MEASURING HUMAN FACTORS IN MAINTENANCE: A LITERATURE REVIEW

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ABSTRACT

Strategies to manage the human factors in maintenance are documented in the maintenance management and human sciences spaces. However, it is unclear from the literature which indicators and measurements should be used for these factors. It is also unclear how to integrate them into traditional maintenance performance frameworks. This article summarises the maintenance human factors and measurements found in the literature. A systematic literature review of the most often cited human factors indicated a statistically significant correlation with the 'human factors analysis and classification system — maintenance extension' framework. A hierarchal maintenance measurement framework that includes these maintenance human factors is proposed.

OPSOMMING

Strategieë vir die bestuur van menslike faktore is goed gedokumenteer in die instandhouding vakgebied, sowel as in die menslike wetenskaplike gebied. Daar is egter baie onsekerheid oor watter indikatore en metings gebruik moet word in die beskikbare literatuur. Dit is ook onduidelik hoe om hierdie metings te integreer in die tradisionele instandhoudings prestasie-model. Hierdie artikel dien as 'n literatuuropsomming oor menslike faktore in instandhouding. 'n Sistematiese opsomming van die literatuur in terme van die instandhouding menslike faktore waarna daar die meeste in die literatuur na verwys word, toon dat daar 'n sterk statistiese korrelasie met die HFACS-ME raamwerk bestaan. As gevolgtrekking, word 'n hiërargiese instandhouding prestasie-model geïllustreer wat bogenoemde instandhouding menslike faktore inkorporeer.

1 INTRODUCTION

The effectiveness of maintenance functions is influenced by the overall human factors of the maintenance staff. The influence of human factors is increasingly acknowledged by technical and organisational specialists, who recognise that achieving greater operating reliability can be achieved by identifying and correcting repeating sources of failure that are within the organisation's control, and the system that contributed to the error [1, 2].

A maintenance function's effectiveness depends on the competency, training, and motivation of its staff [3]. This is validated by Simões, Gomes and Yasin [4], who state that future research needs to be aimed at determining human factor performance measurements for maintenance performance effort.

This literature review is based on the theoretical framework developed by Peach [5]. This framework links the relationship between maintenance human factors, maintenance performance, maintenance performance measurements, and maintenance resources, as illustrated in Figure 1.

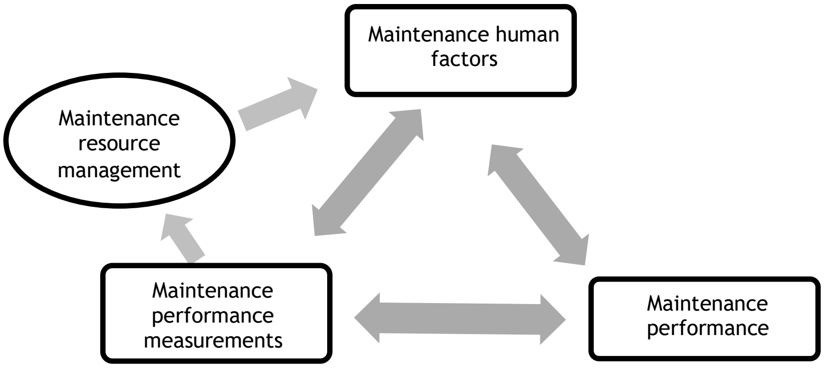

Figure 1: The relationship between maintenance human factors, maintenance performance measures, and maintenance performance

Maintenance performance measurements are used to determine whether the maintenance function's performance is satisfactory. This is done using quantitative values within a measurement framework. Through different psychological factors and theories, maintenance performance measurement influences maintenance human factors, which leads to either a positive or a negative influence on maintenance performance. Maintenance resource management therefore plays a critical role in managing the link between maintenance human factors and maintenance performance measurements. Maintenance resource management is also required to ensure that maintenance human factors are addressed, to influence the maintenance function's performance positively [5, 6].

The purpose of maintenance performance measurements is to manage the maintenance function's performance by tracking the important maintenance elements [7].

Maintenance human factors is a multi-disciplinary approach that focuses on human capabilities and limitations, with the human as the centre point of the system [8]. Meister [9] states that 'human factors' as a discipline is a descendant of psychology, as the first practitioners were experimental psychologists. He argues that the human factor discipline is unique in psychology (considered the 'mother'), as it has an effect on physical equipment. The same argument can be made for engineering (considered the 'stepfather'), as it accounts for the equipment and not the operator's behaviour. Human factors therefore span both the behavioural and physical domains.

A general critique of human factors is that long-term cost availability and ergonomic points of view in a wide range of industries need investigating. Sheikhalishahi [10] states that most studies focused on aviation, nuclear power plants, and chemical processing industries. He also comments that future research should focus on human resource management and allocation / scheduling [10, 11].

2 MAINTENANCE HUMAN FACTOR MEASUREMENTS

The goal of measuring maintenance human factors is to provide a leading indicator to predict future human performance, and to act on that prediction to improve on human performance [12-14]. Kantowitz [13] emphasises that measuring maintenance human factors provides the opportunity not only to determine the performance of an individual, but also the performance of teams, and hence of the department or overall system as well. He also advocates not only measuring human factors, but also discussion and action as a result.

Kantowitz [13] is critical that follow-up action on measurements is seldom done; that a single measure of a complex system is difficult to create (a statistical combination of multiple indicators is needed); that measurements are chosen on the basis of easy obtainability; that some measurements are chosen without the guidance of an adequate theory; and that human factors research needs to be highly generalisable.

Wang, Sun and Yang [15] developed a quantitative and objective method to analyse and evaluate human factors in aviation maintenance processes. This method is mathematically taxing and is not easily implementable at shop floor level.

Peach *et al.* [6] developed a maintenance performance framework that includes maintenance human factors, with training, competence, and motivation as the maintenance human factors to be measured.

Maintenance human factors cannot be considered in isolation from human factors in other literature spheres. Several measurement criteria for human factors are found in the psychosomatic and medical literature, such as for stress, fatigue, and workload. Some measurements are either easily quantified using enterprise resource planning (ERP) systems, such as absenteeism, while others are difficult to obtain [16].

2.1 Measurements of communication

Roberts and O'Reilly [17] developed a 35-item questionnaire to measure 16 facets of organisational communication. Downs and Hazen [18] developed a communication satisfaction questionnaire (CSQ) measuring 10 factors. By using the CSQ, Clampitt and Downs [19] indicated that, for the two companies in their study, communication was perceived to have an above average impact on productivity. This CSQ has been used and adapted in several academic studies [20].

2.2 Measurements of fatigue

Chalder *et al.* [21] developed a rating scale to measure fatigue using 14 questions. Smets *et al.* [22] published a multidimensional fatigue inventory (MFI) designed to measure fatigue in respect of general fatigue, physical fatigue, mental fatigue, reduced motivation, and reduced activity.

Horemans, Nollet, Beelen and Lankhorst [23] compared four measurement questionnaires of fatigue: the fatigue severity scale (FSS), the Nottingham health profile (NHP) energy category, the polio problem list (PPL) fatigue item, and the Dutch short fatigue questionnaire (SFQ).

2.3 Measurements of workload

De Waard [24] provides a simplified definition of workload as "a demand placed upon humans". O'Donnell and Eggemeier [25] provide a more complex definition: workload is "the portion of the operator's limited capacity required to perform a particular task". It can also be divided into physical workload and mental workload. Hwang *et al.* [26] give a generic definition of mental workload: "the amount of resource difference between task demands and capacity provision by an individual".

Some measurements for workload have been summarised by Guhe *et al.* [27]. Hwang *et al.* [26] used the parasympathetic/sympathetic ratio (LF/HF), heart rate, heart rate variability (HRV), diastolic blood pressure, systolic blood pressure, eye blink frequency, and eye blink duration in their study to predict nuclear power plant operators' work performance.

Schulz, Kirschbaum, Prüßner and Hellhammer [28] investigated the correlation between cortisol responses after waking up and work overload, as an aspect of chronic stress. They observed a correlation between work overload and chronic fatigue, and between work overload and chronic exhaustion [28]. The human body releases hormones in response to stress. Severe stress can lead to high levels of cortisol, a metabolite of the primary stress hormone cortisone [33]. Measuring psychological stress through salivary cortisol levels as a biomarker is common practice in the medical and psychological fields.

De Winter [12] argues that (mental) workload is the most used human factor, and is easily measured through questionnaires. But he criticizes the explosive usage of the NASA task load index (NASA-TLX),as a measurement tool for workload, and compares the NASA-TLX, the Cooper Harper rating scale, and the subjective workload assessment technique (SWAT) questionnaires with each other.

2.4 Measurements of stress

In the *Human performance reference manual* of the Institute of Nuclear Power Operations [29], stress is defined as "the body's mental and physical response to a perceived threat in the environment". Active management of fatigue and stress can lead to fewer individual errors and better performance (Park *et al.*, cited in [11]).

Cohen, Kamarck and Mermelstein [30], working in the sociological sphere, published a global measure of perceived stress, the perceived stress scale (PSS), which measures the points at which one's life situations are evaluated as stressful. The PSS consists of 14 questions.

Later works following the PSS include the perceived stress questionnaire, published in the psychosomatic sphere [31], and the Copenhagen psychosocial questionnaire (COPSOQ) [32]. The COPSOQ assesses psychosocial factors at work, stress, the well-being of employees, and some personality factors.

2.5 Measurements of distraction

Distractions have been measured in office, aviation, and automotive environments using self-report and observational methods [34-39]. Noise levels measured in decibels (dB) can also affect the annoyance level of employees, and variable noise has a bigger influence than constant noise [40].

A failure to prevent distraction can also decrease work rate and increase errors. Studies on dual tasks (doing two or more tasks at once) have shown that performance decreases when working memory overlaps and conflicts with the attention processes of the task [41].

2.6 Measurements of teamwork

Generally, either self-report or observational methods are used to measure teamwork. Observational methods are normally costly, and limit the number of observations. Self-reporting of teamwork is still cost-effective, easily distributed, effortless, and provides data to observe the characteristics of relationships in teamwork [42].

Valentine, Nembhard and Edmondson [42] cite behavioural processes and emergent states for teamwork, including communication, coordination, mutual respect, and psychological safety. Ruiz Ulloa and Adams [43] note that team effectiveness is a function of performance, attitude, and behaviour.

Valentine *et al.* [42] reviewed 35 surveys that measure teamwork, and found that most measure communication, coordination, and respect. The authors also tested the surveys for psychometric validity, as this builds confidence in the survey results.

2.7 Summary

From the sections above it can be seen that there are several human factor indicators, with several human factors measurements. Table 1 summarises some of the measurement techniques available in the literature to measure these maintenance human factors.

Table 1: Literature summary of human factor measurements

Indicators	Measurement	Reference
Stress	The perceived stress scale (PSS) Copenhagen psychosocial questionnaire (COPSOQ) Dundee stress state questionnaire (DSSQ) Stress diagnostic survey (SDS) Salivary cortisol levels	Cohen *et al.* [30] Kristensen *et al.* [32] Hellhammer *et al.*[44] Langan-Fox *et al.* [45]
Fatigue	Multidimensional fatigue inventory (MFI) Fatigue severity scale (FSS) Nottingham health profile (NHP) Polio problem list (PPL) Dutch short fatigue questionnaire (SFQ).	Smets *et al.* [22]
Workload	NASA-TLX Trier inventory for the assessment of chronic stress (TICS) Instantaneous self-assessment (ISA) Impact on mental workload (AIM) Rating scale of mental effort (RSME) Galvanic skin response Parasympathetic/sympathetic ratio (LF/HF), heart rate, heart rate variability (HRV), diastolic pressure, systolic pressure, eye blink frequency, and eye blink duration Cortisol responses after wakening	Guhe *et al.* [27] Hwang *et al.* [26] Schulz *et al.* [28] Langan-Fox *et al.* [45]
Motivation / morale	Absenteeism	Galar *et al.* [16]
Communication	Roberts and O'Reilly 35-item questionnaire Communication satisfaction questionnaire (CSQ)	Roberts and O'Reilly [17] Downs and Hazen [18]
Teamwork	Team effectiveness questions NOTECHS (Non-technical skills evaluation system)	Adams *et al.* [46] Flin *et al.* [47]
Distraction	Noise levels Peripheral displays	Kjellberg *et al.* [40] Somervell *et al.* [48]

However, it is both senseless and impractical to implement a system to measure all of these human factors that affect the maintenance worker and, therefore, the maintenance department's performance. It is unclear from the literature which specific performance indicators and measurements should be used to manage these factors.

The next section aims to determine the most often cited maintenance human factors in the literature, and to rank them according to the number of citations.

3 SYSTEMATIC LITERATURE REVIEW TO DETERMINE THE MOST OFTEN CITED HUMAN FACTORS

A meta-analysis using a systematic literature review was used to determine the most often cited maintenance human factors. WorldCat, the world's largest bibliographic database, was used for the systematic literature review [49]. A total of 39 peer-reviewed articles that listed human factors were included in the meta-analysis. The main search criterion for the systematic literature review was peer-reviewed journal articles with the words 'human factor' and 'maintenance' or 'human factor' and 'measure' in the article title. It should also be applicable to the field of engineering or asset management. **Figure 2** illustrates the information flow through the different phases of the systematic review and the different search criteria.

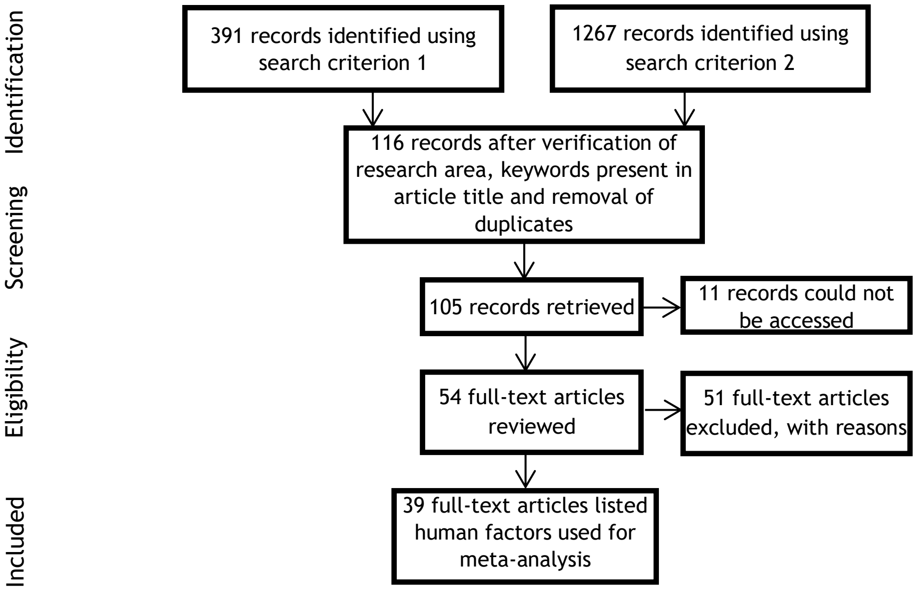

Figure 2: Information flow through the different phases of the systematic review (adapted from Liberati *et al.* [50])

Eleven of the 39 journal articles were published in the *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, and 15 related to aviation maintenance. The article that was most often cited was 'Selecting measures for human factors research' by Kantowitz [13], which was cited 102 times. The second most often cited article was 'Human factors in maintenance: Impact on aircraft mishap frequency and severity' by Krulak [51], followed by 'Human factors measurement for future air traffic control systems' by Langan-Fox, Sankey and Canty. [45]. The date range of the articles spans 1984 to 2019, and the authors with the most articles among the 39 articles were Sheikhalishahi, Pintelon and Azadeh [11].

3.1 Results using minimal coding

From the 39 full-text articles, 832 data points on human factors and 184 data points on human factor categories were gathered. Minimum coding (singular form versus multiple form of the same word) was used on the human factors to establish an unbiased view of the most often cited human factor. The most frequently cited human factors are shown in Table 2.

3.2 PEAR model coding and grouping

The Australian Civil Aviation Safety Authority (CASA) uses the PEAR model in their maintenance human factor training programme, *Safety behaviours: Human factors for engineers*. The aim of the training programme is to supplement existing human factor programmes for engineers and aviation maintenance organisations. It also serves as human factor training according to Australia's civil aviation safety regulations. The four focus points of the PEAR model are ‘people’, ‘the environment’, ‘actions’, and ‘resources’ [52, 53].

3.2.1 *Results using the PEAR model coding and grouping*

By using the PEAR model as a guideline, similar human factors were coded using the PEAR model terminology. In cases where no similar terminology was found in the PEAR model, and human factors were cited a number of times, the human factor was added to the PEAR model. In cases where the human factor was not frequently cited, it was not added to the adapted PEAR model. Human factors from the PEAR model that were not cited anywhere else in the literature were removed. Table 3 illustrates the adapted PEAR model used for the coding in this study. A cumulative percentage of 30 per cent was used to identify the top factors. The 16 most often cited factors using the PEAR model are shown in Table 4.

Table 2: Most frequently cited human factors using minimal coding

Rank	Maintenance human factor	Frequency	Percentage	Cumulative frequency	Cumulative percentage
1	Fatigue	12	1.44%	12	1.44%
2	Illumination	12	1.44%	24	2.88%
3	Communication	11	1.32%	35	4.21%
4	Workload	10	1.20%	45	5.41%
5	Cognitive dimensions	8	0.96%	53	6.37%
6	Decision-making	8	0.96%	61	7.33%
7	Noise level	7	0.84%	68	8.17%
8	Time pressure	7	0.84%	75	9.01%
9	Situation awareness	6	0.72%	81	9.74%
10	Knowledge and experience	5	0.60%	86	10.34%
11	Person factors	5	0.60%	91	10.94%
12	Supervision	5	0.60%	96	11.54%
13	Training	5	0.60%	101	12.14%

Table 3: Adapted PEAR model with subcategories

People	Environment	Actions	Resources
Physical factors Gender Age Strength **Physiological factors** Fatigue **Psychological factors** Workload (physical & mental) Knowledge and skills Experience Stress Training (psychological factors) Cognitive capabilities Situation awareness Motivation Decision-making Attitude Mental or emotional state Beliefs **Psychosocial factors** Interpersonal skills/conflict	**Physical** Lighting Workspace Sound level Weather Shift Vibration Heat Reachability **Organisational** Communication Supervision Time & time pressures Safety & safety culture Team & team work Corporate culture Work pressure Crew structure Personnel	Skill requirements Certification requirements Inspection requirements Information control requirements	Equipment, tools, and parts Procedures/work cards Training (resources) Quality systems Computers/software Technical manuals Materials Other people Paperwork/signoffs

Table 4: Top 16 cited human factors using the PEAR model

Rank	Maintenance human factor	Frequency	Percentage	Cumulative frequency	Cumulative percentage
1	Communication	23	2.77%	23	2.77%
2	Equipment, tools, and parts	22	2.65%	45	5.42%
3	Procedures/work cards	21	2.53%	66	7.94%
4	Knowledge and skills	17	2.05%	83	9.99%
5	Experience	17	2.05%	100	12.03%
6	Fatigue	17	2.05%	117	14.08%
7	Training (resources)	17	2.05%	134	16.13%
8	Workload (physical & mental)	17	2.05%	151	18.17%
9	Time & time pressures	15	1.81%	166	19.98%
10	Supervision	15	1.81%	181	21.78%
11	Lighting	14	1.68%	195	23.47%
12	Safety & safety culture	13	1.56%	208	25.03%
13	Workspace	12	1.44%	220	26.47%
14	Stress	12	1.44%	232	27.92%
15	Training (psychological factors)	11	1.32%	243	29.24%
16	Cognitive capabilities	10	1.20%	253	30.45%

3.3 HFACS-ME framework coding and grouping

One of the best-known error investigation systems, the human factors analysis and classification system (HFACS), originated in aviation [54]. The framework is based on Reason's 'Swiss cheese' model, and was developed by Dr Scott Shappell and Dr Doug Wiegmann. The framework focuses on the underlying human factors that can lead to accidents [55, 56].

The human factors analysis and classification system — maintenance extension (HFACS-ME) is used by the US Navy to classify and categorise maintenance-related factors [51, 54]. The HFACS-ME follows the same structure as the HFACS framework, and is used in a similar way. By using the HFACS-ME in this study, a common vocabulary across industries is established. Table 5 illustrates the HFACS-ME framework together with its underlying factors.

3.3.1 Results using HFACS-ME framework coding and grouping

By using the HFACS-ME framework terminology as a guideline, similar human factors were coded. In cases where no similar terminology was found in the HFACS-ME framework, and the human factor was cited a significant number of times, the human factor was added to the HFACS-ME framework. 'High workload' was thus added under 'Inadequate resources'.

C^8 Sciences [57] lists the eight core cognitive capacities as sustained attention, response inhibition, speed of information processing, cognitive flexibility and control, multiple simultaneous attention, working memory, category formation, and pattern recognition. Although cognition itself is not listed in the HFACS-ME framework, its capabilities are listed under 'Attention/memory errors'.

A cumulative percentage of 30 per cent was used to identify the top factors. Table 6 lists the 17 maintenance human factors that were the most often cited using the HFACS-ME framework terminology.

Table 5: The HFACS-ME framework

Level 1 factors	Level 2 factors	Level 3 factors
Management conditions	Organisational	Inappropriate processes Inadequate documentation Inadequate design Inadequate resources Communication
	Supervisory	Inadequate supervision Inappropriate operations Uncorrected problem Supervisory misconduct
Maintainer conditions	Medical	Adverse mental state Adverse physical state Physical/mental limitation
	Crew coordination	Inadequate communication Inadequate assertiveness Inadequate adaptibility/flexibility Team work
	Readiness	Training/preparation Certification/qualification Infringement
Working conditions	Environment	Inadequate lighting/light Unsafe weather/exposure Unsafe environmental hazards
	Equipment	Damaged/unserviced Unavailable/inappropriate Dated/uncertified
	Workspace	Confining Obstructed Inaccessible
Maintainer acts	Error	Attention/memory Knowledge/rule-based Skill/technique-based Judgement/decision-making
	Violation	Routine Infraction Exceptional Flagrant

Table 6: Top 17 cited human factors using the HFACS-ME framework

Rank	Maintenance human factor	Frequency	Percentage	Cumulative frequency	Cumulative percentage
1	Training/preparation	27	3.37%	27	3.37%
2	Skill/technique-based	21	2.62%	48	5.99%
3	Inadequate communication	18	2.25%	66	8.24%
4	Fatigue	17	2.12%	83	10.36%
5	Inadequate lighting/light	15	1.87%	98	12.23%
6	Inadequate design	13	1.62%	111	13.86%
7	High workload	13	1.62%	124	15.48%
8	Judgement/decision-making	12	1.50%	136	16.98%
9	Inadequate knowledge	12	1.50%	148	18.48%
10	Life stress	12	1.50%	160	19.98%
11	Inadequate supervision	11	1.37%	171	21.35%
12	Attention/memory	10	1.25%	181	22.60%
13	Certification/qualification	10	1.25%	191	23.85%
14	Cognition	9	1.12%	200	24.97%
15	Environment	9	1.12%	209	26.09%
16	High noise levels	9	1.12%	218	27.22%
17	Safety	9	1.12%	227	28.34%

3.4 Results summary

A ranked comparison of the coding (frameworks) used can be seen in Table 7.

Table 7: Ranked comparison of most often cited maintenance human factors

Maintenance human factor	Minimal coding	PEAR model	HFACS-ME framework
Workload	4	8	7
Time pressure	8	9	24
Fatigue	1	6	4
Communication	3	1	3
Equipment, tools, and parts	22	2	22
Cognitive capabilities	5	16	14
Supervision	12	10	11
Inadequate lighting/light	2	11	5
Life stress	20	14	10
Judgement/decision-making	6	26	8
Noise level	7	17	16

The IBM SPSS® software platform was used to perform Spearman's ranked order nonparametric correlation test. This was done to determine whether there was a correlation between the different coding/frameworks used. The output from SPSS can be seen in Table 8.

Table 8: Spearman's ranked order nonparametric correlation test

			MIN coding	PEAR	HFACS-ME
Spearman's rho	MIN coding	Correlation coefficient	1.000	0.155	**.773****
		Sig. (2-tailed)		0.650	0.005
		N	11	11	11
	PEAR	Correlation coefficient	0.155	1.000	0.273
		Sig. (2-tailed)	0.650		0.417
		N	11	11	11
	HFACS	Correlation coefficient	**.773****	0.273	1.000
		Sig. (2-tailed)	0.005	0.417	
		N	11	11	11

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 8 shows a significant correlation between the maintenance human factors cited in the literature with minimum coding and the HFACS-ME framework. It is therefore reasonable to use the most listed maintenance human factor from the HFACS-ME framework as the most often cited maintenance human factors in the literature.

4 MAINTENANCE MEASUREMENT FRAMEWORK

The aim of maintenance measurement frameworks is to manage the maintenance function's performance by tracking the important maintenance elements. Visser and Pretorius [58] developed a total maintenance performance (TMP) scoring system to evaluate a number of performance indicators with weight factors. Galar *et al*. [59] take a downward hierarchical approach to measurement frameworks. This assists middle management to have directed measurements free of ambiguities. Peach *et al*. [6] published a table of maintenance performance measurements, including maintenance human factors. By combining Visser and Pretorius [58] and Peach *et al*. [6], together with the hierarchy approach of Galar *et al*. [59], the framework depicted in Figure 3 is proposed.

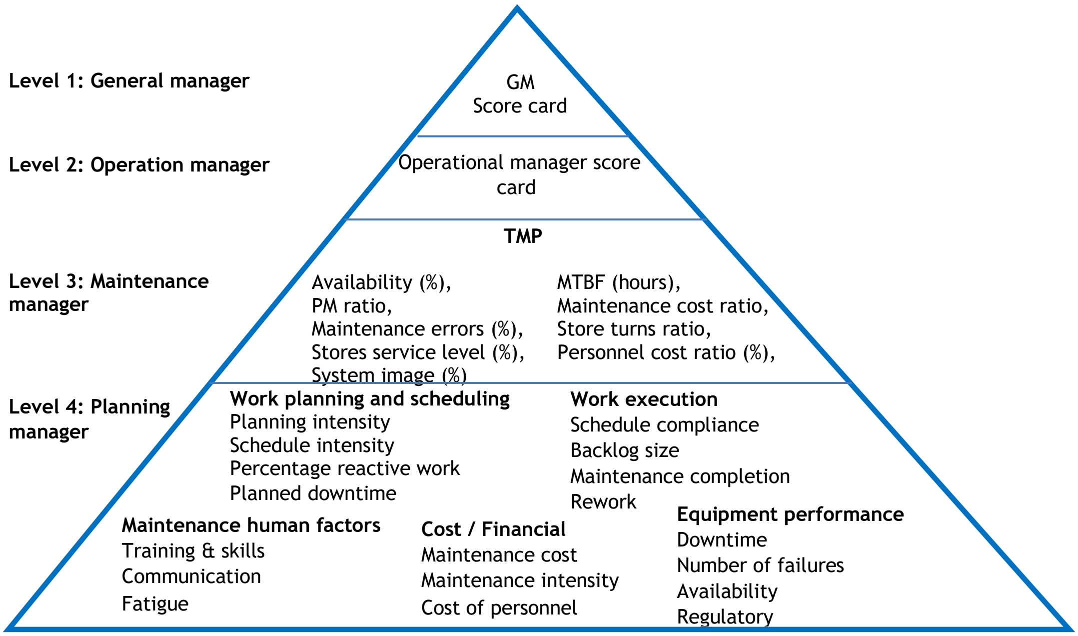

Figure 3: Hierarchical display of the proposed maintenance measurement system

The final Level 4: Maintenance human factors, as illustrated in Figure 3, were chosen from the most often cited HFACS-ME maintenance human factors. It needs to be stressed that a maintenance measurement system should focus on the maintenance human factors that are specific to an industry, rather than on generic factors [1, 60]. By using the most often cited HFACS-ME maintenance human factors, historical organisational data and internal surveys from maintenance staff, the significant maintenance human factors in a specific organisation can be determined. This will ensure that maintenance human efforts will achieve the maximum return on investment.

5 CONCLUSION

This article summarises the maintenance human factor measurements that can be used in a maintenance measurement framework. A systematic literature review determined the most often cited maintenance human factors in the literature. It was shown that there is a statistically significant correlation between the most often cited human factors in the literature and those in the HFACH-ME framework. The most often cited HFACH-ME maintenance human factors were training/preparation, skill/technique, inadequate communication, and fatigue.

A hierarchal maintenance measurement framework that includes the most often cited human factors was provided. This framework, together with the listed measurement methods from Table 1, can be used to calculate the TMP for level 4 of the hierarchal maintenance measurement framework.

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