Human error in industrial maintenance: a systematic literature review

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Abstract: Human factor plays an inevitable role in maintenance activities and the occurrence of human errors impacts on system reliability and safety, equipment performance and economic results. Many factors, such as work environment, organization, individual features, influence the performance of maintenance technicians with a consequent variability in the success of interventions. This paper presents a literature review concerning Human Error in Maintenance (HEM) with the aim of investigating, through a critical analysis, the current HEM state-of-the-art in industrial systems and highlighting the research and practice gaps. A systematic review was conducted using two databases (Scopus and Web of Science) and a set of specific keywords in order to identify and select peer-reviewed papers that presented evidence on the relationship between human performance and maintenance activities. A total of 63 studies were selected and then analysed through a pre-determined systematic methodology. This has allowed to classify and critically assess the selected papers as function of: types and typical human errors in maintenance; error contributing factors; maintenance policies; methodologies for human error analysis; maintenance error consequences; industrial sectors. The analysis outlines the relevance of considering HEM because different error types occur during the maintenance process with non-negligible effects on the system. High-risk sectors, like nuclear power plant or aviation, have strongly taken into account human error in maintenance activities, whereas in manufacturing systems HEM has not received the amount of attention that it deserves. This paper motivates future developments for HEM assessment and management particularly in manufacturing sector, due to the evidenced gap in literature, providing several research opportunities.

Keywords: Human error, human reliability analysis, maintenance, systematic review, industrial systems.

1. Introduction

The maintenance process is essential for a safe and reliable system and efficient performance of devices in different work environment, such as nuclear power plants, aviation, chemical plants, offshore facilities, manufacturing systems or other type of industries. The increase in complexity and size is inviting maintenance and reliability engineers to put more emphasis on system inspection and maintenance process in order to minimize unplanned downtime, overall cost, and risk exposure (Hameed et al. 2016; Asadzadeh & Azadeh 2014), to guarantee economic, environmental and social sustainability (Franciosi et al. 2017; Macchi et al. 2016; Savino et al. 2015) and to assess the impact of human factors (Dhillon 2009; Fruggiero et al. 2016; Sammarco et al. 2014). In particular, Dhillon and Liu (2006) reported the impact of human errors in maintenance as found in the literature as a pressing problem. In fact, although the equipment reliability has significantly improved and the processes are becoming more and more automated, yet human factor continues to be fundamental and maintenance tasks, that are expected to be perfect, are vulnerable to human error (HE). Human error in maintenance tasks may lead to incorrect decisions, actions, or checks and it is influenced by a variety of individual and contextual factors with a wide variability in the success of interventions. The error consequences vary from little to catastrophic effect, depending upon the nature of the error. For example, poor repairs can play an instrumental role in increasing the number of equipment breakdowns which in turn can significantly increase the risk associated with equipment failures and the occurrence of personal accidents (Dhillon 2014). In fact, errors committed by man are responsible for 50-90% of accidents in industries, and most of them are due to wrong maintenance activity (Aalipour et al. 2016; Di Pasquale et al. 2015, 2016). For example, Kim and Park (2009) report that about 63% of human-related unplanned reactor trip events during normal operation are found to be associated with the test and maintenance activities. Bao and Ding 2014 show that, from maintainers perspective, the HE number accounts to 91% and the most significant types of error are inspection and installation of system components. For these reasons, the assessment of the likelihood of human error is essential in maintenance field.

Despite of the increasing attention to the HEM field in recent years, the type of human error, its consequences, the main individual and contextual factors and their impact must be better investigated in order to minimize incidents, to assure effective maintenance strategies, to developed precautionary measures and action to mitigate the error effect. Provide a depth knowledge of such issues can increase the awareness of practitioners concerning the strong impact of human error in maintenance on the industrial system performance. These reasons had lead the authors to conduct a Systematic Literature Review (SLR) concerning human error in maintenance with the aim of investigating, through a critical analysis, the current HEM state-of-the-art in industrial systems and highlighting the research and practice gaps. While traditional literature review is based on the author's knowledge perspective, the SLR comes from a clearly defined objective of the research, structured following a protocol, that minimizes subjectivity and allows the critical evaluation of relevant studies (Pires et al. 2015). The paper is organized as follows. Section 2 presents the research method used for the SLR. Section 3 reports the SLR results, while Section 4 provides a detailed discussion about the results. Finally, Section 5 summarises the main research opportunities and the conclusions of the work.

2. Method

The study presented here is classified as a systematic literature review following the guidelines presented by Neumann et al. (2016) and Pires et al. (2015). This search aims to identify peer-reviewed papers that presented evidence on the relationship between human performance and maintenance activities. Four research questions were addressed in this study: (1) What are the industrial sectors mainly investigated in the field of interest? (2) What are the main causes and contributing factors that lead to human error in maintenance? (3) What are the main HEM consequences? (4) How HE is evaluated and integrated within the maintenance management? The SLR was carried out through the listed steps below:

- Identification of research databases and keywords definition;
- Literature search and paper selection through specific exclusion criteria;
- Analysis process and information extraction strategy.

These steps are discussed in detail in the following sub-sections.

2.1 Identification of research databases and keywords definition

Systematic searches were conducted using two scientific databases (Scopus and Web of Science). A set of keywords, structured in two different groups, was prepared for these databases: Group A, which includes "human error", "human reliability analysis", "human reliability assessment", "human error probability"; and Group B which includes "maintenance". The final keywords list used to search consisted of all possible combinations of keywords from Groups A and B using the Boolean operators that allow to extend the research to make the relationship (AND) and the sum of words (OR).

2.2 Literature search and paper selection through specific inclusion and exclusion criteria

The search took place in December 2016. Articles that had the searched keywords in its title or abstract and were published between 1997 and 2017 were screened. Moreover, only articles in English and published in peer-reviewed journals or conferences were considered. After running the search on the two databases, all papers were uploaded into a database manager (i.e., Mendeley) and all duplicates were removed. The selection process was divided into two stages. The first selection stage was the reading of the title, abstract, keywords. In this screening stage, articles were classified as included, excluded and undefined according to the specific exclusion criteria described below:

1) No full text is available;
2) Articles presenting only one of the main key concepts (maintenance and human error);
3) Papers do not establish a link between maintenance and human error.
4) HEM is a secondary aspect than the main purpose of the paper.

The second stage included the reading of the full text of the papers selected in the previous stage and therefore a definitive assessment based on the 2nd, 3rd and 4th exclusion criteria.

2.3 Analysis process and information extraction strategy

Each paper was methodologically and conceptually classified based on two criteria related to: the innovative contribution that each paper provides to the literature, and the research method used to reach the research paper goals (Table 1). Furthermore, the analysis was performed using a pre-determined systematic methodology based on specific criteria, listed below, to extract and structure the information: (i) industrial sectors; (ii) methodologies for HE analysis; (iii) types and typical HEs in maintenance; (iv) error contributing factors; (v) maintenance policies; (vi) maintenance error consequences. Based on these analysis criteria, all the pertinent information presented in the papers were extracted and reported in a specific worksheet in order to allow a detailed assessment of current HEM state-of-the-art and SLR results.

Table 1: Types of contribution and research method.

CONTRIBUTION
C1. Development of method/methodology/model
C2. State of the art
C3. Proposition of theoretical framework
C4. Development of tool
C5. Accident report analysis
C6. Other type of contribution

RESEARCH METHOD
R1. Case study
R2. Theoretical research/ Literature review
R3. Experimental research/ Simulation
R4. Other type of research method

3. Results

The total number of studies resulted from the database search was 576. After the first screening stage, 120 articles were identified as relevant. Among them, 63 papers were selected after the second screening stage, following the guidelines reported in the Section 2. Appendix A reports the full list of the 63 selected papers and the relative identification number (ID), that will be used in the subsequent section for facilitating the results discussion. As shown in Figure 1, 72% of selected papers are published on journals, 24% are conference proceedings, 3% are book chapters and 1% books. Figure 2 reports the number of papers per journal. The majority of them appears in journals related to categories "Safety, Risk, Reliability and Quality" (about 48%) and "Human Factors and Ergonomics" (about 18%). The other papers belong to miscellaneous categories.

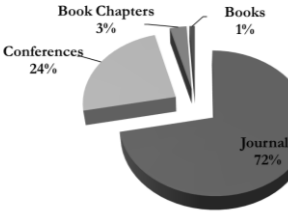

Figure 1: Editorial classification of selected papers.

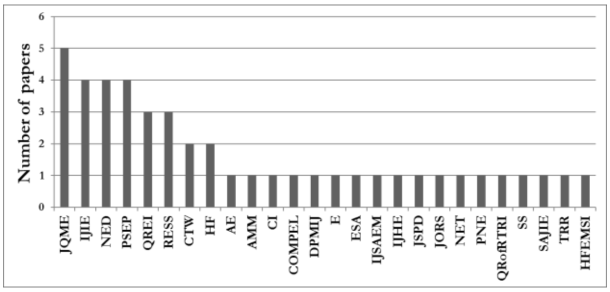

Figure 2: Number of papers per journal.

Acronyms: JQME-Journal of Quality in Maintenance Engineering/ IJIE-International Journal of Industrial Ergonomics/ NED-Nuclear Engineering and Design/ PSEP-Process Safety and Environmental Protection/ QREI-Quality and Reliability Engineering International/ RESS-Reliability Engineering & System Safety/ CTW-Cognition, Technology and Work/ HF-Human factors / AE-Applied ergonomics/ AMM-Applied mathematical modelling/ CI-Chronobiology International/ COMPEL-The International Journal for Computation and Mathematics in Electrical and Electronic Engineering/ DPMIJ-Disaster Prevention and Management: An International Journal/ E-Ergonomics/ ESA-Expert Systems With Applications/ IJSAEM-International Journal of System Assurance Engineering and Management/ IJHE-International Journal of Hydrogen Energy/ JSPD-Journal of Ship Production and Design/ JORS-Journal of the Operational Research Society/ NET-Nuclear Engineering and Technology/ PNE-Progress in Nuclear Energy/ QRofRTRI-Quarterly Report of Railway Technical Research Institute/ SS-Safety Science/ SAJIE-South African Journal of Industrial Engineering / TRR-Transportation Research Record/HFEMSI-Human Factors and Ergonomics in Manufacturing & Service Industries.

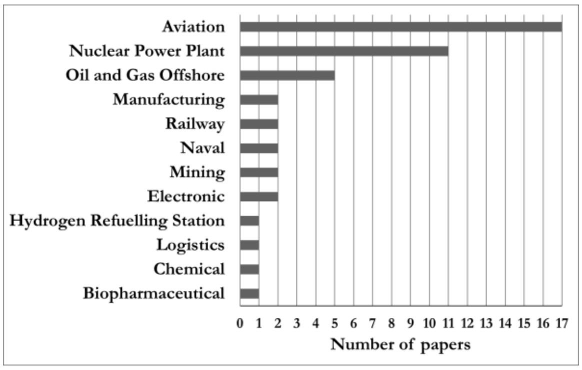

Figure 3: Industrial sector of selected papers.

Different industrial sectors were identified for the 45 papers that belong to specific and well-defined sectors. Figure 3 shows that the majority of papers are related to aviation (38%), nuclear industry (24%) and oil and gas offshore facilities (11%). Figure 4 reports the publication distribution over the years and the presence of 50 papers from 2008 highlights a growing trend in HEM topic.

Table 2 shows the contribution and the used research method of the 63 papers. On one hand, 33 papers (52%) develop methods, methodologies or models; 8 papers (13%) are accident report analysis; 4 papers (6%) are state of the art; 3 papers (5%) propose a qualitative framework and 2 papers (3%) develop a tool. 13 papers (21%) belong to C6 class since they apply one or more existing methodologies or make a comparison between methods. On another hand, the methods used to carry out the research are: 37% case study, 35% theoretical research or literature review and 6% experimental research or simulation. Moreover, 14 papers (22%) belong to R4 class since they are generally accident reports based on surveys or other type of research methods.

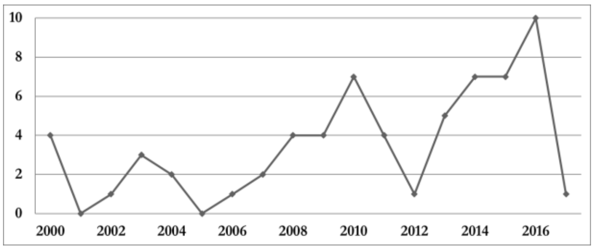

Figure 4: Publication trend by year.

Table 2: Paper classification in respect of contribution and research method.

CONTRIBUTION	#paper	RESEARCH METHOD	#paper
C1. Development of method/methodology/ model	33	R1. Case study	23
C2. State of the art	4	R2. Theoretical research/ Literature review	22
C3. Proposition of theoretical framework	3		
C4. Development of tool	2	R3. Experimental research/ Simulation	4
C5. Accident report analysis	8	R4. Other type of research method	14
C6. Other type of contribution	13		
TOTAL	**63**	**TOTAL**	**63**

Focusing on the papers belonging to C1 class, they present a wide range of different methodologies, as in depth described in next Section 4. In particular, 11 of the aforementioned papers developed new methodologies for the human error analysis based on Human Reliability Analysis (HRA) methods. The HRA methods are also used in most of papers belonging to C6 class (11 of 13 papers). The accident reports, instead, described the typical human errors that may occur during the maintenance activities and may lead to accidents. 50% of the selected accident reports also analysed the errors contributing factors to give suggestions on how to prevent similar accidents. More generally, 31 of the total papers (about 45%) described the typical human error in maintenance activities, while 39 of the total papers (about 62%) analysed the errors contributing factors. Furthermore, the HE consequences were discussed in 26 papers (about 41%), while the maintenance policy was considered only in 16 papers (about 25%).

4. Results discussion

The SLR results underline different discussion topics (methodologies for human error analysis and integration in maintenance management; error contributing factors; maintenance error consequences) deeply described below. Human factors and in particular human errors are a pressing problem in maintenance activities. However, only

[15] and [58] performed a general review of literature on maintenance errors in various sectors of industry, whereas [39] focused on aviation field.

4.1 Methodologies for human error analysis

Various methods and approaches to measure human reliability or human error were found through the SLR. Many researchers proposed new methods based on the HRA theoretical principles [11, 29, 35, 46, 50, 56, 63], which aim to identify the causes and sources of human errors and to pursue quantitative Human Error Probability (HEP) estimates during professional activity (Di Pasquale et al. 2015, 2016). For example, [29] developed a monograph for assessing the likelihood of human error in marine operations that can be applied for instant decision making. [35] introduced human error analysis (HEA) procedures for a predictive HE analysis when maintainers perform test or maintenance actions based on a work procedure or work plan. Each procedure consists of three steps: analysis of basic error potential, evaluation of possible impacts on the system, and identification of deficient work context or PSFs. [50] presented a revised version of the Human Error Assessment and Reduction Technique (HEART) methodology to assess the effects of cold on the likelihood of human error in offshore oil and gas facilities. Instead, other papers applied the existing HRA techniques to real case studies for estimating human error probabilities [2, 10, 28, 43, 44, 45, 48, 49, 60], validating their consistency through the comparison of the obtained results [1, 9] or integrating the HEP estimate within maintenance management methodologies [4, 6, 22, 59]. For example, [2] integrated the Success Likelihood Index Method (SLIM) with the Technique of Human Error Rate Prediction (THERP) for the HEP assessment in an offshore condensate pump maintenance task; whereas [1] compared three common HRA methods (HEART, SPAR-H and Bayesian Network) during the maintenance tasks in a cable manufacturing company in Iran. Among these 22 papers, the most common HRA methods are: SLIM (36%) [2, 4, 6, 22, 28, 29, 48, 56], THERP (23%) [2, 43, 44, 45, 46], HEART) (23%) [1, 49, 50, 59, 60] and the Bayesian Network (3%) [1, 11]. The aforementioned papers are mainly related to nuclear power plants (18%), oil and gas offshore (18%) and aviation (14%). Other methodologies, not based on HRA principles, were developed over the years in order to quantify and integrate HE in maintenance management. [8] analysed the delay-time modelling of inspection maintenance, incorporating the HE existence in the form of fault injection and evaluating HE impact on system reliability or maintenance decisions. [13] established a new analytic process for investigating latent human error and provided a strategy for analysing human error using fuzzy TOPSIS. Khalaquzzaman et al. [30, 31, 32] firstly proposed a new model which considers HEP in maintenance, then identified the effect of human errors during refueling maintenance and periodic maintenance of Nuclear Power Plant (NPP) and finally determined the optimal testing frequency for the minimum value of an objective function that consists of all costs, including the monetary values of the consequence of maintenance human errors and reactor core damage. [37] applied graph theory for quantifying HE in maintenance activities modelling the HE influencing factors and their interactions/ interrelationships. [38] proposed a fuzzy cognitive map methodology evaluating the dynamic behaviour of error inducing factors on human reliability in maintenance. [40] outlined a method for managing human error in the field of aircraft design, maintenance and operations, combining traditional aspects of the aircraft design system safety process with a structured tabular notation called a human error modes and effects analysis (HEMEA).

4.2 Error contributing factors

From analysis of methodologies is evident that work environment, organization and individual features are considered as the major contributors to human error and are the key factors in analysing performance of maintainer. HRA methods use the PSFs for enhancing or degrading the HEP [1, 2, 6, 9, 10, 11, 22, 25, 28, 29, 35, 41, 46, 48, 49, 50, 56, 60, 63], whereas the other methods consider these factors as HE influencing or contributing factors [5, 17, 18, 20, 21, 36, 38, 39, 47, 52]. The analysis of contributing factors is often performed by accident reports analysis, since accidents and incidents are the main evident consequence of human error on system and workforce. The accident reports, found by the SLR, were mainly carried out in high-risk industries, where the consequences of an accident may be catastrophic, as aviation industry and NPP [5, 20, 25-27, 33, 34, 42]. One of the major process to investigate maintenance errors and the factors that contribute to various maintenance-related accidents and analysis turned out the Maintenance Error Decision Aid (MEDA) [5, 7, 26, 53]. Moreover, investigating the impact of human reliability through the retrospective analysis of accidents reports allows to intervene in proactive way, through both the development of monitoring systems, as the Aviation Maintenance Monitoring Process [54, 55], and methods for assessment and management of risk and safety [22, 23, 24, 51, 57].

4.3 Maintenance error consequences

The accidents are the most evident HEM consequence in terms of safety, while other consequences were not deeply analysed in literature respect to the modelling of HE and contributing factors. The human performance, in fact, can affect also the system reliability, the frequency of maintenance interventions, and the length of intervention time. For example, only [14, 16] considered the impact of human errors on the system availability and on the probabilities of system being in unsafe working states; while [3, 4, 6,12, 22] evaluated how the HE can impact on system reliability. In particular, only [4, 6] integrated the HEP and its impact on the system in a maintenance policy: [4] proposed the integration of human reliability model with condition based maintenance (CBM) optimization, taking into account HE impacts on the estimation of remaining useful life (RUL) of system components; [6] considered how HE in periodic maintenance could affect the system availability. Instead, [19] assessed the effect of human error in corrective and preventive maintenance policies in terms of increase the mean maintenance time and the frequency of interventions. Finally, [62] considered recovery factor for latent human errors into maintenance management task to identify the number of maintenance personnel and maintenance cycle time. Furthermore, [41, 61] were manly addressed to maintainers, in fact [41] developed an on-line maintenance assistance platform for preventing human error in the aviation maintenance industry, while [61] proposed a practical framework for enhancing fault recovery ability through knowledge-based system and supporting the maintainers in critical events.

5. Conclusions and research opportunities

This study performed a systematic literature review on human error in maintenance. 63 papers were selected and analysed through specific inclusion and exclusion criteria. The obtained results provide for a wide overview in the field of interest shedding light on relevance of considering HEM and its non-negligible effects on the systems. The SLR introduces two relevant research opportunities.

RO1) Several efforts have been made and are still ongoing in the high-risk industries, like NPP or aviation, in order to understand the main error contributing factors and to develop methodologies for assessment and reduction of human error in maintenance. The same is not true for other industrial sectors, as particularly manufacturing, where this lack need to be filled. Studies could investigate the contributing HEM factors also in manufacturing, for example, through the analysis of the accident reports (as it already occurs in the high-risk industries) or the application of the expert judgment techniques. Thanks to the identification of such factors, a further opportunity could be the appropriate setting of existing and widespread HRA methods to improve the maintainers reliability.

RO2) As shown in the results discussion section, HEM can lead to critical consequences in terms of safety, quality, system reliability and economic and environmental impacts. To date only the safety issue has been deeply investigated, differently than other HEM consequences, due to its relevance in high-risk industries where the majority of studies were conducted. Instead, the HEM impacts on system availability and reliability (e.g. frequency of maintenance intervention or length of intervention time) and the HE economic and environmental consequences have been superficially considered. However, such aspects are essential in manufacturing companies in order to gain competitiveness and to improve their own performance. Future studies could identify and provide a detailed classification of the economic consequences attributable to HEM in order to reduce maintenance costs. Moreover, the SLR showed that HE consequences were not adequately integrated in maintenance management policies: a further opportunity could be the development of methodologies/decision-making approaches to limit HE consequences, as for example the scheduling of the maintainers tasks also as function of the human reliability to increase the probability of intervention success.

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Appendix A. Selected papers.

ID	REFERENCE	ID	REFERENCE	ID	REFERENCE
1	(Aalipour et al. 2016)	22	(Hameed et al. 2016)	43	(McDonnell et al. 2015)
2	(Abbassi et al. 2015)	23	(Hayama et al. 2011)	44	(Mc Leod & Rivera 2009)
3	(Achebo & Oghoore 2010)	24	(Heo & Park 2010)	45	(Mc Leod & Rivera 2011)
4	(Asadzadeh & Azadeh 2014)	25	(Hobbs & Williamson 2002)	46	(Mc Leod & Rivera 2013)
5	(Bao & Ding 2014)	26	(Hobbs & Williamson 2003)	47	(Nicholas 2009)
6	(Bao et al. 2015)	27	(Hobbs et al. 2010)	48	(Noroozi et al. 2013)
7	(Bozkurt & Kavsaoglu 2010)	28	(Islam et al. 2016)	49	(Noroozi, Khan, et al. 2014)
8	(Carr & Christer 2003)	29	(Islam et al. 2017)	50	(Noroozi, Abbassi, et al. 2014)
9	(Castiglia & Giardina 2013)	30	(Khalaquzzaman et al. 2010a)	51	(Okoh 2015)
10	(Chen & Huang 2013)	31	(Khalaquzzaman et al. 2010b)	52	(Papic & Kovacevic 2016)
11	(Chen & Huang 2014)	32	(Khalaquzzaman et al. 2011)	53	(Rankin et al. 2000)
12	(Chiodo et al. 2004)	33	(Kim & Park 2008)	54	(Rashid et al. 2013)
13	(Chiu & Hsieh 2016)	34	(Kim & Park 2009)	55	(Rashid et al. 2014)
14	(Dhillon & Kirmizi 2003)	35	(Kim & Park 2012)	56	(Razak et al. 2008)
15	(Dhillon & Liu 2006)	36	(Kovacevic et al. 2016)	57	(Sheikhalishahi, Azadeh, et al. 2016)
16	(Dhillon & Shah 2007)	37	(Kumar & Gandhi 2011)	58	(Sheikhalishahi, Pintelon, et al. 2016)
17	(Dhillon 2009)	38	(Kumar et al. 2015)	59	(Sheikhalishahi et al. 2016)
18	(Dhillon 2014)	39	(Latorella & Prabhu 2000)	60	(Singh & Kumar 2015)
19	(Emami-Mehrgani et al. 2016)	40	(Lawrence & Gill 2007)	61	(Su et al. 2000)
20	(Geibel et al. 2008)	41	(Liang et al. 2010)	62	(Wang & Hwang 2004)
21	(Gibson 2000)	42	(Lind 2008)	63	(Zhou et al. 2015)