Received 14 December 2015
Accepted 3 April 2016

Human factors in maintenance: a review

Mohammad Sheikhalishahi
Centre for Industrial Management/Traffic and Infrastructure, Katholieke Universiteit Leuven, Leuven, Belgium and School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran
Liliane Pintelon
Centre for Industrial Management/Traffic and Infrastructure, Katholieke Universiteit Leuven, Leuven, Belgium, and
Ali Azadeh
School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran

Abstract

Purpose – The purpose of this paper is to review current literature analyzing human factors in maintenance, and areas in need of further research are suggested.
Design/methodology/approach – The review applies a novel framework for systematically categorizing human factors in maintenance into three major categories: human error/reliability calculation, workplace design/macro-ergonomics and human resource management. The framework further incorporates two well-known human factor frameworks, i.e., the Swiss Cheese model and the ergonomic domains framework.
Findings – Human factors in maintenance is a pressing problem. The framework yields important insights regarding the influence of human factors in maintenance decision making. By incorporating various approaches, a robust framework for analyzing human factors in maintenance is derived.
Originality/value – The framework assists decision makers and maintenance practitioners to evaluate the influence of human factors from different perspectives, e.g. human error, macro-ergonomics, work planning and human performance. Moreover, the review addresses an important subject in maintenance decision making more so in view of few human error reviews in maintenance literature.

Keywords Maintenance, Human factors, Ergonomics, Human error, Review paper
Paper type Literature review

Nomenclature

List of abbreviations

FAA	Federal aviation administration	T&M	test and maintenance
SHELL	Software, Hardware, Environment, and Liveware	NFF	No Fault Found
		MTM	Methods-time measurement
HEA	Human error analysis	UAS	universal analyzing system
SLIM	Success likelihood index method	SAW	Situation Awareness
CBM	Condition based maintenance	RBF	radial basis function
PIFs	Performance influencing factors	ANN	artificial neural network
HEPs	Human error probabilities	FDAS	fault diagnosis assistance system
AMMP	Aviation Maintenance Monitoring Process	on-line MAP	on-line maintenance assistance platform
PSF	performance shaping factors	MRM	Maintenance resource management

Journal of Quality in Maintenance Engineering
Vol. 22 No. 3, 2016
pp. 218-237
© Emerald Group Publishing Limited
1355-2511
DOI 10.1108/JQME-12-2015-0064

ROI	Return on investment	MWSP	Maintenance workforce scheduling problem
AMP	Aircraft maintenance personnel	RAM+C	Reliability, availability, maintainability and cost
CMMS	Computerized maintenance management systems	ABR	Age-based replacement
MOSA	Multi-objective simulated annealing		

1. Introduction

Human role in different phases of a product life cycle including design, installation, production and maintenance is considerable and it cannot completely be replaced with latest technologies, technological systems. According to the International Ergonomics Association definition "Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance" (International Ergonomics Association, 2014). The significant role of human factors in maintenance is studied from different points of view. In this paper recent approaches to considering human factors in maintenance are reviewed. Reason and Hobbs (2003) reviewed the types of error and violation and the conditions that provoke them, and then set out the broader picture, illustrated by examples of three system failures. Central to the book is a comprehensive review of error management, followed by chapters on: managing person, the task and the team; the workplace and the organization; and creating a safe culture. It is then rounded off and brought together, in such a way as to be readily applicable for those who can make it work, to achieve a greater and more consistent level of safety in maintenance activities.

The literature review analyzed in this paper is based on 78 publications published within 2004-2015 period in maintenance and reliability, ergonomics and human factors, and optimization domains. For the literature research, "maintenance," "reliability," "human error," "human factors," "operator/crew allocation," "ergonomics" and other relevant descriptors were used. As a result, 190 publications were identified. Then, the full text of each publication was reviewed carefully by three independent experts to eliminate those that were not dedicated to human factors; most of them incorporated human resource or human error as a constraint or contributing factor. Thus, 78 publications which extensively analyzed human factors in maintenance from different viewpoints are presented and classified by three analysts. Table I shows the list of sources in which these publications are presented. Majority of these publications are appeared in *Quality in Maintenance Engineering* (7.69 percent) and *Reliability Engineering and System Safety* (7.69 percent).

2. Methodology

There are different classification schemes to categorize human error and human factors. Two well-known approaches for human factors and human error classifications are presented. The first one is human factors fields or domains, which is proposed by International Ergonomics Association (2014). In this way all the human factors could be categorized to physical, cognitive and organizational. Table II presents these domains with more details.

Another approach is Swiss Cheese model of accident causation proposed by Reason *et al.* (2006), to show the causal – or temporal – ordering of deficiencies that can explain the accident. Figure 1 shows the structure of Swiss Cheese model.

Source	Number	%
Journal of Quality in Maintenance Engineering	6	7.69
Reliability Engineering and System Safety	6	7.69
International Journal of Production Research	3	3.84
Safety Science	3	3.84
Cognition, Technology and Work	2	2.56
Nuclear Engineering and Design	2	2.56
Process Safety and Environmental Protection	2	2.56
Quality and Reliability Engineering International	2	2.56
International Journal of Industrial Ergonomics	2	2.56
Applied Ergonomics	1	1.28
Expert Systems with Applications	1	1.28
International Journal of Industrial Engineering: Theory Applications and Practice	1	1.28
International Journal of Production Economics	1	1.28
Journal of Loss Prevention in the Process Industries	1	1.28
Applied Energy	1	1.28
Applied Mechanics and Materials	1	1.28
Aviation, Space, and Environmental Medicine	1	1.28
Building Research and Information	1	1.28
Construction Innovation	1	1.28
Engineering Failure Analysis	1	1.28
European Journal of Operational Research	1	1.28
Human Factors	1	1.28
International Journal of Engineering Management and Economics	1	1.28
International Journal of Productivity and Quality Management	1	1.28
Human Factors and Ergonomics in Manufacturing	1	1.28
International Journal for Interactive Design and Manufacturing	1	1.28
Journal of Scientific and Industrial Research	1	1.28
Knowledge-Based Systems	1	1.28
Progress in Nuclear Energy	1	1.28
The International Journal of Aviation Psychology	1	1.28
The Journal of Aviation/Aerospace Education and Research	1	1.28
Total Quality Management and Business Excellence	1	1.28
Theoretical Issues in Ergonomics Science	1	1.28
Sains Humanika	1	1.28
Conferences	10	12.82
Books	9	11.53
Technical reports	5	6.41
PhD thesis	1	1.28
Total	78	100

Table I.
Distribution of publications by source

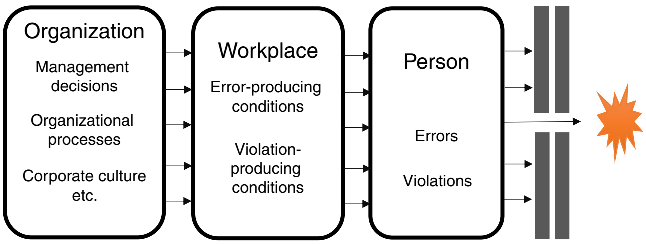
Physical	Human anatomy, anthropometric, physiological, work-related injuries, occupational safety
Cognitive	Mental processes (e.g. perception, memory, reasoning) and mental workload, decision making, human reliability, work stress, human-system
Organizational	Socio-technical systems (including organizational structures, policies, and processes), communication, crew resource management, work design, work systems, design of working times, teamwork, participatory design, virtual organizations, telework, and quality management

Source: International Ergonomics Association (2014)

Table II.
Human factors fields

These classification approaches cover various aspects of human error as well as human factors. However, to fully address the role of human factors in maintenance, a more holistic framework is required. In order to detect gaps in the existing literature, a classification framework is proposed to organize related publications into three main categories. These categories are human error/reliability calculation methods, workplace design/macro-ergonomics and human resource management. Table III shows the detailed structure of the proposed framework and related factors. While choosing these categories, the focus was on the objective of the paper, the human factor in maintenance. However, sometime these categories are used interchangeably in the literature, and there are strong connections between them, there exist substantial differences between them. The first category contains human error calculation models and approaches, which is an obvious choice as this was among the main concern of human factors in maintenance literature, especially in aviation and nuclear industries. Human error/reliability calculation category is mainly related to the primary cause of disaster or accident, as well as qualitative and quantitative methods for measuring human error. Workplace, macro-ergonomics and work situation could affect human reliability, performance and health; therefore this area of research has a close relationship with maintenance criteria. Human resource management deals with workforce planning, teamwork, human performance, training, knowledge management and performance shaping factors (PSF).

The applicability of the proposed framework for classifying related studies is twofold. First, each category may require specific expertise and knowledge from researchers and technicians for analyzing and assessing human factors. For example, to optimize the maintenance department from human error point of view, human error calculation and optimization models are required. Also, one should be familiar with related factors to the human error/reliability. Second, this framework will help the decision makers to evaluate



Source: Reason *et al.* (2006)

Figure 1. Swiss Cheese model II

Table III. The proposed classification for human factors in maintenance

Category	Factors
Human error/reliability calculation	Quantitative/qualitative methods for calculating human error/reliability
	Contributing factors
Workplace design/macro-ergonomics	Organization/environment
	Work/workplace conditions
Human resource management	Workforce planning
	Performance assessment
	Training/knowledge management
	Performance shaping factors

human factors in maintenance from various perspectives. If they are interested to calculate and optimize human reliability or to improve work situation, the first and the second approaches may be applied, respectively. Otherwise, in order to schedule human resource which is required for maintenance task, human resource management criteria, models and approach are applicable. Also, for measuring and improving human performance through training, knowledge management and PSF, the last category of approaches and studies may be applied. Based on this classification it is possible to determine which research has been done and still has to be done on joint maintenance and human factors. In the following section, related literature is reported using proposed framework (Table III). The Swiss Cheese model (Figure 1) and the human factor domains (Table II) will, however, be revisited at Section 4, which gives a detailed discussion of the literature review.

3. Literature review

Before categorizing related publications according to the proposed framework, it is noteworthy to mention some of the comprehensive studies in this area. Krulak (2004) examined 1,016 aircraft mishaps caused by human factors in maintenance using frequency analysis. Inadequate supervision, attention/memory errors and judgment/decision errors were among the most important factors. Dhillon (2007) identified several aspects of human factors and human error in aircraft maintenance. Reasons for the occurrence of human error in maintenance are discussed and different categorizations for human error and human error analysis methods are presented. Hackworth *et al.* (2007) assessed the status of human factors programs in different maintenance and repair organizations. Use of event-data reporting, creation of a fatigue management program, and increased use of data for error tracking purpose are identified as the best targets of opportunity for improvement. Hobbs (2004) investigated different functions of people as elements of maintenance systems in aviation. It is mentioned that in comparison to other threats to the safety, the mistakes of maintenance personnel have the potential to remain latent. Johnson and Hackworth (2008) showed that there are general agreement between two surveys which have been done by the US Federal Aviation Administration in 2006 and 2007, in which the number one challenge is fatigue in maintenance. Dhillon (2009) focussed on human reliability, human error and human factors in engineering maintenance. Aviation and power generation industries are taken into account and different models are presented. Chang and Wang (2010) categorized and examined 77 preliminary and 46 primary risk factors using a modified human factors software, hardware, environment and liveware model and a quantifiable evaluation approach. Labor contracts-related factors and general work culture are known as the most important ones. In a similar study, significant human risk factors are related to the hardware, liveware and environment (Said and Mokhtar, 2014). Also aviation maintenance companies have to consider other significant human risk factors under organizational such as financial strategy, policies, manpower and safety culture. Antonovsky (2010) determined the influence of human factors on maintenance reliability in petroleum operations. Violations, design and maintenance, detection, and decision making are introduced as the most-frequent factors in the incidents ($n = 194$). In another study within a petroleum industry organization, problem-solving behaviors (assumptions), plant design and organizational communication were identified as the human factors contributing most frequently to the failures (Antonovsky *et al.*, 2014). Okoh and Haugen (2014) reviewed 183 detailed, major accident investigation and analysis reports related to the handling, processing and storage of hydrocarbons and hazardous chemicals. It is found maintenance was linked to 80 (44 percent) of major accidents and that the accident trend is decreasing. The results also show that "lack of barrier maintenance" (50 percent), "deficient design, organization and resource management" (85 percent) and "deficient planning/scheduling/fault diagnosis" (69 percent) are the most frequent causes in terms of the active accident, latent accident and work processes, respectively.

Figure 2 shows the share of each category from the reviewed publications. It can be seen that work and workplace conditions have received considerable attention. Human error and reliability calculation and optimization methods are also investigated from different points of view. Work and workplace conditions and human performance-related factors are in the next places. It seems that human resource management and allocation have received less attention comparing to the other fields. In the following sections, related studies are presented in accordance with the proposed framework.

Figure 3 depicts the share of each industry from the reviewed publications. In accordance to the previous review articles, most of the studies are dedicated to the aviation industries. Also chemical processing including refinery, oil and gas, petroleum and power generations as well as nuclear power plants are extensively investigated in the available literature.

3.1 Human error/reliability calculation

Various methods and approach are proposed in literature for measuring human reliability or human error either qualitatively or quantitatively. Wang and Hwang (2004) considered recovery factor for latent human errors to solve the practical parameters such as the number of maintenance personnel and maintenance cycle time. Fogarty (2005) developed, tested and cross-validated models that explain how errors can occur in safety-conscious industries and how they are linked with violations. Dhillon and Liu (2006) presented the impact of human errors in different maintenance environments as found in the literature and found that human error in maintenance is a pressing problem. More *et al.* (2007) presented a methodology for characterization of human reliability based on the API-770 guide for reduction of human errors, aiming at reducing the possibility of human errors in oil refineries. It is suited for operation, maintenance and inspection activities in oil production and distribution units and identified 64 performance factors to obtain a human reliability index. Heo and Park (2010) proposed a framework for estimating the qualitative

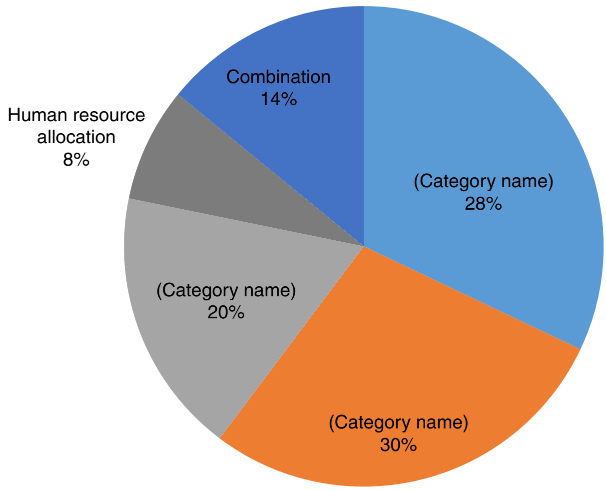


Figure 2.
A pie chart of publication percentages corresponding to the proposed framework

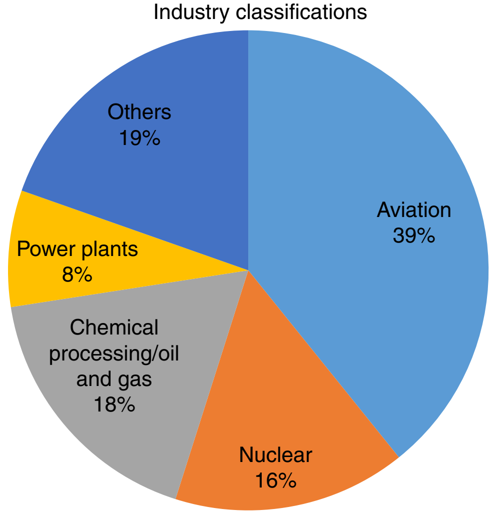


Figure 3.
A pie chart of publication percentages corresponding to industry classifications

and quantitative consequences of human errors that occur during maintenance tasks involving the balance of plant in nuclear power plants. Khalaquzzaman *et al.* (2010) identified the effect of human errors during refueling maintenance and periodic maintenance of nuclear power plants. It is mentioned that optimal frequency of periodic maintenance significantly increases with the increase of hardware failure rate and human error in maintenance tasks in refueling cycle. Aju Kumar and Gandhi (2011) applied graph theory for quantifying human error in maintenance activities that models the human error inducing factors and their interactions/interrelationships in terms of human error digraph. The digraph is converted into an equivalent matrix and an expression based on this is developed, which is characteristic of the human error in maintenance. Kim and Park (2012) introduced four human error analysis procedures for a predictive analysis of human error potentials when maintenance personnel perform test or maintenance actions based on a work procedure or work plan. Each of the procedures is composed of three steps such as analysis of basic error potential, evaluation of possible impacts on the system, and identification of deficient work context or PSFs. Aju Kumar *et al.* (2015) presented a tool to quantitatively analyze the dynamic behavior of error inducing factors on human reliability. Human experience and knowledge on the error enhancing environment are embedded in the fuzzy cognitive map structure, with inbuilt interactions of factors and their degree of influence. Wu and Hwang (1989) proposed a conceptual model of maintenance tasks to facilitate the identification of root causes of maintenance human errors in nuclear power plants. An external/internal classification scheme is also developed to discover the root causes of human errors.

Asadzadeh and Azadeh (2014) proposed a model for the integration of human reliability model with condition based maintenance (CBM) optimization. To quantify human reliability in CBM, the functional characteristics of human error in CBM as well as the main performance influencing factors (PIFs) are identified. Results showed that human error in maintenance, accuracy and relevance of condition monitoring technology had significant effect on system average unit cost. Kiassat *et al.* (2014) presented a novel method to quantify the effects of human-related factors on the risk of failure in manufacturing industries. Two possible intervention methods, including reducing the production rate to provide more cognition time and adding a shift expert to guide the operators, are examined. Noroozi *et al.* (2014) provided an analysis of human factors in pre-maintenance and post-maintenance operations. A pump was analyzed and according to the results, two activities had high human error probabilities: "drain lines" and "open valves, fill pump and test for leaks." Rashid *et al.* (2014) proposed Aviation Maintenance Monitoring Process; a process to proactively monitor existence of human error causal factors. These factors are typically pre-initiated during design practices, manufacturing processes, or at later stages due to organizational, individuals, or workplace conditions within maintenance, repair, and overhaul organizations. Kim *et al.* (2009) analyzed the test and maintenance human errors involved in unplanned reactor trip events in Korean nuclear power plants according to James Reason's basic error types. Four error modes such as "wrong object", "omission", "too little" and "wrong action" appeared to be dominant. Vinnem *et al.* (2012) developed quantitative risk analysis of the platform specific hydrocarbon release frequency by considering operational barriers in event trees and fault trees, as well as risk influencing factors. Conditions such as lack of standardization, operational complexity, operational options and number of malfunctions appear to have substantial impact on the dispositions of human failure as well as for violations. Groth and Mosleh (2012) introduced a hierarchical set of PSF (PIFs) that can be used for both qualitative and quantitative human reliability analysis. Effects of these PIFs on maintenance activities are discussed. Marais and Robichaud (2012) investigated and quantified the contribution of maintenance to passenger airline risk. They found that at least 10 percent of incidents involving mechanical failures such as ruptured hydraulic lines can be attributed to maintenance, suggesting that there may be issues surrounding both the design of and compliance with maintenance plans. Rashid *et al.* (2013) investigated the impact of human reliability on aviation maintenance safety. Parts requiring higher cognitive or intellectual concentration during assembly, installation, alignment or adjustment are found more potential to suffer problems that lead to major consequential undesired outcomes. Many types of maintenance errors were listed, the most common one being improper execution of various inspections with higher risks of associated defects being left undetected. Cardoso *et al.* (2014) discussed if during maintenance turnarounds there is an increase of undesired events and human factor role. They suggested that effective safety management depends on a comprehensive risk assessment that should integrate an assessment of workers perceived risk to diminish the elevated frequency preceded by human failure during maintenance turnarounds.

3.2 Workplace/organization conditions

3.2.1 Organization. Although the immediate causes of major incidents frequently involve "human error" of operators or maintenance personnel, the reasons that these errors occurred in the first place were the responsibility of those more senior in the organization (Collins and Keeley, 2003; Anderson, 2004). Nortje and Visser (2009) stated that an organization that does not have multiple defence layers to protect against human error, experiences higher rates of incidents and accidents, and therefore has a higher probability that a catastrophic incident could occur at some time. Zhang and Yang (2006) proposed a production system continuous improvement model for aviation maintenance quality taking into account human factors and organization management, in which the main maintenance mistakes are assigned to the low standard problem. Hobbs (2004) investigated organizational deficiencies in maintenance operations and emphasized that one of the most pressing challenges facing the maintenance sector is not technical in nature, rather it is how to foster a sprite of glasnost to promote incident reporting and the disclosure of incident information. Reiman and oedewald (2004) utilized the culture-questionnaire that is designed to measure the different cultural aspects of complex organizations to measure maintenance culture and maintenance core task. Four different orientations toward the core task of maintenance were identified, which were independent of age, tenure and task. Eti *et al.* (2006) identified five strategic aspects of maintenance management, namely: maintenance methodology; support processes; organization and work structuring; comparable culture; and general management policy. Three factors that permeate these dimensions are wise leadership, excellent communications and an understanding of the human factors involved. Reiman and Oedewald (2006) illustrated how the cultural conceptions and organizational practices, tools and the organizing of the work and the organizational climate influence each other, and how they relate to the demands of the maintenance work using Nordic nuclear power plant maintenance unit as a case study.

Azadeh *et al.* (2006) described an integrated macro-ergonomics model for operation and maintenance of power plants. Statistical tests on questionnaire survey data shows the importance of total human factors on job pressure. Lind (2008) presented the results of an analysis based on real accident data consisted of public Finnish accident reports describing fatal and severe non-fatal accidents in Finnish industry. Within both types of accidents the most typical latent causes are defects in work instructions and machinery safety equipment. Based on the findings, the most essential roles in accident prevention are played by organizational factors, such as safety management and operations planning. Reiman (2011) dealt with the challenge of understanding maintenance work in safety-critical organizations. The aim was to review the current literature on maintenance work and illustrate the organizational research challenges of managing performance variability in maintenance. The paper concluded by noting that a holistic theory on maintenance work is needed to manage the variability and turn it into a positive force. Khan *et al.* (2014) dealt with the impact of no fault found phenomenon from an organizational culture and human factors point of view. Key issues within the organizational and workforce culture category are identified as time pressure, organizational cultures, inadequate training or lack of training tools, sharing information, reluctance to change, inadequate historical data. An *et al.* (2014) studied the maintenance safety evaluation of the aging aircraft. The safety evaluation index system was built based on human factors, structure factors and management factors. The evaluation indexes of the human factors are body and mind, responsibility and professional ability; and management factors are people oriented, rules and regulations, and communication.

3.2.2 Workplace. Maintenance environment could be so complex, and it is often difficult for personnel to physically access all the system components, and it may leads to the operational risks and occupational hazards. Thus, maintainability is applied to facilitate maintenance tasks and to increase availability. Lind and Nenonen (2008) described the most important occupational risks in maintenance operations. The results indicate that the typical risks in maintenance operations involve poor ergonomics and that the most severe risks among these can lead to direct injury. Severe or even fatal injuries are mainly caused by crushing or falling. Nicholas (2009) described an analytical approach and general design principles to develop practicable solutions that address reasonably foreseeable maintenance errors. Extensive investigation of maintenance error, its causes and consequences are done to enable the designer to consider the impact of physical design on the behavior of the maintainer. Kumar *et al.* (2009) explored potential risk factors especially in Arctic conditions with a view to how human factors/ergonomic principles can help to reduce risk factors and increase maintainability of the oil and gas industry. The introduction of ergonomics principles in the design stages not only reduces the maintenance downtime but also reduces the exposure to cold, thus preventing maintenance personnel from suffering cold injuries. Desai and Mital (2010) presented a methodology to deal with product design for maintenance addressing the human factors associated with the maintenance operation. The authors incorporated this factor into the methodology, given the labor intensive nature of virtually all maintenance operations. Zhou *et al.* (2011) combined the technology of capturing human motion and the technology of virtual reality to carry on assessment of worker working postures, fatigue and human force and torque in the maintenance process. Elbidweihy and Anis (2012) provided numerical comparative assessment of the risk of exposure of maintenance workers on power lines of three different voltage levels and to study the factors affecting the interaction between AC magnetic fields and the human body. Di Gironimo *et al.* (2012) proposed to correct the methods-time measurement universal analyzing system method including in the task analysis the study of human postures and efforts. The proposed approach allows to estimate with an "acceptable" error the time needed to perform maintenance tasks. Lieber *et al.* (2013) explored the physical-physiological requirements for a human to perceive right the meaning of symbolic properties technical objects afford when they are being maintained in variable contextualized situations. They demonstrated that having human factors measurable requirements enable to put all specification process stakeholders into a functional continuum.

Huang *et al.* (2013) constructed index systems of maintenance accessibility based on evaluation purpose. This analysis can be helpful to optimize design scheme, make a decision on product acceptance or improvement, and construct the evaluation index system of all maintainability qualitative requirements. Chen and Huang (2014) constructed an aviation maintenance performance model by the Bayesian Network. The casual dependence between the influence factors and inspection performance is made qualitatively and quantitatively, and applied to the visual inspection case study. Oliveira *et al.* (2014) presented a conceptual framework to structure effective user interfaces for maintenance field operators using situation awareness (SAW). In this sense, SAW is structured around seven entities- including task, equipment, system, environment, team, enterprise and personal- to ensure awareness. The combination of these entities creates a context to analyze and perform operational maintenance processes, improving their efficiency and efficacy (leading to a higher level of safety), and also decreasing the number of errors and their criticality.

3.3 Human resource management

3.3.1 Maintenance human performance. Human performance in the maintenance function is a crucial factor contributing to the performance of this department. Through a case study conducted in an electronic packaging industry, Abdul Razak *et al.* (2008) showed that the reliable technician is someone who had the higher level of quality in terms of all or most of the PSF. Cabahug *et al.* (2004) analyzed 14 personal variables to determine which significantly affected plant operators' maintenance proficiency. Different models are applied and the most efficient model used three personal attributes: years of relevant working experience on the machine, personal disposition and operator reliability. Edwards *et al.* (2005) modeled plant operators' maintenance proficiency using a radial basis function artificial neural network (ANN) through data gathered from plant and equipment experts within the UK. Results indicate that the developed ANN model was able to classify proficiency at 89 percent accuracy using ten significant variables. These variables were: working nightshifts, new mechanical innovations, extreme weather conditions, planning skills, operator finger dexterity, years experience with a plant item, working with managers with less knowledge of plant/equipment, operator training by apprenticeship, working under pressure of time and duration of training period. Liang *et al.* (2009) evaluated engineers' mental workload while maintaining digital systems in nuclear power plants. The results indicated that the mental workload was lower in maintaining digital systems than that in analog systems. Hennequin *et al.* (2009) concluded that considering an imperfect maintenance show that a perfect maintenance model is inaccurate contemplating that human factors (intervention time and technician experience) can result in maintenance imperfections. Galar *et al.* (2011) proposed model to combine the qualitative and quantitative measurements of the quality of work performed considering various human factors that affect maintenance performance measurement. Abdul Razak *et al.* (2011) presented the implementation of a new developed model named "workforce competency model". In the model, the integration of qualitative and quantitative approaches is proposed as a method to quantify the actual competency level of maintenance personnel. A set of individual factors that may influence their performance is considered as the model variables in their evaluation. Park *et al.* (2012) through an empirical study showed that managing individual fatigue and stress causes members in a unit to have more positive feelings and emotions regarding their job and organization leading to fewer individual errors and better performance. Moreno-Trejo *et al.* (2012) identified and discussed various factors that will influence the process of installing and maintaining subsea equipment in the oil and gas industry. They showed that the participants pay a lot of attention to competence and experience factors. Therefore, by recruiting personnel with required level of experience from companies that is specializing on subsea system manufacturing, installation and maintenance will reduce the costs and mitigate the risks. Kumar *et al.* (2013) provided an overview of research and development in the measurement of maintenance performance. It is mentioned that human factor must be included in the selection of the measuring metric, its implementation and the use of the resulting measurement.

3.3.2 Training/assistant systems. Training sessions and on job training improve maintenance skills and knowledge. Also, maintenance assistance systems are proposed to help operators to perform their jobs at highest level of safety and efficiency. Su *et al.* (2006) proposed a fault diagnosis assistance system (FDAS) that applied in the motorcycle maintenance. Result shows that he maintenance workers can understand quickly and detect the faults correctly in using FDAS. Therefore, the diagnostic errors that result in wasting customers' time and money will be reduced. Liang *et al.* (2010) developed an on-line maintenance assistance platform (on-line MAP) for technicians to perform maintenance tasks to increase aviation maintenance and inspection safety. The on-line MAP reminds technicians to consider the effect of human error on systems and humans. The results revealed that teams' risk cognition, situation awareness, technicians' performance and their job satisfaction have all been increased by the proposed on-line MAP instruction comparing to that by the current work card instruction. Patankar and Taylor (2008) described the maintenance resource management (MRM) training, evaluation, and safety management research program as it tracked the evolution of training content as well as the attitudinal, behavioral and performance changes toward the development of proactive safety management programs. The following key issues discovered in the MRM research continue to hold strong in the Aviation Safety Action Programs environment: communication, trust, professionalism and return on investment for MRM training. Usanmaz (2011) developed an aircraft maintenance personnel (AMP) training model by referring to the Part 66 which is in effect in Europe; and based on this model which lets the consideration of the overall AMP training progression in two steps: The basic training before the licence and the on the job and the type/task training after the licence. Bowen (2013) identified the predictive role individual difference variables may play in the impact of MRM training programs in an aviation maintenance setting. Results of the multiple regression procedures yielded unanticipated findings. Demographic variables predicted little variance in overall change intentions, post training attitude change or occurrence of negative ("boomerang") attitude change. It is possible that when organizational norms are particularly strong, personal motivations or individual differences may have less power to affect behavioral change. Ruiz *et al.* (2014) describes a framework for the development of an experience feedback process in maintenance, taking benefit of the potential of computerized maintenance management systems for providing a huge volume of information on past experiences that can be translated into new useful knowledge to improve the decisions related to the maintenance activity.

3.3.3 Crew planning. Maintenance tasks are still labor intensive and maintenance crews are often highly skilled and highly paid (Safaei *et al.*, 2008). Thus, crew resource management and workforce planning significantly affects total maintenance cost. Suryadi and Papageorgiou (2004) presented a mathematical programming approach to optimize process plant performance subject to equipment failure. The preventive maintenance planning and crew allocation problem are used to demonstrate the effectiveness of the proposed approach. Safaei *et al.* (2008) proposed a multi-objective simulated annealing algorithm to solve maintenance workforce scheduling problem with the aim of simultaneously minimizing the workforce cost and the flow time of the work requests. Workforces have different proficiencies and labor requirements are provided from internal and external resources as regular time, overtime and contract. Martorell *et al.* (2010) proposed reliability, availability, maintainability and cost models to explicitly address the effect of human resources and material resources (spare parts) on reliability, availability, maintainability and cost (RAM+C) criteria are proposed. Through a case study they showed how changes in managing human and material resources affect both cost and unavailability.

Langer *et al.* (2010) presented a priority-based dispatching policy, a dynamic bottleneck policy, in which the maintenance worker will service the high-priority machine (i.e. bottleneck machine) first when multiple service requests are received. By extensive numerical simulations they showed that the dynamic bottleneck policy leads to most improvement in system throughput compared with the first-come-first-served policy. Koochaki *et al.* (2013) focussed on the impact of using either CBM or age-based replacement (ABR) in serial and parallel multicomponent systems: first, without worker constraints, second, with a single internal maintenance worker, and third, with external maintenance workers with a significant response time. With an internal maintenance worker, the sequential execution of maintenance activities prevents efficiency gains in the serial configuration and here CBM performs better. Also in the parallel configurations, the efficiency under CBM is generally better than under ABR. However, with external maintenance workers, CBM is not able to group maintenance activities as well as ABR, which results in a lower efficiency in the serial configuration. Ighravwe and Oke (2014) formulated a non-linear integer programming model to solve a maintenance workforce sizing problem with a productivity improvement goal. Inputs into the optimization model include monthly and routine maintenance periods, volume of production, contingency maintenance time, use factor and priority factor among others. Use factor shows how often maintenance crews are busy in a maintenance system. The results obtained showed that the incorporation of use factor in the proposed model yielded a reduction of the number of maintenance technicians.

As mentioned before, in this section literature of human factors in maintenance is reviewed and categorized according to the proposed framework. It is obvious that human error calculation and reduction models and approaches as well as workplace situations have been studied more extensively comparing to the human resource management and performance management. However, there are various probabilistic and cognitive human reliability assessment methods which are not addressed in maintenance management literature. Furthermore, several work condition, workplace and macro-ergonomics factors could be applied in maintenance environment, e.g. occupational hazards for maintenance operators, workplace improvement programs and maintenance department position in organizational charts. Two other categories including human resource management and human performance in maintenance show lots of possible directions for future studies. Employee recruitment, employee turnover, knowledge management, performance assessment and appraisal, and training could be applied in maintenance management area.

4. Human factor domains-Swiss Cheese model

In this section, two aforementioned approaches, which are human factor domains and Swiss Cheese model, are applied to categorize reviewed literature. Table IV shows the result of the classification.

According to Table IV, physical aspect of human factors has received less attention comparing to other domains. Also a few studies are dedicated to workplace and defenses from Swiss Cheese model. Although it seems a lot of studies have been done from organizational point of view, those which are focussed on cognitive aspects of organization as well as workplace are very rare. It is also noteworthy to mention that most of the publications have considered various human factors altogether. This gives better view of the total situation; however, it could be hard to find the contribution of each domain of human factor in maintenance. Thus, it is interesting to specify the exact domain for future studies in this area. Table V shows the classification of reviewed publications considering human error types as well as local factors according to the Reason and Hobbs's model (Reason and Hobbs, 2003).

Table IV. Classification of publication according to the human factor domains-Swiss Cheese model

	Swiss Cheese model					
Ergonomics' domains	Person	Organization	Workplace	Defenses	Combination	Sum
Organizational	1	17	1	1	0	20
Cognitive	15	2	0	0	1	18
Physical	4	0	2	0	0	6
Combination	1	0	1	0	32	34
Sum	21	19	4	1	33	78

	References
Error type	
Recognition failures	Antonovsky (2010), Kim *et al.* (2009)
Memory lapses	Krulak (2004), Kim *et al.* (2009)
Slips of action	
Error of habit	Liang *et al.* (2010)
Mistaken assumptions	
Knowledge-based errors	Oliveira *et al.* (2014)
Violations	Antonovsky (2010), Fogarty (2005), Kim *et al.* (2009), Marais and Robichaud (2012)
Local factors (error provoking factors)	
Documentation	Hackworth *et al.* (2007), Johnson and Hackworth (2008)
Time pressure	Hobbs (2004), Khan *et al.* (2014), Usanmaz (2011)
Housekeeping and tool control	Rashid *et al.* (2014), Martorell *et al.* (2010)
Coordination and communication	Antonovsky *et al.* (2014), Okoh and Haugen (2014), Lind (2008), Cabahug *et al.* (2004), Usanmaz (2011), Suryadi and Papageorgiou (2004), Liang *et al.* (2010), Langer *et al.* (2010)
Tools and equipment	Noroozi *et al.* (2014), Rashid *et al.* (2014), Nicholas (2009), Kumar *et al.* (2009), Chen and Huang (2014)
Fatigue	Hackworth *et al.* (2007), Hobbs (2004), Johnson and Hackworth (2008), Chen and Huang (2014), Park *et al.* (2012)
Knowledge and experience	Johnson and Hackworth (2008), Noroozi *et al.* (2014), Khan *et al.* (2014), Oliveira *et al.* (2014), Cabahug *et al.* (2004), Moreno-Trejo *et al.* (2012), Kumar *et al.* (2013), Usanmaz (2011), Ruiz *et al.* (2014)
Bad procedure	Okoh and Haugen (2014), Marais and Robichaud (2012), Di Gironimo *et al.* (2012), Moreno-Trejo *et al.* (2012)
Procedure usage	Zhang and Yang (2006), Vinnem *et al.* (2012), Liang *et al.* (2010)
Personal beliefs	Chang and Wang (2010), Reiman and Oedewald (2004)
Design deficiencies	Okoh and Haugen (2014), Eti *et al.* (2006)
Stress	Krulak (2004), Chang and Wang (2010), Park *et al.* (2012)
Other	
Lack of barrier maintenance	Okoh and Haugen (2014)
Resource management	Okoh and Haugen (2014)
Tracking errors	Hackworth *et al.* (2007)
Complexity	Vinnem *et al.* (2012), Rashid *et al.* (2013)
Organization culture	Said and Mokhtar (2014), Khan *et al.* (2014)
Labor contract	Said and Mokhtar (2014)
Supervision	Rashid *et al.* (2014)
Adequate support systems	Eti *et al.* (2006)
Defence layers	Nortje and Visser (2009)

Source: Reason and Hobbs (2003)

Table V. Classification of publication based on Reason and Hobbs's model

From Table V, two main conclusions could be drawn. First, most of the studies have addressed local factors, including knowledge, coordination and communication, fatigue, and equipment. This shows the importance of these error provoking factors in maintenance. In other hand, future studies in the area of human factors in maintenance could focus on error types, specially mistaken assumption and slips of actions. Also, as it can be seen, there are some factors in the literature which have not been included in Reason and Hobbs's model (Reason and Hobbs, 2003). This shows there is a need for a general framework.

5. Conclusions, limitations and future research

In this paper, 78 publications on human factors in maintenance are analyzed to identify the criteria and aspects most addressed in this area. A novel framework is proposed to systematically categorize the published literature and also to gap analysis. In the proposed framework three major categories are considered including human error/reliability calculation, workplace design/macro-ergonomics, human resource management. The framework further incorporates two well-known human factor categorization approaches, i.e., the Swiss Cheese model and the ergonomic domain framework. The classification of the existing literature according to the proposed framework of joint maintenance and human factors makes it possible to draw some major conclusions and suggest possible future work in this area. Research on human factors in maintenance has mainly focussed on human errors calculation models and methods, even though social and organizational factors have received increasing attention in recent years, still studies of physical and mental stress, normal work, cultures of maintenance have been scarce. Also, most of the studies are focussed on reliability-centered industries including aviation, nuclear power plant and chemical processing (73 percent). According to the nature of this type of industries, reliability and specifically human error is the main concern. Future direction in this area would be investigating human factors from long-term cost, availability and ergonomics points of view in a wide range of industries.

Another important aspect of human factors in maintenance is maintainability, which should be taken into account from the design phase of equipment and organizations. This would reduce maintenance workload and downtime, fatigue and work injuries, probability of human error, and will improve workplace environment and employee satisfaction. Comprehensive studies in the area of crew resource management, operator allocation and personnel recruitment are very rare. According to the literature fatigue, knowledge and experience, and coordination and communication are among the most important human factors related to the maintenance (Table V). Thus, human resource management and scheduling could be an interesting area for future studies. Finally, other future directions in this area would be to develop: human error models for different types of error (slips of action, mistaken assumption, etc.), error prediction and recognition tools and technologies, intelligent decision aid system.

There exist some other interesting areas that could be addressed in future. Supply chain and sub-contracting in maintenance are among present interest in the area of maintenance. Human factors play an important role in these fields. Also, impact of maintenance on the safety of autonomous systems by considering human factors is another.

References

Abdul Razak, I.H., Kamaruddin, S. and Abdul Azid, I. (2011), "Implementation of the workforce competency model for assessing maintenance workers' performance", *International Journal of Productivity and Quality Management*, Vol. 7 No. 4, pp. 440-462.

Abdul Razak, I.H., Kamaruddin, S. and Azid, I.A. (2008), "Development of human reliability model for evaluating maintenance workforce reliability: a case study in electronic packaging industry", *International Electronic Manufacturing Technology Symposium (IEMT) 33rd IEEE/CPMT, IEEE, Penang*, pp. 1-7.

Aju Kumar, V.N. and Gandhi, O.P. (2011), "Quantification of human error in maintenance using graph theory and matrix approach", *Quality and Reliability Engineering International*, Vol. 27 No. 8, pp. 1145-1172.

Aju Kumar, V.N., Gandhi, M.S. and Gandhi, O.P. (2015), "Identification and assessment of factors influencing human reliability in maintenance using fuzzy cognitive maps", *Quality and Reliability Engineering International*, Vol. 31 No. 2, pp. 169-181.

Anderson, M. (2004), "Behavioral Safety and Major Accident Hazards: Magic Bullet or Shot in the Dark?", *Proceedings of the Hazards XVIII Symposium, IChemE, UMIST, Manchester, November 24*.

An, T., He, Y. and Gao, C. (2014), "Research on Maintenance Safety Evaluation of the Aging Aircraft", *Proceedings of the First Symposium on Aviation Maintenance and Management-Volume II, Vol. 297, Springer, Berlin Heidelberg*, pp. 109-116.

Antonovsky, A.D. (2010), "The relationship between human factors and plant maintenance reliability in a petroleum processing organisation", PhD thesis, Curtin University of Technology, Perth, August.

Antonovsky, A., Pollock, C. and Straker, L. (2014), "Identification of the human factors contributing to maintenance failures in a petroleum operation", *Human Factors*, Vol. 56 No. 2, pp. 306-321.

Asadzadeh, S.M. and Azadeh, A. (2014), "An integrated systemic model for optimization of condition-based maintenance with human error", *Reliability Engineering and System Safety*, Vol. 124, pp. 117-131.

Azadeh, M.A., Keramati, A., Mohammadfam, I. and Jamshidnedjad, B. (2006), "Enhancing the availability and reliability of power plants through macroergonomics approach", *Industrial Research*, Vol. 65 No. 11, pp. 873-878.

Bowen, E.E. (2013), "Predicting impact of maintenance resource management training utilizing individual difference variables", *Journal of Aviation/Aerospace Education & Research*, Vol. 22 No. 3, pp. 9-17.

Cabahug, R., Edwards, D. and Nicholas, J. (2004), "Classifying plant operator maintenance proficiency: examining personal variables", *Building Research & Information*, Vol. 32 No. 2, pp. 119-127.

Cardoso, A.G., do Sameiro Queirós, M., Meireles, J.M. and Diogo, M.T. (2014), "Safety management on a refinery maintenance turnaround", in Arezes, P.M., Baptista, J.S., Barroso, M.P., Carneiro, P., Cordeiro, P., Costa, N., Melo, R.B., Miguel, A.S. and Perestrelo, G. (Eds), *Occupational Safety and Hygiene II*, CRC Press, London, pp. 505-510.

Chang, Y.H. and Wang, Y.C. (2010), "Significant human risk factors in aircraft maintenance technicians", *Safety Science*, Vol. 48 No. 1, pp. 54-62.

Chen, W. and Huang, S.P. (2014), "Human reliability analysis in aviation maintenance by a Bayesian network approach", in Deodatis, G., Ellingwood, B.R. and Frangopol, D.M. (Eds), *Safety, Reliability, Risk and Life-Cycle Performance of Structures and Infrastructures*, CRC Press, London, pp. 2091-2096.

Collins, A. and Keeley, D. (2003), "Loss of containment incident analysis", HSL/2003/07, available at: www.hse.gov.uk/research/hsl_pdf/2003/hsl03-07.pdf (accessed July 18, 2011).

Desai, A. and Mital, A. (2010), "Improving maintainability of products through the adoption of a comprehensive design for maintainability method", *International Journal of Industrial Engineering: Theory Applications and Practice*, Vol. 17 No. 2, pp. 103-114.

Dhillon, B.S. (2007), "Human error in aircraft maintenance", in Pham, H. (Ed.), *Human Reliability and Error in Transportation Systems*, Springer Series in Reliability Engineering, Springer, London, pp. 131-144.

Dhillon, B.S. (2009), *Human Reliability, Error, and Human Factors in Engineering Maintenance with Reference to Aviation and Power Generation*, CRC Press, Boca Raton, FL.

Dhillon, B.S. and Liu, Y. (2006), "Human error in maintenance: a review", *Journal of Quality in Maintenance*, Vol. 12 No. 1, pp. 21-36.

Edwards, D.J., Yang, J., Cabahug, R. and Love, P.E.D. (2005), "Intelligence and maintenance proficiency: an examination of plant operators", *Construction Innovation*, Vol. 12 No. 4, pp. 243-254.

Elbidweihy, H. and Anis, H. (2012), "Comparative exposure to magnetic fields of live-line workers on power lines", *Transmission and Distribution Conference and Exposition (T&D), IEEE PES, Orlando, FL*, pp. 1-8.

Eti, M.C., Ogaji, S.O.T. and Probert, S.D. (2006), "Strategic maintenance-management in Nigerian industries", *Applied Energy*, Vol. 83 No. 3, pp. 211-227.

Fogarty, G. (2005), "The war on error: psychology and aviation maintenance", in Peter, M. (Ed.), *Focus on Human Factors in Aviation*, Australian Defence Force Directorate of Flying Safety, Canberra, pp. 78-82.

Galar, D., Stenström, C., Parida, A., Kumar, R. and Berges, L. (2011), "Human factor in maintenance performance measurement", *International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE*, pp. 1569-1576.

Gironimo, D.G., Martino, C.G., Martino, D., Lanzotti, A., Marzano, A. and Russo, G. (2012), "Improving MTM-UAS to predetermine automotive maintenance times", *International Journal on Interactive Design and Manufacturing*, Vol. 6 No. 4, pp. 265-273.

Groth, K.M. and Mosleh, A. (2012), "A data-informed PIF hierarchy for model-based human reliability analysis", *Reliability Engineering and System Safety*, Vol. 108, pp. 154-174.

Hackworth, C., Holcomb, K. and Dennis, M. (2007), "An international survey of maintenance human factors programs", Federal Aviation Administration, Washington, DC.

Hennequin, S., Arango, G. and Rezg, N. (2009), "Optimization of imperfect maintenance based on fuzzy logic for a single-stage single-product production system", *Journal of Quality in Maintenance Engineering*, Vol. 15 No. 4, pp. 412-429.

Heo, G. and Park, J. (2010), "A framework for evaluating the effects of maintenance-related human errors in nuclear power plants", *Reliability Engineering and System Safety*, Vol. 95 No. 7, pp. 797-805.

Hobbs, A. (2004), "Latent failures in the hangar: uncovering organizational deficiencies in maintenance operations", SJSU/NASA-Ames Research Center, pp. 1-11.

Huang, D., Li, Q., Zuo, C. and Li, J. (2013), "Construction of maintenance accessibility evaluation index based on purpose", *International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE), IEEE, Chengdu*, pp. 1451-1454.

Ighravwe, D.E. and Oke, S.A. (2014), "A non-zero integer non-linear programming model for maintenance workforce sizing", *International Journal of Production Economics*, Vol. 150, pp. 204-214.

International Ergonomics Association (2014), "What is ergonomics", available at: www.iea.cc/whats/ (accessed March 17, 2014).

Johnson, W.B. and Hackworth, C. (2008), "Human factors in maintenance", *Flight Safety Foundation, Aerosafety World*, January 15, pp. 34-40.

Khalaquzzaman, M., Kang, H.G., Kim, M.C. and Seong, P.H. (2010), "Quantification of unavailability caused by random failures and maintenance human errors in nuclear power plants", *Nuclear Engineering and Design*, Vol. 240 No. 6, pp. 1606-1613.

Khan, S., Phillips, P., Jennions, I. and Hockley, C. (2014), "No fault found events in maintenance engineering part 1: current trends, implications and organizational practices", *Reliability Engineering and System Safety*, Vol. 123, pp. 183-195.

Kiassat, C., Safaei, N. and Banjevic, D. (2014), "Choosing the optimal intervention method to reduce human-related machine failures", *European Journal of Operational Research*, Vol. 233 No. 3, pp. 604-612.

Kim, J. and Park, J. (2012), "Reduction of test and maintenance human errors by analyzing task characteristics and work conditions", *Progress in Nuclear Energy*, Vol. 58, pp. 89-99.

Kim, J., Park, J., Jung, W. and Tae, J.T. (2009), "Characteristics of test and maintenance human errors leading to unplanned reactor trips in nuclear power plants", *Nuclear Engineering and Design*, Vol. 239 No. 11, pp. 2530-2536.

Koochaki, J., Bokhorst, J.A.C., Wortmann, H. and Klingenberg, W. (2013), "The influence of condition-based maintenance on workforce planning and maintenance scheduling", *International Journal of Production Research*, Vol. 51 No. 8, pp. 2339-2351.

Krulak, D.C. (2004), "Human factors in maintenance: impact on aircraft mishap frequency and severity", *Aviation, Space, and Environmental Medicine*, Vol. 75 No. 5, pp. 429-432.

Kumar, R., Barabady, J., Markeset, T. and Kumar, U. (2009), "Improvement of performance of oil and gas production facilities in Arctic regions by applying human factors/ergonomic principles at the design phase", *Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions*, *Luleå, June 9-12*.

Kumar, U., Galar, D., Parida, A., Stenstrom, C. and Berges, L. (2013), "Maintenance performance metrics: a state-of-the-art review", *Journal of Quality in Maintenance Engineering*, Vol. 19 No. 3, pp. 233-277.

Langer, R., Li, J., Biller, S., Chang, Q., Huang, N. and Xiao, G. (2010), "Simulation study of a bottleneck-based dispatching policy for a maintenance workforce", *International Journal of Production Research*, Vol. 48 No. 6, pp. 1745-1763.

Liang, G.F., Lin, J.T. and Hwang, S.L. (2009), "Evaluation and prediction of on-line maintenance workload in nuclear power plants", *Human Factors and Ergonomics in Manufacturing*, Vol. 19 No. 1, pp. 64-77.

Liang, G.F., Lin, J.T., Hwang, S.L., Wang, E.M.Y. and Patterson, P. (2010), "Preventing human errors in aviation maintenance using an on-line maintenance assistance platform", *International Journal of Industrial Ergonomics*, Vol. 40 No. 3, pp. 356-367.

Lieber, R., Dupont, J.M., Bouffaron, F. and Morel, G. (2013), "Improving physical-physiological interaction requirements for maintenance enabling systems specification", *12th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human-Machine Systems*, *Las Vegas, NV, August*.

Lind, S. (2008), "Types and sources of fatal and severe non-fatal accidents in industrial maintenance", *International Journal of Industrial Ergonomics*, Vol. 38 Nos 11-12, pp. 927-933.

Lind, S. and Nenonen, S. (2008), "Occupational risks in industrial maintenance", *Journal of Quality in Maintenance Engineering*, Vol. 14 No. 2, pp. 194-204.

Marais, K.B. and Robichaud, M.R. (2012), "Analysis of trends in aviation maintenance risk: an empirical approach", *Reliability Engineering and System Safety*, Vol. 106, pp. 104-118.

Martorell, S., Villamizar, M., Carlos, S. and Sanchez, A. (2010), "Maintenance modeling and optimization integrating human and material resources", *Reliability Engineering and System Safety*, Vol. 95 No. 12, pp. 1293-1299.

More, J.D., Tanscheit, R., Vellasco, M.M., Pacheco, M.A. and Swarcman, D.M. (2007), "A fuzzy approach to the study of human reliability in the petroleum industry", in Castillo, C., Melin, P., Ross, O.M., Cruz, R.S., Pedrycz, W. and Kacprzyk, J. (Eds), *Advances in Soft Computing – Theoretical Advances and Applications of Fuzzy Logic and Soft Computing*, Springer Berlin Heidelberg.

Moreno-Trejo, J., Kumar, R. and Markeset, T. (2012), "Factors influencing the installation and maintenance of subsea petroleum production equipment", *Journal of Quality in Maintenance Engineering*, Vol. 18 No. 4, pp. 454-471.

Nicholas, C. (2009), "Human error in maintenance – a design perspective", in Ben-Daya, M., Duffuaa, S.O., Raouf, A., Knezevic, J. and Ait-Kadi, D. (Eds), *Handbook of Maintenance Management and Engineering*, Springer, London, pp. 711-735.

Noroozi, A., Khan, F., Mackinnon, S., Amyotte, P. and Deacon, T. (2014), "Determination of human error probabilities in maintenance", *Process Safety and Environmental Protection*, Vol. 92 No. 2, pp. 131-141.

Nortje, A.R. and Visser, J.K. (2009), "The effect of human error on maintenance performance in a technology organization", *ICOMS 2009: Asset Management Conference Proceedings, Sydney*, pp. 172-179.

Okoh, P. and Haugen, S. (2014), "A study of maintenance-related major accident cases in the 21st century", *Process Safety and Environmental Protection*, Vol. 92 No. 4, pp. 346-356.

Oliveira, A., Araujo, R. and Jardine, A. (2014), "Human-centered interfaces for situation awareness in maintenance", in Yamamoto, S. (Ed.), *Human Interface and the Management of Information. Information and Knowledge in Applications and Services*, Springer International Publishing, pp. 193-204.

Park, H., Kang, M.J. and Son, S. (2012), "Factors affecting quality and performance – a case study of Korean aircraft maintenance unit", *Total Quality Management*, Vol. 23 No. 2, pp. 197-219.

Patankar, M.S. and Taylor, J.C. (2008), "MRM training, evaluation, and safety management", *The International Journal of Aviation Psychology*, Vol. 18 No. 1, pp. 61-71.

Rashid, H.S., Place, C.S. and Braithwaite, G.R. (2013), "Investigating the investigations: a retrospective study in the aviation maintenance error causation", *Cognition Technology and Work*, Vol. 15 No. 2, pp. 171-188.

Rashid, H.S.J., Place, C.S. and Braithwaite, G.R. (2014), "Eradicating root causes of aviation maintenance errors: introducing the AMMP", *Cognition, Technology and Work*, Vol. 16 No. 1, pp. 71-90.

Reason, J. and Hobbs, A. (2003), *Managing Maintenance Error"*, Ashgate Publishing Company, Aldershot.

Reason, J., Hollnagel, E. and Paries, J. (2006), *Revisiting the "Swiss Cheese" Model of Accidents*, Eurocontrol Experimental Centre, Brussels.

Reiman, T. (2011), "Understanding maintenance work in safety-critical organisations – managing the performance variability", *Theoretical Issues in Ergonomics Science*, Vol. 12 No. 4, pp. 339-366.

Reiman, T. and Oedewald, P. (2004), "Measuring maintenance culture and maintenance core task with culture-questionnaire – a case study in the power industry", *Safety Science*, Vol. 42 No. 42, pp. 859-889.

Reiman, T. and Oedewald, P. (2006), "Assessing the maintenance unit of a nuclear power plant – identifying the cultural conceptions concerning the maintenance work and the maintenance organization", *Safety Science*, Vol. 44 No. 9, pp. 821-850.

Ruiz, P.P., Foguem, B.K. and Grabot, B. (2014), "Knowledge-based systems generating knowledge in maintenance from experience feedback", *Knowledge-Based Systems*, Vol. 68, pp. 4-20.

Safaei, N., Banjevic, D. and Jardine, A.K.S. (2008), "Multi-objective simulated annealing for a maintenance workforce scheduling problem: a case study", in Tan, C.M. (Ed.), *Global Optimization: Focus on Simulated Annealing*, Springer, Berlin, pp. 27-48.

Said, M.N. and Mokhtar, A.Z. (2014), "Significant human risk factors in aviation maintenance", *Structural Equation Modeling. Sains Humanika*, Vol. 2 No. 2, pp. 31-36.

Su, K.W., Hwang, S.L. and Chou, Y.F. (2006), "Applying knowledge structure to the usable fault diagnosis assistance system: a case study of motorcycle maintenance in Taiwan", *Expert Systems with Applications*, Vol. 31 No. 2, pp. 370-382.

Suryadi, H. and Papageorgiou, L.G. (2004), "Optimal maintenance planning and crew allocation for multipurpose batch plants", *International Journal of Production Research*, Vol. 42 No. 2, pp. 355-377.

Usanmaz, O. (2011), "Training of the maintenance personnel to prevent failures in aircraft systems", *Engineering Failure Analysis*, Vol. 18 No. 7, pp. 1683-1688.

Vinnem, J.E., Bye, R., Gran, B.A., Kongsvik, T., Nyheim, O.M., Okstad, E.H., Seljelid, J. and Vatn, J. (2012), "Risk modelling of maintenance work on major process equipment on offshore petroleum installations", *Journal of Loss Prevention in the Process Industries*, Vol. 25 No. 2, pp. 274-292.

Wang, C.H. and Hwang, S.L. (2004), "A stochastic maintenance management model with recovery factor", *Journal of Quality in Maintenance Engineering*, Vol. 10 No. 2, pp. 154-165.

Wu, T.M. and Hwang, S.L. (1989), "Maintenance error reduction strategies in nuclear power plants, using root cause analysis", *Applied Ergonomics*, Vol. 20 No. 2, pp. 115-121.

Zhang, R.Q. and Yang, J.L. (2006), "Association rules based research on man-made mistakes in aviation maintenance: a case study", *Proceedings of the Sixth International Conference on Intelligent Systems Design and Applications*, *Jinan*.

Zhou, D., Guo, Z., Wang, M. and Lv, C. (2011), "Human factors assessment based on the technology of human motion capturing", *Applied Mechanics and Materials*, Vols 44-47, pp. 532-536.

About the authors

Mohammad Sheikhalishahi is currently a joint PhD Candidate in Industrial Engineering at the University of Tehran and KU Leuven. He obtained his Master in Industrial Engineering from the University of Tehran. He has published more than 40 papers in reputable academic journals and conferences. His current research includes Maintenance and Production Planning, Human Factors, Energy Management Planning and Simulation Optimization. Mohammad Sheikhalishahi is the corresponding author and can be contacted at: moh.alishahi@student.kuleuven.be

Liliane Pintelon holds Degrees in Chemical Engineering (1983) and Industrial Management (1984) of the KU Leuven. In 1988-1989 she worked as a Visiting Research Associate at the W. Simon Graduate Business School (University of Rochester, USA). She obtained her Doctoral Degree in Industrial Management (Maintenance Management) from the KU Leuven in 1990. Currently, she is professor at the Center for Industrial Management (KU Leuven); she is also Board Member of BEMAS (Belgian Maintenance Society) and IFRIM (International Foundation for Research in Maintenance). Her research and teaching area is Industrial Engineering and Logistics, with a special interest in maintenance. In this area lays the majority of her academic publications. She also has considerable experience as an industrial consultant in this area.

Ali Azadeh is an Associate Professor and the founder of the Department of Industrial Engineering at the Faculty of Engineering, University of Tehran. He is also co-founder of the Research Institute of Energy Management and Planning at the University of Tehran. He obtained his PhD in Industrial and Systems Engineering from the University of Southern California (1992). He received the 1992 Phi Beta Kappa Alumni Award for excellence in research and innovation of doctoral dissertation in the USA. He is the recipient of the 1999-2000 Applied Research Award and the 2008-2009 Distinguished Researcher Award at the University of Tehran, Iran. Dr Azadeh is recipient of 2009-2010 National Prominent Researcher Award in Iran. Professor Azadeh has published more than 430 papers in reputable academic journals and conferences.