analysis procedure for one micro-task. After simulating all the micro-tasks of the structural design and construction process at hand, the final structural reliability can be obtained. These steps are further elaborated in the following parts of this section.

5.3.1. TASK ANALYSIS

TASK analysis begins with breaking down into detailed micro-tasks, which are the essential elements required to accomplish the structural design or construction process. While there is no consensus on how detailed the decomposition should be, each micro-task should provide distinct, non-overlapping information. This initial step gathers crucial information, such as the content, type, and involved structural parameters of each micro-task, as well as their execution sequence. This forms the foundation and provides essential inputs for subsequent steps in the task-based methodology.

5.3.2. SIMULATION-BASED DYNAMIC HRA

A dynamic, simulation-based HRA method tailored to the AEC industry is introduced. As a critical component, it facilitates the dynamic quantification of HEP for specific micro-tasks by stochastically evaluating the impacts of HOFs on these tasks. Based on a task's type, the baseline Nominal Human Error Probability (NHEP) is modified through simulated variations influenced by HOFs, either increasing or decreasing it, to derive an estimated HEP for the micro-task. This quantitative HRA method is explained in three steps:

Step 2.1: Determine the task type of the micro-task. For each type of task, the NHEP and associated critical HOFs are defined.

Step 2.2: Simulate the impacts of HOFs on the HEP. The positive or negative effects of HOFs on the micro-task performance are simulated by stochastically selecting the multipliers of the HOFs.

Step 2.3: Quantify the HEP of a micro-task. This step calculates the HEP of the micro-task.

Through these three steps, the HEP of a micro-task is obtained, which provides the input for the error effects simulation that determines if a human error occurs and what its consequences are. A more detailed explanation of these three steps is described in the following subsections.

GENERIC TASK TYPES

THROUGH a hierarchical task analysis of the design and construction of a reinforced wide slab floor structural element, frequently performed micro-tasks of similar system interactions, cognitive demands, and influencing factors are summarized as Generic Task Types (GTT) [196]. For the structural design and construction process 14 GTTs are derived and listed in Table 5.1. The derivation and definitions of these GTTs are further explained in [186]. Each GTT is associated with an NHEP and a number of critical HOFs that influence tasks of such type, as shown in Table 5.1. This categorization of tasks avoids determining the NHEP and critical HOFs for a large number of individual micro-tasks, which makes this method practical and reusable.

Table 5.1.: GTTs and associated NHEP and critical HOFs.

ID	GTT	NHEP	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
T1	Diagnosis based on knowledge experience/situation	1.000E-02[a]	x		x	x		x		x	x	x	x	x		
T2	Derive value	1.260E-02[b]	x		x	x	x	x		x	x	x	x			
T3	Consult code	1.500E-02[b]	x		x	x	x	x		x	x	x	x			
T4	Mechanical schematization	3.000E-02[a]	x		x	x		x		x	x	x	x	x		
T5	Calculation	1.000E-02[c]	x		x	x				x	x	x	x	x	x	
T6	Comparison/ranking	4.190E-04[d]	x	x	x	x	x	x			x	x		x		
T7	Interaction with design software	2.224E-03[d]	x		x	x		x		x	x	x	x		x	
T8	Documenting design and prepare specifications	1.000E-02[c]	x		x	x	x	x		x	x	x	x	x		
T9	Follow instructions and act	6.000E-03[a]	x	x	x	x		x		x		x			x	x
T10	Consult drawings and specifications	4.259E-04[d]	x	x	x	x	x	x		x		x	x	x		
T11	Measurement	1.869E-04[d]	x		x	x				x		x			x	x
T12	Interaction with hardware equipment (tools/machine)	1.720E-04[d]	x	x	x	x				x		x			x	x
T13	Communication	6.000E-03[a]	x	x	x	x	x	x	x			x		x		
T14	Checking/inspection	1.095E-03[d]	x	x	x	x		x		x		x	x	x		

[a] value obtained from [275]; [b] value obtained from [55]; [c] value obtained from [112]; [d] value obtained from [239].

HOFS' IMPACTS

THE NHEP of a task represents the baseline HEP under no influence from the task performance shaping HOFs. The impacts of the HOFs are modelled as multipliers (denoted as M) that modify the NHEP. The multipliers increase or decrease the task's HEP from the baseline NHEP value, depending on the negative or positive effects that the HOFs pose.

In contrast to the traditional static HRA methods where the PSF's multipliers are deterministic values, the dynamic HRA proposed here contains the HOFs' multipliers drawn from formulated continuous distributions. This incorporates to some extent the uncertainty considerations in the multiplier value judgement. Via a Structured Expert Judgement (SEJ) study, the 5^{th}, 50^{th}, and 95^{th} percentiles of the M_{neg} (negative effect) or the M_{pos} (positive effect) values were elicited, further details can be found in [206]. The SEJ assumes a minimal information distribution as the elicited distribution for the uncertainty quantification of the judged variable. This assumption adds minimal information to the expert's percentile estimates. In such a distribution, the probability mass is uniformly distributed within each percentile interval to form the Probability Density Function (PDF). This means the Cumulative Distribution Function (CDF) can be built by linearly interpolating between the elicited percentiles. However, a Lower Bound (LB) (corresponding to 0%) and an Upper Bound (UB) (corresponding to 100%) should then still be defined. For a positive effect, the LB is set to 0.0 and the UB is set to 1.0, i.e. a positive effect can only decrease the HEP value. For a negative effect, the LB is set to 1.0 and the UB is set to a 5% overshoot of the 95^{th}-percentile. For the latter UB, a value could also be elicited from [206]: based on the survey design (i.e., how many times an error occurred out of $1.0e5$ times repetition), the UB could be set to 909.1. However, this UB is deemed too large, especially considering the NHEP values should typically lie between $1E-4$ and $1E-2$. The LB, $5th$ percentile, $50th$ percentile, $95th$ percentile, and UB of the M_{neg} and M_{pos} are listed in Table 5.2.

As a result, the multipliers' PDFs for the 14 HOFs can be obtained from the SEJ study [206]. As an example, the PDFs of M_{neg} and M_{pos} for factors *professional competence*, *complexity*, *information flow*, and *quality assurance* are shown in Fig. 5.2.

Table 5.2.: The appearance probabilities and multipliers of the negative and positive impacts of HOFs.

ID	HOFs	P_{neg} (%)	$P_{noeffect}$ (%)	P_{pos} (%)	M_{neg} LB	M_{neg} 5^{th}	M_{neg} 50^{th}	M_{neg} 95^{th}	M_{neg} UB	M_{pos} LB	M_{pos} 5^{th}	M_{pos} 50^{th}	M_{pos} 95^{th}	M_{pos} UB
F1	professional competence	22.2	49.0	28.8	1.00	1.37	8.29	232.55	244.17	0.00	0.24	0.83	0.95	1.00
F2	information flow	36.9	41.2	21.9	1.00	1.37	6.05	89.24	93.70	0.00	0.32	0.84	0.95	1.00
F3	complexity	38.6	43.6	17.9	1.00	1.04	13.55	72.12	75.72	0.00	0.16	0.41	0.90	1.00
F4	quality assurance	32.2	42.2	25.6	1.00	1.09	8.59	88.61	93.04	0.00	0.18	0.77	0.95	1.00
F5	stress	30.8	65.6	3.5	1.00	1.01	12.05	49.53	52.00	0.00	0.43	0.74	0.91	1.00
F6	well-being for duty	25.8	52.1	22.1	1.00	2.73	25.92	49.98	52.48	0.00	0.23	0.56	0.97	1.00
F7	attitude	12.2	57.3	30.5	1.00	1.27	17.32	161.73	169.81	0.00	0.10	0.51	0.89	1.00
F8	trust	23.8	54.2	21.9	1.00	1.09	9.76	24.77	26.01	0.00	0.24	0.66	0.91	1.00
F9	comprehensive abilities	21.6	50.0	28.5	1.00	1.48	4.96	12.03	12.63	0.00	0.20	0.68	0.91	1.00
F10	engineering climate	70.1	1.3	28.6	1.00	1.05	15.80	135.91	142.70	0.00	0.51	0.93	0.95	1.00
F11	fragmentation	24.4	30.9	44.7	1.00	1.38	19.16	56.27	59.09	0.00	0.47	0.87	0.95	1.00
F12	organizational characteristics	39.3	20.5	40.2	1.00	1.38	23.50	90.43	94.95	0.00	0.49	0.87	0.95	1.00
F13	equipment	24.1	26.3	49.6	1.00	1.38	6.36	89.81	94.30	0.00	0.03	0.84	0.95	1.00
F14	working conditions	32.1	29.0	38.9	1.00	1.38	4.65	86.09	90.40	0.00	0.63	0.82	0.91	1.00

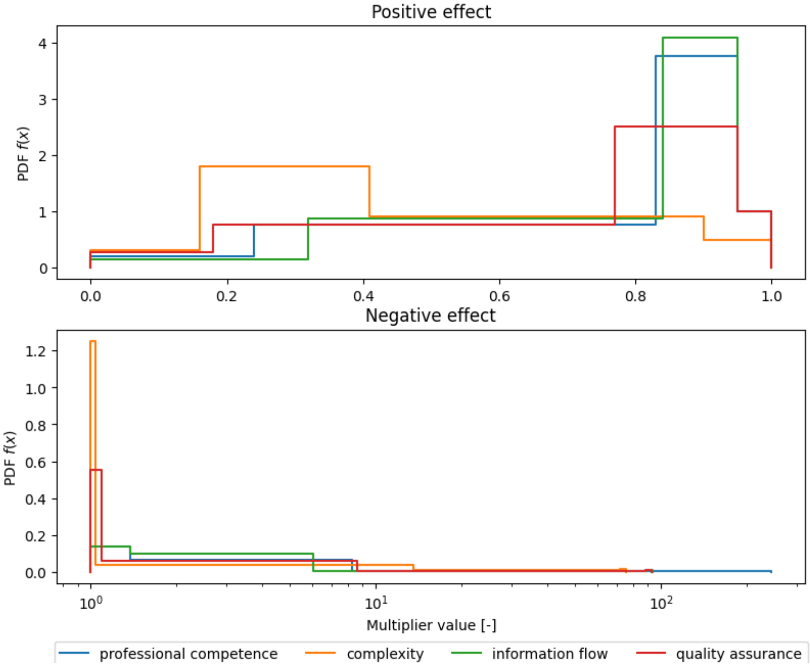


Figure 5.2.: The multiplier's PDF of four HOFs. These distributions are elicited from a SEJ study.

The probability for the negative or positive impacts of a factor was also elicited via the SEJ. The situation when a HOF has no effect on the task performance, or simply no sufficient information is available to assess the factor's impacts is also considered. This is the prior information to determine the multiplier value. The aggregated probabilities for different impacts of each HOF are presented in Table 5.2. An example question from the SEJ study regarding eliciting this probability is shown in Fig. C.1 in C.

The process of determining the multiplier value is simulated as follows: the multiplier value is determined by drawing random values from the M_{neg} or M_{pos} distribution, given the probability that the factor poses such a negative or positive impact. When the factor has no effect on task performance, the multiplier value is 1. For instance, there is 38.6% chance that the factor *complexity*'s multiplier value is drawn from its M_{neg} PDF distribution. As a result, the HOF's impact on the micro-task's HEP is quantified. This process is illustrated in Fig. 5.3.

HEP CALCULATION

In most HRA methods, the HEP of a given task is calculated as the product of the task NHEP and the multipliers of every influencing PSFs, as shown in Eq.5.1:

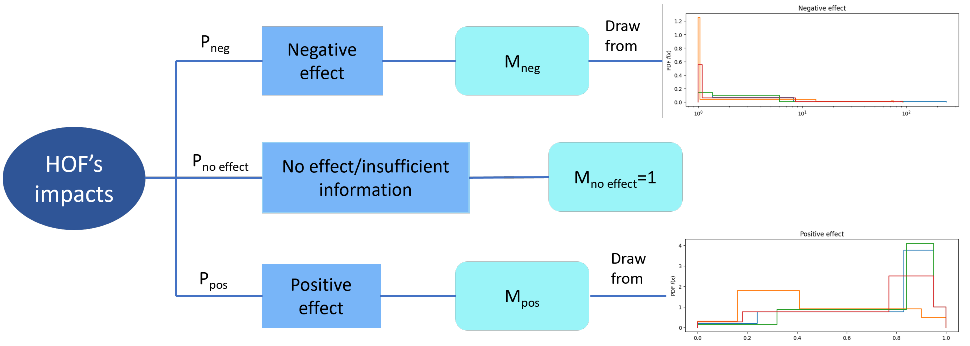


Figure 5.3.: The dynamic simulation process to determine the multiplier value.

$$HEP_{task} = NHEP_{task} \times \prod_{i=1}^{n} PSF_i \tag{5.1}$$

Where PSF_i denotes the multiplier of the i^{th} PSF, and n is the total number of PSFs that influence the HEP of this task. However, this calculation method has two deficiencies. First, it is noted that the NHEP value of diverse task types ranges from 1e−5 to 1e−2 and in other HRA methods the negative effect multipliers typically range from just above 1 to 50 [202, 240]. Therefore, if several PSFs have a relatively large multiplier, the calculated HEP will be above 1, which is the case for the current study. As can be observed from Table 5.1, the number of critical HOFs in each GTT ranges from 7 to 10, mostly 9. While the NHEP of different GTTs lies between 1e−4 and 1e−2, the values for M_{neg} lie mostly around 10 – 20 with maxima in the order of magnitude of 100. This will result in the calculated HEP values above 1 for most micro-tasks. Second, using Eq. 5.1, the dependencies between the involved PSFs are ignored. It also makes the calculation sensitive to the number of PSFs affecting a task, which is undesirable. To overcome these shortcomings, this study proposes to employ the geometric mean of the HOFs' multipliers:

$$GM(M_{Fi}) = \left(\prod_{i=1}^{n} M_{Fi}\right)^{\frac{1}{n}} \tag{5.2}$$

Where M_{Fi} is the simulated multiplier of factor Fi, as explained in Section 5.3.2. And n is the total number of HOFs affecting the micro-task. The HEP of a micro-task can then be calculated as the product of the geometric mean of multipliers and the NHEP of that micro-task:

$$HEP_{micro-task} = NHEP_{micro-task} \times GM(M_{Fi}) \tag{5.3}$$

5.3.3. ERROR EFFECTS SIMULATION MODEL

FOR the third step, an error effects simulation model is developed based on the work of Stewart [61, 119] to evaluate whether a human error occurs in the micro-task. Subsequently, to analyze the changes in the affected parameters. There are two steps involved in this model, which are listed below. Further details are given in the following subsections.

Step 3.1: Simulate error occurrence. This step determines whether an error occurred or not in a micro-task based on the calculated HEP.

Step 3.2: Simulate the effects of error. Once an error occurs, determine the consequence of this error on the structure.

SIMULATE ERROR OCCURRENCE

THE error occurrence is simulated by generating a uniformly distributed random number within $[0,1]$ and comparing it with the calculated HEP value. If the random number is larger than the HEP value, then the current micro-task is deemed as "*error free*", and the existing value of the structural parameter remains unchanged. Conversely, if the random number is smaller than or equal to the HEP value, it indicates an "*error occurred*" within the micro-task, leading to the modification of the affected structural parameter's value.

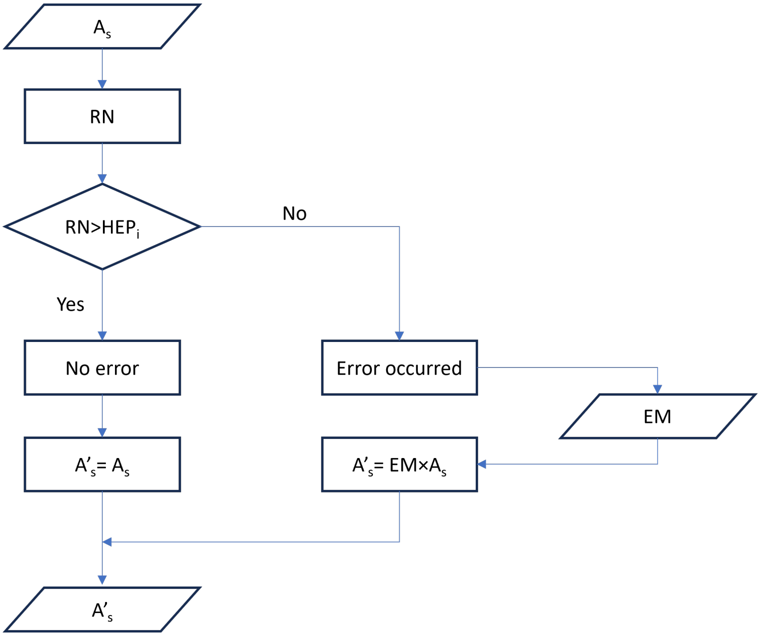


Figure 5.4.: The simulation process to determine error occurrence in a micro-task. The affected structural parameter in this example micro-task is the reinforcement area A_s. RN denotes the random number. HEP_i is the calculated HEP for micro-task i.

SIMULATE ERROR EFFECTS

THE Error Magnitude (EM) parameter quantitatively represents the effects of an error. It implies the deviation of structural parameters from the "correct" design value, given the occurrence of an error scenario. In the event of an error within a micro-task, the affected structural parameter is updated by the product of its original value and the EM, as depicted in Fig. 5.4. The EM value is stochastically drawn from the corresponding EM distribution. Specifically, an EM value greater than 1 leads to an increase in the structural parameter's value, whereas an EM value less than 1 results in a decrease.

Melchers [113] pointed out that the EM is related to the complexity level of a task. Therefore, a complexity level is distinguished based on the multiplier of the *complexity* factor: "Obvious" (< 5th-percentile), "Nominal"(< 50th-percentile), "Moderate" (< 95th-percentile), and "High" (≥ 95th-percentile). An overview of the ranges of $M_{complexity}$ and the corresponding complexity level is given in Table 5.3

According to Stewart [119], the EM follows a lognormal distribution. For the EM, the μ of the underlying normal distribution of its lognormal distribution is assumed to be 0. Thus the EM's distribution can be obtained based on the σ listed in Table 5.3. Note that here, μ and σ are the mean and standard deviation of the corresponding normal distribution (logarithm of the variables) of this lognormal distribution. For clarity, the PDF and CDF of the four EM distributions used for this study are shown in Fig. 5.5.

$$P(0 < EM < 1) = P(EM > 1) = 0.5 \tag{5.4}$$

As can be observed from Fig. 5.5, there is a 50% chance that the EM will increase and a 50% chance it will decrease the parameter value. Additionally, the probability that $EM > 2$ or $EM < 0.5$ is minimal across these four distributions, making it unlikely that the designed structural parameter value is mistakenly doubled or halved, which is deemed realistic for this study.

Table 5.3.: σ of EM by task complexity levels.

$M_{pos,complexity}$	$M_{neg,complexity}$	Task complexity	σ
[0.9 – 1.0]	[72.12 – 75.73]	High	0.4
[0.41 – 0.9)	[13.55, 72.12)	Moderate	0.3
[0.16 – 0.41)	[1.04 – 13.55)	Nominal	0.2
[0.0 – 0.16)	(1.0 – 1.04)	Obvious	0.1

5.3.4. CHECKING PROCEDURE

AFTER the error effects simulation is performed, a check procedure is performed to detect if a human error is included in the micro-task. If the error is spotted and corrected, then the error that was applied in the preceding task is reversed; otherwise, the parameters that were affected by the error are passed on to the next micro-task.

When a micro-task is "*error free*", the check finds no error in the task, and hence takes no action in the check procedure. When a micro-task is "*error included*", then the checking is assumed to have an 80% chance to detect this error and a 20% chance that it fails

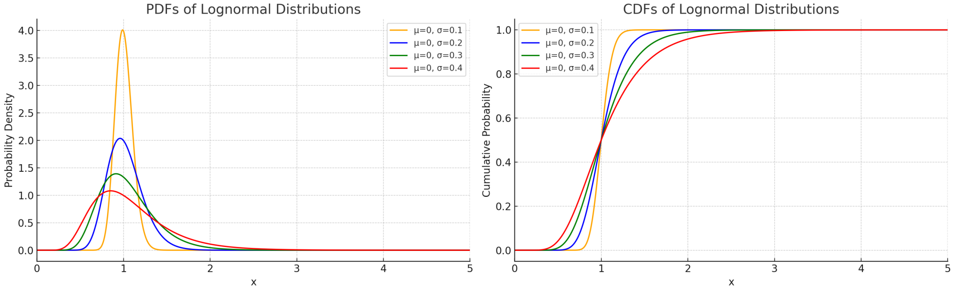


Figure 5.5.: The PDF and CDF of the four EM distributions.

to find the error. Following this, if the checking fails to find the error, then no action will be taken. Whereas if the error is spotted, there is an assumed 90% chance that it corrects the error to the right value and a 10% chance that it ignores the error and takes no action to correct it. The scenario in which the error is corrected wrongly by checking is not considered in this study. The check corrects the identified error by removing the error magnitude that was applied to the affected parameters in the micro-task.

The checking procedure approximates realistic practice in the AEC industry. It indicates the fact that human and organizational influence on the structure is not a linear accumulation, but a dynamic process that requires more nonlinear modeling considerations.

5.3.5. STRUCTURAL RELIABILITY ANALYSIS

FOLLOWING the error checking procedure, if an error has led to modified parameters, a level III reliability analysis is performed to calculate the new structural failure probability. This is achieved through a Monte Carlo Simulation (MCS) in which random values are generated for the structure's parameters using their distributions. The obtained parameter sets are then used to calculate the limit state values Z and the structural failure probability following Eq. 5.5 and Eq. 5.6 respectively.

$$Z = f(R, S) \tag{5.5}$$

$$P_f = P(Z = R - S \leq 0) = \iint_{R \leq S} f_{R,S}(r, s)\, dr\, ds \tag{5.6}$$

In this formula, R represents resistance variables, and S represents load variables. If the limit state Z is smaller than 0, then structural failure occurs; otherwise, no structural failure happens.

5.3.6. SIMULATING EFFECTS OF HOFS ON STRUCTURAL RELIABILITY

BY repeating the HRA, error effects simulation, checking procedure, and structural reliability analysis steps a large number of times, a distribution of structural failure probabilities is obtained. This distribution shows the accumulated, nonlinear, and dynamic influence of HOFs on structural reliability.

5.3.7. IMPLEMENTATION

The steps and the simulation described above have been implemented using the programming language Python. Details of this implementation are omitted for clarity and brevity, however, the code and the input settings have been made available in an online repository [278]. It is noted that the Random Number Generators (RNG) used to determine the stochastic behaviour in the simulations can be seeded using custom values, making simulations reproducible.

5.4. CASE STUDY

As a proof of concept, a case study is presented in this section, in which the bending failure analysis of a simply supported cast-in-situ floor slab is subjected to the methodology presented above. First, the structure and its failure mode are described, followed by the task analysis involved in designing and constructing the structure. In the end, the results of the simulation are presented.

5.4.1. THE CASE STRUCTURE

The slab structure adopts an example provided by the Joint Committee on Structural Safety (JCSS) published in the probabilistic model code [16] (Part IV, example 1). The example concerns a cast-in-situ reinforced concrete floor with a span of 5m, more details are illustrated in Fig. 5.6. Moreover, the parameter values and distributions are given in Table 5.4. The failure criterion is given in Eq. 5.7, in which $q_G = 25\text{e}{-9} \cdot h$ [$\text{N}\,\text{mm}^{-2}$] and $a = c + \varnothing/2.0$ [mm].

$$Z = \theta_R A_s f_y \left(h - a - \left(\frac{A_s f_y}{2 f_c}\right)\right) - \frac{\theta_E (q_G + q_{lt} + q_{st}) L^2}{8} \tag{5.7}$$

It should be noted that the reinforcement in the JCSS example has been complemented, since in the example, the amount of reinforcement was normalized and left to a parametric study. In the case study $A_s = 524\text{mm}^2\,\text{m}^{-1}$ is used which corresponds to rebars $\varnothing$10mm at a center-to-center distance of 150mm, which resembles a realistic design. Consequently, since the rebar diameter is known, the parameter a is no longer drawn stochastically and its distribution type and standard deviation are applied to the concrete cover c.

5.4.2. THE CASE TASK ANALYSIS

The task analysis for this case study is presented in Table E.1 in E. This task analysis specifies the corresponding task type and the execution sequence of the micro-tasks. Furthermore, to detail which parameters and how they are affected in each micro-task, error scenarios are introduced in E, Table E.2. Each scenario specifies a number of parameters that can be increased, decreased, or affected either way. For each micro-task,

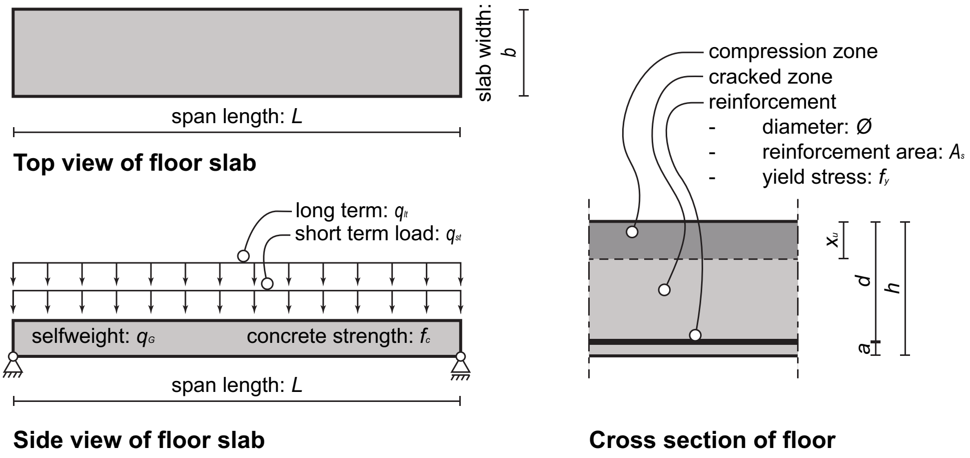


Figure 5.6.: The cast-in-situ slab.

Table 5.4.: Parameter distributions of the slab.

Parameter	Symbol	Unit	Distribution	μ	σ
Short term load	q_{st}	$\mathrm{N\,mm^{-2}}$	gamma	2.00e−4	4.60e−5
Slab span	L	mm	deterministic	5.00e+3	-
Slab width	b	mm	deterministic	1.00e+3	-
Compression strength concrete	f_c	$\mathrm{N\,mm^{-2}}$	lognormal	30.0	5.00
Yield strength	f_y	$\mathrm{N\,mm^{-2}}$	lognormal	560	30.0
Slab depth	h	mm	normal	200	5.00
Long term load	q_{lt}	$\mathrm{N\,mm^{-2}}$	gamma	5.00e−4	7.50e−5
Concrete cover	c	mm	gamma	25.00	5.00
Reinforcement diameter	$\varnothing$	mm	normal	10.00	0.00
Reinforcement area	A_s	$\mathrm{mm^2\,m^{-1}}$	normal	524	0.00
Uncertainty of resistance	θ_R	-	lognormal	1.10	0.077
Uncertainty of load effect	θ_E	-	lognormal	1.00	0.20

the possible scenarios and their likelihood of presence once an error occurs are defined. This study examines a single error occurrence in an individual micro-task, rather than combinations of errors. When a scenario is present, the EM is applied to one randomly selected affected parameter.

5.4.3. SIMULATION RESULTS

IN this subsection, the results of 1.0e5 simulations of the case study are presented. Within each simulation, 5.0e6 iterations of the MCS are performed to calculate the structural failure probability. For a sensitivity check, the above experiment is also conducted without the checking procedure.

In the remainder of this section, (i) the effects of HOFs and checking on the structural failure probability will be analyzed and visualized, and (ii) a means of sensitivity study is proposed and illustrated.

EFFECTS OF HOFS ON STRUCTURAL FAILURE PROBABILITY

THE structural failure probabilities after the final micro-task of each simulation have been plotted in the histograms in Fig. 5.7. The distributions of failure probabilities (on the left) and the zoomed-in reliability degradation distribution segment (on the right) including (in orange) and excluding (in blue) the checking procedure are displayed in this figure. The peak histogram bars contain the simulations with the "correct" initial design failure probability. Consequently, the rest of the histogram bars demonstrate the deviations from this "true" value, revealing the impacts of HOFs on structural reliability. Furthermore, the full simulation was performed twice, the first time with the positive influence of HOFs and the second time without. The results of these two simulations are shown in graphs (a) and (b) respectively in Fig. 5.7.

While the error-free structural failure probability for this floor slab case is 1.61e−4, it can be observed that HOFs can increase or decrease the structural failure probability in the vast range from 2e−7 to 1, in the extreme case. This can, on the left side, be explained by the MCS, which does not allow failure probabilities of less than 2e−7 to be simulated. It should be noted that the values equal to zero are left out of the plots since they cannot be represented on a logarithmic scale. On the right side, the failure probability cannot be larger than 1. The percentages of simulated error-free failure probability, the decreased failure probabilities, and the increased failure probabilities are listed in Table 5.5. It can be seen that HOFs' positive impacts increase the proportion of error-free cases, especially when checking is absent. Therefore, the HRA methods that ignore the positive contributions of PSFs tend to overestimate the HEP and hence the system's risk.

Table 5.5.: The percentage of error-free, failure probability decreased, and failure probability increased cases in the simulation results.

	Error-free (P_f)	Decreased ($< P_f$)	Increased ($> P_f$)
with HOFs' positive influence			
With checking	83.2%	9.4%	7.4%
Without checking	50.9%	27.1%	22.0%
without HOFs' positive influence			
With checking	63.2%	20.3%	16.5%
Without checking	18.6%	44.4%	37.0%

EFFECTS OF CHECKING ON STRUCTURAL FAILURE PROBABILITY

THE peak histogram bar for simulations without error checking represents error-free performance. In contrast, the peak for simulations with error checking includes cases where no errors occurred or where errors were corrected in any of the micro-tasks.

Consequently, the difference in the percentage of such error-free simulations demonstrates the effect of checking on structural reliability. In particular, it can be seen in the increased failure probability segment on the right that checking can significantly decrease the percentage of structural reliability degradation. Furthermore, the error-free simulations with checking are 32.3% (including HOFs' positive effects) and 44.6% (excluding HOFs' positive effects) more than those without checking, showcasing the criticality of checking in human error mitigation and structural safety assurance.

However, simulations with an increased failure probability need special attention, which is zoomed-in on and shown on the right of Fig. 5.7. The less reliable a structure, the larger the area spread at the right will be. From Table 5.5 it can be concluded that the increased failure probabilities take up to a small proportion of the entire failure probability distribution when checking is present.

SENSITIVITY OF FAILURE PROBABILITY TO HOF AND GTT COMBINATIONS

THE sensitivity of the structural failure probability per task type to a factor can yield valuable insights into HOFs' impacts on the design and construction processes in the AEC industry. Thus, a method to compute a metric that can provide insights into the critical HOF and GTT combinations is proposed.

For this methodology it is assumed that the results of each simulation are stored in a data frame in which each row is the result of a performed micro-task, including (1) the GTT, (2) the failure probability after the micro-task is performed, (3) the multipliers that were drawn for the HOFs that affect this task, (4) the HEP, and (5) whether or not an error occurred. The proposed method is then defined in the following steps:

Step 1: Compute the change in the structural failure probability for each micro-task.

Step 2: Filter out the micro-tasks in which no error occurred.

Step 3: Combine the remaining data over all simulations.

Step 4: Calculate the contribution of each HOF to the HEP used in each micro-task.

Step 5: Compute the metric per task type and per HOF.

The change in failure probability in Step 1 is calculated as $\Delta P_{f,i}$ for task i using Eq. 5.8.

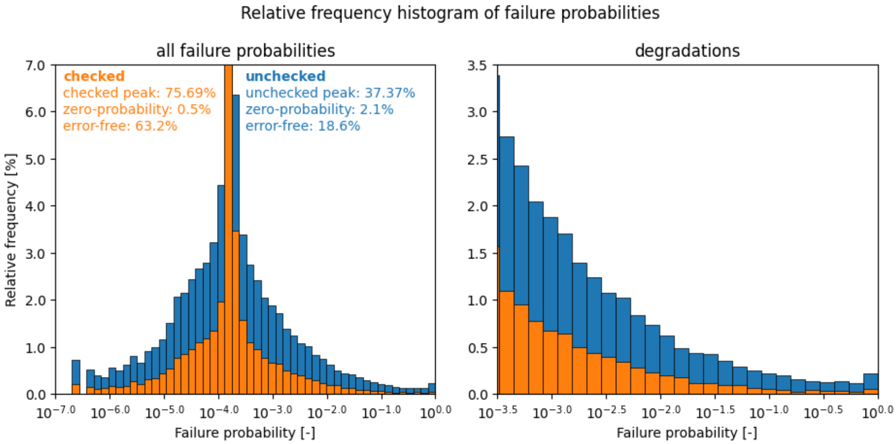
$$\Delta P_{f,i} = P_{f,i} / P_{f,i-1} \qquad\qquad i \neq 0 \tag{5.8}$$

In each data frame, the micro-task indexed at $i = 0$ contains the initial failure probability, i.e. the failure probability in case no human errors occur during the design and construction process.

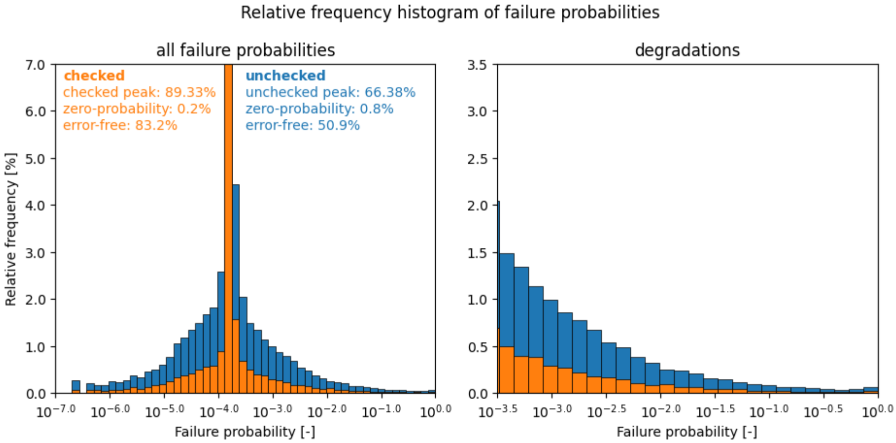
For Step 4, the contribution $C_{i,j}(HOF_j)$ of each HOF j to the HEP of task i is calculated according to Eq. 5.9 (also see Eq. 5.2 for the definition of the geometric mean (GM)):

$$C_{i,j}(HOF_j) = HEP_i / GM(M_{Fk}) \qquad\qquad \{j \in X \wedge \forall k \in X \wedge k \neq j\} \tag{5.9}$$

where X is the set of all the HOFs affecting micro-task i. Following this equation the contribution of a HOF to the HEP of a micro-task is calculated as the division of the HEP by the geometric mean of all other HOFs affecting that task.



(a) Simulation results without HOFs' positive influence.



(b) Simulation results with HOFs' positive and negative influence.

Figure 5.7.: The case study simulation results. The relative frequency of structural failure probabilities, including the checking procedure (coloured in orange) and excluding the checking procedure (coloured in blue), are shown on the left. The relative frequency is calculated using the observed number of simulated certain failure probability divided by the total number of simulations. The increased failure probability segments for both histograms are zoomed in and shown on the right. Simulations in which the failure probability is too small to be captured with the MCS may yield a failure probability of zero. Since the logarithm value of zero is not possible, these simulations are not plotted. Instead, the relative frequency of these simulations is shown in text within the plot.

Finally, in Step 5, the sensitivity metric $M_{j,\ell}$ of GTT ℓ to HOF j is calculated by Eq. 5.10:

$$M_{j,\ell}(HOF_j, Y_\ell) = log_{10}(Mean(\Delta P_{f,k}^{C(HOF_j)})) \qquad \forall k \in Y_\ell \tag{5.10}$$

where Y_l is the set of all tasks that belong to GTT ℓ.

Following this method, the sensitivity of failure probabilities in the case study are computed and presented in Fig. 5.8. Note that the metric and its values do not necessarily have a physical meaning. However, they do allow for a comparative analysis showcasing the relative contributions of HOFs combined with GTTs to structural reliability.

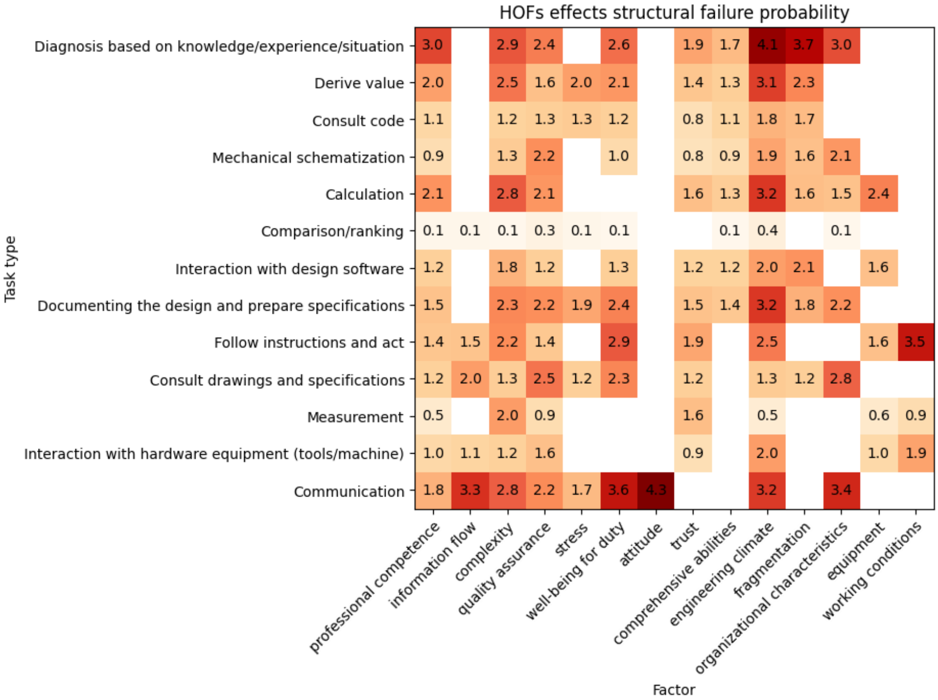
For example, it can be observed from Fig. 5.8 that *communication* is a critical task in structural design and construction. A bad attitude (e.g., lack of motivation or commitment to the job) in a *communication* task can heavily affect structural reliability. Besides, when *well-being for duty*, *organizational characteristics*, and *information flow* pose negative effects on *communication*, the failure probability tends to be modified to a great extent. It can also be observed that the structural failure probability is sensitive to the diagnosis type of task when the influences of several HOFs such as *engineering climate*, *fragmentation*, *professional competence*, and *organizational characteristics* are present. In addition, *engineering climate* is recognized as very influential in most GTTs, followed by *complexity* and *professional competence*. Interestingly, *working conditions* is most impactful on structural reliability in task type *follow instructions and act*. This sensitivity analysis allows for the identification of HOF and GTT combinations that are critical for structural reliability. Consequently, these insights can guide and assist quality assurance and structural safety management in practice.

5.5. DISCUSSION

IN this section, the results of the current case study are roughly compared with existing studies. Additionally, the advantages and limitations of this proposed methodology are discussed.

De Haan [122] adapted the CREAM method for HEP quantification of structural design tasks and modelled the human error influence on structural reliability. De Haan observed a marginal difference in the structural reliability of a beam element designed by an experienced engineer and by an inexperienced engineer. Thus, experience is not identified as critical for structural safety. On the contrary, in the current case study, experience, as covered by the factor *professional competence*, widely affects structural reliability in every task type, especially for the diagnosis type of task. While this study modelled the checking procedure in a simple probabilistic manner, De Haan modelled both "self-checking" and "normal supervision" and concluded that "normal supervision" has a more significant effect on improving structural reliability.

Stewart [80] modelled the design and construction process of a reinforced concrete beam and studied the impacts of human errors on structural reliability. The structural failure probability after simulating the whole process with one check performed after each design or construction task is calculated as 1.07e−4, while the error-free failure probability is 3.82e−5. In the current study, the slab structural failure probabilities with checking are distributed around the "correct" design value of 1.61e−4 and span from



Task type	professional competence	information flow	complexity	quality assurance	stress	well-being for duty	attitude	trust	comprehensive abilities	engineering climate	fragmentation	organizational characteristics	equipment	working conditions
Diagnosis based on knowledge/experience/situation	3.0		2.9	2.4		2.6		1.9	1.7	4.1	3.7	3.0		
Derive value	2.0		2.5	1.6	2.0	2.1		1.4	1.3	3.1	2.3			
Consult code	1.1		1.2	1.3	1.3	1.2		0.8	1.1	1.8	1.7			
Mechanical schematization	0.9		1.3	2.2		1.0		0.8	0.9	1.9	1.6	2.1		
Calculation	2.1		2.8	2.1				1.6	1.3	3.2	1.6	1.5	2.4	
Comparison/ranking	0.1	0.1	0.1	0.3	0.1	0.1			0.1	0.4		0.1		
Interaction with design software	1.2		1.8	1.2		1.3		1.2	1.2	2.0	2.1		1.6	
Documenting the design and prepare specifications	1.5		2.3	2.2	1.9	2.4		1.5	1.4	3.2	1.8	2.2		
Follow instructions and act	1.4	1.5	2.2	1.4		2.9		1.9		2.5			1.6	3.5
Consult drawings and specifications	1.2	2.0	1.3	2.5	1.2	2.3		1.2		1.3	1.2	2.8		
Measurement	0.5		2.0	0.9				1.6		0.5			0.6	0.9
Interaction with hardware equipment (tools/machine)	1.0	1.1	1.2	1.6				0.9		2.0			1.0	1.9
Communication	1.8	3.3	2.8	2.2	1.7	3.6	4.3			3.2		3.4		

Figure 5.8.: The structural reliability sensitivity analysis result heatmap. The larger the number is on each tile, the more sensitive the structural failure probability is to the corresponding HOF and GTT combination. The blank tiles indicate that no such HOF and GTT combination in the simulation has resulted in a changed structural failure probability.

2e−7 to 1. The large probability variation in this study is most likely due to the EM, which can half and double the structural parameters in the extreme case. However, Stewart made the EM more realistic by limiting its distribution to a reasonable range based on the design code and allowable construction tolerance. Moreover, the checking efficiency is 72% for the checking procedure in this proposed methodology, while Stewart's simulation shows an approximately 80% reduction of design errors and around 90% reduction in construction errors with one check performed after each task. Stewart acknowledged that the remaining errors after construction checking seem to be high. Thus, the checking efficiency in this methodology is even more conservative, which may explain the wide spread of the simulated failure probability distribution. This urges the need for empirical research to provide evidence and data for a thorough analysis of the checking effectiveness.

To highlight, this proposed methodology moves one step further to investigate the HOFs behind human errors of their influence on structural safety. Additionally, this study provides insights into the combinations of critical factors (HOFs) and tasks (GTTs) to which structural reliability is sensitive. These are the unique contributions that no existing study has delivered.

The proposed methodology, while promising, has limitations. It is a proof-of-concept that relies on various assumptions and simplifications due to the absence of adequate data, such as the applied EM distributions and the assumed checking efficiency. Consequently, the outcomes of this methodology should be regarded as indicative and relative. Additionally, the results are heavily dependent on the initial task analysis step. It is likely that the decisions made within the task analysis can introduce substantial variability in the simulation outcomes. However, this is the case for most of the task-based or scenario-based risk analysis methods. The interdependence among HOFs is only roughly accounted for, using the geometric mean of their multipliers. This approach may result in an underestimation or an overestimation of their overall effects. Nevertheless, it remains valid for comparing values and identifying relative significance. Although these dependencies are not thoroughly explored in this proof-of-concept methodology, they are identified as crucial for modelling HOFs' impacts in future research. Despite these limitations, this methodology demonstrates potential, especially for optimizing quality assurance resource allocations in practice.

5.6. CONCLUSION AND FUTURE WORK

THIS study develops a methodology to model the influence of critical HOFs behind human errors on the reliability of structures. The methodology employs a dynamic and nonlinear model that quantitatively evaluates how human errors in structural design and construction affect the calculated structural reliability. It effectively integrates human reliability analysis with structural reliability assessment, offering a more realistic estimation of structural reliability. Insights derived from a case study involving a floor structure depict the critical HOF and GTT combinations. For instance, for better structural reliability assurance, in a simple *interaction with design software* type of task, the structural designer should be aware of the factor *fragmentation* in this job and its potential influence on human error occurrence. Therefore, such findings can play an instrumental role in informing resource allocation strategies for quality and safety assurance in practice for the AEC industry.

Future research should be directed towards enhancing this methodology by developing a more sophisticated approach to account for the interdependence of HOFs. Moreover, EM is a critical parameter that heavily influences the model outcome and thus needs more robust data to define. The current methodology simplifies the checking procedure, which could be modelled as a task itself, allowing for the determination of checking efficiency through its task HEP. Different types of checking procedures can also be added to the simulation. Furthermore, while this study focused on a single structural component, future efforts could extend the model to more complex structures, thereby enabling a detailed examination of vulnerable structural connections that are prone to human error.

6

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes this research and provides an outlook for future research. Answers to all the research questions are summarized. Insights are raised based on the findings of this study. Additionally, future research works are recommended.

6.1. CONCLUSIONS

THE research presented in this dissertation analyzes the critical HOFs behind human errors in the structural design and construction process. It steps forward from the existing studies that stopped at the human error level by taking on a socio-technical systems perspective towards structural safety. It focuses on identifying the critical HOFs and quantifying their impacts on the likelihood of human error occurrence. Moreover, this study develops an innovative methodology to assess the dynamic and nonlinear influence of these HOFs on structural reliability. As a result, this research enhances structural reliability analysis by incorporating human reliability analysis to account for the non-technical human and organizational influences. In addition, the findings from this study provide insights into the influential HOF and error-prone task combinations in structural design and construction, assisting risk-informed structural safety management in practice.

A summary of answers to the research questions raised in each chapter is presented in the following.

Chapter 1 This chapter provides a general introduction to the research subject of this study.

Chapter 2 This chapter reviewed the knowledge development and the state-of-the-art on the research topic of HOFs and human error influencing structural safety. It aims to answer research question RQ1:

> *"What are the HOFs that have been identified in existing studies? And how are the impacts of human errors on structural reliability evaluated?"*

Initially, scholars introduced mathematical and probabilistic approaches to account for the human error effects, primarily modelled as variations in the structure's load and resistance parameters. These variations are error scenario dependent. Thus, the structure reliability is calculated based on the error-modified parameters. Another approach integrated uncertainties associated with human errors into the existing reliability distributions. Both approaches incorporate error-induced uncertainties in the reliability assessment. Apart from this, fuzzy theory and Bayesian theory have also been employed to include human error influence in structural safety evaluation. Additionally, efforts were made to quantify the HEP within structural engineering tasks, evolving from initial approximations using well-known distributions to more sophisticated human reliability methods. These methods further enhanced the HEP estimation for tasks and structural reliability analysis when combined with simulation models. Further studies explored the integration of existing HRA methods from the nuclear industry to structural reliability analysis. Interestingly, the first comprehensive method that goes beyond human error and analyzes the HOFs' impacts on structural reliability is found in the offshore industry. An overview showing the key points (e.g., method used, structure type, focused phase) of the reviewed human error effect modelling studies is presented in Fig. A.1 in Appendix A.

With regard to the identification of HOFs that affect structural safety, primitive studies reviewed structural failure cases to spot common contributing factors. The widely identified factors include, to name a few, knowledge, qualified personnel, communication, and supervision. Subsequent research recognized the distinctions and interrelations among these causal factors, thereby categorizing them into human-oriented and management-oriented factors. This led to the development of structured models and frameworks that integrate a refined assembly of HOFs. More recently, the potential impacts of technological advancements such as the application of BIM, over-reliance on computer analysis, and information overload have become the latest concerns for structural safety. An overview of the acknowledged HOFs from existing studies is presented in Chapter 2, Fig. 2.3. This comprehensive collection of HOFs can assist in hazard identification in engineering practice for the AEC industry.

Chapter 3 This chapter identified the critical HOFs in each GTT of the structural design and construction process in the Dutch construction industry. It aims to answer research question RQ2:

> *"What are the critical HOFs in structural design and construction tasks that influence structural safety?"*

Based on the broad literature review in Chapter 2, the HOPE framework that encompasses human factors, organizational factors, project factors, and environmental factors is introduced. It is a comprehensive, hierarchical taxonomy of latent factors behind human errors, facilitating qualitative structural failure risk analysis and management guidance for practitioners in the AEC industry. Moreover, 14 GTTs in the structural design and construction process are summarized based on a task analysis. More importantly, the critical HOFs that lead to high human error potential in each GTT are identified through a survey study in the Dutch construction industry, as shown in Chapter 3, Fig. 3.6. Several HOFs are recognized as critical for every GTT, including *professional competence*, *well-being for duty*, *complexity*, and *attitude*. Findings from this research yield an enhanced understanding of task-specific underlying conditions contributing to human errors. The identified critical HOFs can assist professionals in implementing more effective quality assurance measures for structural safety within structural design and construction.

Chapter 4 This chapter quantified the HOFs' impacts on the likelihood of human error occurrence, aimed at answering research question RQ3:

> *"How much do the critical HOFs contribute to human error occurrence?"*

This study measures the impacts of the critical HOFs, as identified in Chapter 3, on human error occurrence in structural design and construction tasks. Via an SEJ involving experts in the Dutch construction industry, survey results are obtained employing the CM. The negative and positive effects of HOFs on task HEP are quantified as multipliers, as listed in Chapter 4, Table 4.1. The results reveal that *well-being for duty*, *organizational characteristics*, and *fragmentation* are the primary factors associated with the highest negative effects on task performance. On the other hand, the factors *complexity*, *attitude*, and *well-being for duty* demonstrate considerable potential of positive influence to decrease the human error occurrence probability. These results offer valuable insights for quality assurance strategies in practice and provide parametric references for a potential quantitative human error risk assessment.

Chapter 5 This chapter developed a methodology to model the influence of critical HOFs on structural reliability. It aims to answer research question RQ4:

> *"How and how much do the critical HOFs affect structural reliability?"*

This chapter proposed a methodology that enables the modelling of the dynamic and nonlinear influence of HOFs on structural reliability. It contributes to a quantitative approach towards enhanced structural reliability analysis by bridging human reliability to structural reliability to account for the human and organizational influences in the structural design and construction process on structural safety. This task-based simulation model integrates several methods involving task analysis, HRA method, error effects simulation, checking procedure simulation, and structural reliability analysis, as shown in Chapter 5, Fig. 5.1. A case study of a simply supported flat floor slab has been carried out to illustrate this proof-of-concept methodology. It is found that with checks performed after each task, a small portion (7.4%) of the calculated structural failure probabilities deviated towards a larger value from the error-free "correct" failure probability under the influence of HOFs, whilst this proportion is much higher (22%) when checking is absent. This demonstrates the impact of HOFs on structural reliability and the critical role of checking as an effective quality assurance measure. Furthermore, the simulation outcomes reveal the critical HOF and GTT combinations that are impactful on the reliability of this case structure. It is observed that the structural failure probability is more sensitive to the situations when a bad *attitude* affects *communication* task and when *engineering climate* negatively affects the diagnosis type of task. As a result, the outcomes of applying this methodology can optimize resource allocation strategies for better quality and safety assurance in the AEC industry's practice.

6.2. RECOMMENDATIONS FOR FUTURE RESEARCH

GIVEN the insights gained in this study, some future research works are suggested in the following.

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. In addition, the proposed method only modelled the scenario of a single error in one task. However, the case of error combinations in one task and their impacts on structural parameters need further study.

2. The growing application of emerging technologies like BIM, AI, 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. Consequently, their impacts on task performance, error occurrence, and structural safety need further investigation.

3. The HOFs impacts should be validated with other forms of data sources. Due to the limitations of the SEJ study, the HOFs' impacts were measured based on a checking task, with an assumption of its relevance to broader structural design and construction tasks. Future research is required to validate this assumption. Moreover, the HOFs' influence ought to be assessed in a more complex setting, considering various task types and error modes. Thus, creating other forms of data sources than expert judgement, such as task record data and experiment data, for HEP estimation in the construction industry is a worthwhile future endeavour to validate the results of this study.

4. The future development of a quantitative HRA method tailored specifically to assess human reliability for tasks in the AEC industry is in need. The identified critical HOFs and quantified HOFs' impacts can serve as initial parametric inputs for the development of such an HRA. Though a preliminary dynamic HRA is proposed in Chapter 5, the dependencies between HOFs are inadequately addressed. Many researchers have added Bayesian Networks in HRA to account for the factor's dependency. However, its tree structure restricted the modelling of the non-linear inter-correlations among factors. Alternatively, agent-based modelling is a promising approach to model this dependency in a dynamic HRA.

5. Data on how much the structural parameters are affected under error impacts are absent (EM data). Most existing models either avoid detailed demonstrations in this regard or make assumptions about this important variable. This crucial information should receive more research attention, given its potential to heavily influence the outcomes of the structural reliability analysis. Thus, a careful investigation into reliable EM data is desired. On one hand, experiments could be conducted to obtain such data. On the other hand, machine learning techniques can be applied to gain insights from historic failure data.

6. In the developed methodology, the checking procedure is modelled with simple probabilistic representations. However, given the known NHEP and the identified influencing HOFs for the checking task, it is feasible to simulate the checking process as an independent task. This approach allows for the calculation of the checking task's HEP, which determines the success of the checking process. This provides a more realistic depiction of the performance of the checking task. Additionally, different types of checking, such as normal supervision and third-party checking, can be integrated into the design and construction simulation process. As a result, insights into effective and cost-efficient checking (combination) procedures can be obtained.

7. The studied structures are mostly one structural element or an overly simplified structure that consists of limited structural members. The analysis of a realistic structure composed of multiple elements on a more detailed level could be explored with the assistance of sophisticated structural analysis software. In this case, the critical structural connections can also be investigated. Moreover, the HOFs' impacts on the involved structural elements can be incorporated into the reliability analysis of the entire structure. This comprehensive risk assessment

can act as a proactive safety measure, providing insights into the critical structural parts and related tasks.

8. Despite insights derived from numerous structural failures, it is evident that previously recognized failure sources continue to play a role, indicating inadequate learning and transfer of knowledge into practical quality assurance protocols. Thus, it is recommended that a just culture in the AEC industry be promoted and that research be conducted regarding how to integrate the HOF's impact analysis results into concrete and practical risk-informed decision-making, proactive safety management programs, and effective quality assurance measures for practice.

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ACRONYMS

ABM Agent-Based Modelling.

AEC Architecture, Engineering, and Construction.

AHP Analytic Hierarchy Process.

APJ Absolute Probability Judgement.

ASEP Accident Sequence Evaluation Program.

ATHEANA A Technique for Human Event Analysis.

CDF Cumulative Distribution Function.

CM-SEJ Classical Model for Structured Expert Judgement.

CPC Common Performance Condition.

CREAM Cognitive Reliability and Error Analysis Method.

DM Decision Maker.

DSB Dutch Safety Board.

EM Error Magnitude.

EQ EQual weight decision maker.

FMEA Failure Mode and Effect Analysis.

GEMS Generic Error Modelling System.

GL GLobal weight decision maker.

GTT Generic Task Type.

HEART Human Error Assessment and Reduction Technique.

HEP Human Error Probability.

HFACS Human Factors Analysis and Classification System.

HOE Human and Organizational Error.

HOF Human and Organizational Factor.

HOPE Human-Organization-Project-Environment.

HRA Human Reliability Analysis.

HREC Human Research Ethics Committee.

HTA Hierarchical Task Analysis.

IT ITem weight decision maker.

JCSS Joint Committee on Structural Safety.

LB Lower Bound.

MCDM Multi-Criterion Decision Making.

MCS Monte Carlo Simulation.

NARA Nuclear Action Reliability Assessment.

NHEP Nominal Human Error Probability.

PDF Probability Density Function.

PIF Performance Influencing Factor.

PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analysis.

PSF Performance Shaping Factor.

QMAS Quality Management Assessment System.

QRA Quantitative Risk Analysis.

RNG Random Number Generator.

SEJ Structured Expert Judgement.

SLIM Success Likelihood Index Method.

SMS Safety Management System.

SPAR-H Standardized Plant Analysis Risk-Human Reliability Analysis.

SRK Skill-Rule-Knowledge.

SYRAS SYstem Risk Analysis System.

THERP Technique for Human Error Rate Prediction.

UB Upper Bound.

A

MODEL REVIEW

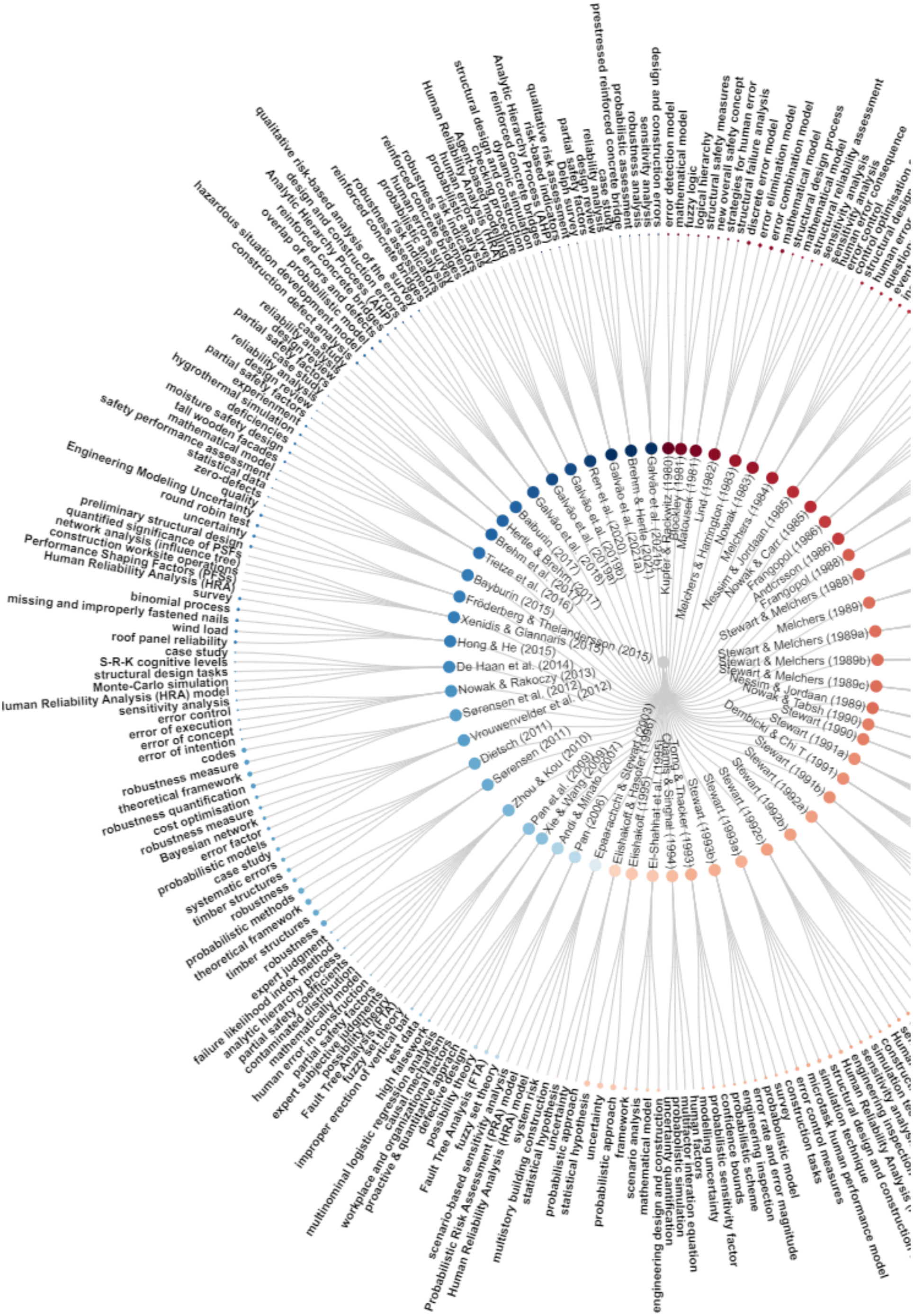
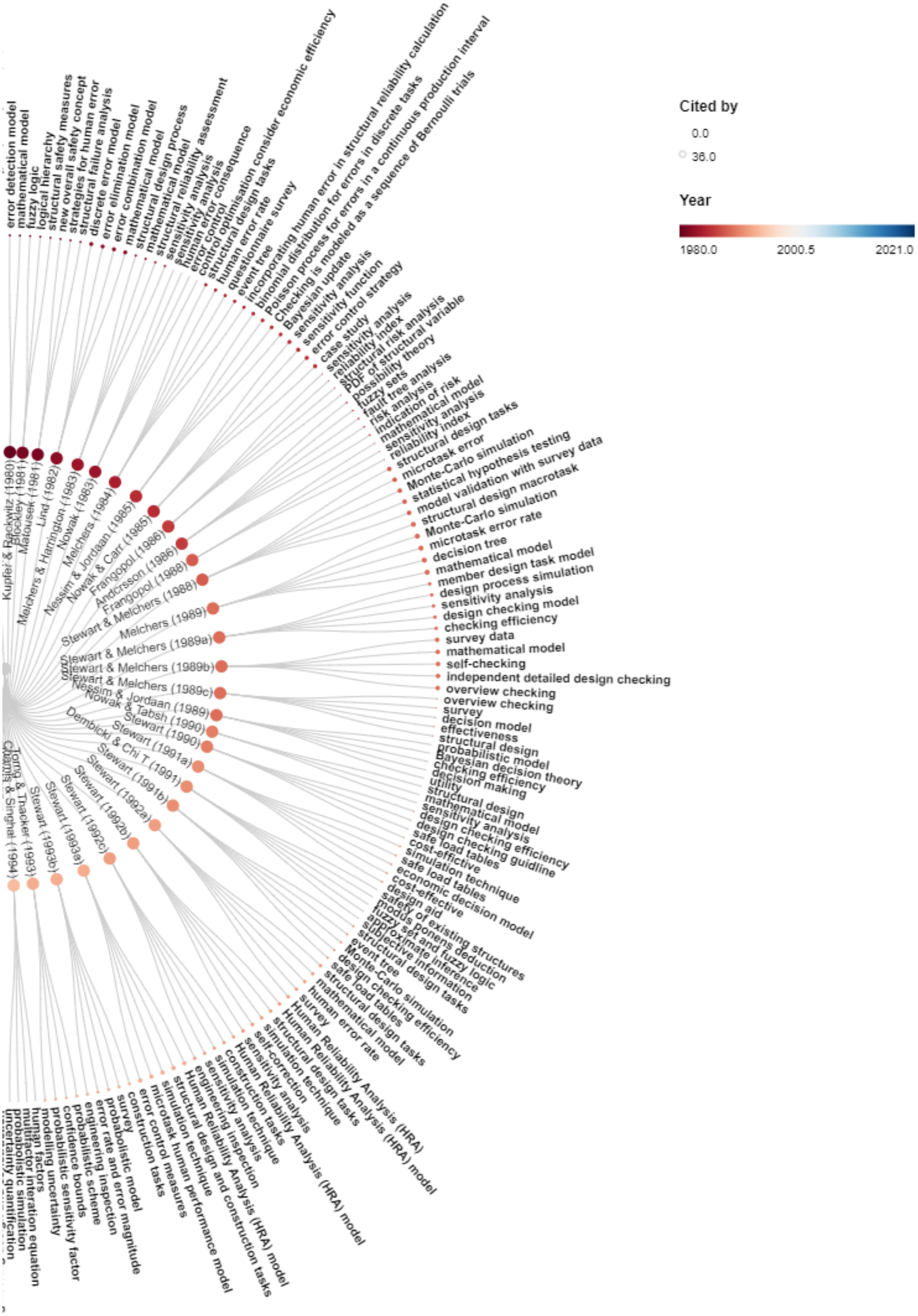


Figure A.1.: Overview of publications on modelling human error effects on structural reliability. The inner circle shows the publications, and the outer circle shows the keywords relating to the model or method (not author keywords). The dot colour indicates the publication time, and its size denotes the number of times it has been cited.


Cited by
0.0
36.0
Year
1980.0
2000.5
2021.0
error detection model
mathematical model
fuzzy logic
logical hierarchy
structural safety measures
new overall safety concept
strategies for human error
structural failure analysis
discrete error model
error elimination model
error combination model
mathematical model
structural model
structural design process
mathematical model
structural reliability assessment
sensitivity analysis
sensitivity analysis
human error control
error consequence
control optimisation consider economic efficiency
structural design tasks
human error rate
questionnaire survey
event tree
incorporating human error in structural reliability calculation
binomial distribution for errors in discrete tasks
Poisson process for errors in a continuous production interval
Checking is modeled as a sequence of Bernoulli trials
Bayesian update
sensitivity analysis
sensitivity function
error control strategy
case study
sensitivity analysis
reliability index
structural risk analysis
PDF of structural variable
possibility theory
fuzzy sets
fault tree analysis
risk analysis
indication of risk
mathematical model
sensitivity analysis
reliability index
structural design tasks
structural error
microtask error
Monte-Carlo simulation
statistical hypothesis testing
model validation with survey data
structural design macrotask
Monte-Carlo simulation
microtask error rate
decision tree
mathematical model
member design task model
design process simulation
sensitivity analysis
design checking model
checking efficiency
survey data
mathematical model
self-checking
independent detailed design checking
overview checking
overview checking
survey
decision model
effectiveness
structural design
probabilistic model
Bayesian decision theory
checking efficiency
decision making
utility
structural design
mathematical model
sensitivity analysis
design checking efficiency
design checking guidline
safe load tables
cost-effictive
simulation technique
safe load tables
economic decision model
cost-effective
design aid
safety of existing structures
modus ponens deduction
fuzzy set and fuzzy logic
approximate inference
subjective information
structural design tasks
event tree
Monte-Carlo simulation
design checking efficiency
safe load tables
structural design tasks
mathematical model
human error rate
survey
Human Reliability Analysis (HRA)
Human Reliability Analysis (HRA) model
structural design tasks
simulation technique
self-correction
sensitivity analysis
Human Reliability Analysis (HRA) model
construction tasks
simulation technique
sensitivity analysis
engineering inspection
Human Reliability Analysis (HRA) model
structural design and construction tasks
simulation technique
microtask human performance model
error control measures
construction tasks
survey
probabolistic model
error rate and error magnitude
engineering inspection
probabilistic scheme
confidence bounds
probabilistic sensitivity factor
modelling uncertainty
human factors
multifactor interation equation
probabolistic simulation
uncertainty quantification
Kupfer & Rackwitz (1980)
Blockley (1981)
Matousek (1981)
Lind (1982)
Melchers & Harrington (1983)
Nowak (1983)
Melchers (1984)
Nessim & Jordaan (1985)
Nowak & Carr (1985)
Frangopol (1986)
Andersson (1986)
Frangopol (1988)
Stewart & Melchers (1988)
Melchers (1989)
Stewart & Melchers (1989a)
Stewart & Melchers (1989b)
Stewart & Melchers (1989c)
Nessim & Jordaan (1989)
Nowak & Tabsh (1990)
Stewart (1990)
Dembicki & Chi T (1991)
Stewart (1991a)
Stewart (1991b)
Stewart (1992a)
Stewart (1992b)
Stewart (1992c)
Stewart (1993a)
Stewart (1993b)
Torng & Thacker (1993)
Chamis & Singhal (1994)

B

SURVEY-I

The next two questions concern the following task type:
Diagnosis based on knowledge / experience / situation (e.g. listing all load combinations)

Please indicate below, for each factor, how influential that factor is on causing (a) human error(s) when performing the type of task mentioned above.

	Not at all influential	Slightly influential	Somewhat influential	Very influential	Extremely influential
Professional competence	○	○	○	○	○
Trust	○	○	○	○	○
			○	○	○
Fit-for-duty	○	○	○	○	○
Comprehensive abilities	○	○	○	○	○
Information flow	○	○	○	○	○
Task management	○	○	○	○	○
Organizational characteristics	○	○	○	○	○
Quality control	○	○	○	○	○
Risk analysis and management	○	○	○	○	○
Engineering climate	○	○	○	○	○
Complexity	○	○	○	○	○
Stress	○	○	○	○	○
Fragmentation	○	○	○	○	○
Equipment	○	○	○	○	○
Working conditions	○	○	○	○	○

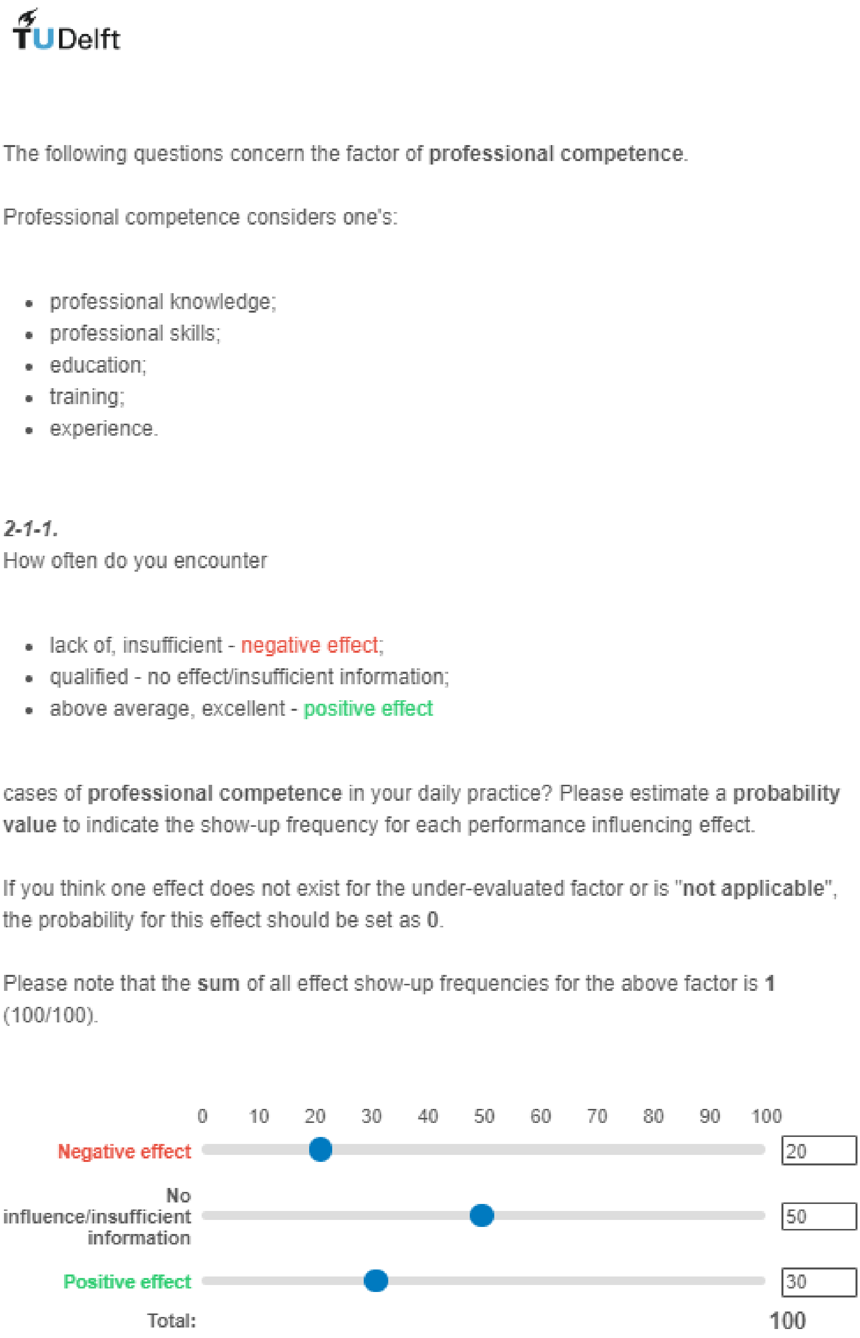
Whether or not the task performer is physically and mentally capable of accomplishing the task successfully. For instance, fatigue, drug effects and emotional instability might lead to errors while performing a task.

Are there any very influential factors for the above-mentioned task type that are not listed above? Please write them down in the blank box below.

Figure B.1.: Survey question example. The question description furnishes both the definition of the queried Generic Task Type (GTT) and an example task. Additionally, the definition of each factor is accessible to the respondent through an information box, which becomes visible when the cursor hovers over the respective factor label. The inclusion of this reference serves the purpose of enhancing the reliability of the collected data by establishing a shared understanding of the meaning of each factor and the aspects to be considered when providing the rating.

C

SURVEY-II



TUDelft

The following questions concern the factor of **professional competence**.

Professional competence considers one's:

- professional knowledge;
- professional skills;
- education;
- training;
- experience.

2-1-1.

How often do you encounter

- lack of, insufficient - negative effect;
- qualified - no effect/insufficient information;
- above average, excellent - positive effect

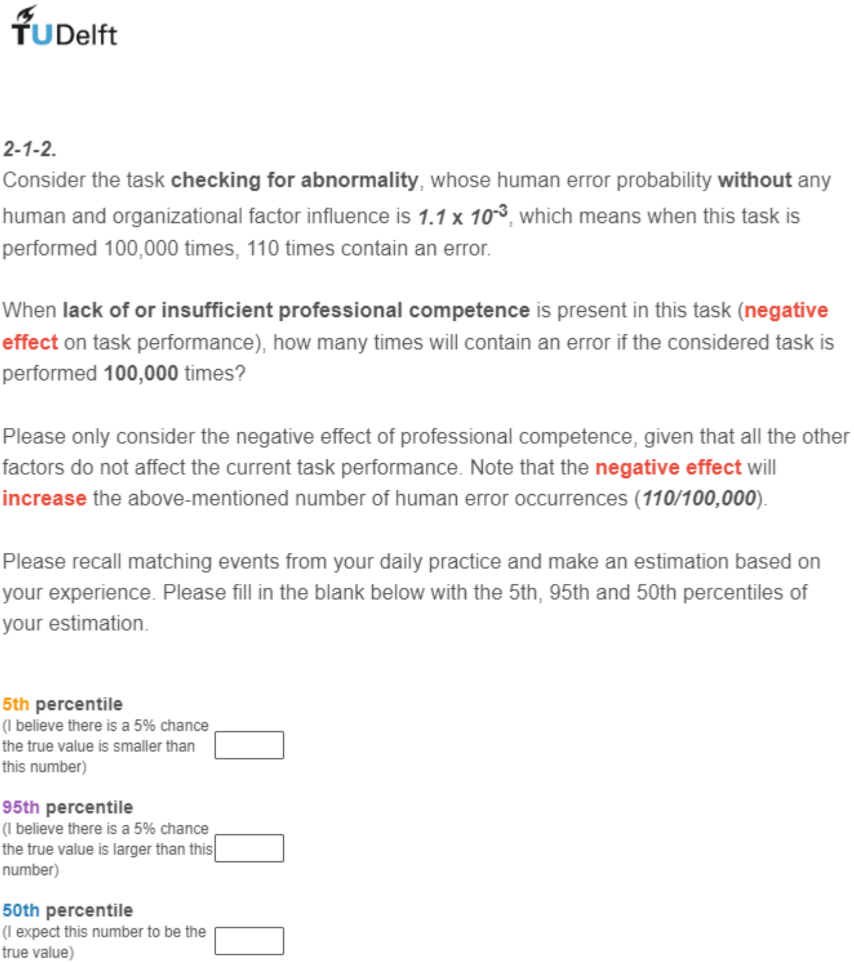
cases of **professional competence** in your daily practice? Please estimate a **probability value** to indicate the show-up frequency for each performance influencing effect.

If you think one effect does not exist for the under-evaluated factor or is "**not applicable**", the probability for this effect should be set as **0**.

Please note that the **sum** of all effect show-up frequencies for the above factor is **1** (100/100).

Negative effect	20
No influence/insufficient information	50
Positive effect	30
Total:	100

Figure C.1.: Example question from Survey-II for the SEJ study to elicit the present probability of HOFs' different impacts.



TU Delft

2-1-2.

Consider the task **checking for abnormality**, whose human error probability **without** any human and organizational factor influence is ***1.1 x*** 10^{-3}, which means when this task is performed 100,000 times, 110 times contain an error.

When **lack of or insufficient professional competence** is present in this task (**negative effect** on task performance), how many times will contain an error if the considered task is performed **100,000** times?

Please only consider the negative effect of professional competence, given that all the other factors do not affect the current task performance. Note that the **negative effect** will **increase** the above-mentioned number of human error occurrences (***110/100,000***).

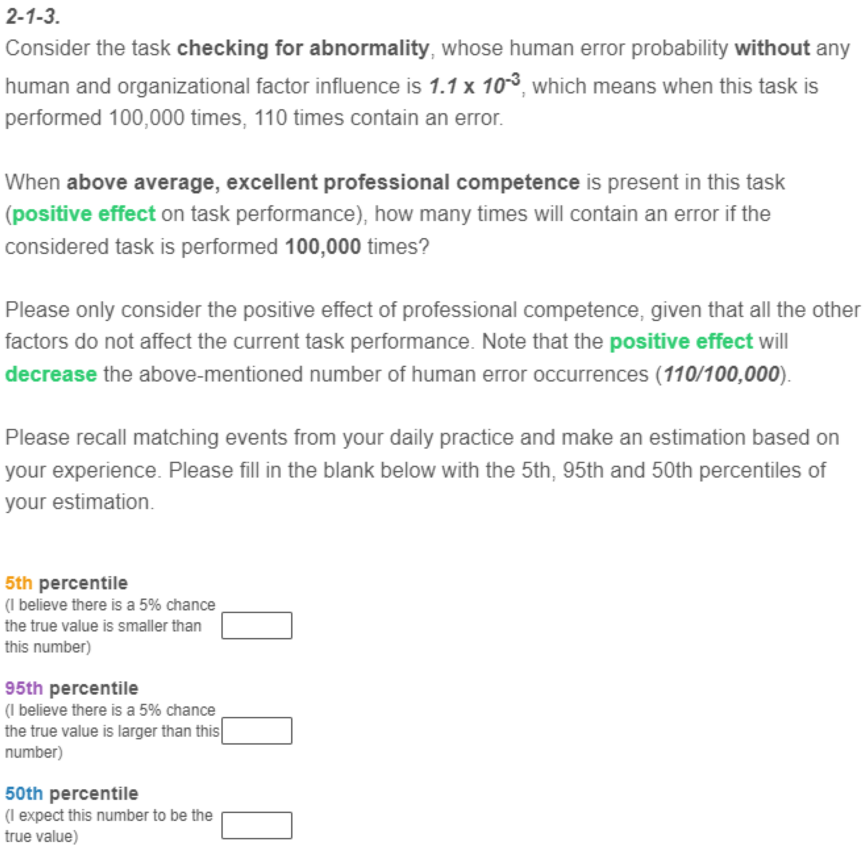
Please recall matching events from your daily practice and make an estimation based on your experience. Please fill in the blank below with the 5th, 95th and 50th percentiles of your estimation.

5th percentile
(I believe there is a 5% chance the true value is smaller than this number)

95th percentile
(I believe there is a 5% chance the true value is larger than this number)

50th percentile
(I expect this number to be the true value)

Figure C.2.: Example question from Survey-II to elicit the negative impacts of the *professional competence* factor.



2-1-3.

Consider the task **checking for abnormality**, whose human error probability **without** any human and organizational factor influence is 1.1×10^{-3}, which means when this task is performed 100,000 times, 110 times contain an error.

When **above average, excellent professional competence** is present in this task (**positive effect** on task performance), how many times will contain an error if the considered task is performed **100,000** times?

Please only consider the positive effect of professional competence, given that all the other factors do not affect the current task performance. Note that the **positive effect** will **decrease** the above-mentioned number of human error occurrences (***110/100,000***).

Please recall matching events from your daily practice and make an estimation based on your experience. Please fill in the blank below with the 5th, 95th and 50th percentiles of your estimation.

5th percentile
(I believe there is a 5% chance the true value is smaller than this number)

95th percentile
(I believe there is a 5% chance the true value is larger than this number)

50th percentile
(I expect this number to be the true value)

Figure C.3.: Example question from Survey-II to elicit the positive impacts of the *professional competence* factor.

Table C.1.: SEJ questions.

ID	Type[1]	Panel	Question
Q1-1	CQ	Panel 1&2	When the task of deriving a value from a table is performed 100,000 times, how many times contain an error of deriving the wrong value?
Q1-2	CQ	Panel 1&2	When the task of comparing and ranking numbers is performed 100,000 times, how many times contain an error of the wrong order?
Q1-3	CQ	Panel 1&2	When the task of one-step calculation is performed 100,000 times, how many times contain an error of incorrect result?
Q1-4	CQ	Panel 1&2	When the task of interpreting code into design requirements is performed 100,000 times, how many times contain an error of wrong interpretation?
Q1-5	CQ	Panel 1&2	When the task of placing reinforcing bars is performed 100,000 times, how many times contain an error resulting in reduced tensile steel area?
Q1-6	CQ	Panel 1&2	When the task of placing reinforcing bars is performed 100,000 times, how many times contain an error resulting in increased tensile steel area?
Q1-7	CQ	Panel 1&2	When the task of placing reinforcing bars is performed 100,000 times, how many times contain an error resulting in decreased effective depth to tensile steel?
Q1-8	CQ	Panel 1&2	When the task of placing reinforcing bars is performed 100,000 times, how many times contain an error resulting in increased effective depth to tensile steel?
Q1-9	CQ	Panel 1&2	When the task of preparing (configuring, mixing) concrete mix is performed 100,000 times, how many times contain an inadequate mix resulting in reduced concrete compressive strength after 28 days?
Q1-10	CQ	Panel 1&2	When the task of removing framework or shoring is performed 100,000 times, how many times contain an error of premature removal?
Q2-1-2	TQ	Panel 1&2	When lack of or insufficient professional competence is present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-1-3	TQ	Panel 1&2	When above average, excellent professional competence is present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-2-2	TQ	Panel 1&2	When bad communication, necessary information being not available, information overload are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?

ID	Type	Panel	Question
Q2-2-3	TQ	Panel 1&2	When good and in-time communication, clear and good quality information being available are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-3-2	TQ	Panel 1&2	When high complexity is present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-3-3	TQ	Panel 1&2	When low complexity is present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-4-2	TQ	Panel 1&2	When lack of or insufficient checking, supervision and procedures are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-4-3	TQ	Panel 1&2	When checking, supervision and procedures present and in good order are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-5-2	TQ	Panel 1	When a high workload, tight or insufficient time and budget are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-5-3	TQ	Panel 1	When a low workload, more than sufficient time and budget are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-6-2	TQ	Panel 1	When fatigue, unfit, unstable mental/emotional condition are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-6-3	TQ	Panel 1	When a fit, energetic, clear mind staff is present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-7-2	TQ	Panel 1	When a bad attitude, intentional violation of rules are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-7-3	TQ	Panel 1	When a very motivated and committed to the job and rules attitude is present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-8-2	TQ	Panel 1	When blind trust, overconfidence/over-reliance on others are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?

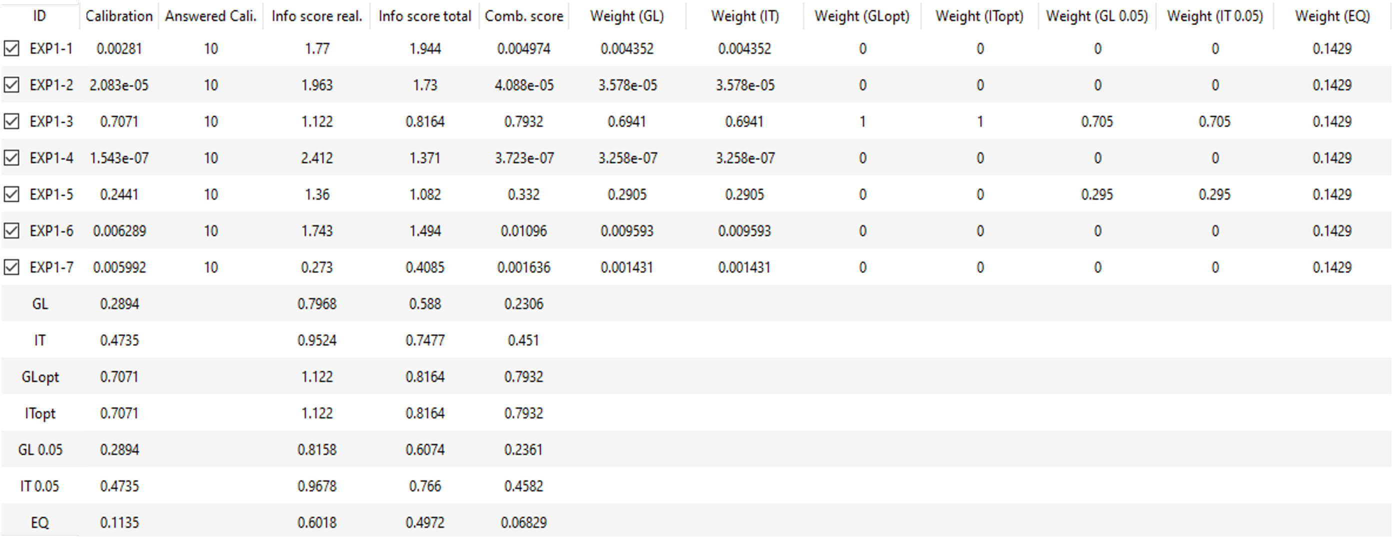
ID	Type	Panel	Question
Q2-8-3	TQ	Panel 1	When trusting while still adhering to procedure/verifying is present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-9-2	TQ	Panel 1	When lack of or insufficient comprehensive abilities are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-9-3	TQ	Panel 1	When above-average or excellent comprehensive abilities are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-5-2	TQ	Panel 2	When unclear structural safety goals, structural safety goals not put to a prioritized position, underdeveloped safety culture, a safety engineering climate not integrated into daily practice are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-5-3	TQ	Panel 2	When clear and prioritized structural safety goals, mature safety culture well integrated into practice and keep improved are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-6-2	TQ	Panel 2	When high fragmentation, frequent personnel change, lack of project overview and network thinking, low planning and coordinating capability are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-6-3	TQ	Panel 2	When low fragmentation, seldom personnel change, possessing project overview and network thinking, high planning and coordinating capability are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-7-2	TQ	Panel 2	When chaotic and unstable organization, complex organizational structure, needed support from the parent company not available, redundant team size, confusing allocation of responsibilities are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-7-3	TQ	Panel 2	When clear, simple and stable organization, available support from the parent company, small and effective team size, clear responsibility allocation are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?

ID	Type	Panel	Question
Q2-8-2	TQ	Panel 2	When needed equipment being not available or in bad condition (cannot perform as designed), equipment with bad ergonomics or misleading Human-Machine-Interface are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-8-3	TQ	Panel 2	When the right equipment being available and in good condition, with good ergonomics are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-9-2	TQ	Panel 2	When bad or disrupting working conditions are present in this task (negative effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?
Q2-9-3	TQ	Panel 2	When very good and promoting working conditions are present in this task (positive effect on task performance), how many times will contain an error if the considered task is performed 100,000 times?

[1] CQ denotes the Calibration question and TQ denotes the Target question.

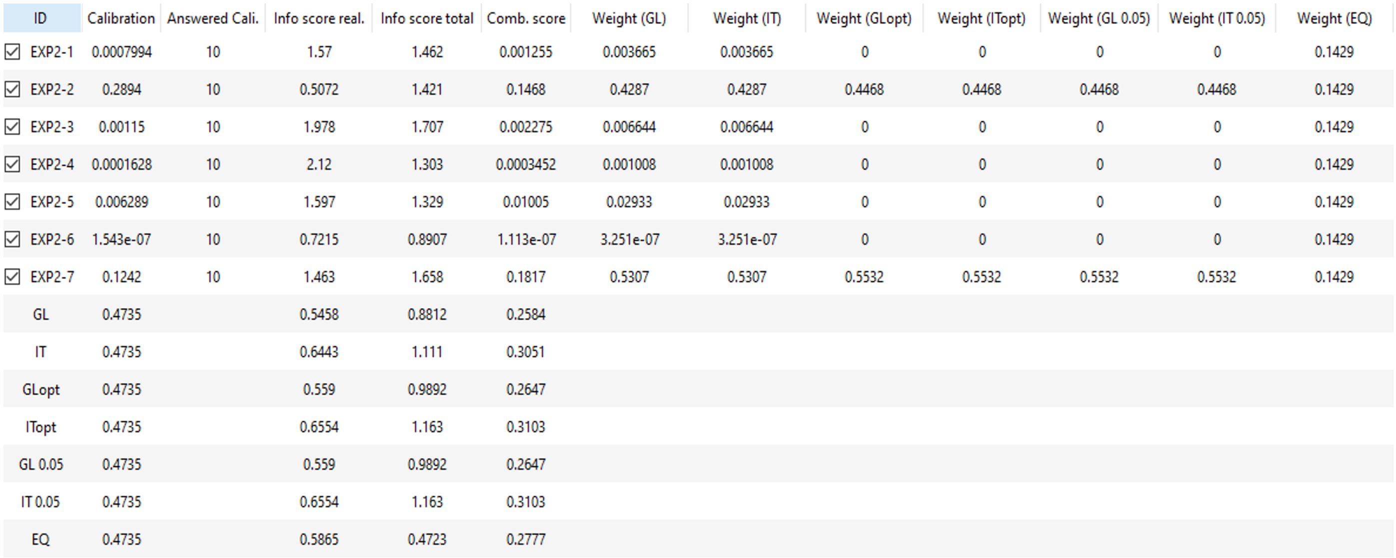
D

SEJ STUDY EXPERT WEIGHTS AND ESTIMATION RESULTS



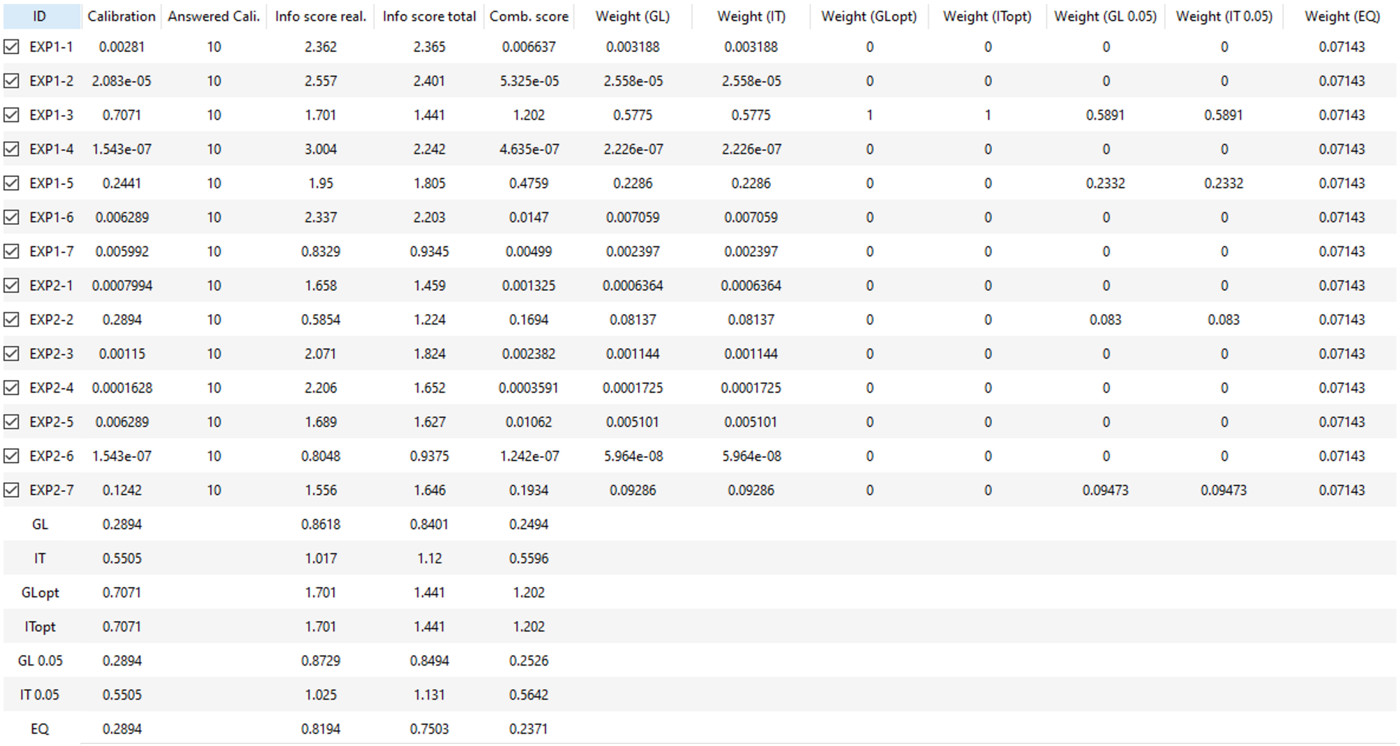
ID	Calibration	Answered Cali.	Info score real.	Info score total	Comb. score	Weight (GL)	Weight (IT)	Weight (GLopt)	Weight (ITopt)	Weight (GL 0.05)	Weight (IT 0.05)	Weight (EQ)
☑ EXP1-1	0.00281	10	1.77	1.944	0.004974	0.004352	0.004352	0	0	0	0	0.1429
☑ EXP1-2	2.083e-05	10	1.963	1.73	4.088e-05	3.578e-05	3.578e-05	0	0	0	0	0.1429
☑ EXP1-3	0.7071	10	1.122	0.8164	0.7932	0.6941	0.6941	1	1	0.705	0.705	0.1429
☑ EXP1-4	1.543e-07	10	2.412	1.371	3.723e-07	3.258e-07	3.258e-07	0	0	0	0	0.1429
☑ EXP1-5	0.2441	10	1.36	1.082	0.332	0.2905	0.2905	0	0	0.295	0.295	0.1429
☑ EXP1-6	0.006289	10	1.743	1.494	0.01096	0.009593	0.009593	0	0	0	0	0.1429
☑ EXP1-7	0.005992	10	0.273	0.4085	0.001636	0.001431	0.001431	0	0	0	0	0.1429
GL	0.2894		0.7968	0.588	0.2306							
IT	0.4735		0.9524	0.7477	0.451							
GLopt	0.7071		1.122	0.8164	0.7932							
ITopt	0.7071		1.122	0.8164	0.7932							
GL 0.05	0.2894		0.8158	0.6074	0.2361							
IT 0.05	0.4735		0.9678	0.766	0.4582							
EQ	0.1135		0.6018	0.4972	0.06829							

Figure D.1.: Scores and weights for Panel 1 experts.



ID	Calibration	Answered Cali.	Info score real.	Info score total	Comb. score	Weight (GL)	Weight (IT)	Weight (GLopt)	Weight (ITopt)	Weight (GL 0.05)	Weight (IT 0.05)	Weight (EQ)
☑ EXP2-1	0.0007994	10	1.57	1.462	0.001255	0.003665	0.003665	0	0	0	0	0.1429
☑ EXP2-2	0.2894	10	0.5072	1.421	0.1468	0.4287	0.4287	0.4468	0.4468	0.4468	0.4468	0.1429
☑ EXP2-3	0.00115	10	1.978	1.707	0.002275	0.006644	0.006644	0	0	0	0	0.1429
☑ EXP2-4	0.0001628	10	2.12	1.303	0.0003452	0.001008	0.001008	0	0	0	0	0.1429
☑ EXP2-5	0.006289	10	1.597	1.329	0.01005	0.02933	0.02933	0	0	0	0	0.1429
☑ EXP2-6	1.543e-07	10	0.7215	0.8907	1.113e-07	3.251e-07	3.251e-07	0	0	0	0	0.1429
☑ EXP2-7	0.1242	10	1.463	1.658	0.1817	0.5307	0.5307	0.5532	0.5532	0.5532	0.5532	0.1429
GL	0.4735		0.5458	0.8812	0.2584							
IT	0.4735		0.6443	1.111	0.3051							
GLopt	0.4735		0.559	0.9892	0.2647							
ITopt	0.4735		0.6554	1.163	0.3103							
GL 0.05	0.4735		0.559	0.9892	0.2647							
IT 0.05	0.4735		0.6554	1.163	0.3103							
EQ	0.4735		0.5865	0.4723	0.2777							

Figure D.2.: Scores and weights for Panel 2 experts.



ID	Calibration	Answered Cali.	Info score real.	Info score total	Comb. score	Weight (GL)	Weight (IT)	Weight (GLopt)	Weight (ITopt)	Weight (GL 0.05)	Weight (IT 0.05)	Weight (EQ)
☑ EXP1-1	0.00281	10	2.362	2.365	0.006637	0.003188	0.003188	0	0	0	0	0.07143
☑ EXP1-2	2.083e-05	10	2.557	2.401	5.325e-05	2.558e-05	2.558e-05	0	0	0	0	0.07143
☑ EXP1-3	0.7071	10	1.701	1.441	1.202	0.5775	0.5775	1	1	0.5891	0.5891	0.07143
☑ EXP1-4	1.543e-07	10	3.004	2.242	4.635e-07	2.226e-07	2.226e-07	0	0	0	0	0.07143
☑ EXP1-5	0.2441	10	1.95	1.805	0.4759	0.2286	0.2286	0	0	0.2332	0.2332	0.07143
☑ EXP1-6	0.006289	10	2.337	2.203	0.0147	0.007059	0.007059	0	0	0	0	0.07143
☑ EXP1-7	0.005992	10	0.8329	0.9345	0.00499	0.002397	0.002397	0	0	0	0	0.07143
☑ EXP2-1	0.0007994	10	1.658	1.459	0.001325	0.0006364	0.0006364	0	0	0	0	0.07143
☑ EXP2-2	0.2894	10	0.5854	1.224	0.1694	0.08137	0.08137	0	0	0.083	0.083	0.07143
☑ EXP2-3	0.00115	10	2.071	1.824	0.002382	0.001144	0.001144	0	0	0	0	0.07143
☑ EXP2-4	0.0001628	10	2.206	1.652	0.0003591	0.0001725	0.0001725	0	0	0	0	0.07143
☑ EXP2-5	0.006289	10	1.689	1.627	0.01062	0.005101	0.005101	0	0	0	0	0.07143
☑ EXP2-6	1.543e-07	10	0.8048	0.9375	1.242e-07	5.964e-08	5.964e-08	0	0	0	0	0.07143
☑ EXP2-7	0.1242	10	1.556	1.646	0.1934	0.09286	0.09286	0	0	0.09473	0.09473	0.07143
GL	0.2894		0.8618	0.8401	0.2494							
IT	0.5505		1.017	1.12	0.5596							
GLopt	0.7071		1.701	1.441	1.202							
ITopt	0.7071		1.701	1.441	1.202							
GL 0.05	0.2894		0.8729	0.8494	0.2526							
IT 0.05	0.5505		1.025	1.131	0.5642							
EQ	0.2894		0.8194	0.7503	0.2371							

Figure D.3.: Scores and weights for all experts.

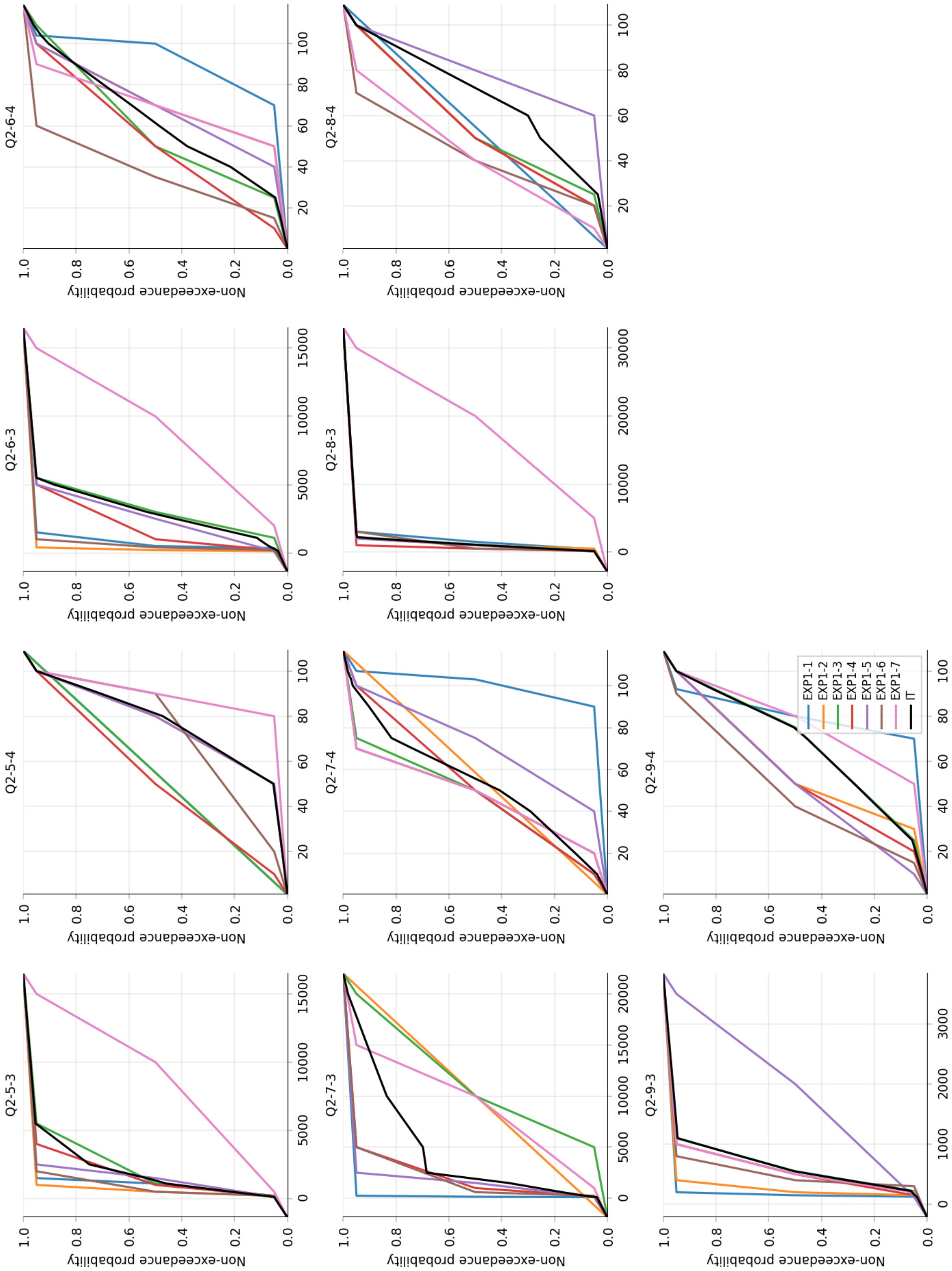


Figure D.4.: The elicited CDFs of the expert's estimates by Panel 1 experts and the aggregated IT.

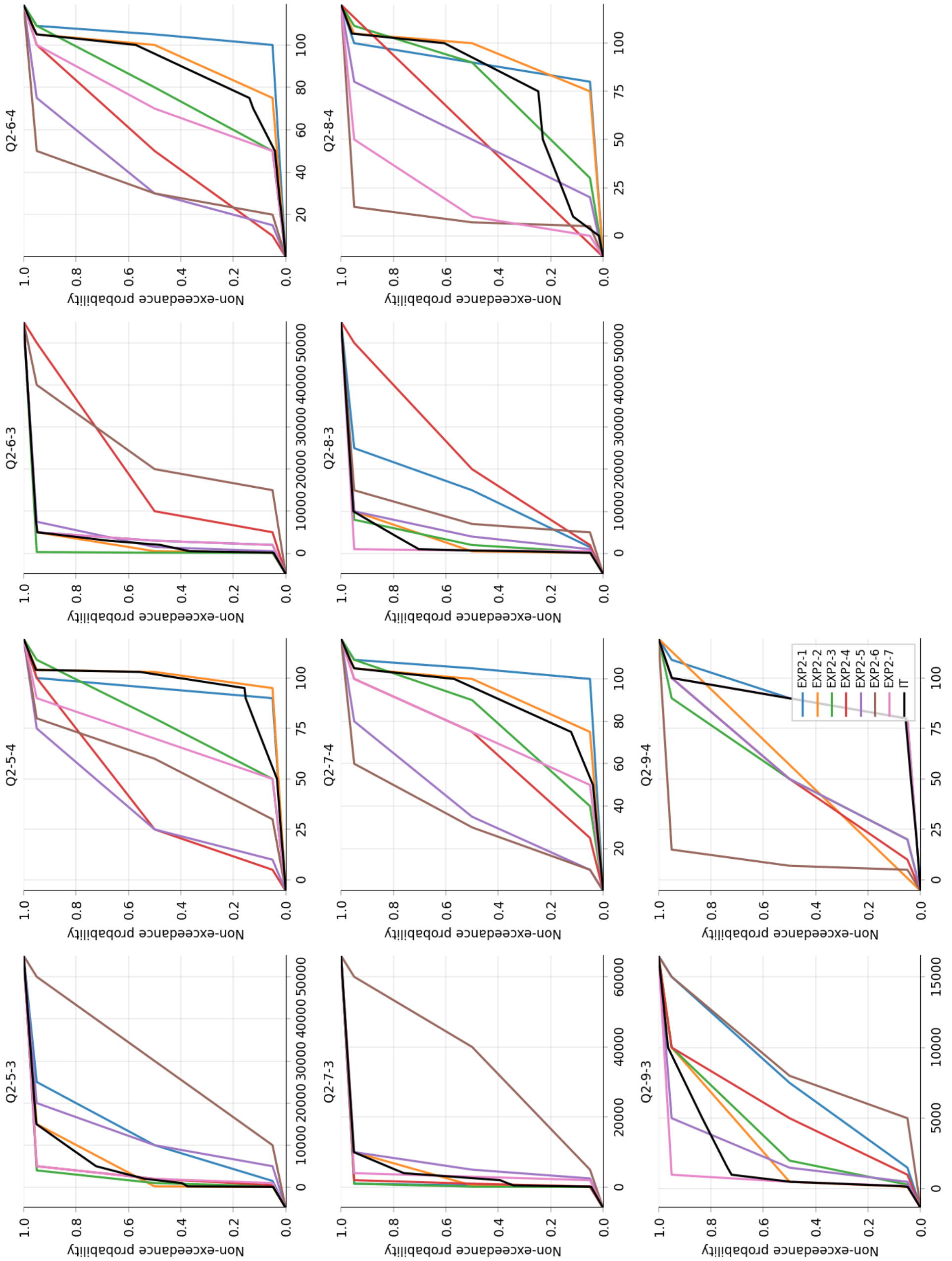


Figure D.5.: The elicited CDFs of the expert's estimates by Panel 2 experts and the aggregated IT.

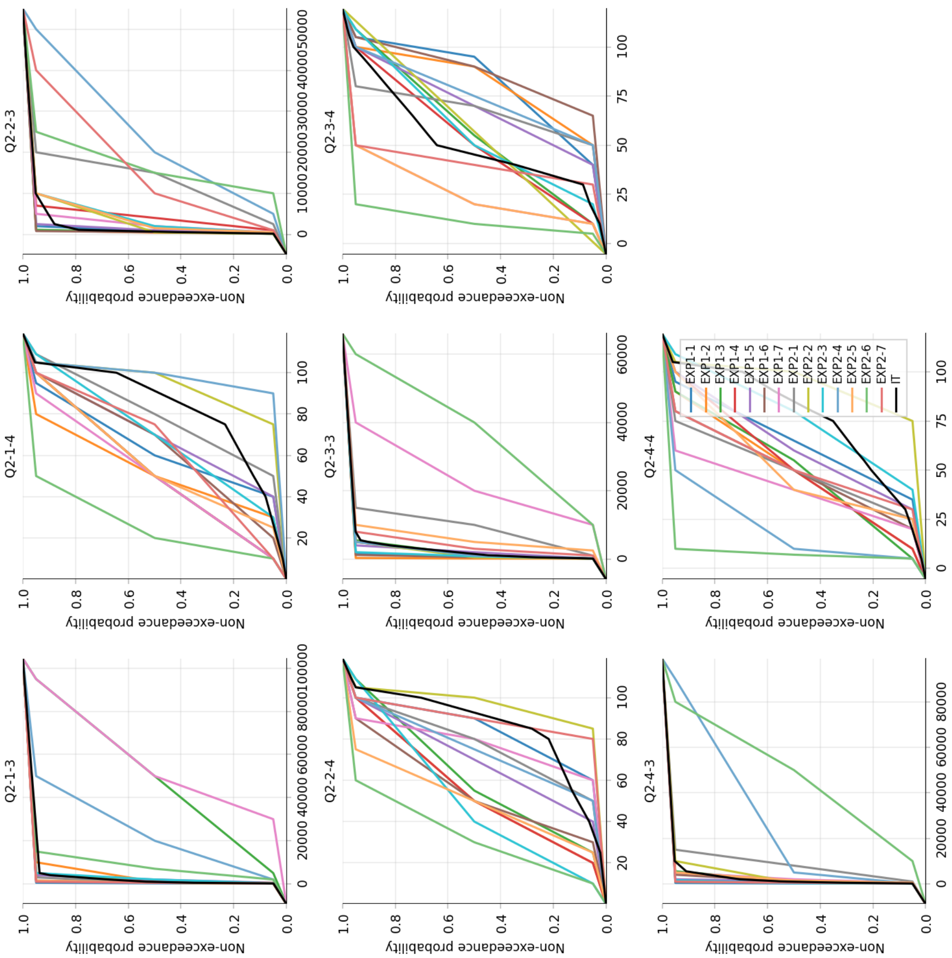
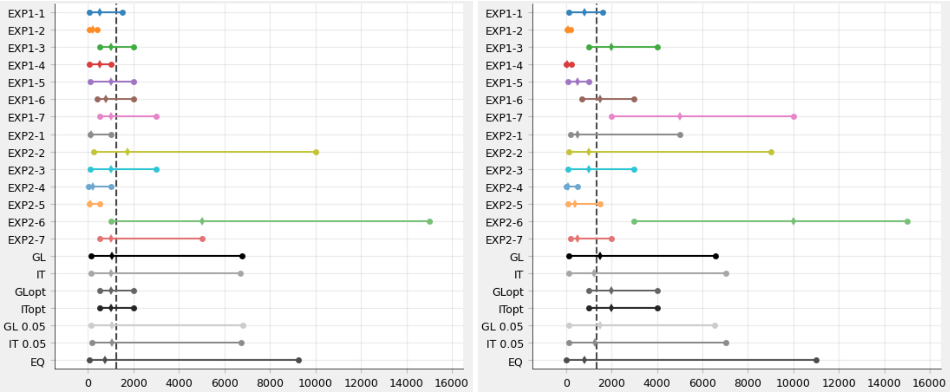
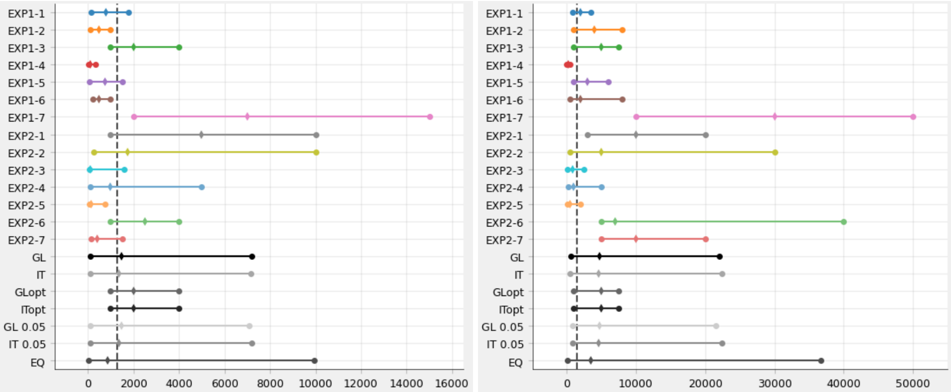


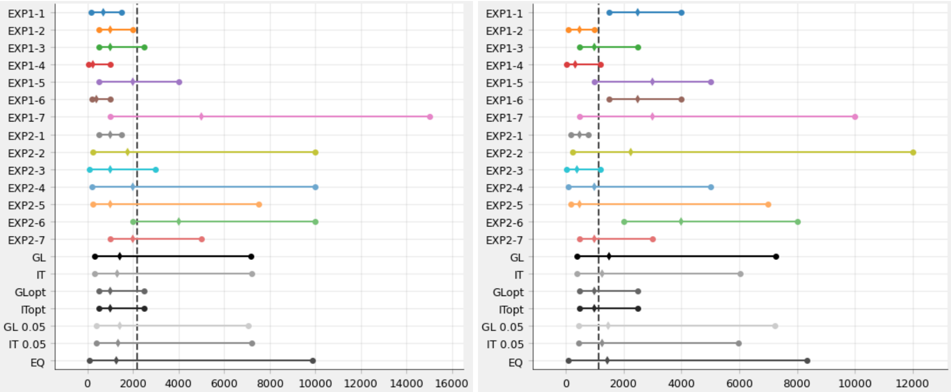
Figure D.6.: The elicited CDFs of the expert's estimates by Panel 1&2 experts and the aggregated IT.



(a) Q1-1 (b) Q1-2

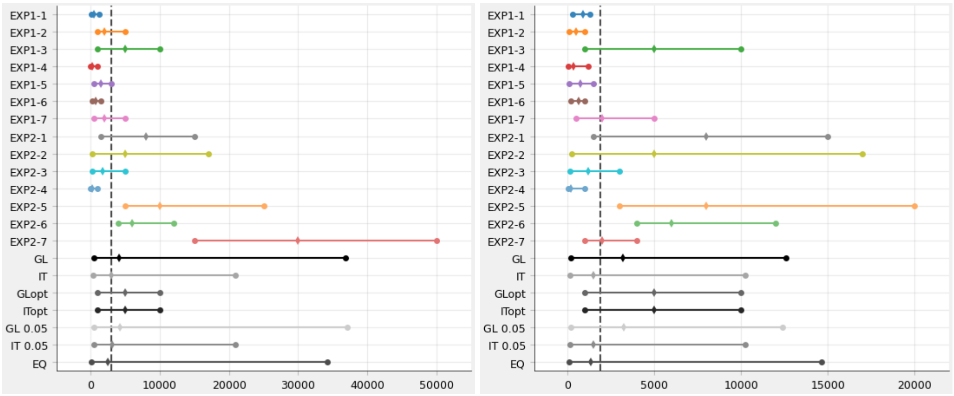


(c) Q1-3 (d) Q1-4

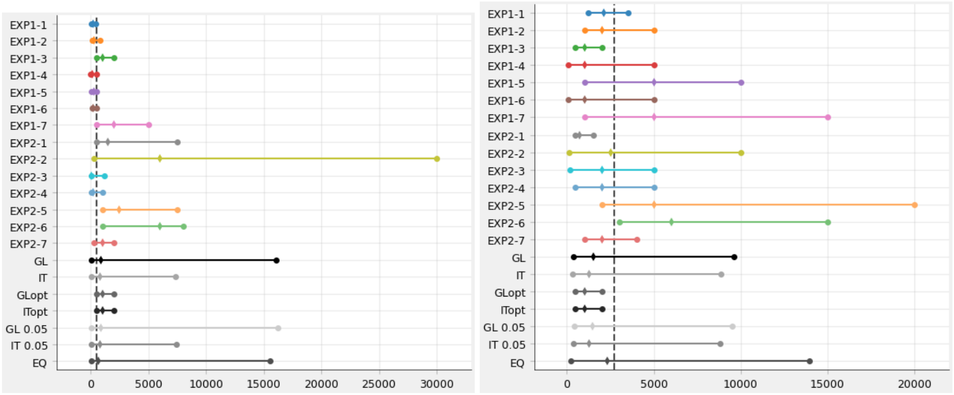


(e) Q1-5 (f) Q1-6

Figure D.7.: Continues on next page.



(a) Q1-7 (b) Q1-8



(c) Q1-9 (d) Q1-10

Figure D.7.: (Continued) Expert judgements and the aggregated DMs compared with the realizations for the calibration questions. In each sub-figure, the x-axis shows how many times contain an error out of the 100,000 repetition of the task; the y-axis displays the experts and DMs. The horizontal segment lines exhibit the elicited 90% confidence intervals and the dotes within the segments denote the best estimates. The vertical dash line shows the realization for each calibration question.

E

CASE STUDY

Table E.1.: Micro-tasks of the cast in-situ slab structural design and construction process.

name	description	type	scenarios and likelihoods
D1	Determine slab span	T1	D1-S1&0.5;D1-S2&0.5
D3	Determine structural scheme	T4	D3-S1&1
D7	Exposure classification and durability requirements	T2	D7-S1&0.5;D7-S2&0.5
D10	Determine critical load case	T4	D10-S1&0.5;D10-S2&0.5
D12	Determine loads combination partial safety factor	T1	D12-S1&0.5;D12-S2&0.5
D13	Determine concrete quality	T3	D13-S1&0.5;D13-S2&0.5
D14	Determine steel quality	T3	D14-S1&0.5;D14-S2&0.5
D15	Determine material strength partial safety factor	T1	D15-S1&0.5;D15-S2&0.5
D16	Determine slab height with design rule	T1	D16-S1&0.5;D16-S2&0.5
D17	Calculate self weight	T5	D17-S1&0.5;D17-S2&0.5
D18	Calculate design moment	T5	D18-S1&0.5;D18-S2&0.5
D20	Assume reinforcement diameter	T1	D20-S1&0.5;D20-S2&0.5
D21	Determine concrete cover	T1	D21-S1&0.5;D21-S2&0.5
D22	Estimate effective height	T1	D22-S1&0.5;D22-S2&0.5
D23	Calculate required reinforcement area	T5	D23-S1&0.5;D23-S2&0.5
D27	Round up As to a practical value	T3	D27-S1&0.5;D27-S2&0.5
D28	Check maximum reinforcement area if necessary increase floor height or concrete quality	T6	D28-S1&0.5;D28-S2&0.5
D33	Calculate moment resistance	T5	D33-S1&0.5;D33-S2&0.5
D42	Draw floor plan and sections	T7	D42-S1&1
D51	Write floor specifications and installation instructions	T8	D51-S1&1

continues on next page

Table E.1.: Tasks that were identified within the case study (*continued from previous page*).

name	description	type	scenarios and likelihoods
D57	design briefing to main contractor	T13	D57-S1&1
C1	Consult design and specifications	T10	C1-S1&1
C2	Set out dimensions	T11	C2-S1&1
C3	Placing temporary struts and moulds	T9	C3-S1&1
C4	Placing bottom reinforcement and top reinforcement with distance holders	T9	C4-S1&0.25;C4-S2&02.5;C4-S3&0.25;C4-S4&0.25
C5	Prepare concrete mix	T12	C5-S1&0.5;C5-S2&0.5
C6	Cast concrete	T12	C6-S1&0.5;C6-S2&0.5
C7	Cure concrete	T9	C7-S1&1
C8	Remove temporary struts and moulds	T9	C8-S1&1

Table E.2.: Scenarios that are deemed possible to occur after an error occurs within a micro-task.

task	name	description	increasing parameters	decreasing parameters	deviating parameters
D1	D1-S1	Design slab span longer than conceptual design	L		
D1	D1-S2	Design slab span shorter than conceptual design		L	
D3	D3-S1	Wrong boundary conditions			Θ_E
D7	D7-S1	Reliability index larger	Θ_E		
D7	D7-S2	Reliability index smaller		Θ_E	
D10	D10-S1	Design load case magnitude higher than reality	q_{st}		
D10	D10-S2	Design load case magnitude lower than reality		q_{st}	
D12	D12-S1	Choose a higher safety factor for a load case	Θ_E		
D12	D12-S2	Choose a lower safety factor for a load case		Θ_E	
D13	D13-S1	Choose higher concrete quality	f_c		
D13	D13-S2	Choose lower concrete quality		f_c	
D14	D14-S1	Choose higher steel quality	f_y		
D14	D14-S2	Choose lower steel quality		f_y	
D15	D15-S1	determine material strength partial safety factor higher	Θ_R		
D15	D15-S2	determine material strength partial safety factorlower		Θ_R	

continues on next page

Table E.2.: Scenarios that are deemed possible to occur after an error occurs within a task (*continued from previous page*).

task	name	description	increasing parameters	decreasing parameters	deviating parameters
D16	D16-S1	Estimate the height higher	h		
D16	D16-S2	Estimate the height lower		h	
D17	D17-S1	Calculate self weight higher	q_G		
D17	D17-S2	Calculate self weight lower		q_G	
D18	D18-S1	Calculate design moment higher	q_{st}		
D18	D18-S2	Calculate design moment lower		q_{st}	
D20	D20-S1	Assume reinforcement diameter higher	$\varnothing$		
D20	D20-S2	Assume reinforcement diameter lower		$\varnothing$	
D21	D21-S1	Determine concrete cover higher	c		
D21	D21-S2	Determine concrete cover lower		c	
D22	D22-S1	Estimate effective height higher	$\varnothing$		
D22	D22-S2	Estimate effective height lower		d	
D23	D23-S1	Calculate required reinforcment area higher	A_s		
D23	D23-S2	Calculate required reinforcment area lower		A_s	
D27	D27-S1	Choose practical value higher than As	A_s		
D27	D27-S2	Choose practical value lower than As		A_s	
D28	D28-S1	Check wrong (A_s<$A_{s,max}$) increase floor height or concrete quality	f_c		
D28	D28-S2	Check right (A_s>$A_{s,max}$) but not increase floor height or concrete quality			
D33	D33-S1	Calculate moment resistance higher	A_s; f_y; h; c; $\varnothing$; f_c; L; q_G; q_{st}; Θ_E; Θ_R		
D33	D33-S2	Calculate moment resistance lower		A_s; f_y; h; c; $\varnothing$; f_c; L; q_G; q_{st}; Θ_E; Θ_R	

continues on next page

Table E.2.: Scenarios that are deemed possible to occur after an error occurs within a task (*continued from previous page*).

task	name	description	increasing parameters	decreasing parameters	deviating parameters
D42	D42-S1	Draw floor plan and sections wrong			A_s; f_y; h; c; $\varnothing$; f_c; L; q_G; q_{st}; Θ_E; Θ_R
D51	D51-S1	Write floor specifications and installation instructions wrong			A_s; f_y; h; c; $\varnothing$; f_c; L; q_G; q_{st}; Θ_E; Θ_R
D57	D57-S1	design briefing to main contractor contain error			A_s; f_y; h; c; $\varnothing$; f_c; L; q_G; q_{st}; Θ_E; Θ_R
C1	C1-S1	Consult design and specifications wrongly			A_s; f_y; h; c; $\varnothing$; f_c; L; q_G; q_{st}; Θ_E; Θ_R
C2	C2-S1	Measure dimensions wrong			q_{st}
C3	C3-S1	Placing temporary struts and moulds wrongly.			L; h; q_G
C4	C4-S1	More reinforcement	A_s		
C4	C4-S2	Less reinforcement		A_s	
C4	C4-S3	Wrong distance between reinforcement			A_s
C4	C4-S4	Wrong type of reinforcement			f_y
C5	C5-S1	Higher concrete strength	f_c		
C5	C5-S2	Lower concrete strength		f_c	
C6	C6-S1	Cast more concrete than required	q_G		
C6	C6-S2	Do not cast enough concrete		h	
C7	C7-S1	Wrong curing time or condition decrease concrete quality		f_c	
C8	C8-S1	Remove temporary struts and moulds earlier than required		f_c	

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Xin Ren
August 15th, 2024
Delft, the Netherlands

CURRICULUM VITÆ

Xin REN

1988	Born in Rizhao, China.

EDUCATION

2008–2012	Bachelor of Science in Construction Engineering & Management Ludong University, Yantai, China
2013–2016	Master of Engineering in Construction Engineering & Management China University of Mining and Technology, Beijing, China
2018–2024	PhD in Safety Science Delft University of Technology *Thesis:* Human and Organizational Factors Influencing Structural Safety *Promotor:* Prof. dr. ir. P. H. A. J. M. van Gelder *Copromotor:* Dr. ir. K. C. Terwel

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List of Publications

11. X. Ren, S. Boonstra, K. C. Terwel, and P. H. A. J. M. van Gelder. "Modelling the influence of human and organizational factors on structural reliability". In: *Submitted to journal* (2024)
10. X. Ren, K. C. Terwel, M. Yang, and P. H. A. J. M. van Gelder. "Critical human and organizational factors for structural safety in the Dutch Construction industry". In: *Under review by American Journal of Industrial Medicine* (2024)
9. X. Ren, G. F. Nane, K. C. Terwel, and P. H. van Gelder. "Measuring the impacts of human and organizational factors on human errors in the Dutch construction industry using structured expert judgement". In: *Reliability Engineering & System Safety* (2024), p. 109959. DOI: `10.1016/j.ress.2024.109959`
8. X. Ren, K. C. Terwel, and P. H. A. J. M. van Gelder. "Human and organizational factors influencing structural safety: A review". In: *Structural Safety* 107 (2024), p. 102407. DOI: `10.1016/j.strusafe.2023.102407`
7. R. Qin, C. Shi, T. Yu, C. Ding, X. Ren, and J. Xiao. "Analysis of Factors Influencing Fire Accidents in Commercial Complexes Based on WSR-DEMATEL-ISM Model". In: *Fire* 7.7 (2024), p. 224. DOI: `10.3390/fire7070224`
6. R. Qin, X. Dai, C. Ding, Z. Zhang, Y. Jiao, and X. Ren. "A Study on the Impact of Window Partition Walls on the Spread of Fire on Building Facades". In: *Fire* 7.7 (2024), p. 253. DOI: `10.3390/fire7070253`
5. M. Chaal, X. Ren, A. BahooToroody, S. Basnet, V. Bolbot, O. A. V. Banda, and P. Van Gelder. "Research on risk, safety, and reliability of autonomous ships: A bibliometric review". In: *Safety science* 167 (2023), p. 106256. DOI: `10.1016/j.ssci.2023.106256`
4. J. Zhao, F.-Q. Yang, Y. Guo, and X. Ren. "Mapping knowledge domains for mine heat hazard: a bibliometric analysis of research trends and future needs". In: *Environmental Science and Pollution Research* 30.7 (2023), pp. 17076–17093. DOI: `10.1007/s11356-023-25207-1`
3. J. Zhao, F. Yang, Y. Guo, and X. Ren. "A CAST-based analysis of the metro accident that was triggered by the Zhengzhou heavy rainstorm disaster". In: *International journal of environmental research and public health* 19.17 (2022), p. 10696. DOI: `10.3390/ijerph191710696`
2. X. Ren, K. C. Terwel, J. Li, and P. H. A. J. M. van Gelder. "A Science Mapping Review of Human and Organizational Factors in Structural Reliability". In: *Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference*. RSP Research Publishing. 2020. DOI: `10.3850/978-981-14-8593-0_4139-cd`
1. X. Ren, K. Terwel, I. Nikolic, and P. van Gelder. "An Agent-based Model to Evaluate Influences on Structural Reliability by Human and Organizational Factors". In: *Proceedings of the 29th European Safety and Reliability Conference, ESREL 2019*. 2019, pp. 1889–1896. DOI: `10.3850/978-981-11-2724-3_0441-cd`