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A Science Mapping Review of Human and Organizational Factors in Structural Reliability

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In the structural safety field, it is widely acknowledged that human error is the major contributor to structural failure. Since Human and Organizational Factors (HOFs) are critical latent conditions that can lead to human errors and further structural failures, it is essential to study into HOFs in the building industry to prevent the occurrence of failures. In this research, a bibliometric review of the existing literature on HOFs influencing structural reliability was conducted and results have been visualized in science maps. Insights into the publication output and trend, the key topics and its evolvement over time, the publication sources, as well as the contributing academics and their collaborations have been gained from the science mapping review. Apart from this, HOFs were collected from literature, after which a meta-analysis has been performed to identify the critical factors for structural reliability. In conclusion, this review provides a holistic picture of the current status for studies concerning HOFs influencing structural reliability and outlines the possible critical HOFs identified by existing research.

Keywords: Human and organizational factors, structural reliability, literature review, science mapping, human error, meta-analysis.

1. Introduction

While structural safety has long been viewed and treated with great importance in the construction industry, structural failures occur constantly. It is observed that structural failures can originate from technical or human failures. However, human errors are widely acknowledged in the structural safety field as the major contributors to structural failures and near-miss cases (Nowak and Carr, 1985; Frangopol, 1986; Ellingwood, 1987; Stewart, 1993). Therefore it is important that sufficient attention is paid to the issue of human error concerning structural safety. According to Reason (2000), 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 enduring holes or weaknesses such as human errors in the safety defences. HOFs are pivotal latent conditions to be taken into consideration when dealing with human errors resulting in structural failures, as pointed out by Terwel (2017). HOFs that influence structural reliability is therefore the research focus of this paper.

To gain a better understanding of the HOFs that shadow impacts on the reliability of structures in the building industry, a review of related literature is conducted. Two major results from the literature review are presented in this paper. One is a macroscopic overview of the existing research efforts made on HOFs influencing structural re-

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liability, that provides a holistic picture on the research trends and topics, impacting presenting platforms, as well as scholars and their collaborations from a bibliometric review. The other result is generated by a detailed review of the collected literature, which gives answer to the question of what are the important HOFs that have been identified in the existing research.

Following the introduction, the research data and methods that are applied in this paper is presented in Section2. Then Section 3 discusses the results obtained from the bibliometric review. Subsequently, Section 4 outlined the identified HOFs from literature. Finally, conclusions are given in Section 5.

2. Methodology

In this section, the data collection process for this review is presented in Subsection 2.1. The bibliometric review method and the used tool is subsequently presented in Subsection 2.2, followed by an introduction to meta-analysis in Subsection 2.3.

2.1. *Data collection*

The data used in this study were retrieved from the Scopus database on November 20, 2019. The Scopus database was used for literature collection due to the fact that it provides more results than the Web of Science database when inputting the same search keywords, after trying both. The combined term ("structur* safe*" OR "structur* reliab*" OR "structur* fail*") AND ("human* factor*" OR "organi* factor*" OR "human* error*") was searched among article title, abstract and keywords in Scopus and this has yielded 177 initial documents from this database. Then the results were further refined by limiting the document language to English and document source type to journals and conference proceedings. Finally, 140 publications were selected out as the data for the literature review. These collected documents consist of 61 articles, 76 conference papers, 2 reviews and 1 note, as denoted in Figure 1, covering a publication period of a bit more than four decades from 1978 to 2019.

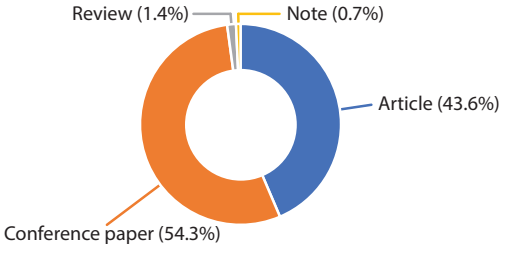

Fig. 1. Composition of different document type of the literature search result.

2.2. *Bibliometric analysis*

Bibliometric analysis is a quantitative method that applies statistics to describe the development of the knowledge structure of a scientific domain based on the analysis of the metadata of related literature. The metadata are details of publication properties such as authors and their affiliations, publication source and time, citation information, etc. Science mapping is the process of bibliometric network visualization, which provides a general picture of the current research status. There are many existing tools available for science mapping, such as VOSviewer, CiteSpace and Gephi. VOSviewer, developed by Van Eck and Waltman (2010), is chosen as the visualization software in this research due to the fact that it is freely available and has been widely applied in the science mapping of many safety research domains, such as Li and Hale (2015), van Nunen et al. (2018), and Jin et al. (2019). VOSviewer implements the similarity mapping method to create distance-based networks in which the distance between two terms represents the similarity or relatedness between them. In addition, the size of the term node or label shows the frequency of occurrence of that term. Moreover, closely related terms are grouped into clusters, which are distinguished with different colours (Van Eck and Waltman, 2013). In this study, the metadata of the 140 publications have been exported from the Scopus database as input for the bibliometric analysis using VOSviewer. Results concerning research topics, publication sources, as well as academics and their collaborations have been obtained subsequently from the analysis, which will be presented with details in the following section.

2.3. *Meta-analysis*

Meta-analysis is a method which includes a set of mathematical techniques that can systematically combine the results of multiple selected qualitative and quantitative scientific studies to achieve a single conclusion which possesses greater statistical power, in order to approach the truth of a question under study. A meta-analysis usually includes five steps: define a research question, conduct a systematic literature review, extract results data from literature, standardize data and set weight to different results, and reach to the final conclusion (Shorten and Shorten, 2013). A meta-analysis has been performed to obtain the HOFs that are identified as critical to structural reliability in the building industry from published literature after the bibliometric review.

3. Results and discussions

The science mapping results are presented and discussed in this section, with the publication output and trend shown in Subsection 3.1, keywords

analysis in Subsection 3.2, publication sources analysis in Subsection 3.3, and author collaboration analysis in Subsection 3.4.

3.1. *Publication output and trend*

The research attention and the knowledge development on one topic can be revealed by the number of publications in that domain. Figure 2 presents the annual and the cumulative number of publications of the 140 collected literature concerning HOFs influencing structural safety and reliability that were published in the past four decades from year 1978 to 2019. The publication number across different years fluctuates significantly, from 0 in 1979, 2003, 2004, and 2005 respectively, to 11 in 1989 and 2017. The two peaks in the publication number in 1989 and in 2017 are mostly contributed by two conferences that intend to draw research attention to the human error issue in structural engineering. These two conferences are "ICOSSAR '89, the 5th International Conference on Structural Safety and Reliability" and "International Association for Bridge and Structural Engineering (IABSE) Workshop 2017: Ignorance, Uncertainty and Human Errors in Structural Engineering". As can be seen from Figure 1, there are more conference papers than journal articles that contribute to this topic. The research on human errors and HOFs influencing structural reliability are mostly the interest of focused conference or expert group discussions. This research topic has gained much attention from 1983 to 1993, as shown in Figure 2, where the cumulative number of publication grew fast, but was largely neglected during the 1990s and 2000s, where the increase of the cumulative publication number was very marginal. The research on this topic began to accelerate again until after 2009. And there are in general more research output during this period than in the 1980s. But there is no evidence that shows an increase in the publication trend after 2017, which reminds us that there is still inadequate attention paid to this research topic, given the fact that structural failures caused by latent conditions related to HOFs still occur constantly.

3.2. *Keywords analysis*

Keywords are the brief representation of the core research contents and indicate the topic of a study. Therefore a keywords analysis can lead to insightful results such as the existing research focus of a given domain. In this subsection, a keywords analysis has been performed using VOSviewer to provide a clear view of the topics that have been explored in the study of HOFs and human errors influencing structural safety and reliability.

It is found out from Figure 2 that there is a break with zero publications from 2003 to 2005. However, there was obvious growth in the cumulative number of publications before and after

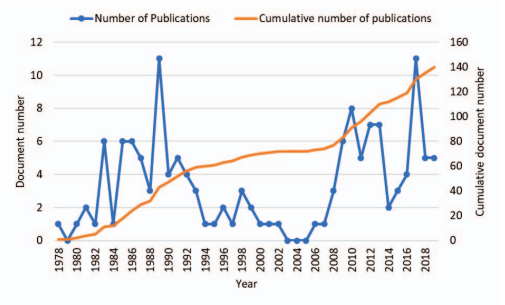

Fig. 2. Publication output by year and cumulative publication output of HOFs research in structural engineering.

this steady period. Therefore, we divided the collected literature into two period groups: one is the period from 1978 to 2002, which contains 72 documents; the other period is from 2006 to 2019, which includes 68 documents. Two keywords analyses have been created respectively based on the bibliographical data of the documents from these two groups using the "co-occurrence" analysis of "author keywords" that recommended by Van Eck and Waltman (2014). These keywords analyses were further visualized into author keywords density maps. From the group of earlier publications, 49 author keywords are recorded and 46 closely connected keywords are visualized in the keywords density map, as shown in Figure 3. And for the group of later publications, 167 author keywords are recorded. To simplify the result and at the same time emphasize the key topics that have gained the most research efforts, only the keywords that present equal to or more than twice have been selected to map the keywords density distribution for this group. In the end, 31 author keywords were selected and presented in Figure 4.

These maps highlight the key topics that have gained more research attention in each period. The differences between the heat topics in these two maps illustrate the evolution of research interests over time in this field. As shown in Figure 3 that the key research topics lie in human error and human performance in structural design and construction and their influence on structural reliability. Structural failure and its risk analysis were also widely studied during this time. In this period, simulation technique, fault tree analysis and fuzzy set were popular research methods to study the impacts of human errors on structural reliability. While in the later period, human error was still a key research topic, but human factors, and especially the newly appeared organizational factors and HOFs began to earn research interest, as can be seen from Figure 4. In addition, a focus on failure risk analysis began to fade. Alternatively, the hot subjects shifted to design checking, quality control and safety management. More-

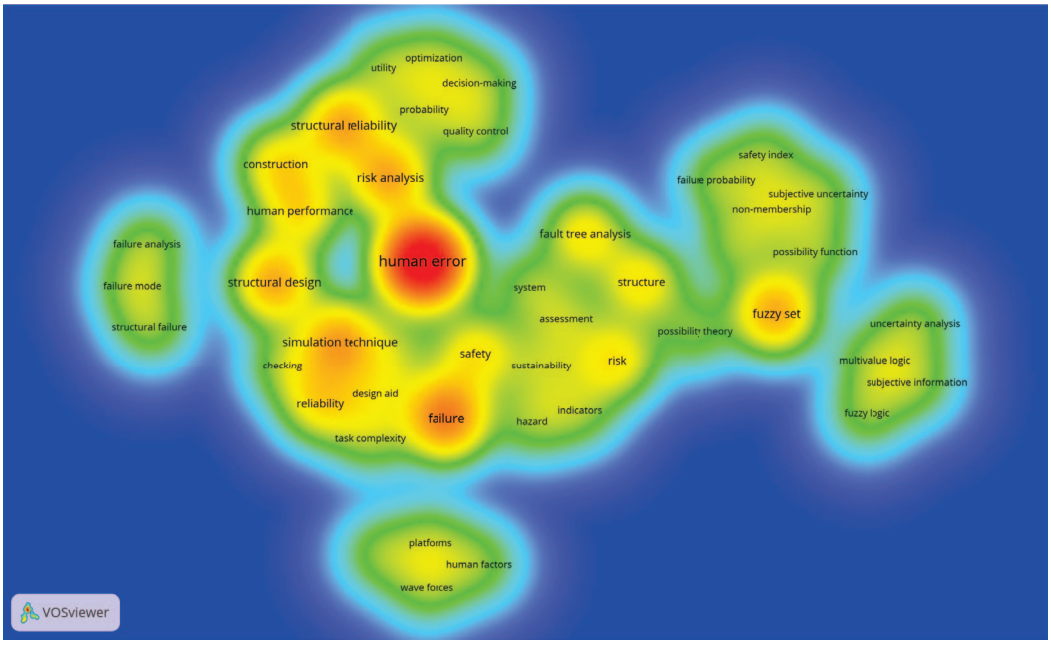

Fig. 3. Research topics identified from author keywords (1978-2002).

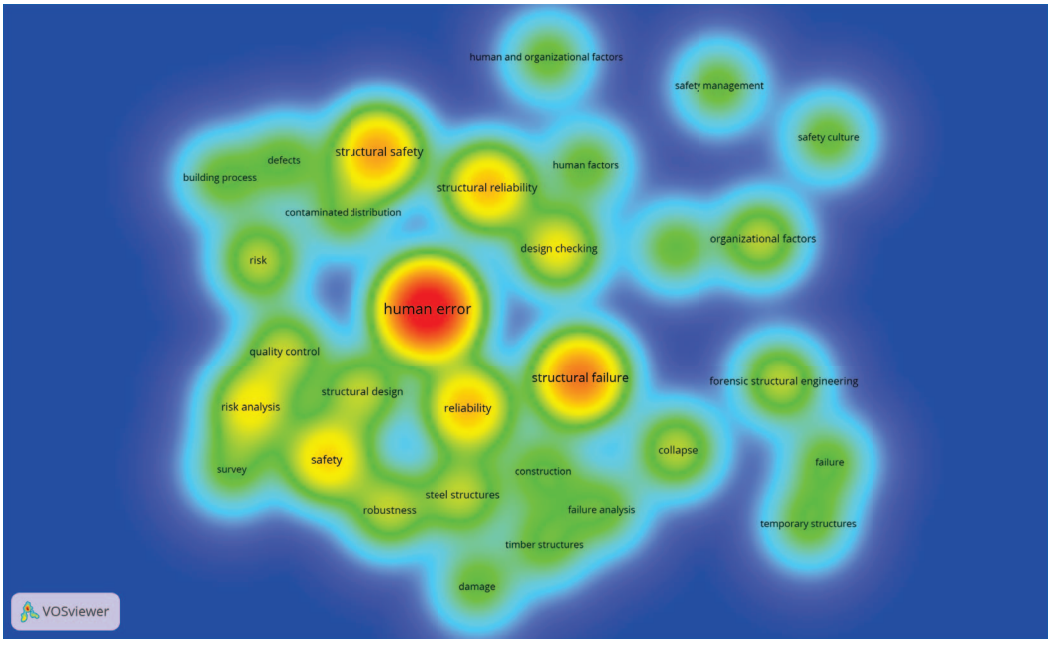

Fig. 4. Research topics identified from author keywords (2006-2019).

over, forensic structural engineering showed up and a clear switch from emphasis on probabilistic quantitative risk analysis towards qualitative analysis and safety management has been noticed.

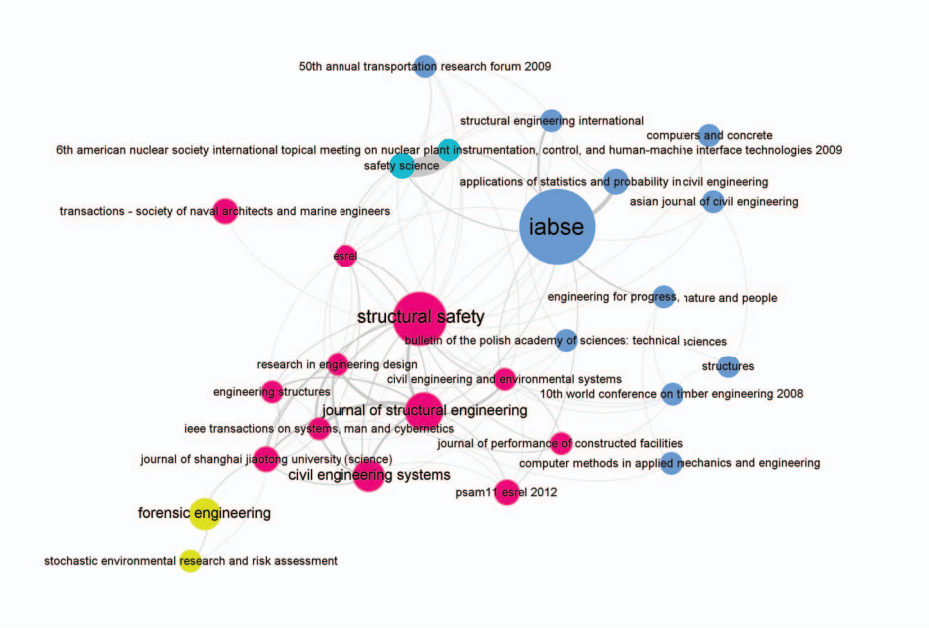

Fig. 5. Publication source network.

3.3. *Publication sources*

Journals and conferences that make scientific contributions to the study field of HOFs influencing structural safety have been identified with the bibliometric analysis. A bibliographic coupling analysis of the document sources has been performed to obtain the most influential publication sources in this research field. In total 69 journals and conferences with at least one publication and minimum zero citation were identified and 27 of them have close relationships with each other. Later these 27 connected sources were mapped in a publication source network, as shown in Figure 5. This science mapping can provide academics working in this domain with a clear view of choice options where to present their research.

It can be seen from Figure 5 that the journal which has made the most contribution to this topic is Structural Safety, with 11 documents and 98 citations. Following that, the second productive journal is the Journal of Structural Engineering, with 6 publications and having been cited for 71 times. Then the journal of the Civil Engineering Systems and the Forensic Engineering rank as the third contributor at the same time with 4 articles and 12 citations, and 4 articles and 11 citations respectively. However with regards to the normalized citations, Safety Science become the third impacting journal with 2 articles that have been cited for 113 times. In terms of conferences, it can be observed that the IABSE conferences have promoted many discussions that focused on this research topic. Other contributing conferences include the International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP), the European Safety and Reliability Conference (ESREL) and the Probabilistic Safety Assessment and Management Conference (PSAM).

3.4. *Authors and collaboration*

Scientific studies are performed by researchers of various domains. Therefore the author information within each publication is core bibliographic data. Associated with author names are the regional and institutional affiliations, as well as existing and potential collaboration information. Interesting results can be obtained by a bibliometric analysis of scholars and their collaborations. In this research, a co-authorship analysis of all the authors from the 140 publications was conducted to examine the author cooperation. As a result, influential academics and the collaborations among them have been visualized into a co-authorship network. There are in total 191 authors recorded by the collected literature, among whom 28 have at least two publications with minimum zero citation. These 28 authors and their bibliographic data were mapped into a co-authorship network as shown in Figure 6.

There are several significant contributing academics working on the topic of human error or HOFs influencing structural reliability. As can be seen from Figure 6, the high impact scholars

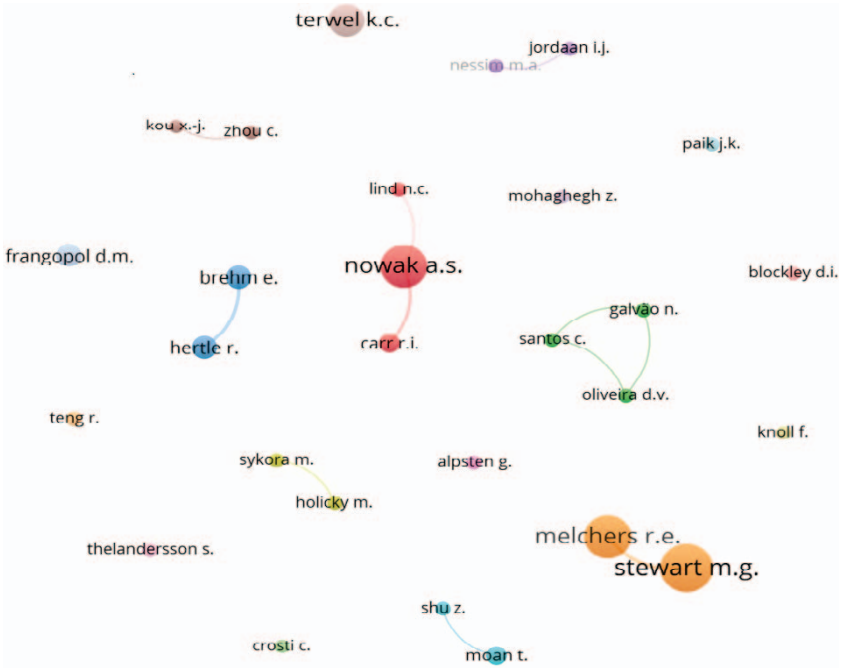

Fig. 6. Co-authorship network.

are R.E. Melchers, M.G. Stewart and A.S. Nowak, who have contributed the early works to this field, then comes K.C. Terwel and E. Brehm, who are the newly rising researchers that are promoting the latest development on this topic. More details of these top productive authors are listed in Table 1.

It can be observed from the visualized network that there are very limited collaborations among the scholars who work on the topic of HOFs influencing structural reliability. A strong collaboration can be found between R.E. Melchers and M.G. Stewart. They two together have developed a series of models for the probabilistic evaluation of the structural reliability that is influenced by human errors in different building phases such as structural design and construction. Another cooperation can be found among A.S. Nowak, R.I. Carr and N.C. Lind, who attempt to classify human errors in structural engineering as well as quantitatively model these human errors with mathematical methods such as statistical distributions. Moreover, other collaborations exist between Brehm E. and Hertle R., as well as Holicky M., and Sykora M., etc. It is noticeable that most author collaborations exist within the same country. In general, it is safe to conclude from the co-authorship network that the research community working on this topic is small. In addition, there is a lack of cooperation among researchers in this research field, especially collaboration across different countries and regions. Therefore, the collaboration network for researchers working on the topic needs to be extended largely, and more cooperation should be promoted on personal, institutional and regional level.

4. Human and organizational factors in structural reliability

As mentioned in Section 1, human errors are widely acknowledged as the major causes for structural failures in the structural safety field. The recent development in the safety science paradigm has shifted to view human as one inseparable component of the whole project system, whose performance is shaped by the system environment, management decisions, and organizational processes (Reason, 1995). Therefore, it is essential to investigate further into both the human factors and the organizational factors behind human errors that lead to structural failures. In order to gain a better understanding of what are the HOFs that affect the structural reliability in the building industry, a review of the 140 literature is conducted to collect the identified HOFs from existing publications. Subsequently, a meta-analysis has been performed to obtain insights into the most acknowledged HOFs that are believed to impact structural reliability in a significant manner.

Initially 285 factors have been recorded by 34 publications that mention HOFs among the 140

Table 1. Top productive authors contributed at least three publications to the topic.

Author	Author country	Number of publications	Total citations	Normalized citation	Avg publication year	Avg citation	Avg normalized citation
M.G. Stewart	Australia	12	100	18.2	1990	8.3	1.5
R.E. Melchers	Australia	10	92	22	1989	9.2	2.2
A.S. Nowak	USA	10	28	8	1989	2.8	0.8
K.C. Terwel	the Netherlands	7	4	3.7	2015	0.6	0.5
E. Brehm	Germany	4	1	1.4	2017	0.3	0.4
D.M. Frangopol	USA	4	1	0.2	1988	0.3	0
R.I. Carr	USA	3	19	3.2	1985	6.3	1.1

Note: Avg is short for Average.

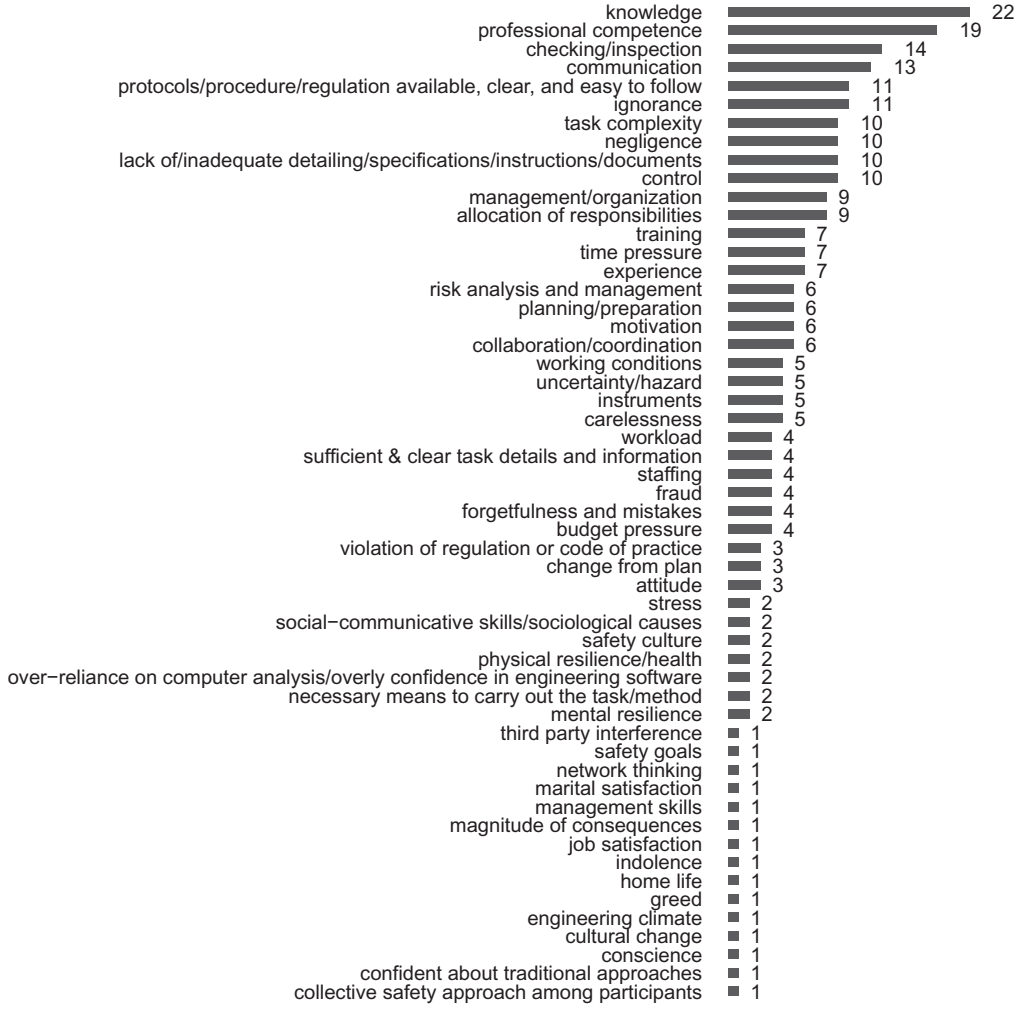

Fig. 7. Identified HOFs and the number of publications that identify each factor.

documents. These factors were further grouped into 54 unique HOFs based on their similarities and the intended meaning by the authors of these studies, with the same weight. Moreover, the number of publications where each factor is identified has been recorded and plotted together with the HOFs in a histogram. The preliminary factor analysis result is shown in Figure 7.

As can be clearly seen in Figure 7, knowledge is the most widely acknowledged factor influencing structural reliability, which has been recognized in 22 publications in total. Following knowledge, professional competence ranks the second in significance for its impacts on structural reliability, mentioned in 19 papers. Besides, checking and inspection are also highly valued by researchers of their potential for causing structural failure if missing or misconduct. In addition, communication is—not surprisingly—a high impact factor due to its importance in team collaboration and information flow within the project participants.

5. Conclusions

Human errors cause most structural failures and near-miss cases, thus they are critical for structural reliability. Due to this, it is therefore vital to study the latent HOFs that contribute to human errors in the building industry. To gain a clear view of the current research status and the developed knowledge structure in the field of HOFs influencing structural reliability, a bibliometric analysis has been performed and science maps have been created to visualize the past and current key topics, publication channels and author collaborations. It is found out that there is a slight change of research interest from a quantitative structural failure risk evaluation and probabilistic modelling of the human error impacts with mathematical methods, to HOFs, quality control and structural safety management. Moreover, Structural Safety is found to be the most influential journal that has published the most research articles in this field. Also, IABSE has organized the most conference discussions contributing to this topic. Additionally, a small group of scholars have been identified focusing on this topic and a lack of collaboration between them and countries was spotted from the scientific mapping.

Apart from this, 54 important HOFs that have been identified by the collected literature resulted from a meta-analysis. In the preliminary result, knowledge, professional competence, checking and inspection, as well as communication are recognized as the most influential factors for structural reliability. Further examination and verification of these HOFs are needed to acquire a set of final critical HOFs in the building industry. Potential approach to take for achieving this goal can be survey or investigation into structural failure reports. A final touch on proposed future work is to structure the ultimate set of HOFs into a framework that is applicable for practical structural safety management.

To conclude, this review provides a holistic picture of the current status for studies concerning HOFs influencing structural reliability and outlines the possible critical HOFs identified by existing research, which can be beneficial for both academics and professionals.

Acknowledgement

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