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MAINTENANCE HUMAN FACTORS IN THE SOUTH AFRICAN ELECTRICITY TRANSMISSION INDUSTRY

by

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ABSTRACT

MAINTENANCE HUMAN FACTORS IN THE SOUTH AFRICAN ELECTRICITY TRANSMISSION INDUSTRY

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The introduction of Industry 4.0 highlights a strong focus on the social dimensions within Maintenance 4.0. Highly skilled staff will be required to interpret data analytics, perform smart work procedures and do maintenance planning with a systems perspective. Maintenance performance measurements have always reflected the changes in industry and maintenance revolutions. To enable the move to Maintenance 4.0, a clear strategy will be needed to include these social dimensions into a maintenance performance measurement framework.

Theory on maintenance human factors are mainly based in the aviation sphere. It focusses on training managers, supervisors and accident investigators to identify and mitigate maintenance human factors that can lead to severe and fatal accidents. Significant maintenance human factors outside of the aviation sphere are rarely studied. Literature on how these maintenance human factors should be measured and incorporated into maintenance performance measurement frameworks has been greatly neglected. This thesis aims to address these shortcomings.

The aim of this thesis was to determine measurements for maintenance human factors, that when applied to a maintenance measurement framework, will have a significant impact to improve both maintenance performance, reduce maintenance errors and the maintenance technician's mental state. It additionally aimed to expand the body of knowledge on maintenance human factors to include the South African electricity transmission industry.

To achieve the inclusion of significant maintenance human factors into a maintenance performance measurement framework, possible measurements had to be determined for each maintenance human factor. This was done through an explorative literature review that applied to all industries. To determine the most mentioned maintenance human factors, a systematic literature review was done. The outcome of the systematic literature was used as a starting point for data collected from maintenance technicians within the South African electricity transmission industry.

High workload, time pressure, fatigue and communication were found to have the most significant impact on personal maintenance errors made from maintenance technician's perspective. A maintenance human factor performance (MHFP) framework, MHFP indicators (high workload, time pressure, fatigue and communication) and weightings was developed. A total maintenance performance (TMP) framework for the South African electricity transmission industry was developed. The TMP consisted of 9 indicators: system performance, equipment performance, maintenance planning, maintenance completion percentage, maintenance human factor performance (MHFP), maintenance cost ratio percentage, maintenance errors, personnel cost ratio percentage and safety.

Measurement methods for the MHFP indicators were chosen: eight questions from the chronic work overload scale of the Trier Inventory of Chronic Stress (TICS), the adapted time pressure scale questionnaire, the Fatigue Severity Scale and the adapted Downs-Hazen Communication Satisfaction Questionnaire were chosen to be used as measuring methods for these maintenance human factors.

The MHFP and TMP frameworks were included into a proposed hierarchical maintenance performance framework for the South African electricity transmission industry. The frameworks provides a methodology to calculate a measurable value by using measuring methods.

A two-round Delphi method was used to validate the proposed hierarchical maintenance performance framework for the South African electricity transmission industry, inclusive of maintenance human factors.

Four significant maintenance human factors were identified by the maintenance technicians. Time pressure and communication were validated with the Delphi questionnaire. High workload was not validated in the Delphi questionnaire as there was no clear consensus achieved. There were, however, contradictions between the responses from the various questionnaire target groups, the prevailing opinion in literature and the prior findings of this thesis. The contradictions were discussed and it was concluded that high workload will remain as a significant contributor that leads to maintenance human errors.

The Delphi questionnaire, posed to a panel of experts, that included top management decision makers who can utilize the outcomes of the Delphi study, confirmed that:

- Measuring the most influential maintenance human factors could have benefits in terms of performance, reduction in human error and better management of these influential maintenance human factors.
- Inclusion of Maintenance Human Factor Performance within a TMP framework could benefit maintenance performance within Transmission.

This validated the final research output from an organisational view.

Identifying the most significant maintenance human factors that lead to maintenance human errors within the electricity transmission industry will provide a contribution to academic knowledge as research in this field is limited. Incorporation of measurements of these factors into an organisational performance measurement frameworks is uncommon in industry. Performance measurement frameworks needs to be industry specific. This research output contributes to academic knowledge by providing a method of doing this within the South African electricity transmission industry.

A practical, implementable contribution is made with the thesis providing a calculation methodology to calculate an exact total maintenance performance score for both maintenance and maintenance human factors.

Finally, by implementing a maintenance performance framework that includes the up-and-coming social dimensions of Industry 4.0, the successful implementation of Maintenance 4.0 can be improved.

Keywords: Maintenance human factors, maintenance performance measurements, maintenance KPIs, electricity transmission, power transmission, maintenance 4.0, M4.0, industry 4.0 and IR4.0

PAPERS AND PUBLICATION BY THE AUTHOR

Peach, R., Ellis, H. and Visser, J.K. 2016. A maintenance performance measurement framework that includes maintenance human factors: a case study from the electricity transmission industry. *South African Journal of Industrial Engineering,* vol. 27, no. 2, pp.177-189.

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For Schalk and Pieter

ETHICS AND ORIGINALITY DECLARATION

I, **Rina Helena Peach**, declare that the dissertation/thesis, **Maintenance Human Factors in the South African Electricity Transmission Industry**, which has been submitted in partial fulfilment of the requirements for the degree of **PHILOSOPHIAE DOCTOR (Engineering Management)**, at the University of Pretoria, is my own work and has not previously been submitted by me for any degree at the University of Pretoria or any other tertiary institution.

I declare that I obtained the applicable research ethics approval in order to conduct the research that has been described in this dissertation / thesis.

I declare that I have observed the ethical standards required in terms of the University of Pretoria's ethic code for researchers and have followed the policy guidelines for responsible research.

Signature:

Date: **30 July 2021**

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DEFINITIONS

Term	Definition	Source
Maintenance	“All activities aimed at keeping an item in, or restoring it to, the physical state considered necessary for the fulfilment of its production function,”	Tsang et al. (1999)
Maintenance resource management	Subset of human resource management applying organisational psychology, work sociology and anthropology,	Shanmugam and Paul Robert (2015a)
Maintenance human factors	“Characteristics which define the way in which an individual or group behaves or acts that influence the way the maintenance department operates,”	Kelly (2005)
Human error	“The failure to perform a specified task (or the performance of a forbidden action) that could lead to disruption of scheduled operations or result in damage to property and equipment.”	Dhillon (2002)
Workload	“The portion of the operator's limited capacity required to perform a particular task.”	O'Donnell and Eggemeier (1986)
Stress	“The body’s mental and physical response to a perceived threat in the environment.”	INPO (2006)
Fatigue	“Fatigue is the reduction in performance with either prolonged or unusual exertion. Fatigue can be sensory, motor, cognitive or subjective.”	DeLuca (2005)
Cognitive capabilities	”A general mental capability involving reasoning, problem solving, planning, abstract thinking, complex idea comprehension, and learning from experience.”	Gottfredson (1997)
Situation awareness	“The detection of the elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future.”	Endsley (1988)
Distraction	“A thing that prevents someone from concentrating on something else.”	Oxford Online Dictionary (2020)
Vagal tone	“The effect produced on the heart when only the parasympathetic nerve fibres (which are carried in the vagus nerve) are controlling the heart rate. The parasympathetic nerve fibres slow the heart rate from approximately 70 beats per minute to 60 beats per minute.”	Encyclopedia.com (2020)
Heart rate variability	“The physiological phenomenon of the variation in the time interval between consecutive heartbeats in milliseconds”	Firstbeat (2020)
Motivation	“The processes that account for an individual’s intensity, direction and persistence of effort toward attaining a goal.”	Robbins (2001)
Communication	“The imparting or exchanging of information by speaking, writing, or using some other medium”	Oxford Online Dictionary (2020)
Supervision	“Observe and direct the execution of a task or activity.”	Oxford Online Dictionary (2020)
Time pressure	“Terms of the amount of information that has to be considered and processed during one time	Zur and Breznitz (1981)

Term	Definition	Source
	unit or in terms of the time allotted for processing a fixed amount of information.”	
Teamwork	“The combined action of a group, especially when effective and efficient.”	Oxford Online Dictionary (2020)
Maintenance resources	“Anything that the maintenance engineer (or anyone else) needs to get the job done.”	CASA (2013)

ABBREVIATIONS

Abbreviation	Term
ATM	Air Traffic Management
ATWIT	Air Traffic Workload Input Technique
CASA	Civil Aviation Safety Authority
COPSOQ	Copenhagen Psychosocial Questionnaire
CSQ	Communication Satisfaction Questionnaire
DSSQ	Dundee Stress State Questionnaire
ECG	Electrocardiograph
EEG	Electroencephalogram
EMG	Electromyograph
EMT	Eye Movement Tracking
EPC	Error Producing Conditions
EPRI	Electric Power Research Institute
ERP	Enterprise Resource Planning
FAA	Federal Aviation Administration
FSS	Fatigue Severity Scale
GFMAM	Global Forum on Maintenance and Asset Management
GTT	Generic Task Types
HEART	Human Error Assessment and Reliability Technique
HFACS	Human Factors Analysis and Classification System
HFACS-ME	Human Factors Analysis and Classification System Maintenance Extension
HPAA	Hypothalamic–pituitary–adrenal axis
HPEP	Human Performance Evaluation Process
HR	Heart Rate
HRV	Heart Rate Variability
HV	High Voltage
IEA	International Ergonomics Association
INPO	Institute of Nuclear Power Operations
ISA	Instantaneous Self-Assessment
ISTA	Stress-oriented job analysis instrument
KPI	Key Performance Indicator
MEDA	Maintenance Error Decision Aid
MEIMS	Maintenance Error Information Management System
MFI	Multidimensional Fatigue Inventory
MPM	Maintenance Performance Measurements
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NASA-TLX	National Aeronautics and Space Administration Task Load Index
NHP	Nottingham Health Profile
NOTECHS	Non-Technical Skills Evaluation System
OEE	Overall Equipment Effectiveness

Abbreviation	Term
PEAR	People, Environment, Actions and Resources
PERS	Proactive Error Reduction System
PPL	Polio Problem List
PSS	Perceived Stress Scale
RSME	Rating Scale of Mental Effort
SAGAT	Situation Awareness Global Assessment Technique
SALSA	Measuring Situation Awareness of Area Controllers within the Context of Automation
SART	Situation Awareness Rating Technique
SASHA_L	Situation Awareness SHAPE Online
SASHA_Q	Situation Awareness SHAPE* Questionnaire
SAVANT	Situation Awareness Verification and Analysis Tool
SBT	Simulation-Based Training
SCTA	Safety Critical Task Analysis
SFQ	Short Fatigue Questionnaire
SHAPE	Solutions for Human-Automation Partnership in European ATM
S-IGA	Selective Immunoglobulin A
SOF	Scale Of Feelings
SPAM	Situation Present Assessment Method
SWAT	Subjective Workload Assessment Technique
TICS	Trier Inventory for the Assessment of Chronic Stress
TMP	Total Maintenance Performance

1. INTRODUCTION AND BACKGROUND

This doctoral thesis was written to contribute to the domain of maintenance management. This was done by addressing a critical literature gap: “What are some of the most influential maintenance human factors and how to include them in a maintenance performance system.” The focus of this thesis is to answer these questions within the South African electricity industry.

The first chapters provide a brief summary of the research objectives and research questions; an explorative literature review; a systematic literature review and the research methodology used in this thesis.

Thereafter, the data gathering process was explained and the data gathered was tabulated and illustrated. This data was used to analyse and perform correlation tests. Using this data a hierarchical maintenance performance framework for the South African electricity transmission industry, with measurements and calculations for the most influential maintenance human factors were developed.

In Chapter 8 the research output was validated by using a Two-round Delphi method. The last two chapters reviewed the research questions and answered the research objective.

1.1. Background

Maintenance Management, a cornerstone of Asset Management, has proven widely in literature that an increase in proactive maintenance leads to an increase in asset performance. This was reflected in a paradigm shift in the way that maintenance management is regarded. Maintenance is now seen as a value adding, an essential part of the business process (Parida and Kumar, 2006).

Maintenance human factors can be seen as the human root cause factors when a maintenance human error was made. Human error analysis normally relate to the cause of the accident or disaster. Not all maintenance human factors cause human errors. However, the causes of human errors share similar factors with maintenance human factors. Human error probability calculations can be done through human reliability analysis which mathematically calculates a quantitative probability that a human error will occur. Unfortunately, these concepts are often used interchangeably because of the similarities between the concepts (Sheikhalishahi et al., 2016).

Maintenance human factors originated in the aviation sector after a series of fatal accidents. The aviation sector made several improvements to their original safety campaigns on maintenance human factors. ISO55000 recognises that factors such as leadership, culture, motivation and behaviour can have a substantial influence on the realisation of asset management objectives. This is validated through a study done by Reynolds et al. (2010), showing that the number of maintenance-related errors is statistically significantly reduced when human factor training was implemented in aviation.

The maintenance function’s effectiveness is influenced by the overall human factors of the maintenance staff. The influence of human factors is increasingly being acknowledged by technical and organisational specialists. They recognize that higher operating reliability can be achieved through identifying and correcting repeating sources of failure within the organisation’s control and the system that contributed to the error (Antonovsky et al., 2014; Reynolds et al., 2010; Shanmugam and Paul Robert, 2015a). To implement this new approach the training program, “maintenance resource management”, was developed (Reynolds et al., 2010).

A maintenance function’s effectiveness depends on the competency, training, and motivation of its staff (Ljungberg, 1998). It can be concluded that the next evolution in maintenance management will be maintenance performance frameworks that includes maintenance human factors.

This is validated by Simões et al. (2011) as he indicated that future research needs to be aimed at determining human factor performance measurements for maintenance performance effort. In his literature review of maintenance performance measurements he found that the least used measurements were employee satisfaction, training/learning, maintenance capacity, skills/competences, process performance, customer satisfaction, resource utilisation and work incentives (Simões et al., 2011).

1.2. Current state of maintenance human factors in the Electricity Transmission industry

In the South African context, the wording “electricity transmission industry” is used. Internationally this is mostly referred to as “power transmission industry”. To align the thesis with the intent of focussing the findings in the South African context, the wording “electricity transmission industry” will be used in this thesis.

General criticism of human factors is that the investigation of ergonomic points of view in a wide range of industries and long-term cost availability are needed. Most studies are focusing on petroleum processing industries, chemical industries, nuclear power plants and aviation (Sheikhalishahi et al., 2017b; Torres et al., 2018). A lack of human factor focus within electrical systems is noted by Torres et al. (2018) and Bao et al. (2018).

Where literature is found within the general electricity industry regarding maintenance human factors the literature focused on nuclear power generation, power generation and to a smaller extent on distribution networks. These industries cannot be compared to a transmission industry as the size of the geographical area, operational goals and scale of equipment differs.

Limited research attention have been given to human error root causes, human reliability and human factor analysis within non-nuclear power systems (Tavakoli and Nafar, 2021a; Tavakoli and Nafar, 2020; Tavakoli and Nafar, 2019; Torres et al., 2018; Bao et al., 2018; Xie et al., 2016; Bao et al., 2014).

Additionally, the lack of documented information of influential human factors that lead to human error hinders actionable turnaround plans to reduce human errors. This is not a unique problem as quantitative data on human factors within maintenance departments are rare (Bao et al., 2018; Sheikhalishahi et al., 2017b).

1.3. Rationale of the study

Maintenance human errors within power systems not only affect maintenance availability, but the loss of energy can also negatively affect the income of the electricity company (Tavakoli and Nafar, 2020; Bao et al., 2018). Electricity unavailability also have economic effects on a country's businesses and communities (Torres et al., 2018).

The organisation has recognised that human error can severely impact one of its key performing indicators, System Minutes. With this, an attempt is made to reduce human error to improve its technical performance. Some strategies have been tabled by management to address this. These strategies unfortunately focus on the more superficial points of human performance and on the authoritative role of supervision and does not acknowledge the deep influence that maintenance human factors have on human errors.

This organisation is, however, not unique in this regard. Academic literature regarding maintenance human factors and human error investigation within the electricity transmission industry has only in the recent years gained attention (Bao et al., 2018; Tavakoli and Nafar, 2020).

Kumar et al. (2013) related that a limited number of organisations are using measurements for human factors within their maintenance functions performance measurements. By incorporating maintenance human factors into standard maintenance performance measurements, the uniqueness of maintenance performance measurements will be improved (Kumar et al., 2013). Sheikhalishahi et al. (2016) concurs with this statement that performance assessment and appraisal as a subsection of human performance in maintenance indicates future possibilities of research studies.

1.4. Research problem

Within the last number of years the South African electricity transmission industry has seen an increase in both operating and maintenance human errors. To reduce these human errors, knowledge of the maintenance human factors that have the most influence on maintenance human errors is needed.

Preliminary investigation supports the importance of acknowledging and managing maintenance human factors. Strategies to manage maintenance human factors are documented in the maintenance management space and in the human sciences space. These strategies mainly focus on the aviation sphere. It is also unclear from literature which performance indicators and measurements should be used. No clear strategies are given to integrate these maintenance human factors into traditional maintenance performance frameworks.

By including maintenance human factors in a traditional maintenance performance framework, managers will be able to have a better overview of maintenance human factors' performance.

1.5. Research objectives and research questions

To address this problem, a research project with the following objective is proposed:

"The objective of this research is to determine the most influential maintenance human factors and corresponding measurements that have a positive impact to reduce maintenance human error and that could be included in an organisation's performance system for the maintenance department."

The following list indicates the research questions to be answered in this research.

- Research Question 1 (RQ1): What maintenance human factors have the most influence on maintenance human errors?
- Research Question 2 (RQ2): How should these maintenance human factors performance indicators and measurements be incorporated into a traditional maintenance performance framework?

1.6. Research boundaries and limitations

This thesis is limited to the South African electricity transmission industry. In the last year of this thesis, the novel Coronavirus: Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) resulted in the global COVID-19 pandemic. Accordingly, in the management questionnaire, participants were not solicited to obtain a higher response rate.

1.7. Factors for consideration

While addressing the research objective of this thesis, the ethical considerations of obtaining medical data from maintenance staff should be considered. This is elaborated on in Section 4.1.

1.8. Contribution to literature

Maintenance management is a cornerstone of leading Asset Management strategies. Maintenance management cannot be regarded in isolation from changes within the industrial revolutions. Industry 1.0 utilised water and steam energy sources for mechanical production. Industry 2.0 used electricity to power mass production assembly lines. Industry 3.0 was based on electronics and computerisation for automation of manufacturing. Industry 4.0 is based on cyber-physical systems, the Internet of Things and smart technologies. Figure 1.1 graphically illustrates the different industrial revolutions.

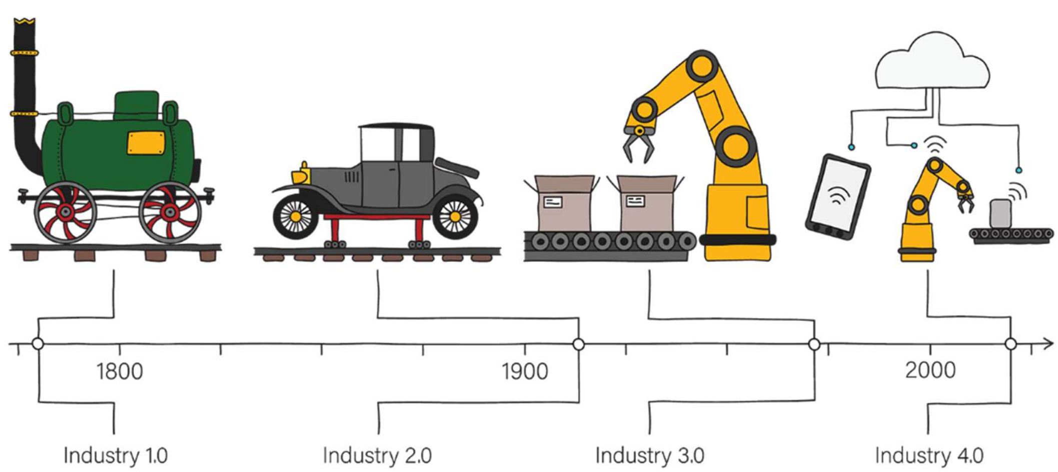

Figure 1.1 Graphical illustration of the industrial revolution
Source: LLC (2020)

To illustrate the influence each industrial revolution has on the downstream aspects of asset management Table 1.1 was constructed. It combines key focus points relating to this research to the different industrial revolution.

- Maintenance strategies and principles.
- Maintenance focus points and resources.
- Maintenance performance measurements.

Some terms in Table 1.1 are synonymous, but were not removed from the table to illustrate consensus between authors. The authors used to construct Table 1.1 were:

- Dunn (2003),
- Schmidt et al. (2014),
- Seow et al. (2016),
- Technologu Buiness Research (2016),
- Bokrantz et al. (2017),
- Galar and Kans (2017),
- Nowakowski et al. (2018) ,
- Jasiulewicz-Kaczmarek (2018),
- Infinity for Cement Equipment (2020), and
- Jakob (2020).

Table 1.1. Industrial revolutions

	Industrial revolution			
	1.0	2.0	3.0	4.0
Technologies	• Mechanical production • Water and steam	• Electric powered assembly lines • Mass production	• Automation • Computers • Electronics	• Cyber physical systems • Internet of Things • Smart technologies • Information acquisition • Connectivity between system elements • Responsiveness to internal and external changes
Maintenance strategies and principles	• Breakdowns • Run to fail • Reactive fault finding	• Preventative • Maintain at set intervals • Scheduled overhaul • Proactive analysis	• Predictive • Maintain and replacement based on condition automated detection • Maintenance as source of benefit	• Digitization of maintenance management • Cloud-based approach using large amount of data, failure elimination, increased quality • Data analytics and big data management • Interoperable information systems • Fact-based maintenance planning • Maintenance planning with a systems perspective • Smart work procedures • Emphasis on education and training • Change with regard to soft (social) dimensions • Additionally, to technical skills, soft skills such as social and communication skills as well as team working and self-management abilities
Maintenance focus points and resources	• Fundamental repair skills	• Planning and controlling systems • Big slow computers	• Design for maintainability and reliability • FMEA • Small and faster computers • Expert systems • Commitment by all departments	• Focus on equipment selection and design • Increasing understanding and appreciation of the “soft” people related skills • Greater alignment between maintenance, production, engineering with application of soft people skills
Maintenance performance measurements	• Accounting centric • Lagging indicators • Minimal data	• Data driven • Technology centric • Lack of trust in results • Bloated IT support • One size fits all • Chasing the numbers	• Objective driven • Process centric • Strategic alignment • Business ownership • Accountability • Proactive response planning • Data confidence	• Addition to greater safety • Compliance to stronger environmental legislation and standards • More pressure on cost effectiveness • Inclusion of maintenance human factors (people-related aspects)

The maintenance department is responsible to execute maintenance in order to keep the assets in a good physical condition in order to reduce failures and fulfil its production function (Tsang et al., 1999). The purpose of maintenance performance measurements is to manage the maintenance function's performance by tracking important maintenance elements (Muchiri et al., 2011). From the framework developed by Peach (2014), Chapter 2: Literature review, it can be seen that the maintenance functions' effectiveness is influenced by the overall human factors of the maintenance staff. Peach (2014) reiterates Kumar et al. (2013) by stating that maintenance performance measurements' uniqueness could be improved by including maintenance human factors.

Literature indicates that human factors and performance shaping factors are receiving attention, but that maintenance human factor analysis and assessment is still lacking (Sheikhalishahi et al., 2017b). From Table 1.1, maintenance 4.0 will have strong elements of social dimensions. Maintenance performance measurements have always followed the changes in maintenance revolutions. This indicates that maintenance performance measurements 4.0 should include maintenance human factors. This is shared by Simões et al. (2011) and Bokrantz et al. (2017). Furthermore authors Antonovsky et al. (2014) and Tsang et al. (1999) stress that maintenance human factor measurements should be specific within the industry they are used in.

Literature on maintenance human factors and human error investigation within the electricity transmission industry is gaining traction with analyses in transmission system protection and electrical system operation reliability (Bao et al., 2018; Tavakoli and Nafar, 2020). These studies only focus on a small subsection of the transmission system and not on a holistic combination of all the sections: high voltage plant, secondary plant systems (protection, metering, telecommunication and DC systems) and line and servitude. Additionally, human error root causes, human reliability and human factor analysis within non-nuclear electricity system have received limited research attention (Tavakoli and Nafar, 2021a; Tavakoli and Nafar, 2020; Tavakoli and Nafar, 2019; Torres et al., 2018; Bao et al., 2018; Xie et al., 2016; Bao et al., 2014).

Table 1.2 and Table 1.3 serves as a summary of present literature on maintenance human factors in the electricity transmission industry. The purpose thereof is to illustrate the known literature in academia as well as the literature gap within academia relating to maintenance human factors within the electricity transmission industry.

In Table 1.2 several comments from the different authors were stated regarding human factors in the electricity industry, as highlighted below.

- Most human factor studies focus on aviation, nuclear power, chemical processing, medical devices, petroleum and mining and not on non-nuclear electricity systems (Sheikhalishahi et al., 2017b; Dhillon and Liu, 2006a; Antonovsky et al., 2014).
- Human reliability studies within non-nuclear electricity systems are still in the initial stages of research (Tavakoli and Nafar, 2021b; Bao et al., 2014; Tang et al., 2013).
- Human error root causes, human reliability and human factor analysis within non-nuclear electricity system have received limited research attention (Tavakoli and Nafar, 2021a; Tavakoli and Nafar, 2020; Tavakoli and Nafar, 2019; Torres et al., 2018; Bao et al., 2018; Xie et al., 2016; Bao et al., 2014).
- Quantitative assessments of human reliability and human factor analysis are required but are scarce (Bao et al., 2018; Sheikhalishahi et al., 2017b).

In Table 1.3 several comments by the different authors were stated regarding human factors in maintenance performance frameworks, as highlighted below.

- Insufficient attention is given to human factor analysis and assessment in the maintenance environment (Sheikhalishahi et al., 2017b; Peach et al., 2016).

Table 1.2: Literature articles in the non-nuclear electricity industry in relation to the research questions of this study.

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	**Identifying and classifying systems used**	**Maintenance human factors performance indicators or measurements**	**Included in maintenance performance framework**	**Author notes, comments and findings.**
Tavakoli and Nafar (2021b)	Reduce maintenance costs by improving human reliability in power grids.	Power transmission grids: Fars Regional Electrical Company The article provides a communication model between human reliability and maintenance cost. The goal of the model is to improve maintenance productivity to reduce maintenance cost by taking into account the probability of error by maintenance personnel.	The study identified 33 maintenance error root causes within the organisation and classified them into five categories. The study found that social dissatisfaction was the main cause of profit loss in the organization.	Not addressed	Not addressed	Not addressed	• Repeated comments from Bao et al. (2014) and Tang et al. (2013) that human reliability research in power system are still in the beginning stages.
Tavakoli and Nafar (2021a)	Improvement of human reliability by identifying and evaluating potential and actual root causes of maintenance team errors in the power transmission grids.	Power transmission: Fars Electricity Maintenance Company The article poses a methodology of analysing maintenance human reliability, the estimate the probabilities of the factors affecting human reliability in order to reduce human error.	Only the abstract of the article is available in English. The corresponding author was contacted and he proposed to use their article written in 2019: “The Improvement in Human Reliability in Power Grids by Identifying and Assessing the Risk of Failures Caused by Maintenance Operations”.	HFACS			• Human error root causes within power transmission grids have not been thoroughly studied.
Tavakoli and Nafar (2020)	Human reliability analysis in maintenance team of power transmission system protection.	Power transmission: Fars Electricity Maintenance Company The article focuses on identifying human error causes in maintenance teams of power transmission system protection.	The top four ranked causes to human error: • salary system, • the inadequacy of test equipment, • the shortage of personnel, and • their tiredness due to high workload.	HFACS	Not addressed	Not addressed	• Insufficient identification of human error roots causes and human factor studies that leads to electricity supply interruptions. • Factors in the power industry are different from power grid operators and maintenance.

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	Identifying and classifying systems used	Maintenance human factors performance indicators or measurements	Included in maintenance performance framework	Author notes, comments and findings.
Tavakoli and Nafar (2019)	The Improvement in Human Reliability in Power Grids by Identifying and Assessing the Risk of Failures Caused by Maintenance Operations.	Power transmission grids: Fars Regional Electrical Company The article proposes a method to estimate the probability of equipment failure due to the effects maintenance human error have on specified electrical equipment. The article also relates this to the financial consequences of these failures.	The main focus was to determine the failure probability of specific equipment classes caused by human error. Specific human error factors were not addressed.	Not addressed	Not addressed	Not addressed	• Human reliability in relation to system reliability within power system have not been emphasized.
Sheikhalishahi et al. (2017b)	Human Factors Effects and Analysis in Maintenance: A Power Plant Case Study.	Power plant in Kenya Case study focusing on human factors' effect and analysis (HFEA) to identify human factors in a Kenyan electrical power plant's maintenance department.	Most important human factors: • procedure usage, • fatigue, • knowledge and experience, and • time pressure.	Human factors effect and analysis (HFEA)	Not addressed	Not addressed	• Human factors within maintenance mainly focus on aviation and nuclear power plants. • Significant research and data on human error calculation and quantification methods, but insufficient attention to human factor analysis and assessment in maintenance. • Low implementation of human factor programs in maintenance departments. • Quantitative data is uncommon.
Torres et al. (2018)	State of the art of Human Factors Analysis Applied to Industrial and Commercial Power Systems.	Power systems Literature review on human reliability analysis (HRA) techniques, methods and applications within industries.	Mentions factors: • workload, • stress, and • fatigue. No research were done to determine influential factors within the article.	Classification system focused on human reliability and not on human factor analysis.	Not addressed	Not addressed	• Limited studies of human reliability analysis on power systems, specifically industrial and commercial power systems. • There is a need to include human reliability analysis within power systems. There are challenges to doing so. • Benefits of expanding human reliability analysis can be included in academia (protection courses), distribution system models and future standards.

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	Identifying and classifying systems used	Maintenance human factors performance indicators or measurements	Included in maintenance performance framework	Author notes, comments and findings.
Bao et al. (2018)	Impact analysis of human factors on power system operation reliability.	Power systems The article focuses on imperfect maintenance caused by human errors and the influence on dispatching operation and power system cascading failures.	Mentions factors: • external environment stress, • complexity of task, • knowledge and experience, • operation period, and • physical state. No research were done to determine influential factors within the article.	Classification system focused on human reliability and human error but not on human factor analysis.	Not addressed	Not addressed	• Lack of extensive research regarding human reliability analysis and human factors in power systems. • Quantitative assessments are required.
Peach et al. (2016)	A maintenance performance measurement framework that includes maintenance human factors: a case study from the electricity transmission industry.	Electricity transmission: South Africa The article focus on maintenance human factors that influence the maintenance department performance. Five human factors were selected and then ranked according to a survey result.	Selected factors that were ranked: • skill level, • motivation, • supervision, • workload, and • performance feedback.	PEAR Model was noted.	Basic performance measurements were given for skill level (training and competence), motivation, workload and performance feedback.	These measurement were included in an adapted framework based on Muchiri et al. (2011)mainten ance function performance measurement.	• Industries other than aviation, nuclear power, chemical processing, medical devices and mining have been slow to adapt maintenance performance measurements inclusive of maintenance human factors. • Maintenance performance measurements are industry specific.
Xie et al. (2016)	Study on Human Factor Risk Quantification and Evaluation Model in Power Grid Dispatching Risk Assessment.	Power grid: Guangdong dispatching operation. The article focuses on defining a human risk factor evaluation model (quantitative) within dispatching operations.	Singled out factors: • fatigue, • continuous working hours, • operation task intensity, and • empirical judgement, subjective experience.	Classification system focused on human factor risk assessment and not on human factor analysis.	Not addressed	Not addressed	• Limited studies on human risk factors assessment of power system planning and operation. Where studies have been identified there are absences of objective and quantitative analysing models.
Konovalov and Kuznetsova (2016)	The Role of Human Factor in Ensuring the Safety of Electric Power Objects after their Intellectualization.	Electric power industry The article focuses on guaranteeing safety within intellectual power systems through exploratory the role of human factors.	Singled out factors: • knowledge and understanding of safety rules and procedures, • adherence to the culture of safety, • professional expertise,	Not addressed	Not addressed	Not addressed	• Human factor are crucial to ensure reliability and safety of electrical power objects. • General background research of human factors to improve reliability of human factor is needed.

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	Identifying and classifying systems used	Maintenance human factors performance indicators or measurements	Included in maintenance performance framework	Author notes, comments and findings.
			• moral and psychological stability, and • absence of addictions high vulnerability to external environment.				
Tang et al. (2013)	A Bayesian network approach for human reliability analysis of power system.	Power systems The article provides a quantitatively measure the human reliability of power system.	Selected factors: • Task Scheduling • Operational Procedure • Training Quality • Personnel Arrangement • Available Time • Work Load • Work Environment • Equipment Operability • Pressure • Attention Skill & Experience	Selected factors were used from a Human Error Causal Framework	Not addressed	Not addressed	• Power system reliability and safety has been placed under great risks from Human error • Human reliability analysis along with quantitative measures for human reliability research in power systems is only at an early stage. • Work environment, training quality, available time and personnel arrangement are suggested to be influencing factors to human reliability.
Bao et al. (2014)	Analysis of power system operation reliability incorporating human errors.	Power systems The article proposed a power system operation reliability model incorporating human errors.	Mentions factors: • Competency, • Communication, • procedural factors, • mental and physical factors, • socio–environmental factors, • motivation, and • ergonomic factors. No research was done to determine influential factors within the article.	Classification system focused on human reliability and not on human factor analysis.	Not addressed	Not addressed	• Human factors on the operation of powers systems and power system reliability are mostly ignored by research. • Human factors should receive more focus along with management of human errors to maintain system reliability.
Hubenova and Gergov (2014)	Evaluation of the Influence of the Human Factor on the Reliability of the Information and Control Systems in the Electric Power Industry.	Electric power industry, The article focuses on mathematically analysing the reliability of the operator.	Not addressed	Classification system focused on human reliability and human error but not human factor analysis.	Not addressed	Not addressed	

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	Identifying and classifying systems used	Maintenance human factors performance indicators or measurements	Included in maintenance performance framework	Author notes, comments and findings.
Bodrogi et al. (2004)	Evaluation methods and key performance indicators for Transmission maintenance.	Power transmission maintenance The article evaluated 32 transmission maintenance departments' performance indicators. The most common performance indicators were work-related with reliability and equipment performance being the most important. The article did not address maintenance human factors or maintenance human errors in measuring maintenance performance.	Not addressed	Not addressed	Not addressed	Not addressed	• Only 6% of the utilities mentioned failures caused by human error.

Table 1.3: Literature articles in engineering maintenance in relation to the research questions of this study

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	**Identifying and classifying systems used**	**Maintenance human factors performance indicators or measurements**	**Included in maintenance performance framework**	**Author notes, comments and findings.**
Bokrantz et al. (2017)	Maintenance in digitalised manufacturing: Delphi-based scenarios for 2030.						•
Sheikhalishahi et al. (2016)	Human factors in maintenance: a review	Maintenance environment The article focuses on a literature review within the maintenance domain that analyses human factors.	Mentions several human factors. No research was done to determine influential factors within the article, although the article did identify some important factors.	The paper classifies maintenance human factors into 3 categories: • human error/reliability calculation, • workplace design/macro-ergonomics, and • human resource management.	Not addressed	Not addressed	• A maintenance department's performance is greatly influenced by human performance. • Future studies in the direction of human performance in maintenance are possible, especially in a wider range of industries. • Human factors in maintenance primarily focus on human error calculations.
Aju Kumar et al. (2015)	Identification and assessment of factors influencing human reliability in maintenance using fuzzy cognitive maps.	Maintenance environment The article acknowledges human behaviour that contributes to maintenance reliability. 15 factors are selected and assigned weightings through a fuzzy cognitive map (FCM) to identify the most influential factors. The article did not focus on maintenance within the electricity transmission industry.	Selected factors: • emotional stability, • knowledge and skill, • attention and alertness, • perception and memory , • motivation, • human reliability, • task compatibility, • design compatibility, • workplace environment , • management commitment , • clarity of instructions, • supervision, • communication , • resource availability, and • time pressure.	Classification system focused on human reliability. Human factors affecting human reliability were listed.	Not addressed	Not addressed	• Determining the most influential human factors from human reliability analysis is a constraint; a systematic approach is needed for this within the maintenance environment • Limited studies are available in the maintenance environment to assess factors on human reliability.

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	Identifying and classifying systems used	Maintenance human factors performance indicators or measurements	Included in maintenance performance framework	Author notes, comments and findings.
Parida et al. (2015)	Performance measurement and management for maintenance: a literature review						•
Kumar et al. (2013)	Maintenance performance metrics: a state-of-the-art review	Maintenance environment The article focused on a literature review on the approaches and techniques that can be used in maintenance performance measurements.	Not addressed	Mentions the use of mathematical models to assess performance probability.	Not addressed	Summary from literature gave categories of indicators found: • financial indicators, • indicators related to human resource, • indicators relating to the internal processes of the department, and • technical indicators	• The influence that human factors have is crucial to maintenance measurements. • The addition of measures relating to human resources reveals the distinctiveness of maintenance services. • Subjective approaches to include human factors exist to some extent, but objective (qualitative) measuring tools are lacking due to the intrinsic limitations of effectivity. • The author does mention indicators related to human resource, but these are seen as soft indicators that are of interest, but measurement is problematic due to the lack of hard objectivity. • The quality of employees' performance in the maintenance environments is difficult to measure due to several factors such as knowing the personnel's experience, education, training and skills. • Few organizations measure the human factors or include these factors in their maintenance performance frameworks.
Razak et al. (2011)	Towards human performance measurement from the maintenance perspective: a review.	Maintenance environment The paper provides a literature review on models to evaluate and manage human	Mentions factors: • staffing policies, • work scheduling, • performance or skill evaluation,	Human reliability models were also mentioned as well as the factors analysis and classification system (HFACS)	Not addressed	The importance of including human performance into maintenance	• Detailed studies on the effects of human performance on maintenance are required. • Key indicators for maintenance still favours equipment performance, overall equipment effectiveness,

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	Identifying and classifying systems used	Maintenance human factors performance indicators or measurements	Included in maintenance performance framework	Author notes, comments and findings.
		performance in the maintenance environment. The importance of identification and evaluation of influential human factors through human reliability studies was elaborated on. The article did not focus on maintenance within the electricity transmission industry.	• training requirement, and • work environment. No research was done to determine influential factors within the article.			performance was addresses but how to include this was not addressed.	availability, performance efficiency and quality.
Simões et al. (2011)	A literature review of maintenance performance measurement: A conceptual framework and directions for future research	Maintenance environment: maintenance performance measurement. This article reviewed literature on aspects of maintenance activity measures and manage maintenance performance.	Mentions factors: • years of relevant work experience on a specific machine, • personal disposition, • operator reliability, • work environment, • motivational management, • training, and • continuing education.	Not addressed	Not addressed	Mentioned most used measures in maintenance performance: • Cost, • OEE, • availability, and • MTBF. No weightings were given for these factors, nor were maintenance human factors included.	• Maintenance performance should be tailored for industry specific factors. • The importance of human factors on the effectiveness of maintenance performance was acknowledged.
Dhillon and Liu (2006b)	Human error in maintenance: a review.	Maintenance environment The article provided a literature review of human errors in maintenance according to the following industries: • aviation,	Mentions factors: • inadequate lighting, • inadequate training or skill, • poor equipment design, • high noise levels,	Not addressed	Not addressed	Not addressed	• Human error in maintenance is a critical problem and has not received adequate attention. • Reviewed journals and conference papers published between 1981-2003, per industry, only mentioned the nuclear power section of the electrical industry.

Author	Article Title	Industry & Focus area	RQ1		RQ2		Literature gap
			Most influence on maintenance human errors	**Identifying and classifying systems used**	**Maintenance human factors performance indicators or measurements**	**Included in maintenance performance framework**	**Author notes, comments and findings.**
		• nuclear power, • chemical processing, • medical devices, and • mining. The article did not focus on maintenance within the electricity transmission industry.	• inadequate work layout, • improper tools, and • poorly written equipment maintenance and operating procedures. No research was done to determine influential factors within the article.				

Academic literature exploring maintenance human factors within the non-nuclear electricity industry has only recently started to receive attention. This is repeatedly acknowledged in the articles listed in Table 1.2. Most articles only focused on human reliability calculation methods and only three articles identified influential human factors within maintenance. Articles focusing specifically on the electrical transmission industry were written by Tavakoli and Nafar (2019 – 2021) and Peach et al. (2016). RQ1 will therefore provide additional academic knowledge on influential maintenance human factors in the electricity transmission industry as well as in the overall electricity industry.

The only article that addresses items from both RQ1 and RQ2 was Peach et al. (2016) that provided basic performance measurements for four maintenance human factors. The measurements were based on five pre-selected factors that were ranked. Thereafter these maintenance human factor were incorporated into an adapted framework based on Muchiri et al.'s (2011) maintenance function performance measurement. The adapted framework only addressed some aspects of the maintenance process such as work planning, scheduling and execution and then three overall maintenance performance indicators (cost, equipment performance and safety). No weightings were given for these elements, hence a total maintenance performance score cannot be calculated. This thesis continues the work from Peach (2014) and the published article Peach et al. (2016). RQ2 will therefore provide a significant addition to academic knowledge by providing a calculation methodology to calculate an exact total maintenance performance score inclusive of maintenance human factors.

1.9. Brief overview of chapters

Chapter 1 is a brief introduction to this thesis. It provides the current state of the research problem along with the research objectives and research questions.

Chapter 2 focus on expanding the theory and practical implementation of the framework developed by Peach (2014). An explorative literature review is used to determine different measurements and measurement methods for maintenance human factors. A systematic literature review is used to determine the most noted maintenance human factors in literature. This will be used as a starting point to determine the most influential maintenance human factors within the electricity transmission industry.

Chapter 3 used the results from the systematic literature review to provide an adapted PEAR Model and HFACS-ME Framework. Analysis of the theory needed to choose performance indicators to develop a maintenance measurement framework was done. This was used to develop a maintenance performance framework for this thesis.

Chapter 4 addresses the considerations, processes and methodology followed to answer the research questions linked to the research objective.

Chapter 5 provides the data that was gathered from the maintenance technician and management questionnaires. This data was analysed in Chapter 6, where correlation testing was also done.

The analysis and correlations from Chapter 6 are evaluated in Chapter 7 to answer the research questions linked to this thesis' research objective. The proposed maintenance performance framework for this thesis was validated through a Delphi method.

Chapter 8 illustrates how the previous chapters contributed to achieve the research objective. It also provides a final closing of the thesis.

1.10. Chapter summary

This research will determine the most influential maintenance human factors and corresponding measurements. Thereafter, a maintenance performance measurement framework will be derived. This will address measurement issues within the next maintenance revolution (M4.0), but also the social aspects of Industry 4.0. A significant contribution within the overall electricity industry will also be made by addressing maintenance human factor measurements specifically focussed on the electricity transmission industry.

The benefits of this research will be in the cost reduction of maintenance without neglecting maintenance; the improved quality of maintenance tasks that directly leads to reduced maintenance errors; improved technical performance and reduced unplanned outages.

The following chapter will provide more detail around maintenance human factors, their measurements and measurement methods. This will ensure that the reader has a basic understanding of these maintenance human factors that will be discussed throughout the remaining part of the thesis.

2. LITERATURE REVIEW

This chapter will provide an overview of the theory relating to this thesis. An explorative literature review is used to identify maintenance human factors measurements and measurement methods. This will be used to answer the first part of RQ2 "How should these maintenance human factors performance indicators and measurements be incorporated into a traditional maintenance performance framework?" Thereafter a systematic literature review on the most noted maintenance human factor in literature was done. The findings from this will be used as a starting point to answer RQ1 "What maintenance human factors have the most influence on maintenance human errors?" The research questions within this thesis are phrased to answer a gap in literature both human factors within the electricity industry as well as a gap in measuring maintenance human factor in the maintenance environment. This gap in literature is investigated and verified in Section 2.1.5

It is acknowledged that several frameworks are known within literature. In Section 1.8, Contribution to literature, it was noted that only the article by Peach et al. (2016) addressed some items from both RQ1 and RQ2. This thesis continues the work by Peach (2014) and the published article by Peach et al. (2016). The literature review is therefore based on expanding the theory and practical implementation of the framework developed by Peach (2014) as illustrated in Figure 2.1.

The relationship between maintenance performance, maintenance performance measurements, maintenance human factors and maintenance resource management was published as a journal article (Peach et al., 2016).

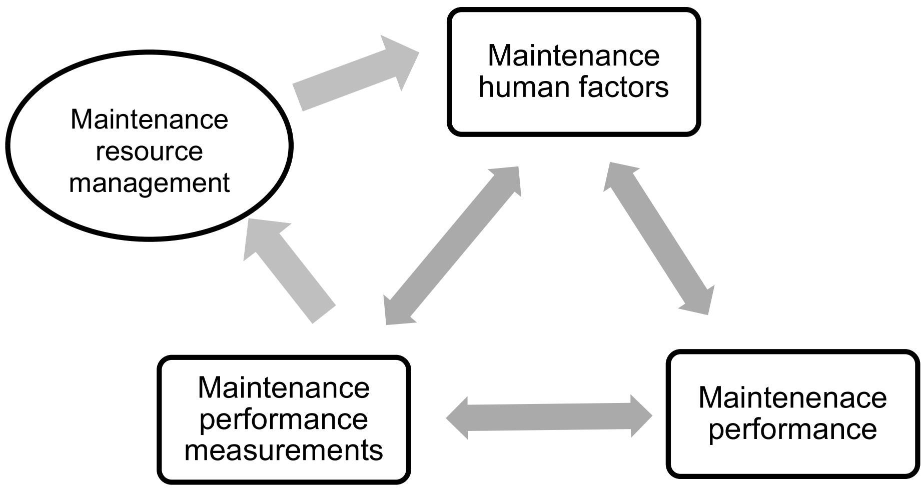

Figure 2.1: The relationship between maintenance performance, maintenance performance measurements and maintenance human factors

Source: Peach (2014)

Maintenance performance measurement is used to determine if 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 measurements influence maintenance human factors. This leads to either a negative or positive influence on maintenance performance. Maintenance resource management therefore plays a critical role in managing the link between maintenance performance measurements and maintenance human factors. Maintenance resource management is also required to ensure that maintenance human factors are addressed in order to positively influence the maintenance function’s performance (Peach et al., 2016).

2.1. Theory and research review

For the purpose of this study, the terms “maintenance staff”, “maintenance field worker”, “maintenance worker”, and “maintenance technician” are used interchangeably. The reason for this is that, although there are differences, these terms are used to illustrate the concept that these are the frontline workers responsible to execute maintenance. The term “maintenance technician” is used from Chapter 4 onwards as this is the terminology used within the applicable organisation.

2.1.1. Maintenance performance

Galar et al. (2011b) states that the empowerment of human capital can be the distinguishing factor in the performance of an organisation. He defines human factors as the "physical and psychological capabilities of the individual."

Narayan (2012) focused on aligning business and maintenance performance. Focusing on three main drivers, it was shown that including human behaviour provided a holistic business approach. By managing this approach, improved performance can be attained throughout the business' lifespan. Narayan's (2012) identified factors are: human reliability, sustainability and productivity. These factors are further expanded to elements as illustrated in Figure 2.2. 9 of these 14 expanded elements form part of the maintenance human factor, PEAR model, as shown later on in Table 2.9.

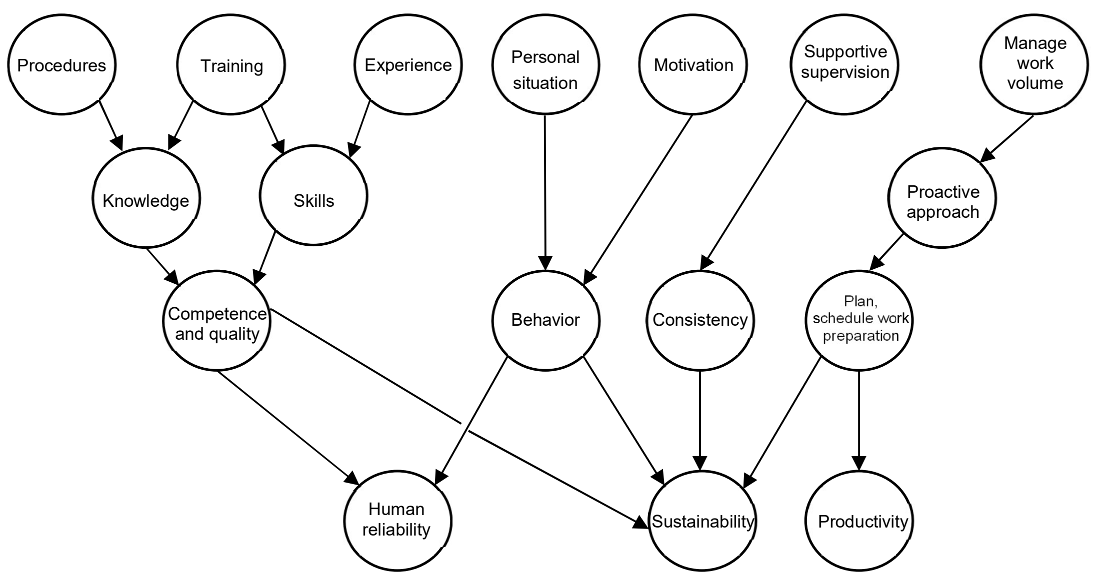

Figure 2.2: Main drivers of performance

Source: Narayan (2012)

The maintenance worker is accountable for the effectiveness, efficiency and quality of the maintenance work being done (Galar et al., 2011b; Peach et al., 2016). It is critical to acknowledge that a maintenance worker's state of mind can be influenced by internal and external factors. Maintenance performance can be improved by improving the maintenance worker's human factors and therefore the maintenance department's overall performance (Galar et al., 2011b; Hibit and Marx, 1994; Peach et al., 2016).

Dhillon (2002) states that more focus on human factors within maintenance will be seen this century. General critique from literature also refers to the need of including human factors in measurement frameworks (Kumar et al., 2013).

2.1.2. Maintenance performance measurements

To keep up with the change of perception regarding the maintenance function, changes in maintenance performance frameworks have also been seen. Maintenance performance frameworks have changed from first being driven by lagging cost indicators to a more proactive approach including leading indicators.

The purpose of maintenance performance measurements is to manage the maintenance function's performance by tracking important maintenance elements (Muchiri et al., 2011). The following benefits can be realized by effectively managing maintenance performance measurements:

- lower maintenance cost (Tsang et al., 1999),
- lower proportions of reactive maintenance (Tsang et al., 1999),
- to identify performance gaps (Muchiri et al., 2011; Parida and Kumar, 2006),
- to identify processes to be improved (Gilbert, 2013),
- to justify the investment made in maintenance (Kumar et al., 2013; Parida and Kumar, 2006; Parida et al., 2015),
- to provide a link between strategies and management action,
- it can be used to benchmark the performance against that of competitors within the same sector,
- to ensure that maintenance objectives are achieved (Alsyouf, 2006; Kotze and Visser, 2012; Muchiri et al., 2011; Tsang et al., 1999), and
- to achieve continuous improvement and prioritization of maintenance management efforts. (Parida and Kumar, 2006).

Performance measurements have the ability to influence human behaviour as seen with the popular saying by Goldratt (1991 as cited in Galar et al. (2011b)), "Tell me how you will measure me, and I will tell you how I will behave" (Galar et al., 2011b). This emphasizes the importance of choosing maintenance performance measurements that lead to a maintenance culture that is in line with the organisation's needs (Tsang et al., 1999).

Galar et al. (2011b) emphasizes that there needs to be a connection between the measurements chosen to facilitate decision making and that clear objectives needs to be defined at every level of the organisation. Neely et al. (1997) tabled recommendations for performance measures based on literature found on designing effective measures as seen in Table 2.1.

Table 2.1: Performance measures recommendations

Number	Recommendation
1	Performance measures should be derived from strategy
2	Performance measures should be simple to understand
3	Performance measures should provide timely and accurate feedback
4	Performance measures should be based on quantities that can be influenced, or controlled, by the user alone or in co-operation with others
5	Performance measures should reflect the "business process" – i.e. both the supplier and customer should be involved in the definition of the measure
6	Performance measures should relate to specific goals (targets)
7	Performance measures should be relevant
8	Performance measures should be part of a closed management loop
9	Performance measures should be clearly defined
10	Performance measures should have visual impact
11	Performance measures should focus on improvement
12	Performance measures should be consistent (in that they maintain their significance as time goes by)
13	Performance measures should provide fast feedback
14	Performance measures should have an explicit purpose
15	Performance measures should be based on an explicitly defined formula and source of data
16	Performance measures should employ ratios rather than absolute numbers
17	Performance measures should use data which are automatically collected as part of a process whenever possible
18	Performance measures should be reported in a simple consistent format
19	Performance measures should be based on trends rather than snapshots
20	Performance measures should provide information
21	Performance measures should be precise – be exact about what is being measured
22	Performance measures should be objective – not based on opinion

Source: Neely et al. (1997)

Muchiri et al. (2010) highlights the key performance measurements found in literature as seen in Figure 2.3. He continues his work with a summary of leading and lagging performance measurement for the maintenance process as seen in Table 2.2 and Table 2.3.

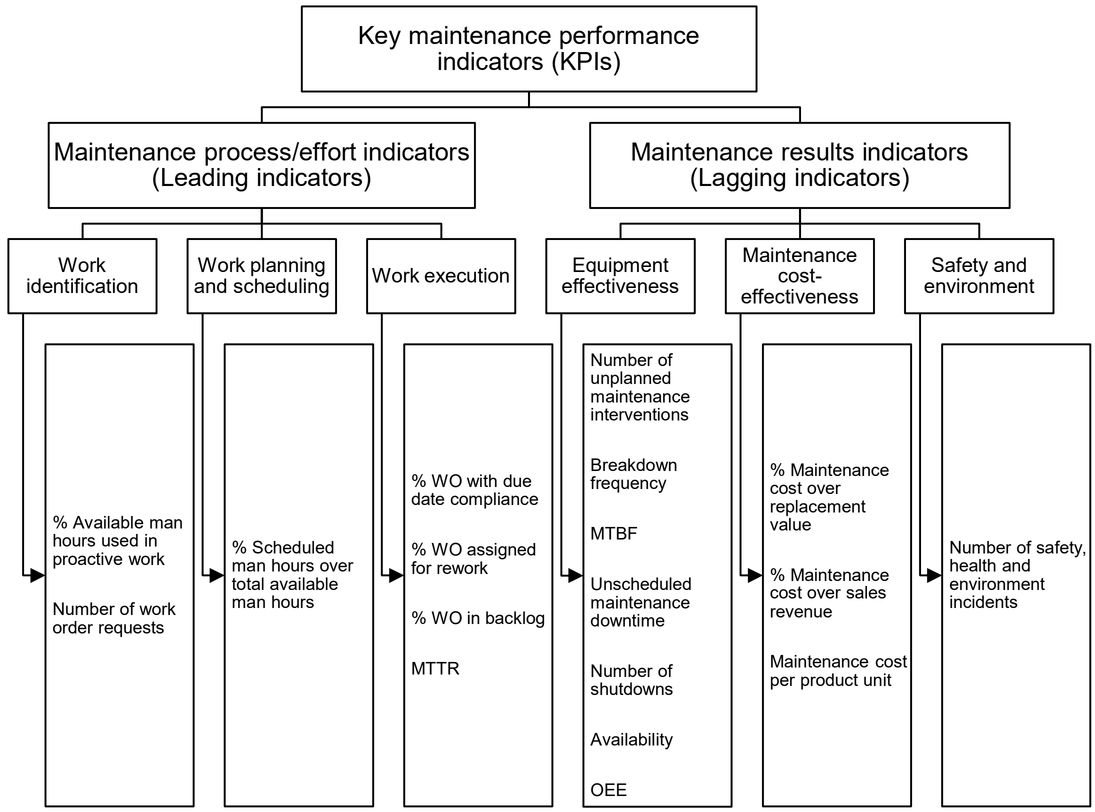

Figure 2.3: Key maintenance measurements

Source: Muchiri et al. (2010)

Table 2.2: Lagging performance indicators

Category	Measures/ Indicators	Units	Description
Measures of equipment performance	No. of failures	No.	No. of failures classified by their consequences: operational, non-operational, safety etc
	Failure / Breakdown frequency	No/ Unit Time	No. of failures per unit time (a measure of reliability)
	MTBF	Hours	Mean time between failure (a measure of reliability)
	Availability	%	MTBF / (MTBF + MTTR)= uptime / (uptime + downtime)
	OEE	%	Availability * performance rate* quality rate
Measures of cost performance	Direct maintenance cost	$	Total corrective and preventive maintenance cost
	Breakdown severity	%	Breakdown cost / Direct maintenance cost
	Maintenance intensity	$ / Unit production	% Maintenance cost per unit of products produced in a period
	% Maintenance cost component over manufacturing cost	%	% Maintenance cost / Total manufacturing cost
	ERV (Equipment Replacement Value)	%	Maintenance cost / New condition value
	Maintenance stock turnover	No.	Ratio of cost of materials used from stock within a period
	Percentage cost of personnel	%	Staff cost / total maintenance cost
	Percentage cost of subcontractors	%	Expenditure of subcontracting / Total maintenance cost
	Percentage cost of supplies	%	Cost of supplies / Total maintenance cost

Source: Muchiri et al. (2011)

Table 2.3: Leading performance indicators

Category	Measures / Indicators	UNITS	Description	Recommended Targets
Work Identification	Percentage of Proactive work	%	Man-hours envisaged for proactive work / Total man hours available	75% - 80%
	Percentage of Reactive work	%	Man-hours used for reactive work / Total man-hours available	10% - 15%
	Percentage of Improvement work	%	Man-hours used for improvement & modification / Total man-hour available	5% - 10%
	Work request response rate	%	Work requests remaining in 'request' status for <5days / Total work requests	80% of requests
Work Planning	Planning Intensity/Rate	%	Planned work / Total work done	95% of all work orders
	Quality of planning	%	Percentage of work orders requiring rework due to planning / All WO	<3% of all WO
	Planning Responsiveness	%	Percentage of WO in planning status for <5days / All WO	>80% of all WO
Work Scheduling	Scheduling Intensity	%	Scheduled man-hours / Total available man-hours	> 80% of available man-hours
	Quality of scheduling	%	Percentage of WO with delayed execution due to material or manpower	<2%
	Schedule realization rate	%	WO with scheduled date earlier or equal to late finish date / All WO	>95% of all WO
Work Execution	Schedule Compliance	%	Percentage of wok orders completed in scheduled period before late finish date	>90%
	Mean Time To Repair (MTTR)	Hours	Total downtime / No. of failures	
	Manpower Utilization rate	%	Total hours spent on tasks /Available hours	>80%
	Manpower Efficiency	%	Time allocated to tasks / Time spent on tasks	
	Work order turnover	%	No. of completed tasks / No. of received tasks	
	Backlog size	%	No. of overdue tasks / No. of received tasks	
	Quality of execution (Rework)	%	Percentage of maintenance work requiring rework	<3%

Source: Muchiri et al. (2011)

Peach et al. (2016) published a table of maintenance performance measurements, inclusive of maintenance human factors, adapted from Muchiri et al. (2011) shown in Table 2.4.

Table 2.4: Maintenance performance measurement inclusive of maintenance human factors

Category	Sub-category	Type	Measurements
Work planning and scheduling	Planning intensity	Leading	Man hours for planned maintenance work/ available man hours
	Schedule intensity	Leading	Scheduled man hours / available man hours
	Percentage reactive work	Leading	Man hours used for unplanned / available man hours
	Planned downtime	Leading	Planned number of maintenance related shutdowns
Work execution	Schedule compliance	Leading	Percentage of work orders completed as per schedule
	Backlog size	Leading	Percentage of work orders in backlog
	Work order turnover (Maintenance completion)	Leading	Number of work orders completed / number of work orders issued
	Quality of execution (Rework)	Leading	Percentage of maintenance work requiring rework
Maintenance human factors	Training	Leading	Number of training (skill improvement) interventions / number of maintenance staff
	Competence	Leading	Number of certified maintenance staff / number of maintenance staff
	Motivation	Leading	Overall staff motivation level
Cost / Financial	Maintenance cost	Lagging	Total maintenance cost
	Maintenance intensity	Lagging	Maintenance cost per product unit
	Cost of personnel	Lagging	Maintenance staff cost / total maintenance cost
Equipment performance	Downtime	Lagging	Number of maintenance related shutdowns / planned number of maintenance related shutdowns
	Number of failures	Lagging	Number of failures classified by their consequences: Operational, non-operational, safety etc
	Availability	Lagging	Availability (MTBF / (MTBF + MTTR))
	Regulatory	Lagging	SAIRI Average interruption duration [min.]
Safety	Safety	Lagging	Number of accidents / incidents

Source: Peach et al. (2016)

General critique of performance measures is given below.

- Too much data and not enough information (Galar et al., 2011b; Neely, 2002).
- The reasons and cost of data collection (Galar et al., 2011b).
- Time delay between action and monitoring of results (Galar et al., 2011b).
- Time delay between results and management feedback (Ziebell et al., 2000).
- Measurements are chosen based on ease of measuring and not relevance (Neely, 2002).
- Misalignment between the measured performance and the business objectives/ issues of importance/context and strategies (Galar et al., 2011b; Kennerley and Neely, 2003).
- Measurements that are no longer relevant/reflect old objectives (Kennerley and Neely, 2003).
- Measurement does not guarantee improvement; management action is still needed (Neely, 2002).

Kennerley and Neely (2003) derived a test of relevance for individual performance measures that can be used in order to address this general critique of performance measures as can be seen in Table 2.5.

Table 2.5: Test of relevance for individual performance measures

Test	Question
The truth test	Is the measure definitely measuring what it’s meant to measure?
The focus test	Is the measure only measuring what it’s meant to measure?
The consistency test	Is the measure consistent whenever or whoever measures?
The access test	Can the data be readily communicated and easily understood?
The clarity test	Is any ambiguity possible in interpretation of the results?
The so what test	Can, and will, the data be acted upon?
The timeliness test	Can the data be analysed soon enough so that action can be taken?
The cost test	Is it worth the cost of collecting and analysing the data?
The gaming test	Does the measure encourage any undesirable behaviours?

Source: Kennerley and Neely (2003)

2.1.3. Maintenance resource management

Maintenance management has evolved in the last 40 years. This can be validated through the changes in the definition of maintenance management, first being technical or functional in nature and now inclusive of management functions to strategically control reliability and availability (GFMAM, 2016; Moubray, 1997; Shanmugam and Paul Robert, 2015a; Tsang et al., 1999).

The Global Forum on Maintenance and Asset Management (GFMAM) defines maintenance management as “the decision-making process that align maintenance delivery activities with corporate objectives and strategies” (GFMAM, 2016).

Jonsson (1997) listed five components to maintenance management: Organisation, Tools and Techniques, Support Mechanisms, Human Aspects and Strategy. These components are a prequel to the components of maintenance resource management.

Galar et al. (2011b) emphasizes the importance that management can influence and change human factors and, therefore, improve aspects of maintenance. He further states that human factors can affect maintenance through targets or through efficient resource use. Therefore, a manager’s focus should be to identify the main factors influencing the maintenance department’s objectives.

Maintenance management can be seen as the management of the following five areas (Eti et al. (2006 cited in Sheikhalishahi et al. (2016)): general management policy, comparable culture, organisation and work structuring, support processes and maintenance methodology. Eti emphasizes that communication and human factors strongly influence these five areas.

Maintenance resource management originated within the aviation sphere and has shown to improve operational efficiency and safety as well as a reduction in lost time injuries, ground damage, and logbook error (Reynolds et al., 2010; Shanmugam and Paul Robert, 2015a).

Maintenance resource management can be seen as a subset of human resource management that applies organisational psychology, work sociology and anthropology (Shanmugam and Paul Robert, 2015a). Some of these factors include teamwork, training, workforce planning, competency, human performance, skills and knowledge management, performance shaping factors and maintenance human factors (Kelly, 2006; Sheikhalishahi et al., 2016). This supports Jaiswal et al. (2019) that administration, organization, communication, policies and procedures and accountabilities are elements of maintenance resource management.

Reiman (2011, as cited in Sheikhalishahi et al. (2016)) summarized his paper by stating that, to manage maintenance variability, holistic theory is needed. Maintenance resource management is a critical aspect to managing maintenance holistically.

2.1.4. Maintenance human factors

Maintenance human factors is a multi-disciplinary approach that focusses on human capabilities and limitations, with the human as the centre point of the system (Shepherd, 1995). Meister (2001) 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 from psychology (considered the 'mother') as it has effects on physical equipment. The same argument can be made for engineering (considered the 'stepfather') as it accounts for equipment and not the operator's behaviour. Human factors span both the behavioural domain and the physical domain.

The International Ergonomics Association defines Ergonomics (or human factors) as "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." The International Ergonomics Association also differentiates between three different ergonomics: "Cognitive Ergonomics, Physical Ergonomics and Organisational Ergonomics" (International Ergonomics Association, 2014).

More than 134 definitions for "human factor" have been recorded by 1989 and this term has evolved throughout time. These definitions have also been classified in different characteristic and application groups within eight categories. (Shanmugam and Paul Robert, 2015a). The definitions cited below indicate newer focus areas and supports the purpose of this study.

Dempsey et al. (2000) defines human factors as "designing and engineering of human-machine system; applying science to people performing in working environments; studying workers' limited capabilities related to safe job operation; improving knowledge on the fit between users and tasks; and the interface between people and machine in systems."

The Civil Aviation Safety Authority (CASA, 2013) defines human factors as "the wide range of issues that affect how people perform tasks in their work and non-work environments." CASA emphasizes the importance of complimenting technical skills with social and personal skills in order to safely and efficiently execute maintenance.

Different human factors have been identified in literature. Herzberg classified security factors affecting job attitudes, relationship with peers, relationship with subordinates, relationship with supervisor, status, salary, recognition, advancement, achievement, growth, responsibility, supervision, work itself, work conditions, personal life and company policies and administration (Kelly, 2006).

Kelly (2005) defines maintenance management human factors as "characteristics which define the way in which an individual or group behaves or acts that influence the way the maintenance department operates."

Sheikhalishahi et al. (2017a) and Sheikhalishahi et al. (2017c) have broadened human factor research into the field of maintenance planning by considering a maintenance scheduling approach that includes two human factors (time pressure and fatigue) in a power plant and in a petrochemical plant. The authors concluded that ignoring these human factors in the planning phase can decrease the savings from grouping maintenance activities by 67.8%. They also stated that failing to acknowledge these human factors can lead to increased operational, environmental or human related risks.

Human factors are now being researched in a subsection of ergonomics as neuro ergonomics. The aim, inter alia, of this field is to study the human brain's relation to work performance. By using neuro-imaging and molecular genetics, multitasking, mental workload and human error are being researched (Parasuraman, 2011; Shanmugam and Paul Robert, 2015a).

2.1.5. Human error

A discussion on maintenance human factors cannot be done without discussing human error. Not all maintenance human factors cause human error; however, the cause of human error share similar factors with maintenance human factors. Hobbs (2004) relates that human factors contribute to most accidents, but that literature has not always focused on the causation thereof; this is illustrated in Figure 2.4. In recent years this has changed with the view that by assessing human error the goal would be to understand and reduce human error. This is proven by human factor studies that have linked human factors with an error reduction in maintenance and an increase in operational efficiency (Shanmugam and Paul Robert, 2015a).

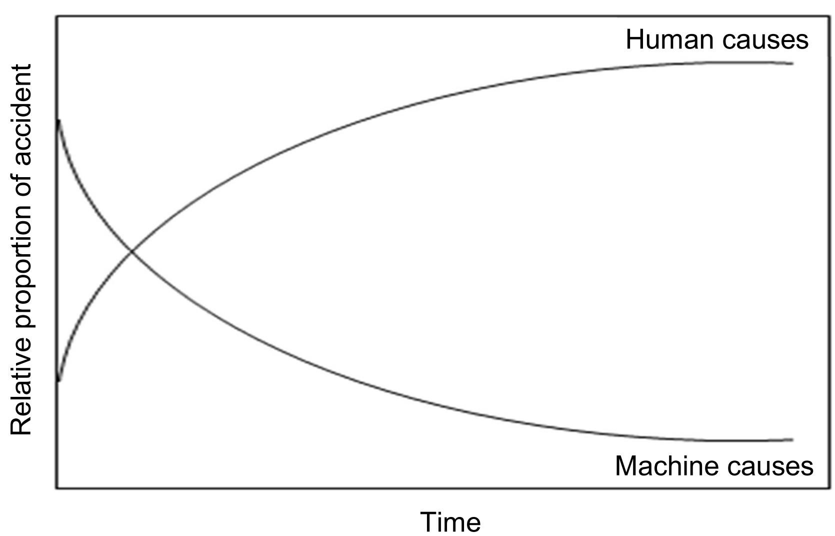

Figure 2.4: Link between human and machine factors to aviation accidents
Source: Hobbs (2004)

Reason ((1991), cited in Mearns (2017)) defines Human Error as “a generic term to encompass all the occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome and when these failures cannot be attributed to the intervention of some chance agency.”

The Dirty Dozen, developed by Gordon Dupont in 1993, are the 12 most common factors that predict human error in aviation maintenance. These common factors are: lack of communication, distraction, lack of resources, stress, complacency, lack of teamwork, pressure, lack of awareness, lack of knowledge, fatigue, lack of assertiveness and norms.

Reiman (2011) developed an opposite list named the ‘Pure Dozen’. This list focuses on the common factors that creates success in the maintenance organisation based on the work of Patankar and Taylor 2004b. These common factors are: vigilance and energy, assertive attitude to safety issues, motivation and mental resources, adequate task and safety knowledge, self-criticism and reflection, situation awareness, social permission to carry work thoroughly, norms supporting safety, clear communication, flexible organisation and slack resources, good task and work design and lastly functioning teamwork and cooperation.

Rogan (in Latorella and Prabhu (2000)) lists organisational structure, people management, tools and equipment, training and selection, commercial and operational pressures, planning and scheduling, maintenance of buildings and equipment, and communications as the factors that can influence maintenance human errors. These categories are parent categories to the Dirty Dozen.

Dhillon (2002) defines human error as “the failure to perform a specified task (or the performance of a forbidden action) that could lead to disruption of scheduled operations or result in damage to property and equipment”. He classifies human error into 6 categories: design, assembly, inspection, installation, operation, and maintenance.

In his 2001 publication, Drury (2000), lists three error investigation systems:

- the Human Factors Analysis and Classification System – HFACS,
- the Proactive Error Reduction System – PERS, and
- and the Maintenance Error Decision Aid – MEDA.

Dillion's guidelines to reduce human error in maintenance are categorized as maintenance incident feedback, towing aircraft, shift handover, communication, supervision, design, training, tools and equipment, human error risk management and procedures (Dhillon, 2002). He continued his work with Liu by listing factors that are predictors of human error (Dhillon and Liu, 2006a).

Another assessment tool for human error is the Human Error Assessment and Reliability Technique (HEART) that describes 9 Generic Task Types (GTTs) and 38 Error Producing Conditions (EPCs) that may influence task reliability (Mearns, 2017).

Safety Critical Task Analysis (SCTA) uses 6 human error guidewords: action failures, checking failure, retrieval failures, selection failures, communication failures and planning failures.

Sheikhalishahi et al. (2016) states that the main focus of human factors in literature has been on human error calculation models and methods rather than on social and organisational factors. He highlights that few studies focus on factors such as mental stress, cultures of maintenance and on normal work.

2.1.6. Human factor categories/classifications

Rasmussen (1982) illustrated the influence of system and environmental factors on the human operator as seen in Figure 2.5. This aligns will the human factor categories found in literature (Antonovsky et al., 2014).

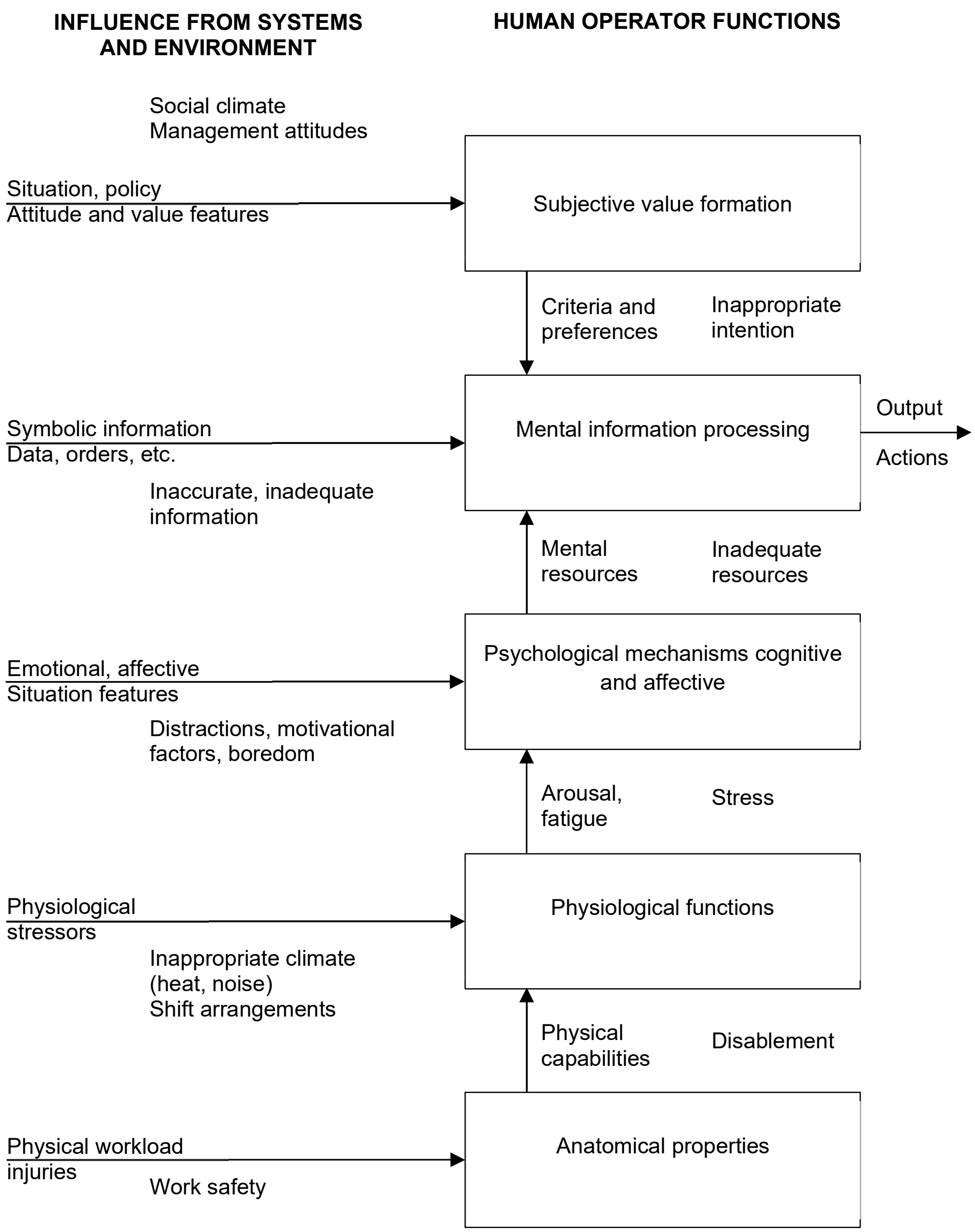

Figure 2.5: The influence of system and environmental factors on the human operator

Source: Rasmussen (1982)

Drury (2000) categorized several human factors that contribute to maintenance performance:

- written or computerized source information used by maintenance technicians to do their job,
- equipment, tools, and parts,
- airplane design and configuration,
- jobs and tasks,
- technical knowledge and skills,
- factors affecting individual performance,
- environment and facilities,
- organisational environment issues,
- leadership and supervision, and
- communication.

The Human Performance Evaluation Process (HPEP) has identified 11 categories to classify 50 human factors that can affect performance (Barnes et al., 2002):

- fitness for duty,
- knowledge, skills and abilities,
- attention and motivation,
- procedures and reference documentation,
- tools and equipment,
- staffing,
- supervision,
- human-system interface,
- task environment,
- communications, and
- coordination and control.

Galar et al. (2011b) classified three groups of human factors affecting maintenance (Table 2.6).

Table 2.6: Human factor categories

Personal factors	Conditional factors	Environment
• Skill level • Motivation • Experience • Attitude • Physical capability • Vision • Self-discipline • Training • Liability • Characteristics related to the personnel involved	• Operating environment physical condition • Geometry	• Temperature • Humidity • Noise • Light • Vibration • Time of day • Season • Wind

Source: Galar et al. (2011)

An et al. (2014) validated management and human factors' influence on maintenance and classified human factors into three categories: body and mind, responsibility and professional ability.

The International Ergonomics Association's (IEA) three categories can be seen in Table 2.7 (International Ergonomics Association, 2014).

Table 2.7: IEA's human factor fields

Physical	Cognitive	Organisational

• Human anatomy
• Anthropometric
• Physiological
• Work-related injuries
• Occupational safety
	• Mental processes
	  ○ Perception
	  ○ Memory
	  ○ Reasoning
	• Mental workload
	• Decision making
	• Human reliability
	• Work stress
	• Human system
		• Socio-technical systems
		  ○ Organisational structures
		  ○ Policies
		  ○ Processes
		• Communication
		• Crew resource management
		• Work design
		• Work systems
		• Design of working time
		• Teamwork
		• Participatory design
		• Virtual organisations
		• Telework
		• Quality management

Source: International Ergonomics Association (2014)

Based on 78 publications on human factors in maintenance, Sheikhalishahi et al. (2016) developed a novel framework to categorize human factors into three main categories: workplace design/macro-ergonomics, human error/reliability calculation and human resource management as shown in Table 2.8.

Table 2.8: Maintenance human factor classifications

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

Source: Sheikhalishahi et al. (2016)

Table 2.9: PEAR Model with subcategories

People	Environment	Actions	Resources
Physical Factors	**Physical**	Steps to perform a task	Procedures/work cards
Physical size	Weather	Sequence of activity	Technical manuals
Gender	Workspace	Number of people involved	Other people
Age	Location inside/outside	Communication requirements	Test equipment
Strength	Shift	Information control requirements	Tools
Sensory limitations	Lighting	Knowledge requirements	Computers/software
	Sound level	Skill requirements	Paperwork/signoffs
Physiological factors	Safety	Attitude requirements	Ground-handling equipment
Nutrition		Certification requirements	Work stands and lifts
Health	**Organisational**	Inspection requirements	Fixtures
Lifestyle	Personnel		Materials
Fatigue	Supervision		Task lighting
Chemical dependency	Labour-management relations		Training
	Pressures		Quality systems
Psychological factors	Crew structure		Time
Workload	Size of company		
Experience	Profitability		
Knowledge	Morale		
Training	Corporate culture		
Attitude			
Mental or emotional state			
Psychosocial factors			
Interpersonal conflict			

Source: CASA (2013); Johnson and Maddox (2007)

The four focus points of CASA's PEAR model used in their maintenance human factor program are People, The Environment, Actions and Resources, as shown in Table 2.9 (CASA, 2013; Johnson and Maddox, 2007). CASA highlights certain human factors that need to be well managed in their training manuals. These factors are error management, fatigue, stress, workload and time pressure, and communication.

One of the best known error investigation systems, the HFACS framework, originated in the aviation sphere (Kang, 2017). 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 underlying human factors that can lead to accidents (Reason, 1991; Skybrary, 2019).

The various airlines, together with the FAA, used the HFACS to classify aircrew error related accident/incident causal factors (Federal Aviation Administration, 2006).

The HFACS framework can be used during accident investigations and with historical data. The HFACS framework use a systematic approach to analyse applicable human factors. The Human Factors Analysis and Classification System – Maintenance Extension (HFACS-ME), used by the U.S Navy, classifies and categorizes maintenance related factors (Kang, 2017; Krulak, 2004). This enables organisation to develop intervention strategies (Schmidt and Lawson, 2000). The HFACS-ME follows the same structure and is used similarly to the HFACS framework. A common vocabulary can be established throughout industries by using the HFACS-ME framework within this study. Table 2.10 illustrate the HFACS-ME framework and its underlying factors.

Table 2.10: The HFACS-ME framework

Level 1 Factors	Level 2 Factors	Level 3 Factors
Management Conditions	Organizational	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 Adapt/Flexibility Teamwork
	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 Judgment/Decision-making
	Violation	Routine Infraction Exceptional Flagrant

Source: Krulak (2004)

2.2. Human factor measurements

The goals of measuring maintenance human factors are to provide a leading indicator to predict future human performance and to act on that prediction to improve on human performance (de Winter, 2014; Kantowitz, 1992; Ziebell et al., 2000). Kantowitz (1992) emphasizes that measuring maintenance human factors provided the opportunity to not only determine the performance of an individual but also the performance of teams and hence the performance of the department or overall system. He advocates not only measuring human factors but also discussions and actions afterwards.

Langan-Fox et al. (2009) summarized human factor measurements available in air traffic control systems for over-reliance, complacency, trust, motivation and stress, monotony and vigilance, boredom, workload and situation awareness.

Peach et al. (2016) developed a maintenance performance framework inclusive of maintenance human factors. They included training, competence and motivation as the maintenance human factors to be measured.

Several problems and critique exist with measuring human factors. Bittner Jr (1990) listed several barriers to human factor measurements mentioned below:

- Difficulty selecting appropriate criteria and measures,
- Complexities of experimental control and generalization,
- Need for subjective data to supplement objective data and its complications,
- Difficulties integrating or trading-off measures within and between facets,
- Difficulty relating human performance to overall system performance,
- Little validation of understanding-orientated research results in operational settings,
- Failures to explore operationally derived results for purposes of understanding their nature, and
- Proliferation of under-evaluated measures and assessment methods.

Kantowitz (1992) criticises that follow-up action on measurements are seldom done; that a single measure of a complex system is difficult to create (a statistical combination of multiple indicator are needed); that measurements are chosen on the basis of easy obtainability, some measurements are chosen without guidance of an adequate theory and that human factor research needs to be highly generalizable. He elaborates on the representation and uniqueness problem. He defines the representation problem as “How is the assignment of numbers to objects or phenomena justified?” and the uniqueness problem as “To what degree is this assignment unique?”

Jaiswal et al. (2019) reinforces that human factors within aviation is at an advanced stage and significant effort has been devoted to this. Aviation human factors psychologists have the same responsibilities and values of regular psychologists. His research aimed at analysing social psychology elements in human factors to determine the effect it has on maintenance performance. Aviation psychology is seen as a method to sustain emotional and physical health in its workforce. Maintenance human factors cannot be considered separate from human factors in other literature spheres. Several measurement criteria exist in aviation, military, psychology, medical and medical services literature. These criteria include stress, fatigue, workload and time pressure.

Additional to this section, an explorative literature review was used to identify maintenance human factors, their measurements and their measurement methods. An extensive literature review on 12 human factors was done. The detail of this literature review is in Appendix A. The summary of the explorative literature review is categorized according to the PEAR Model and shown in Table 2.11, Table 2.12 and Table 2.13. The findings from this section are to inform RQ2 on what measurements can be used to measure the identified maintenance human factors.

The explorative literature review will, therefore, not exclude different literature domains, as it is intended to provide possible measuring strategies. These measuring strategies are either already applicable or can be adapted to be applicable to the maintenance human factors domain.

Table 2.11: Literature summary of human factor measurements: people

Indicators	Measurement	Measurement methods	Reference
Workload	National Aeronautics and Space Administration Task Load Index (NASA-TLX) Trier Inventory for the Assessment of Chronic Stress (TICS) Cooper Harper rating scale Subjective Workload Assessment Technique (SWAT) Galvanic Skin Response Parasympathetic/sympathetic ratio, HR, HRV, diastolic pressure, systolic pressure, eye blink frequency and eye blink duration Cortisol responses after wakening Pupil size, average fixation time, fixation frequency, saccade frequency and average saccade velocity changed considerably with mental workload. Air Traffic Workload Input Technique (ATWIT) Instantaneous Self-Assessment (ISA) Impact on Mental Workload (AIM) Rating Scale of Mental Effort (RSME) Primary task performance Secondary task performance Performance and Usability Modelling (PUMA) Physiological measures	Questionnaire, physiological measurement	Guhe et al. (2005) Hwang et al. (2008) Schulz et al. (1998) de Winter (2014) He et al. (2012) Kovesdi et al. (2018) Langan-Fox et al. (2009)
Stress	The Perceived Stress Scale (PSS) Copenhagen Psychosocial Questionnaire (COPSOQ) Salivary cortisol levels Stress-oriented job analysis instrument (ISTA) Clinical Stress Assessment Dundee Stress State Questionnaire (DSSQ) Scale of Feelings (SOF) Copenhagen Psychosocial Questionnaire (CPQ) Observable behaviour Physiological measures	Questionnaire, physiological measurement	Cohen et al. (1983) Kristensen et al. (2005). Hellhammer et al. (2009) Zapf (1993) Bayer-Hohenwarter (2009) Langan-Fox et al. (2009)

Indicators	Measurement	Measurement methods	Reference
Motivation/moral	Absenteeism	HR Data	Galar et al. (2011)
Distraction	Noise levels Peripheral displays Physiological measures Deviations noticed Error detection Dundee stress state Questionnaire (DSSQ) Standard SSI	Physical Measurement	Kjellberg et al. (1996) Somervell et al. (2001) Langan-Fox et al. (2009)
Situation Awareness	Situation Awareness Global Assessment Technique (SAGAT) Situation Awareness Rating Technique (SART) Situation Awareness SHAPE* Questionnaire (SASHA_Q) Measuring Situation Awareness of Area Controllers within the Context of Automation (in its German translation) (SALSA) Situation Present Assessment Method (SPAM) Situation Awareness Verification and Analysis Tool (SAVANT) Situation Awareness SHAPE Online (SASHA_L) Physiological measures (e.g. EMT) Solutions for Human-Automation Partnership in European ATM* (SHAPE) Air Traffic Management (ATM)		Langan-Fox et al. (2009)
Fatigue	Multidimensional Fatigue Inventory (MFI) Fatigue Severity Scale (FSS) Nottingham Health Profile (NHP) Polio Problem List (PPL) Dutch Short Fatigue Questionnaire (SFQ). Burnout Clinical Subtype Questionnaire (BCSQ-36) Maslach Burnout Inventory-Human Service Scale (MBIHSS) Sleep Quality measurement (nocturnal polysomnography)	Questionnaire, physiological measurement	Smets et al. (1995) Harrington (1994) Horemans et al. (2004) Montero-Marín and García-Campayo (2010) Grunfeld et al. (2000) Maslach and Jackson (1981)

Indicators	Measurement	Measurement methods	Reference
Cognitive Capabilities	Stanford-Binet Intelligence Scale Kaufman scales Wechsler Adult Intelligence Scale Cognitive Abilities Test (CogAT) Differential Aptitude Tests (DAT) Comprehensive Ability Battery Hawaii Battery with Raven Intelligence quotient (IQ) score Armed Services Vocational Aptitude Battery (ASVAB) Armed Forces Qualifying Test (AFQT) Inhibition control, fluid intelligence, executive attention and working memory capacity Controller Aptitude (CONAPT) battery Air Traffic Selection and Training (AT_SAT) battery Air Traffic Controller Performance Model (ATC-PM) Air Traffic Controller Specialist Performance Ecole Nationale d'Aviation Civile (ATC STP ENAC) Cognitive Reserve Index questionnaire (CRIq)	Psychological testing Intelligence, aptitude and cognitive tests, questionnaire	Reynolds (1998) Motta and Joseph (2000) Ivnik et al. (2001) Wechsler (2008) Johnson and Bouchard Jr (2011) AllPsych (2018) de la Jara (2018) Mind Ware (2020) Sternberg (2015) National Research Council (2015) Langan-Fox et al. (2009) Nucci et al. (2011)

Table 2.12: Literature summary of human factor measurements: environment

Indicators	Measurement	Measurement methods	Reference
Communication	Roberts and O'reilly 35-item questionnaire Communication Satisfaction Questionnaire (CSQ) Listening characteristics Questionnaire Rosenfeld and Berko (1990) Questionnaire Roberts and O'reilly (1974) Questionnaire	Questionnaire	Roberts and O'reilly (1974) Downs and Hazen (1977) Federal Aviation Administration (2006) Rosenfeld and Berko (1990) Roberts and O'reilly (1974)
Teamwork	Team Effectiveness Questions NOTECHS (Non-Technical Skills evaluation system) Team performance measurement in simulation-based training Oxford NOTECHS System	Questionnaire, Observations	Adams et al. (2002) Flin et al., (2003) Mishra et al. (2009)
Supervision	Supervisory ratio (ratio of supervisors to supervised as a proxy for supervisory intensity) Supervision attitude item test Satisfaction and perception questionnaires Clarke (1999) structural and 'quality' aspects questionnaire Psychotherapy Supervisor Development Scale (PSDS) Clinical Outcomes in Routine Evaluation - Outcome Measure (CORE-OM) Competencies of Supervisors Supervision Outcomes Survey Supervisee Satisfaction Questionnaire – SSQ Supervisor perception form Supervisory Relationship Questionnaire Maintenance Resource Management Technical Operations Questionnaire (MRM/TOQ)	Questionnaire	Larsen et al. (1979) Heppner and Handley (1982) Borders and Leddick (1987) Kantowitz (1992) Flin et al. (2000) Mearns et al. (1997) Clarke (1999) Atzinger et al. (2016) Ögren et al. (2014) Worthen and Isakson (2000) Farber (2003) Taylor and Thomas Iii (2003)
Time Pressure	Roxburgh (2004) time pressure scale Teng et al. (2010) questionnaire Instrument for Stress Oriented Task Analysis (ISTA)	Questionnaire	Roxburgh (2004) Teng et al. (2010) Widmer et al. (2012)

Table 2.13: Literature summary of human factor measurements: resources

Indicators	Measurement	Measurement methods	Reference
Equipment, Tools, And Parts	Human Factors Guide for Aviation Maintenance and Inspection Questions Maintenance Behaviour Questionnaire (MBQ) Maintenance Environment Questionnaire (MEQ)	Questionnaire	Hobbs and Williamson (2002) Federal Aviation Administration (2006) Hobbs and Tada (2007)

2.3. Determining the most frequently noted human factors

A meta-analysis using a systematic literature review was used to determine the most frequently noted maintenance human factors. WorldCat, the world's largest network of library content and services, was used as the database for the systematic literature review (WorldCat, 2021). A total of 39 peer-reviewed articles that listed human factors were included in the meta-analyses.

A systematic review aims to populate empirical evidence through a systematic method. This is done to limit bias. By setting a pre-defined criterion reproducibility is increased (Liberati et al., 2009). The following elements of a systematic review were defined by Liberati et al. (2009):

- a clearly stated set of objectives with an explicit, reproducible methodology,
- a systematic search that attempts to identify all studies that would meet the eligibility criteria,
- an assessment of the validity of the findings of the included studies, and
- a systematic presentation and synthesis of the characteristics and findings of the included studies.

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. A second search criterion was that the peer-reviewed journal article should be applicable to the field of engineering or asset management. The search operator “Ti” was used to limit the search to articles with the keywords in the title. This can be the journal title or the article title. A later criterion to exclude article titles that do not include these keywords was used. Table 2.14 and Figure 2.6 shows the information flow through the different phases of the systematic literature review and the search criteria used. The original starting articles for the systematic literature review were identified in April 2019.

Table 2.14: Systematic literature review search phrases

<table>
<tr><th>Search Phrases Used</th><th>Search Criterion 1</th><th>Search Criterion 2</th></tr>
<tr><td>(eu:Peerreviewed) AND ti:("human factor*") AND ti:("maintenance*")</td><td>391 results</td><td></td></tr>
<tr><td>(eu:Peerreviewed) AND ti:("human factor*") AND ti:("measure*")</td><td></td><td>1 267 results</td></tr>
<tr><td>Apply criteria:
• remove duplicates
• field of engineering or asset management
• human factor* in article title</td><td colspan="2">116 results</td></tr>
<tr><td>Access to articles</td><td colspan="2">105 results</td></tr>
<tr><td>Apply criteria:
• remove duplicates
• field of engineering or asset management
• "human factor*" with "maintenance*" or "measure*" in article title

Excluded results that are:
• books,
• book reviews,
• conference/symposium abstracts,
• interviews, or
• special focus/technical opinion articles.</td><td colspan="2">54 results</td></tr>
<tr><td>Articles that list human factors</td><td colspan="2">39 results</td></tr>
</table>

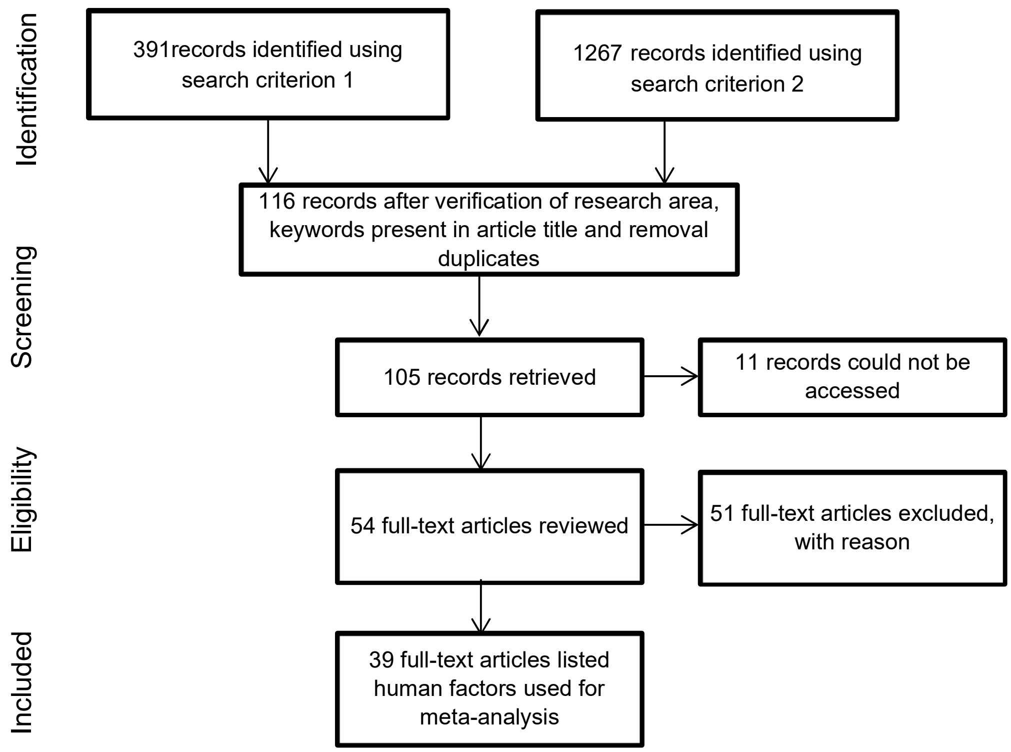

Figure 2.6: Information flow through the different phases of the systematic review. Adapted from Liberati et al. (2009)

The list of 39 articles is shown in Table 2.15. 11 of the 39 of the journal articles were published in the Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 15 of the 39 journal articles related to aviation maintenance. The article that was the most cited was “Selecting Measures for Human Factors Research” by H. Kantowitz Barry which was recited 102 times. The second most cited article was “Human factors in maintenance: impact on aircraft mishap frequency and severity” by D. C. Krulak, followed by “Human factors measurement for future air traffic control systems” by J. Langan-Fox, M. J. Sankey and J. M. Canty. The date range of the articles is from 1984 to 2019. The authors with the most articles of the 39 articles are Azadeh, A ; Pintelon, Liliane and Sheikhalishahi, Mohammad.

Table 2.15 Articles selected from the systematic literature review

Article Number	Year	Title	Author
1	2019	Human Factor Analyser for work measurement of manual manufacturing and assembly processes	Faccio et al. (2019)
2	2018	Human factors' complexity measurement of human-based station of assembly line	Fan et al. (2018)
3	2018	Application of eye tracking for measurement and evaluation in human factors studies in control room modernization	Kovesdi et al. (2018)
4	2018	Categories of measures to guide choice of human factors methods for nuclear power plant control room evaluation	Simonsen and Osvalder (2018)
5	2017	Dynamic maintenance planning approach by considering grouping strategy and human factors	Sheikhalishahi et al. (2017a)
6	2017	Human factors effects and analysis in maintenance: A power plant case study	Sheikhalishahi et al. (2017b)
7	2017	An integrated approach for maintenance planning by considering human factors: Application to a petrochemical plant	Sheikhalishahi et al. (2017c)
8	2017	Using evidential reasoning approach for prioritization of maintenance-related waste caused by human factors—a case study	Ahmadzadeh and Bengtsson (2017)
9	2016	An approach for integrated analysis of human factors in remote handling maintenance	Guo et al. (2016)
10	2016	Human factors in maintenance: a review	Sheikhalishahi et al. (2016)
11	2016	An interactive virtual lighting maintenance environment for human factors evaluation	He et al. (2016)
12	2016	A maintenance performance measurement framework that includes maintenance human factors: a case study from the electricity transmission industry	Peach et al. (2016)
13	2015	Applying human factor analysis tools to a railway brake and wheel maintenance facility	Singh et al. (2015)
14	2015	Human factors engineering in aircraft maintenance: a review	Shanmugam and Paul Robert (2015a)
15	2015	Ranking of aircraft maintenance organization based on human factor performance	Shanmugam and Paul Robert (2015b)
16	2014	Controversy in human factors constructs and the explosive use of the NASA-TLX: a measurement perspective	de Winter (2014)
17	2014	Human factors automatic evaluation for entire maintenance processes in virtual environment	Qiu et al. (2014)
18	2014	Identification of the human factors contributing to maintenance failures in a petroleum operation	Antonovsky et al. (2014)
19	2013	Using reliability indicators to explore human factors issues in maintenance databases	Karanikas (2013)
20	2011	Integrating human factors and operational research in a multidisciplinary investigation of road maintenance	Ryan et al. (2011)

Article Number	Year	Title	Author
21	2011	Supporting the changing roles of maintenance operators in mining: A human factors perspective	Alem et al. (2011)
22	2010	Opportunities for human factors measures in military operational test and evaluation	Ockerman et al. (2010)
23	2010	Human Factors Training in Aviation Maintenance: Impact on Incident Rates	Reynolds et al. (2010)
24	2010	Outsourcing aviation maintenance: human factors implications, specifically for communications	Drury et al. (2010)
25	2009	Human factors measurement for future air traffic control systems	Langan-Fox et al. (2009)
26	2008	Maintenance human factors: Introduction to the special issue	Kanki and Hobbs (2008)
27	2004	Human factors in maintenance: impact on aircraft mishap frequency and severity	Krulak (2004)
28	2003	Human factors considerations in the design of an aircraft maintenance hangar	Rantanen et al. (2003)
29	2000	Human factors analysis of naval aviation maintenance related mishaps	Schmidt et al. (2000)
30	1999	Outsourcing aviation maintenance: Human factors implications	Drury et al. (1999)
31	1996	Skill maintenance in extended spaceflight: A human factors analysis of space and analogue work environments	Sauer et al. (1996)
32	1995	Human factors in aviation maintenance and inspection: research responding to safety demands of industry	Shepherd and Johnson (1995)
33	1994	Introducing a practical human factors Guide into the aviation maintenance environment	Maddox (1994)
34	1992	Selecting measures for human factors research	Kantowitz (1992)
35	1992	Human factors challenges in aviation maintenance	Shepherd (1992)
36	1990	Human factors measurement: Nature, problems, and strengthening	Bittner Jr (1990)
37	1990	A program to study human factors in aircraft maintenance and inspection	Shepherd (1990)
38	1988	Operational Reality and Human Factors Measurement	Meister (1988)
39	1984	Human factors considerations in aviation maintenance	Strauch and Sandler (1984)

Table 2.16: Journal distribution where more than one article were used

Journal Name	Number of Articles
Proceedings of the Human Factors and Ergonomics Society Annual Meeting	11
Journal of Quality In Maintenance Engineering	3
Assembly Automation	2
Proceedings of the Human Factors Society Annual Meeting	2
Process Safety And Environmental Protection	2
The International Journal of Advanced Manufacturing Technology	2

Table 2.17: Journal distribution where only one article was used

Journal Name	
Acta Astronautical	International Journal of Aviation Psychology
Cognition, Technology & Work	Nuclear Technology
Computers & Industrial Engineering	South African Journal of Industrial Engineering
Ergonomics	Safety Science
Human Factors	The Ergonomics Open Journal
Human Factors and Ergonomics in Manufacturing & Service Industries	The International Journal of Aviation Psychology
Human Factors: The Journal of Human Factors and Ergonomics Society	International Journal of Quality & Reliability Management
Quality and Reliability Engineering International	Aviation, Space and Environmental Medicine
Science And Technology of Nuclear Installations	

Table 2.18: Industry distribution where more than one article were used

Article Industry	Number of Articles
Aviation Maintenance	15
General Maintenance	3
Manufacturing	3
Control Rooms: Nuclear	2
General	2
General Operations	2
Maintenance Planning	2

Table 2.19: Industry distribution where only one article was used

Article Industry	
Control Rooms: Air Traffic	Radioactive Remote Handling Maintenance
Electricity Transmission	Railway Maintenance
Military	Road Maintenance
Mining	Space
Petroleum	Power Plant Maintenance

2.3.1. Results using minimal coding

From the 39 full-text articles 832 data points on human factors were gathered and 184 data points on human factor categories were gathered. Each human factor mentioned in an article were only counted once and represented 1 data point. For this section, minimal coding was used on the human factor to get an unbiased indication of the most noted human factor. Minimal coding represents minimum manipulation of the data points. An example of this would be to only change a data point that is in the plural form of the word to the singular form. The most frequently noted single human factors are shown in Figure 2.7.

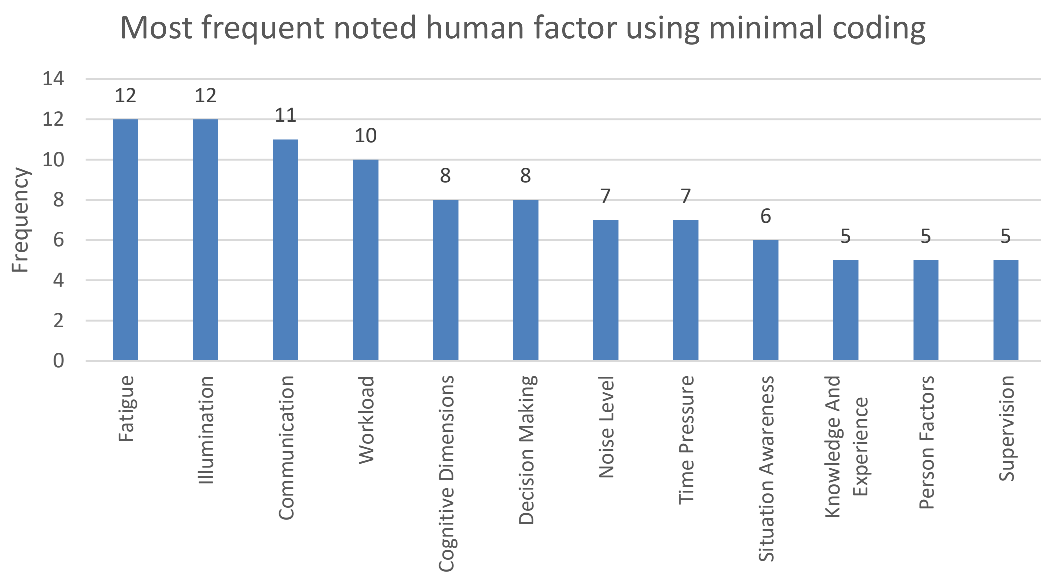

Figure 2.7: Most frequent noted human factor using minimal coding

2.3.2. Results using PEAR Model coding and grouping

By using the PEAR model as a guideline similar human factors were coded using PEAR model terminology. In cases where no similar terminology was found in the PEAR model and the human factor was noted a multiple numer of times, the human factor was added to the PEAR model. In cases where the human factor was not sufficiently noted it was not added to the adapted PEAR model. Human factor from the PEAR model that was not noted anywhere else in literature was removed. The top 13 (26%) human factors are shown in Figure 2.8.

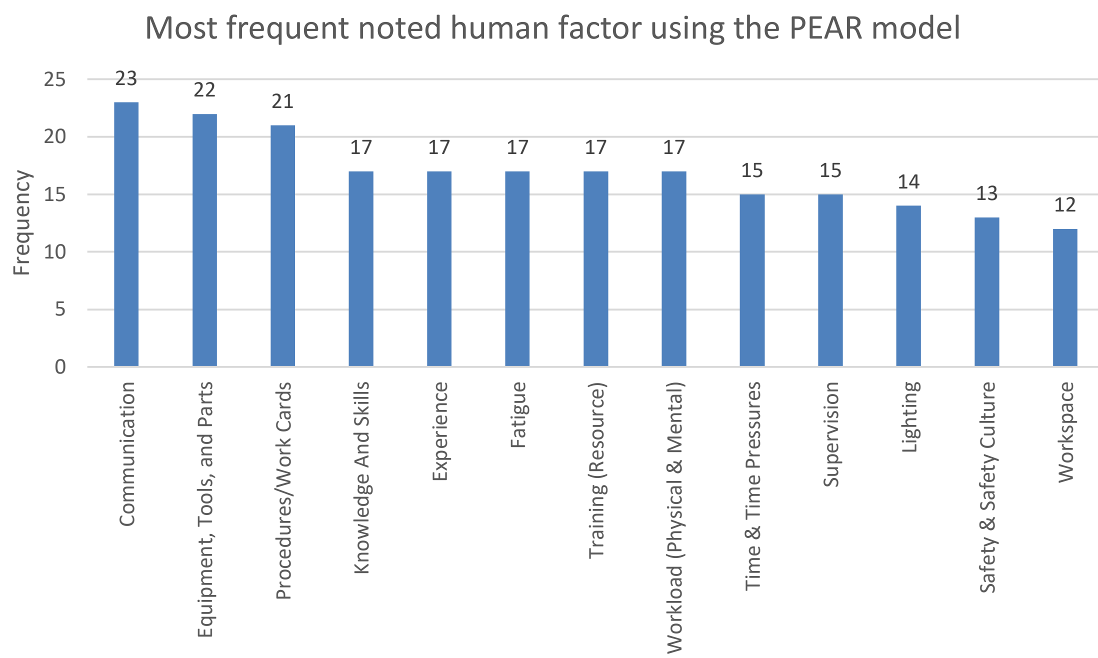

Figure 2.8: Most frequent noted human factor using the PEAR Model

2.3.3. 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 noted multiple times, the human factor was added to the HFACS-ME framework. An example of a human factor that was added to the HFACS-ME framework was “high workload”, which was added under Inadequate Resources.

C8 Sciences (2018) list the 8 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.

The top 13 (22%) of the listed factors are shown in the Figure 2.9.

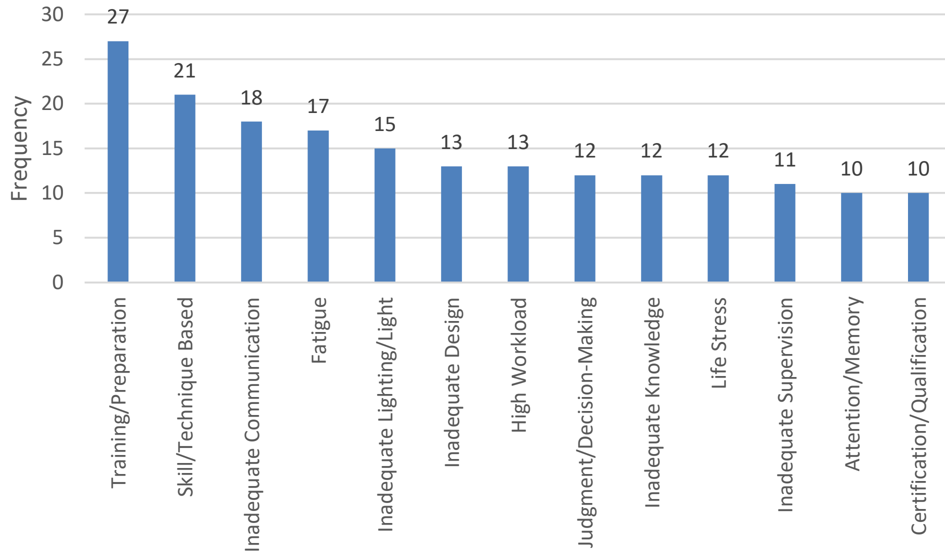

Figure 2.9: Most frequent cited human factor using the HFACS-ME framework

2.4. Literature on influential (dominant) maintenance human factors

Hobbs and Williamson (2003) list pressure as the factor that contributes most often to maintenance error occurrences. Other factors, such as training, fatigue and supervision are also noted as in the figure below.

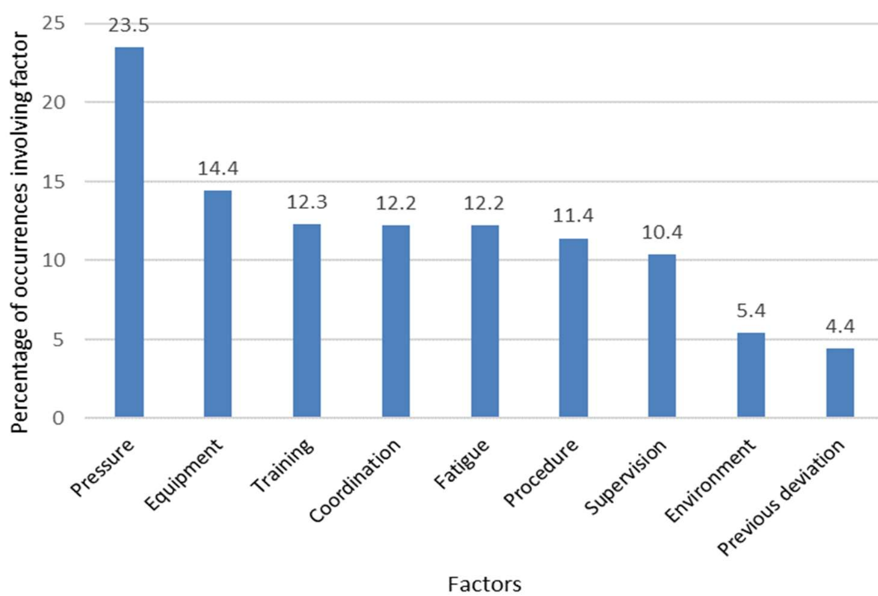

Figure 2.10: Factors contributing to maintenance occurrences
Source: Hobbs and Williamson (2003)

Krulak (2004) analysed 1016 aircraft mishaps caused by maintenance human factors between 1996 and 2001. These mishaps were classified using the HFACS-ME framework. The factors most often found in aircraft mishaps were inadequate supervision, attention/memory errors and judgment/decision-making errors.

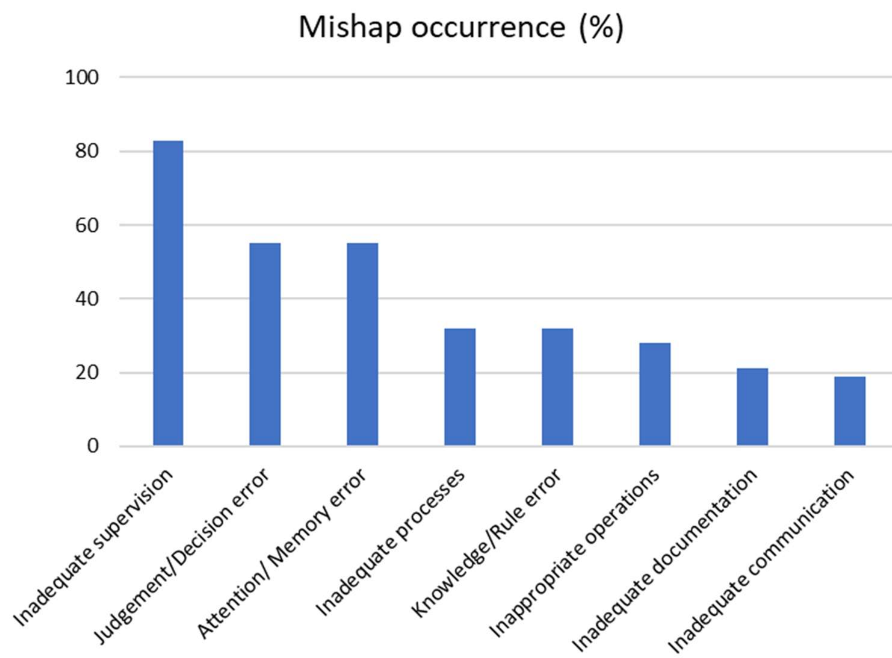

Figure 2.11: Mishap occurrence for HFACS-ME factors

Source: Krulak (2004)

Johnson and Hackworth (2008) identified fatigue as the number one challenge in maintenance based on the US Federal Aviation Administration surveys in 2006 and 2007.

Antonovsky et al. (2014) ranked the top 5 contributing factors using the Human Factors Investigation Tool (HFIT) within for the petroleum industry as:

- assumption,
- design and maintenance,
- communication,
- omission, and
- decision-making.

Sheikhalishahi et al. (2016) identified the most important maintenance human factors as fatigue, knowledge and experience, and coordination and communication.

Mearns (2017) published that, in her experience within the chemical process industries, poor design, poor procedures, lack of supervision, fatigue, poor safety climate/culture and lack of safety leadership, and underinvestment by senior management in safety improvements are generally the performance influencing factors that contribute to human error.

Reason (1995), known for his accident causation model (Swiss cheese model), lists unfamiliarity with the task as the leading error producing condition. According to Reason time constraints is the second most significant factor.

2.5. Chapter summary

Once maintenance human factors are measured and tracked it can be managed through the maintenance resource management principles. This chapter described and analysed previous research and showed that there are several human factor categories and that human factors had several measurements. It is senseless and impractical to implement a measuring system for all human factors affecting the maintenance worker and thereby the maintenance department's performance. It is unclear from literature what specific performance indicators and measurements should be used to measure and manage these factors. It is crucial to identify the most influential human factors for the specific maintenance department and to rank them according to importance.

In the following chapter, a systematic literature review will determine the most noted maintenance human factors in literature. These maintenance human factors will be used to determine the most influential maintenance human factors in the South African Transmission sector.

3. THEORETICAL FRAMEWORK

The first part of Chapter 3 describes the frameworks and methodologies used in literature to choose maintenance performance indicators. In this chase, it is used specifically to choose which maintenance human factors should be measured. Thereafter, a systematic literature review was used to determine the most noted maintenance human factors in literature.

3.1. Adapted maintenance human factor models

3.1.1. Results using PEAR Model coding and grouping

In Table 3.1 the adapted PEAR model used for the coding in this study is shown. Factor that are formatted with strikethrough were removed and factors formatted in italic were added. Some factors were moved between the four sections.

Table 3.1: Adapted PEAR Model

People	Environment	Actions	Resources
Physical Factors • Gender • Age • Strength • ~~Physical size~~ • ~~Sensory limitation~~ **Physiological factors** • Fatigue • ~~Nutrition~~ • ~~Health~~ • ~~Lifestyle~~ • ~~Chemical dependency~~ **Psychological factors** • Workload *(Physical & Mental)* • Experience • Knowledge *And Skills* • Training *(Psychological factors)* • Attitude • Mental or emotional state • *Stress* • *Cognitive capabilities* • *Situation Awareness* • *Motivation* • *Decision Making* • *Beliefs* **Psychosocial factors** • Interpersonal skills/conflict	**Physical** • Weather • Workspace • Shift • Lighting • Sound level • *Vibration* • *Heat* • *Reachability* • ~~Location inside/outside~~ • ~~Safety~~ **Organisational** • Personnel • Supervision • Communication • *Time & Time* Pressures • *Work* pressure • Crew structure • Corporate culture • *Safety & Safety Culture* • *Team & Teamwork* • ~~Labour-management relations~~ • ~~Size of company~~ • ~~Profitability~~ • ~~Morale~~	• Information Control Requirements • Skill Requirements • Certification Requirements • Inspection Requirements • ~~Steps to perform a task~~ • ~~Sequence of activity~~ • ~~Number of people involved~~ • ~~Communication requirements~~ • ~~Knowledge requirements~~ • ~~Attitude requirements~~	• Procedures/work cards • Technical manuals • *Equipment, Tools, And Parts* • Computers/software • Paperwork/signoffs • Training *(Resource)* • Quality systems • ~~Other people~~ • ~~Ground-handling equipment~~ • ~~Work stands and lifts~~ • ~~Fixtures~~ • ~~Materials~~ • ~~Task lighting~~ • ~~Time~~

3.1.2. Results using HFACS-ME framework coding and grouping

Although cognition is not listed in the HFACS-ME framework, its capabilities are listed under Attention/Memory Errors. In Table 3.2 the adapted HFACS-ME framework used for the coding in this study is indicated. Factor that are formatted with strikethrough were removed and factors formatted in italic were added.

Table 3.2: Adapted HFACS-ME Framework

First Order	Second Order	Third Order	Fourth Order
Management Conditions	Organisational	Inappropriate Processes	Task Complex/Confusing
			Procedures Incomplete
			Non-Existing Procedures
		Inadequate Documentation	Not Understandable
			Information Unavailable
			Conflicting Information
		Inadequate Design	Poor Layout/Configuration
			Poor/No Accessibility
			Easy to Incorrectly Install
		Inadequate Resources	Parts Unavailable
			Manning Shortfall
			High Workload *(Physical & Mental)*
			Funding Constraint
		Communication	*Cross Industry Communication*
			General Communication
	Supervisory	Inadequate Supervision	Task Planning/Organisation
			Task Delegation/Assignment
			Amount of Supervision
		Inappropriate Operations	Information Not Used
			Unrealistic Expectations
			Improper Task Prioritization
		Uncorrected Problem	Manual Not Updated
			Parts/Tool Incorrectly Labelled
			Known Hazards Not Controlled
		Supervisory Misconduct	Policy/Procedures Not Followed
			Policy/Procedures Not Enforced
			Assigned Unqualified Maintainer
Maintainer Conditions	Medical	Adverse Mental State	~~Peer~~ Pressure *(time, work, etc.)*
			Complacency
			Life Stress
		Adverse Physical State	Health/Illness
			Fatigue
			Circadian Rhythm
		Physical/Mental Limitation	Body Size/Strength
			Eyesight/Hearing
			Reach/View

Table 3.2: Adapted HFACS-ME Framework (continued)

First Order	Second Order	Third Order	Fourth Order
Maintainer Conditions	Crew Coordination	Inadequate Communication	Non Standard Hand Signals
			Inappropriate Log Entry
			Inadequate Shift pass down
			Inadequate Task Coordination
		Inadequate Assertiveness	Peer Pressure
			Rank Gradient
			New to Group
		Inadequate Adapt/Flexibility	Non-adherence to Change
			Different from Similar Tasks
			Disregard of Constraint
		Teamwork	*Team Composition*
			Team Cognition
	Readiness	Training/Preparation	New/Changed Task
			Inadequate Skills
			Inadequate Knowledge
			Inadequate Experience
		Certification/Qualification	Not Certified for Task
			Incomplete PQS
			Not Licensed to Operate
		Infringement	Self-Medication
			Alcohol Use
			Crew Rest
Working Conditions	Environment	Inadequate Lighting/Light	Inadequate Natural Light
			Inadequate Artificial Lighting
			Dusk/Night time
		Unsafe Weather/Exposure	Temperature
			Precipitation
			Wind
		Unsafe Environmental Hazards	High Noise Levels
			Housekeeping/Cleanliness
			Hazardous/Toxic Substances
	Equipment	Damaged/Unserviced	Unsafe/Hazardous
			Unreliable/Faulty
			Inoperable/Uncontrollable
		Unavailable/Inappropriate	Unavailable for Use
			Inappropriate for Task
			Power Sources Inadequate
		Dated/Uncertified	Unreliable/Faulty
			Inoperable/Uncontrollable
			Miscalibrated
	Workspace	Confining	Constrained Tool Use
			Constrained Equipment Use
			Constrained Position
		Obstructed	Not Visible
			Not Directly Visible
			Partially Visible
		Inaccessible	Totally Inaccessible
			Not Directly Accessible
			Partially Accessible

Table 3.2: Adapted HFACS-ME Framework (continued)

First Order	Second Order	Third Order	Fourth Order
Maintainer Acts	Error	Attention/Memory	Omitted Procedural Step
			Distraction/Interruption
			Failed to Recognize Condition
			Failed to Anticipating Future Event
		Knowledge/Rule Based	Inadequate Task Knowledge
			Inadequate Process Knowledge
			Inadequate Aircraft Knowledge
		Skill/Technique Based	Poor Technique
			Inadequate Skills
			Inappropriate Technique
		Judgment/Decision-making	Exceeded Ability
			Misjudged/Misperceived
			Misdiagnosed Situation
	Violation	Routine	Inappropriate Tools/Equipment
			Procedures Skipped/Reordered
			Did Not Use Publication
		Infraction	Inappropriate Tools/Equipment
			Procedures Skipped/Reordered
			Did Not Use Publication
		Exceptional	Gundecking Qualifications
			Not Using Required Equipment
			Signed-off Without Inspection
		Flagrant	Gundecking Qualifications
			Not Using Required Equipment
			Signed-off Without Inspection

3.2. Maintenance performance indicators and frameworks

3.2.1. Choosing maintenance performance indicators

Visser and Pretorius (2003) indicated that maintenance performance indicators cannot simply be selected at random from published literature. They propose the following criteria for selecting maintenance performance indicators.

Maintenance performance indicators:

- should have strategic relevance to the organisation,
- should measure inputs, conversion and outputs of the maintenance function,
- should have elements of a balanced scorecard perspective, and
- should include elements of the maintenance function such as preventative maintenance and work order systems.

Galar et al. (2011b) listed the following guidelines when choosing human factors indicators:

- distinguish measurements that affect human factors,
- remember the interlinked relationships of human factors such as morale and motivation,
- determine dominant human factors, and
- use already known performance indicators that measure human factors for example “absenteeism as indicator of morality”.

Dominant maintenance human factors can be identified using several frameworks, namely the PEAR model, HFACS, HFACS-ME or HFIT. Once the dominant or most influential factors are identified, measurements for them can be chosen. Managers should focus on maintenance human factors specific for the industry rather than generic factors (Antonovsky et al., 2014; Tsang et al., 1999). By identifying the dominant maintenance human factors using a chosen framework for the applicable industry, the organisation can align it to the strategic goal of the organization.

To provide a starting point to determine the dominant or most influential maintenance human factors, a systematic literature review (Section 3.2) was done. The systematic literature review determined the most noted maintenance human factors using the PEAR model and the HFACS-ME framework. After determining the most noted maintenance human factors the most influential factors in the electricity transmission industry can be determined using a research Delphi method.

3.2.2. Choosing a maintenance measurement framework

Several maintenance management frameworks have been developed. Many of these frameworks discuss processes for choosing performance measurements applicable to the organisations’ maintenance management framework (Kennerley and Neely, 2003; Muchiri et al., 2011).

After the dominant maintenance human factors have been identified, a measurements system or framework to implement these maintenance human factors needs to be chosen.

Kennerley and Neely (2003) summarize their research with a list of several enabling factors that influence the relevance of measurement systems, as seen in Table 3.3.

Table 3.3: Enabling factors that influence the relevance of measurement systems

Process	Systems	People	Culture
• Regular process to review measure with predetermined review dates and allocated resources	• Maintenance of IT development capabilities	• Availability of dedicated resources to facilitate review and modification of measures	• Culture conducive to measurement Senior management driving measurement Understanding of the benefit of measurement
• Integration of measurements with improvement initiatives and strategy formulation	• Flexible IT systems enabling modification of data collection, analysis and reporting tools (e.g. in-house systems)	• Maintenance of internal performance measurement capabilities	• Acceptance of need for evolution
• Measurement managed to ensure consistent approach to continuity	• Integration of IT and operational objectives and resources	• Availability of appropriate skills to use measures effectively and quantify performance objectives (including in-depth knowledge of operations and stakeholder requirements; systems development skills, etc.)	• Effective communication of measures and measurement issues using accepted media
• Processes pro-actively identify internal and external triggers of change	• Resources dedicated to the development of measurement systems	• Development of a community of users of measures to transfer best practice (e-mail, user groups, benchmarking)	• Use of measures to prompt actions, reflect on strategy and processes, etc.
• Availability of mechanisms to transfer best practice	• Maximise data availability, minimise reporting		• Open and honest use of measures

Source: Kennerley and Neely (2003)

The following key aspects need consideration before implementing new measurement systems.

- The process of sectioning measurements should be systematic (Kantowitz, 1992).
- The resistance to change if no measurements were previously taken (Galar et al., 2011b).
- Determine a strategy of providing feedback of the measured results to employees (Ziebell et al., 2000)..
- Determine the frequency of measurements as well time frames to provide feedback (Galar et al., 2011b).
- Take lag time and reactivity of the system into consideration when determining the frequency of measurements (Galar et al., 2011b).
- Involve maintenance staff in selecting relevant factors that will be measured, hence use a participative approach (Arca and Prado, 2008).
- It is essential that staff see management is "paying attention to" the measurements and that managements provide feedback on remedial actions (Ziebell et al., 2000).
- The benefit of maintenance human factor focus needs to be clearly communicated to the maintenance staff as maintenance staff will only collect data if they see the benefits from their efforts (Hartwick and Barki, 1994; Kumar et al., 2013).
- Calculations and data collection of measurement should not add substantially to the workload of managers, supervisors, and workers (Ziebell et al., 2000).
- The number of measurements selected should relate to the number of resources available to process them (Campbell et al., 2016).
- Measurements should be industry specific (Kumar et al., 2013).
- The chosen measurements should have the greatest impact (Woodhouse, 2000).

Meister (2001) states that measurement system components consist of:

- measurement elements,
- measurement personnel,
- measurement processes,
- measurement venues,
- measurement outputs,
- measurement influencing, and
- measurement attributes.

Meister (2001) measurement system components that are relevant to this thesis are shown in Figure 3.1.

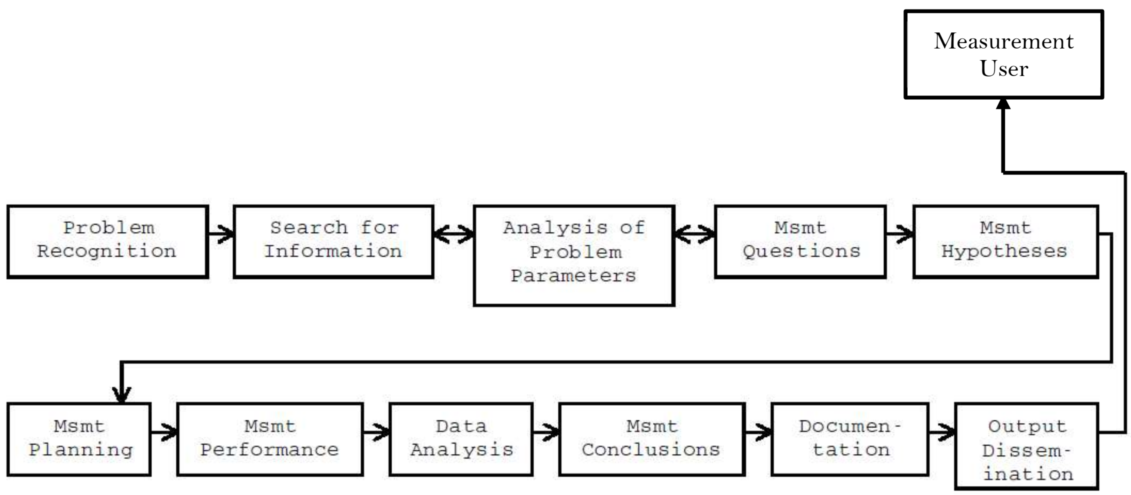

Figure 3.1: Measurement process

Source: adapted from Meister (2001)

An extracted summary of the important elements of the measurement process is shown in Table 3.4. The process starts by identifying system problems. When these questions cannot be answered, additional questions can be asked. Questions relating to maintenance human factors to address the system problem, are extracted as per the table.

Table 3.4: Extracted element of the measurement process

Problem Recognition	System status problems/questions requiring measurement.
Is a question relating to the status of the system: • does the system satisfy the design goal? • which of two or more potential system configurations is best? • workers are experiencing an excessive number of injuries?	• How well can system personnel operate/maintain the new system? • What personnel-related design deficiencies still exist in the operational system? • What preferences do potential users have in relation to prototype designs? • How have personnel operated a predecessor system?

Source: adapted from Meister (2001)

Visser and Pretorius (2003) propose a 6-step, systematic, top-down approach to developing a maintenance performance system. This process should be followed yearly, although the same maintenance parameters could be used for several years.

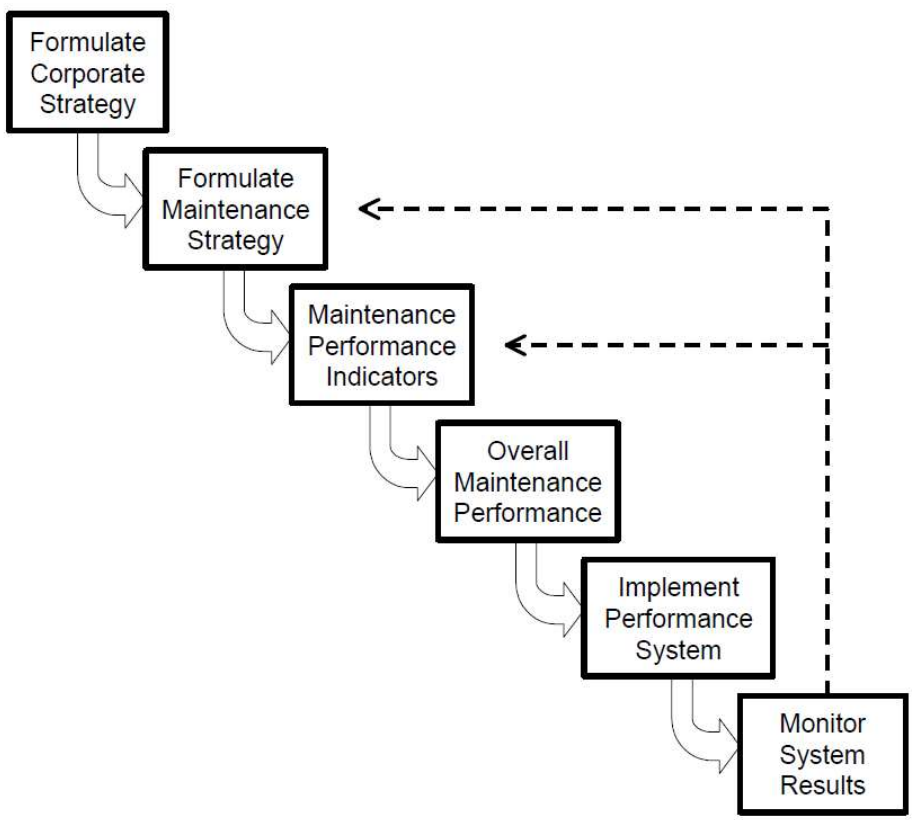

Figure 3.2: 6-step systematic, top-down approach to developing a maintenance performance system
Source: Visser and Pretorius (2003)

The maintenance performance indicators can be identified by following similar guidelines as mentioned throughout Chapter 2 and Chapter 3. Once these indicators are identified, an overall Total Maintenance Performance (TMP) score can be calculated using the TMP framework. Visser and Pretorius (2003) define the overall performance as "a linear combination of the product of a number of performance indicators and weight factors". This can be calculated using equation 1. Table 3.5 illustrates an example of the calculation of a TMP score.

$$TMP = \sum_{i}^{n} W_i \cdot B_i \tag{1}$$

Where: B_i is the benefit value, W_i is the weight for factor i, and n is the number of factors.

Table 3.5: Example of TMP indicators with a TMP score

Maintenance Indicator	W_i (%)	Min	Max	Value	B_i	B_i*W_i
Availability (%)	15	85	95	91	0.60	0.09
MTBF (hours)	15	100	200	165	0.65	0.10
PM Ratio	15	20	40	32	0.60	0.09
Maintenance Cost Ratio	15	10	30	24	0.30	0.05
Maintenance Errors (%)	10	0	10	2	0.80	0.08
Store Turns Ratio	5	0.8	1.2	1.1	0.75	0.04
Stores Service Level (%)	10	80	100	97	0.85	0.09
Personnel Cost Ratio (%)	5	30	40	32	0.80	0.04
System Image (%)	10	50	100	85	0.70	0.07
TMP Score						**0.64**

Source: Visser and Pretorius (2003)

Maintenance performance indicators can also be organized into an organizational hierarchy as shown in Figure 3.3 (Galar et al., 2011a). The downward hierarchical approach ensures that top management translates organisational objectives to lower levels. This assists middle management to have directed measurements free of ambiguities. Financial, learning and growth, client and internal process perspectives should be included in each level to avoid only these indicators being reported to top management. The hierarchical approach also ensures that the maintenance function is seen as a support function (Galar et al., 2011a).

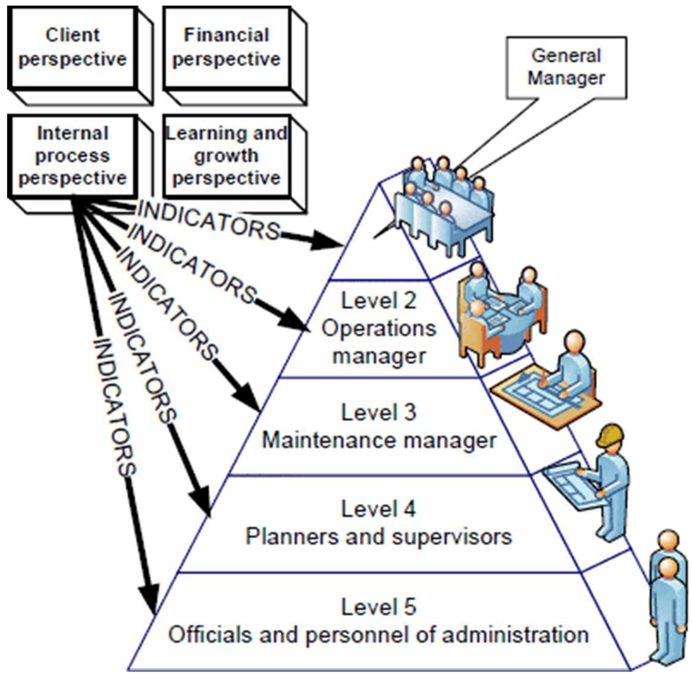

Figure 3.3: Organisational levels in the hierarchy of indicators

Source: Galar et al. (2011a)

Kumar et al. (2013) supports that a multi-hierarchical framework with multi-criteria's can be efficient and effective. It provides a relationship between the maintenance indicator and the different organisational levels. Kumar et al. (2013) presents a hierarchical level maintenance performance measurement model in Figure 3.4

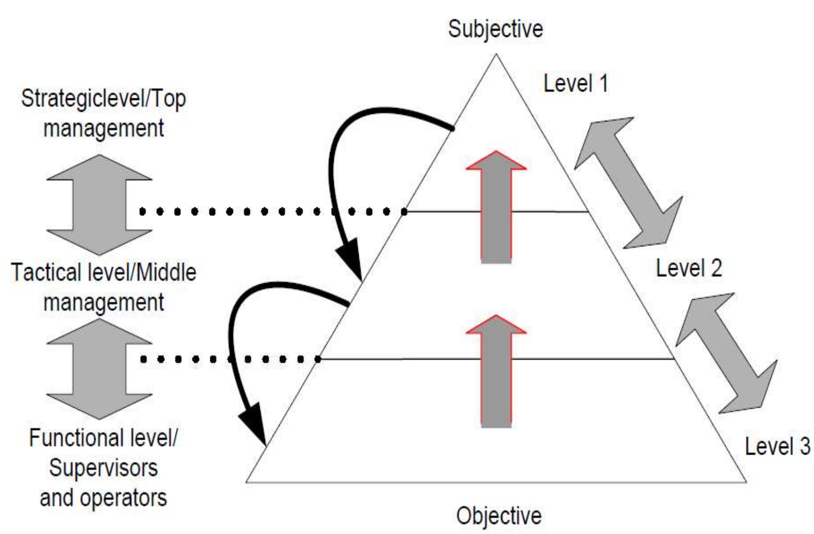

Figure 3.4: Hierarchy level of maintenance performance measurement model
Source: Kumar et al. (2013)

3.3. Developed maintenance performance framework used for this study

Galar et al.'s (2011a) hierarchy approach (Figure 3.3) will form the basis for the maintenance performance framework used within this thesis. Visser and Pretorius's (2003) TMP indicators can be seen as a level 3 indicator, aimed at the maintenance manager. Peach et al.'s (2016) maintenance performance measurement (Table 2.4) can be seen as level 4 indicators focusing on the planning manager, planners and supervisors. Figure 3.5 shows the detailed organisational performance indicator hierarchy. No changes to the indicators from the above author's were made at this stage.

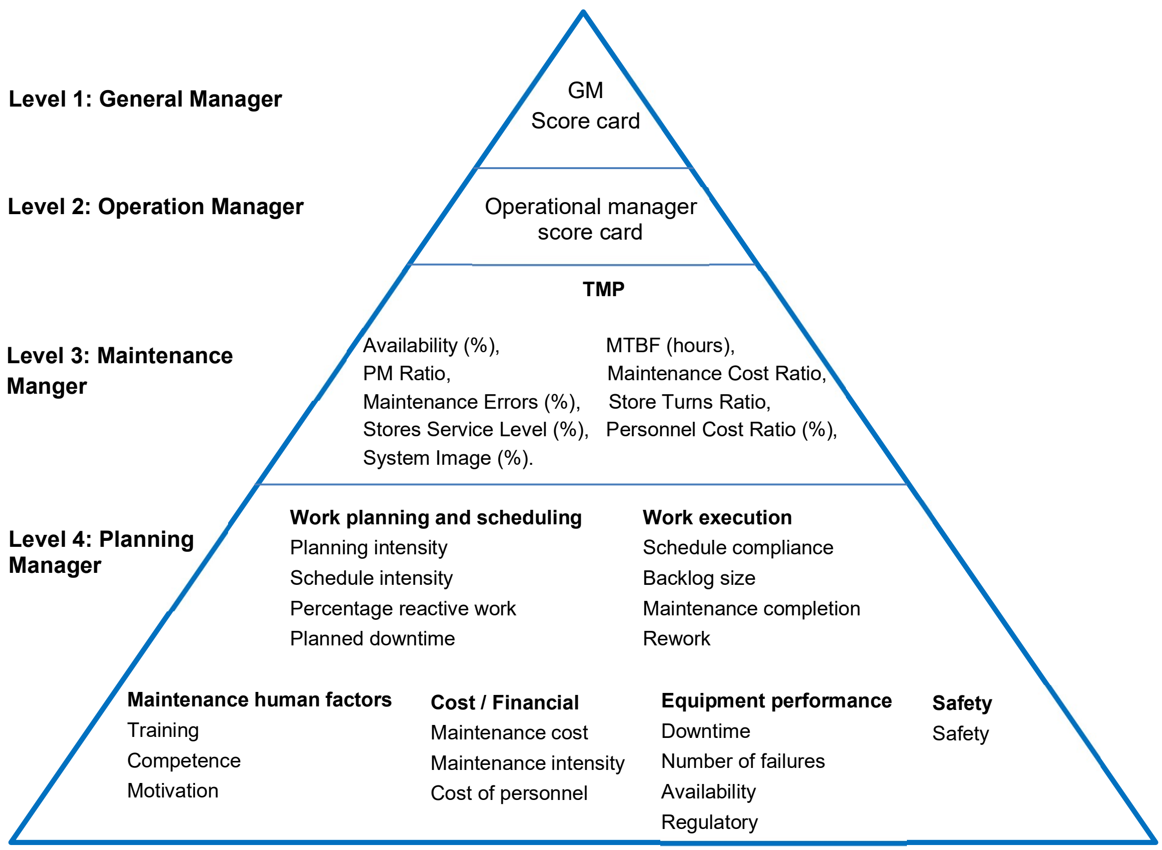

Figure 3.5: Detailed hierarchal display of organisational indicators

As noted by Visser and Pretorius (2003), the TMP indicators should be dependent on both the corporate and maintenance strategies. Maintenance indicators should be chosen carefully following due process. The performance indicators mentioned in their TMP framework, and in Figure 3.5, are used for demonstrative purposes only. In order to align the TMP indicators to the electricity transmission industry, changes were made in accordance to the industry's priorities. The maintenance indicators used from Visser and Pretorius's (2003) TMP framework were changed, with explanations shown in Table 3.6. These changes are based on the author's experience within the electricity transmission industry and were validated through the Delphi method.

In the same way, changes to the performance measurements and subcategories from Peach et al.'s (2016) maintenance performance measurement were made. Peach et al.'s (2016) maintenance human factors are aligned to the electricity transmission industry. Only 3 maintenance human factors are listed in the performance measurement. The objective of this thesis is to determine the most influential maintenance human factor as per RQ1. These factors will then be included in the final level 3 TMP score. This is to facilitate the importance of measuring maintenance human factors. The changes that will be made to the maintenance performance measurement from Peach et al.'s (2016) are shown in Table 3.7.

Table 3.6: Alignment of TMP indicators to the electricity transmission industry

Maintenance indicator	Action	Reasoning
Availability (%)	Excluded	This will fall under System Performance
MTBF (hours)	Excluded	System minute interruptions and equipment performance will provide a more accurate indication of the indicator.
PM Ratio	Excluded	Similar is reflected under level 4 as the percentage reactive work.
Maintenance Cost Ratio (%)	No change will be made	
Maintenance Errors	No change will be made	
Store Turns Ratio	Excluded	This should fall under a level 4 score aimed at stores management.
Stores Service Level (%)	Excluded	This should fall under a level 4 score aimed at stores management.
Personnel Cost Ratio (%)	No change will be made	
System Image (%)	Changed to System performance: System Minute Interruptions (SMI), SAIRI, Composite Availability, and Quality of supply	This forms a critical part of the organisations main KPI's.
Equipment Performance	Addition to TMP indicator. Equipment performance will be determined by a combination of: • the performance of the different asset classes, • number of failures, and • number of severe failures,	This forms a critical part of the organisations main KPI's. Due to the mature age of the equipment, maintenance plays a crucial role in equipment performance.
Maintenance Planning	Addition	This is to include the consolidated level 4 score into level 3.

Table 3.7: Changes to Peach et al.'s maintenance performance measurements

Category	Subcategory	Action	Reasoning
Work planning and scheduling	All	No change will be made	
Work execution	All, except maintenance completion	Maintenance completion (%) will move to level 3	This forms a critical part of the organisations main KPI's.
Maintenance human factors	New subcategories will be determined from RQ1	Move to level 3	Due to the importance of maintenance human factors, as discussed within the literature of this thesis, maintenance human factors can no longer just be seen as a subsection of planning. The level 3 name will change to maintenance human factor performance (MHFP)
Cost / Financial	All	Exclude	2 out of the 3 subcategories are reflected in level 3
Equipment performance	Downtime	Move to level 2	This should be a combined performance indicator between maintenance and production.
	Number of failures	Move to level 3	This will be reflected under the additional added level 3 equipment performance indicator
	Availably	Exclude	This is reflected in level 3 under system performance
	Regulatory: SAIRI	Move to level 3	System Image (%), will change to System Performance. This is critical focus point for the particular transmission organisation.
Safety	Number of accidents / incidents	Move to level 3	Overall safety for maintenance staff falls under the accountabilities of the maintenance manager within the applicable organisation

By combining the movements, additions and exclusions of Table 3.6 and Table 3.7, the final TMP indicators used within this thesis are shown in Table 3.8. The weight factor (Wi) along with the minimum and maximum values should be decided on by the maintenance manager or maintenance management team. In the case of the South African electricity transmission industry, these values are determined by the maintenance management team along with the Business Improvement and Performance Department. The numeric values used in Table 3.8 represents a specific evaluation in time, typically once a month, and are for demonstration purposes only.

Table 3.8: TMP indicators and TMP score inclusive of maintenance human factors

Maintenance Indicator	W_i (%)	Min	Max	Value	B_i	B_i*W_i
System performance	25	0.00	1.05	0.64	0.61	0.15
Equipment performance	15	0.88	1.05	0.95	0.41	0.06
Maintenance planning	10	0.80	1.20	1.00	0.50	0.05
Maintenance completion %	10	95.00	100.00	98.50	0.70	0.07
Maintenance human factor performance (MHFP)	10	0.60	1.00	0.71	0.28	0.03
Maintenance cost ratio %	10	90.00	110.00	96.00	0.70	0.07
Maintenance errors	5	1.00	20.00	9.00	0.58	0.03
Personnel cost ratio %	5	90.00	110.00	94.00	0.80	0.04
Safety	10	0.00	0.36	0.15	0.58	0.06
TMP score						**0.56**

From the above table, some indicators might have sub indicators to determine the final value used within the level 3: TMP framework. An example of this is equipment performance that will be determined by a combination of the performance of the different asset classes, number of failures, and the number of severe failures.

Maintenance human factors will be reflected in level 3 as maintenance human factor performance (MHFP) and will be calculated using the TMP calculation methodology as illustrated in Table 3.9. The numeric values used in Table 3.9 represents a specific evaluation in time, typically once a month, and are for demonstration purposes only.

Table 3.9: MHFP score calculation

Maintenance human factors	Wi (%)	Min	Max	Value	Bi	Bi*Wi
Maintenance human factor 1	35	5	35	8	0.90	0.32
Maintenance human factor 2	20	9	63	15	0.89	0.18
Maintenance human factor 3	15	11	77	68	0.86	0.13
Maintenance human factor 4	15	5	35	26	0.30	0.05
Maintenance human factor 5	10	9	63	50	0.24	0.02
Maintenance human factor 6	5	11	77	23	0.18	0.01
MHFP score						**0.70**

Figure 3.6 shows the detailed organisational performance indicator hierarchal with the final reflected indicators used for this thesis.

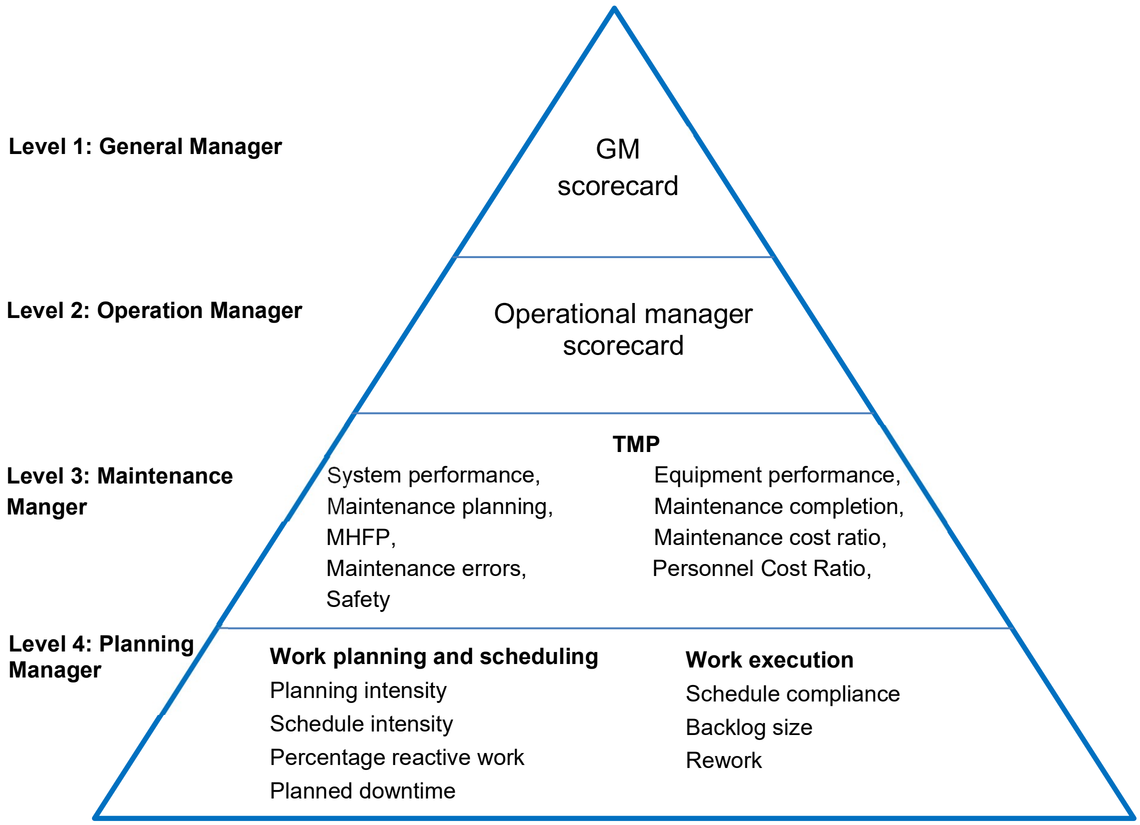

Figure 3.6: Proposed hierarchical maintenance performance framework for the South African electricity transmission industry

3.4. Chapter summary

This chapter described frameworks and methodologies used in literature to choose maintenance human factors as part of maintenance performance indicators. A systematic literature review determined the most frequently cited maintenance human factors. These maintenance human factors will be used to determine the most influential maintenance human factors to incorporate into the chosen maintenance performance framework.

Chapter 4 briefly discusses the ethical elements considered in this thesis. Thereafter it focusses on data collection methods from maintenance technicians and management. The maintenance technician's questionnaire focused on the maintenance technician's perception and the management questionnaire on the maintenance manager’s perspective of the most influential maintenance factors. A Delphi method is used as the research methodology to validate the research problem and the proposed maintenance performance framework.

4. RESEARCH DESIGN AND METHODOLOGY

4.1. Ethical considerations

The University of Pretoria has a Faculty Committee for Research Ethics and Integrity in the Faculty of Engineering, Built Environment and IT. The role of this committee is to ensure that all studies follow the University's regulations on ethics before any data relating to humans or animals may be collected.

All questionnaires started by asking the respondents to give informed consent before starting the questionnaire. The respondents were assured of their confidentiality and anonymity. For the first two survey questionnaires, anonymity was insured by the fact that no questions were asked in a way that allows identification of the respondents. Emphasis was placed on the assurance of anonymity to reassure the respondents that this questionnaire will not be used to prosecute them for maintenance human errors that they have made.

The maintenance performance framework validation questionnaires followed the Delphi method. For this the experts were pre-identified and were asked for their identities in the questionnaires. The author made additional disclaimers before the questionnaire started, stating that:

- All information obtained from the questionnaire is strictly confidential and will only be used for research purposes.
- Their comments and opinions will not be shared with any other participant.
- Their comments and opinions shall in no way influence their continued relationship with the research team.

A permission letter for the collection of data in the organisation was obtained from the Electricity Transmission organisation.

In this study humans are regarded as informants and not as research subjects. Informants provide information regarding their opinions and perceptions in the forms of questionnaires. For this reason, no personal medical data or invasive medical measurements was used or asked for. The last section of the first survey questionnaire asked questions that can be perceived as sensitive personal information. These questions are, however, not medical data but the respondent's perception of these factors. A motivation letter to ask approval for using these questions was submitted to and approved by the Faculty Committee for Research Ethics and Integrity. The participants were informed that the information may be seen as sensitive personal information and that they are not compelled to complete that section.

The Electricity Transmission organisation should take note of the ethical considerations and medical regulations within South Africa before implementing measurements needing personal medical data. The invasiveness of the information should be considered as there are differences between non-invasive measurements gathered from smart watches and more invasive measurements such as blood testing. The organisation has processes and procedures in place to obtain medical data from staff through fitness of duty testing. These fitness of duty tests are performed by medical trained personal and are sanctioned by labour laws and regulatory medical bodies. Therefore, it may be possible to align the needed information with the regular fitness of duty tests. The questionnaire explicitly askes the respondents their opinion of providing medical data if collected by medical trained personnel.

4.2. Research strategy

The electricity transmission sector in South Africa was identified as a focus point for this study. Record keeping of maintenance errors is a known concern in the identified company. Due to this reason empirical data was collected by means of a survey questionnaire. The survey followed a quantitative research approach. Surveys were sent out to maintenance technicians and maintenance managers to rank the influence that identified maintenance human factors have on maintenance errors in the electricity transmission industry.

The maintenance human factors used in the questionnaires were identified through a systematic literature review methodology as described in Chapter 2. The human maintenance factors most noted in the systematic review reflected maintenance human factors noted in literature, mostly in literature concerning the aviation industry.

These factors were used as baseline maintenance human factors to be used in the maintenance technicians and management questionnaires.

It was clearly communicated to the participants of the survey that information obtained through the questionnaire will not be used against them. This was done to ensure that they can answer the questionnaire honestly without fear of prosecution by their management.

The maintenance human factors as per the questionnaire results were statistically analysed. From these analyses the most influential maintenance human factors were identified and then validated using the Delphi method.

This strategy is similar to define human factor risk with the proposed human factors effect and analysis (HFEA) approach used by Sheikhalishahi et al. (2017b) within the power plant sector. He proposed that, when no actual maintenance and failure data is available, questionnaires should be created to identify maintenance human factors. Thereafter, they should be ranked. Expert judgment can then be used to validate the findings. Tavakoli and Nafar (2020) used the same methodology when they analysed human errors in power transmission system protection.

Thereafter, a proposed maintenance performance framework was adapted using the identified maintenance human factors and measurements. This proposed maintenance performance framework was also validated using the Delphi method.

Table 4.1 indicates the strategy for answering the research questions posed in Chapter 1.

Table 4.1: Data collection and Analysis for research questions

Research Question (RQ)	Data collection and Analysis
1. What maintenance human factors have the most influence on maintenance human errors?	Quantitative research, using a systematic literature review methodology and a quantitative survey questionnaire. Validation through survey questionnaire aligned with the Delphi method (quantitative and qualitative).
2. How should these maintenance human factors performance indicators and measurements be incorporated into a traditional maintenance performance framework?	Qualitative research, using exploratory literature to determine maintenance human factor measurements. Qualitative research, using exploratory literature to determine a base maintenance performance framework. Validation through survey questionnaire aligned with the Delphi method (quantitative and qualitative).

4.3. Research methodology

4.3.1. Influential maintenance human factors: maintenance technician level

This questionnaire focused on data collection at maintenance technician level. The questionnaire was developed to obtain data as per the systematic literature review's identified maintenance human factors. The results of the questionnaire were then analysed according to the research strategy.

The survey respondents were homogeneous in the fact that all the respondents of the survey were responsible for maintenance work in the electricity transmission industry in South Africa. The types of maintenance that these respondents are responsible for are either High Voltage Plant/Outdoor Yard Equipment, Control Plant/Secondary Plant or Lines and Servitudes.

4.3.2. Influential maintenance human factors: management level

The second survey questionnaire focused on data collection at management level. The managers were asked to ranked the maintenance human factors identified with the systematic review.

4.3.3. Validation of research deliverables

The research deliverables could not be tested through implementation in the organisation and was therefore validated through a Delphi method. Based on the validation of the research deliverables a compelling case can be made to the organisations management to implement the proposed maintenance performance framework.

In the Delphi method validation phase feasible survey questions were derived. The research design follows a macro to a micro perspective (Skulmoski et al., 2007). The Delphi method supports both qualitative and quantitative methods. Selecting the research sample and the expert opinions were the critical steps in the process as this was the main component of the Delphi method.

Adler & Ziglio (1996, as cited in Skulmoski et al. (2007)) provide the following requirements for “expertise”:

- knowledge and experience with the issues under investigation,
- capacity and willingness to participate,
- sufficient time to participate in the Delphi, and
- effective communication skills.

Rowe and Wright (1999 as cited in Skulmoski et al. (2007)) characterize the classical Delphi method by four key features:

- anonymity of Delphi participants,
- iteration,
- controlled feedback, and
- statistical aggregation of group response.

Benefits of a Delphi method are that non-response and attrition tends to be very low in Delphi surveys. It has been found that data is richer in information due to the multiple iterations. Delphi studies can answer research questions that have high uncertainty and speculation where the general population does not have sufficient knowledge of the subject. The power of the combined expertise allows for the study to not depend on statistical power. The Delphi method has the benefit where experts can be asked to validate the researcher's findings (Okoli and Pawlowski, 2004).

The research methodology used was an adapted Two-round Delphi method, based on the typical Thee-round Delphi method by Skulmoski et al. (2007). The Three-round Delphi method has been successfully used in Skulmoski et al.'s (2007) master's and PhD level research. The adapted 2 round methodology is shown in Figure 4.1.

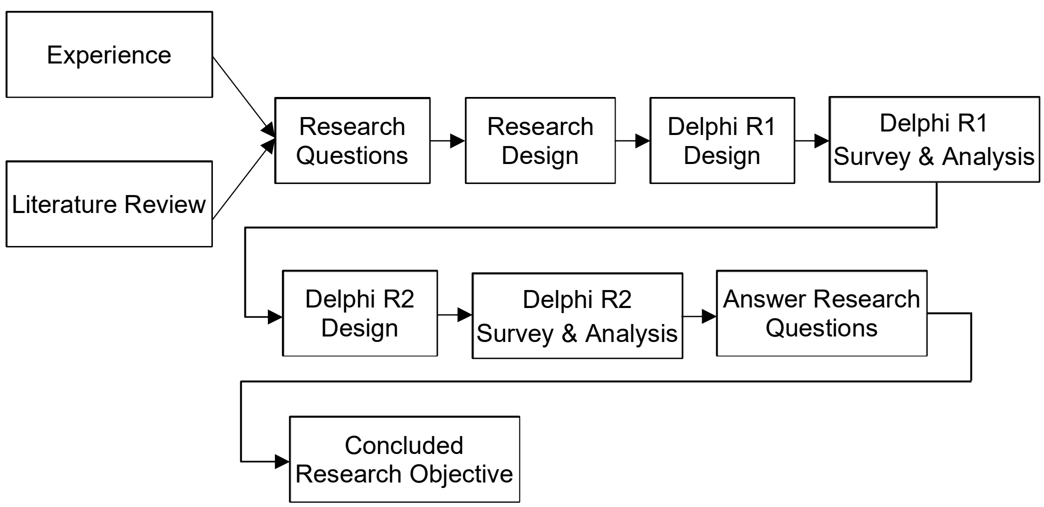

Figure 4.1: Adapted Two-round Delphi method
Source: Adapted from Skulmoski et al. (2007)

4.4. Descriptive Statistics and Analysis

4.4.1. Analysis of Likert-type questionnaires

The research instruments used within this thesis were questionnaires that consisted mostly of questions using 5-point Likert-type items from strongly disagree to strongly agree.

This type of Likert-type response options are known as bipolar response options. Each question was to test a stand-alone concept and thus require that they be analysed as Likert-type items. Furthermore, Likert-type responses gather ordinal data (data that does not have equal-interval characteristics), making parametric analyses inappropriate. Therefore, descriptive statistical methods (non-parametric tests) are recommended (Cooper and Johnson, 2016; Boone and Boone, 2012; Bertram, 2007). These include:

- analysis of mode or mean for central tendency (Cooper and Johnson, 2016; Boone and Boone, 2012; Bertram, 2007; Sullivan and Artino Jr, 2013),
- frequency for variability (Boone and Boone, 2012), and
- graphical analysis (bar-charts) illustrating frequencies for each response (Cooper and Johnson, 2016; Boone and Boone, 2012; Bertram, 2007; Sullivan and Artino Jr, 2013).

Caution should also be given to neutral responses that do not really provide a definitive opinion (Cooper and Johnson, 2016; Boone and Boone, 2012).

4.4.2. Analysis of ranking data correlations

Kendall’s Tau and Spearman’s Rank Correlation tests were performed to measure the strength between the ranked data from the questionnaires. Both Kendall’s Tau and Spearman’s Rank Correlation tests are non-parametric tests.

The resulting correlation coefficients (Kendall's tau_b and Spearman's rho) range from a value of ±1 that indicates the degree of association. Negative values indicate negative relationship (-1 indicates a perfect negative monotonic relation), positive values indicate a positive relationship (1 indicates a perfect positive monotonic relation) and zero indicates no monotonic relation at all.

No exact rules to interpret the resulting correlation coefficients could be found. The interpretation rules found are mostly based on practice rather than theory.

The below values were used to indicate associations:

- |Kendall′s tau_b | ≤ 0.1 indicates a very small correlation.
- 0.1 < |Kendall′s tau_b | ≤ 0.21 indicates a small correlation.
- 0.1 < |Kendall′s tau_b | ≤ 0.33 indicates a medium correlation.
- |Kendall′s tau_b | > 0.33 indicates a strong correlation.

SPSS does indicate if the correlation coefficient is significant at a 0.05 (2-tailed) or a 0.01 (2-tailed) level. The SPSS calculation for significant correlation is based on the correlation coefficient and the sample size of the data. In SPSS the result for significance is indicated by Sig. (2-tailed) and then marks the correlation coefficient as significant by indicating the correlation coefficient result as either value* or value**.

4.5. Research instrument

4.5.1. Influential maintenance human factors

To determine the most influential maintenance human factors within the electricity transmission industry two identified groups (maintenance technicians and management) were used. A survey questionnaire was compiled to ask the participant to identify the most influential maintenance human factor that lead to a personal maintenance error made.

In the medical field Brennan et al. (2015) was able to develop and validate an HFACS based questionnaire to examine human factors in clinical examinations. Sunaryo et al. (2019) adopted the DoD's HFACS 7.0 questionnaire to determine the cause of medication error. Zhou et al. (2018) developed and implemented an HFACS-based questionnaire for aviation professionals working in the Ulaanbaatar International Airport in Mongolia in 2017. Vijayanarayanan (2011) developed an HFACS-based framework for the systems engineering domain. Interviews with experienced engineers were used as a method of qualitative data collection. The results from the interview were coded using HFACS-based themes.

Hobbs and Tada (2007) developed and validated a Maintenance Environment Questionnaire (MEQ). The questionnaire was designed to gather data on maintenance human factors that would be otherwise unobtainable.

Self-report behaviour checklists have been widely used in cognitive psychology and safety studies (Hobbs and Tada, 2007). As discussed in Section 4.1, a concern with self-reporting is that the participants withhold information due to a fear of prosecution by their management. In two studies (Broadbent et al. (1982) and Burdekin (2003)) it was found that participants provided consistent and accurate self-assessments of their behaviour (Hobbs and Tada, 2007). In Hobbs and Williamson (2002), with their Maintenance Behaviour Questionnaire (MBQ), found that maintenance personnel demonstrated the willingness to disclose information if their anonymity is protected (Hobbs and Tada, 2007).

The studies mentioned in the previous paragraph indicates that an anonymous questionnaire is acceptable from a research perspective.

4.5.2. Maintenance technicians questionnaire

The aim of the questionnaire was to answer RQ1. The questionnaire was compiled and sent to all High Voltage Plant/Outdoor Yard Equipment, Control Plant/Secondary Plant and Lines and Servitudes maintenance technicians in the identified organisation.

The questions were categorised into the following categories:

- general work information,
- ranking of maintenance human factors,
- willingness to provide feedback and be measured on maintenance human factors,
- frequency influence of maintenance human factors, and
- and personal sleep and stress levels.

The first questions of the questionnaire confirmed that the respondents worked in the Electricity Transmission sector. It established the type and subtype of maintenance they are responsible for and their educational level. Question 7 and Question 8 aimed to determine the maintenance human factor that contributed the most to a maintenance error made by the maintenance technician. In Question 9 the maintenance technicians ranked the maintenance human factors that they felt led to making maintenance errors.

The systematic literature review in Chapter 2 was used to determine the most noted maintenance human factors in literature as shown in Table 4.2.

The most frequently noted maintenance human factors with minimal coding was used as a starting point. The corresponding rankings of the other coding methods were then aligned. Thereafter, the most frequent noted maintenance human factors from the other coding methods were added.

Table 4.2: Ranking of survey results compared to cited ranking systematic literature review

Maintenance Human Factor	Minimal coding	PEAR Model	HFACS-ME framework
Fatigue	1	6	4
Illumination	2	11	5
Communication	3	1	3
Workload	4	8	7
Cognitive Dimensions	5	16	14
Decision Making	6		8
Noise Level	7		16
Time Pressure	8	9	
Situation Awareness	9		
Knowledge And Experience	10	4	2
Person Factors	11		
Supervision	12	10	11
Training	13	7	1
Equipment, Tools, And Parts		2	
Procedures/Work Cards		3	
Safety & Safety Culture		12	17
Workspace		13	15
Stress		14	10
Inadequate Design			6
Certification/Qualification			13

By using Kendall's tau_b and Spearman's rho nonparametric correlation tests, there is a statistically significant correlation between the rankings of the PEAR Model and those of the HFACS-ME framework. No correlation can be seen between the rankings of the minimal coding and the PEAR or HFACS-ME frameworks. This is shown in Table 4.3.

Table 4.3: Kendall's tau_b and Spearman's rho nonparametric correlations test between minimal coding, the PEAR model and HFACS-ME framework

			Minimal coding	PEAR	HFACS
Kendall's tau_b	Minimal coding	Correlation Coefficient	1.000	0.056	0.067
		Sig. (2-tailed)	0	0.835	0.788
		N	13	9	10
	PEAR	Correlation Coefficient	0.056	1.000	**0.564***
		Sig. (2-tailed)	0.835	0	0.016
		N	9	14	11
	HFACS	Correlation Coefficient	0.067	**0.564***	1.000
		Sig. (2-tailed)	0.788	0.016	0
		N	10	11	15
Spearman's rho	Minimal coding	Correlation Coefficient	1.000	0.067	-0.006
		Sig. (2-tailed)	0	0.865	0.987
		N	13	9	10
	PEAR	Correlation Coefficient	0.067	1.000	**.791****
		Sig. (2-tailed)	0.865	0	0.004
		N	9	14	11
	HFACS	Correlation Coefficient	-0.006	**0.791****	1.000
		Sig. (2-tailed)	0.987	0.004	0
		N	10	11	15

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

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

Table 4.4 lists the maintenance human factors that were chosen in the survey. Situation awareness, knowledge and experience, training, certification/qualification and inadequate design were included in the frequency test for maintenance situations experienced. Perceived life stress was not included in the influence testing or the frequency testing as it was measured under personal Sensitive Information (question 47 – 48). Person factors was not included as it would have been an intrusion into the maintenance technician's personal lives and might have compromised the response rate of the survey.

Table 4.4: Maintenance human factors chosen for the survey

Maintenance Human Factor	Minimal coding	PEAR Model	HFACS-ME framework	Chosen in survey
Fatigue	1	6	4	Y
Illumination	2	11	5	Y
Communication	3	1	3	Y
Workload	4	8	7	Y
Cognitive Dimensions	5	16	12 & 14	Y
Decision Making	6		8	Y
Noise Level	7		16	Y
Time Pressure	8	9		y
Situation Awareness	9			
Knowledge And Experience	10	4 & 5	2 & 9	
Person Factors	11			
Supervision	12	10	11	y
Training	13	7 & 15	1	
Equipment, Tools, And Parts		2		y
Procedures/Work Cards		3		
Safety & Safety Culture		12	17	
Workspace		13	15	
Stress		14	10	y
Inadequate Design			6	
Certification/Qualification			13	

Kendall's tau_b and Spearman's rho nonparametric correlation tests were repeated; the results are reported in Table 4.5. This was done to ensure that there is still correlation between the chosen maintenance factors for the survey and maintenance factors reported in literature. The results indicate that the remaining maintenance human factors from the HFACS-ME framework had a statistically significant correlation between both the minimal coding and the PEAR Model.

Table 4.5: Kendall's tau_b and Spearman's rho nonparametric correlations test for Table 4-4

			Minimal coding	PEAR	HFACS
Kendall's tau_b	Minimal coding	Correlation Coefficient	1.000	0.333	**0.643***
		Sig. (2-tailed)	0	0.293	0.026
		N	9	7	8
	PEAR	Correlation Coefficient	0.333	1.000	**0.714***
		Sig. (2-tailed)	0.293	0	0.024
		N	7	9	7
	HFACS	Correlation Coefficient	**0.643***	**0.714***	1.000
		Sig. (2-tailed)	0.026	0.024	0
		N	8	7	9
Spearman's rho	Minimal coding	Correlation Coefficient	1.000	0.393	**0.810***
		Sig. (2-tailed)	0	0.383	0.015
		N	9	7	8
	PEAR	Correlation Coefficient	0.393	1.000	**0.821***
		Sig. (2-tailed)	0.383	0	0.023
		N	7	9	7
	HFACS	Correlation Coefficient	**0.810***	**0.821***	1.000
		Sig. (2-tailed)	0.015	0.023	0
		N	8	7	9

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

The above validated the 3 questions that were asked in Part B: Maintenance human factors as seen in Table 4.6.

The SPSS calculation for significant correlation is based on the correlation coefficient and the sample size of the data. With the first test, rankings of survey results compared to cited rankings in the systematic literature review. Table 4.2 listed a total of 20 elements, where minimal coding listed 13 data elements, the PEAR model 9 elements and the HFACS-ME framework 10 elements.

The test was then repeated, testing only the elements used in the survey, a total of 11 elements. Minimal coding had 9 data elements, the PEAR model 7 elements and the HFACS-ME framework 7 elements. The results of this test were that the Spearman's rho correlation relationship between the rankings of the PEAR Model and the HFACS-ME framework increased from 0.791 to 0.821. With the reduction in the data points, there now exists a significant Spearman's rho correlation (0.81) between minimal coding and the HFACS-ME framework, although the correlation relation between minimal coding and the PEAR model still remains statistically insignificant.

Table 4.6: Questions asked within questionnaire Part B

Question Number	Question	Possible Answers provided to respondents
7.	When you think of a maintenance error you have made, which of the following do you think contributed **the most** to it.	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision Life Stress Equipment, Tools, And Parts
8.	When you think of a maintenance error you have made, which of the following do you think contributed **the second most** to it.	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision Life Stress Equipment, Tools, And Parts
9.	Please rank the following factors that you feel led to you making the maintenance error	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision Life Stress Equipment, Tools, And Parts

Several questions in this section were meant to determine whether staff would be willing to provide feedback on how well these maintenance human factors are managed by their supervisors and the organisation. The last few questions in this section asked respondents about their willingness to share their fatigue, stress and heart rate data with the organisation.

Questions 16 to 46 were used to determine how often maintenance technician were placed in situations that impact the maintenance human factors of the maintenance technician. These questions were adapted from Hobbs and Williamson (2002) and Hobbs and Tada (2007) and can be seen in Table 4.7, with a rating scale of every day, to never, not relevant. The questions were coded to represent a maintenance human factor. This coding was not given to the participants.

Table 4.7: Adapted questionnaire of frequency of maintenance situation experiences

Baseline question: "In the last year, on average, how often have you":	Relating Factors (Not to be given to participants – used for coding only)
Done a job without the correct tool or equipment	Equipment, Tools, And Parts
Not made a system safe before working on it, or in its vicinity	Situation Awareness
Found a part (e.g. in your pocket) after a job was completed	Skill – based error Cognitive Dimensions Attention/Memory
Started to work on the wrong equipment	Situation Awareness Cognitive Dimensions Attention/Memory
Been interrupted part-way through a job and forgotten to return to it	Attention/Memory
Been interrupted part-way through a task to perform another more urgent task.	Workload
Had to rush an inspection.	Time Pressure
Had to rush a maintenance task due to time pressure	Time Pressure
Been delayed on a task because you could not obtain a consumable part (for example, an 'O' ring, oil, etc).	Equipment, Tools, And Parts
Had trouble concentrating because you were tired.	Fatigue
Found an error in a maintenance document.	Procedures/Work Cards
Worked more than 12 hours in a 24-hour period.	Fatigue
Been delayed on a task because you could not obtain a major part (for example, a wheel or pump).	Equipment, Tools, And Parts
Worked more than two night shifts in a row.	Fatigue

Baseline question: "In the last year, on average, how often have you":	Relating Factors (Not to be given to participants – used for coding only)
Been unable to obtain a special tool or item of maintenance equipment.	Equipment, Tools, And Parts
Started to do a job the wrong way because you didn't realize that the equipment was different to what you were used to	Skill – based error Cognitive Dimensions Attention/Memory
Done a task without the correct lighting / illumination	Illumination
Voluntary Survey exit point: 32 / 46 Completed :) You are almost done with the survey ;) Just hang in there! Do you want to continue?	
Been asked to work overtime to complete the current workload	Workload
Had to rush a job to ensure that all your workload gets completed	Workload
Had to reduce maintenance activities on jobs to ensure that all your workload gets completed	Workload
Done a task without in a high noise level environment	Noise Level
Felt that important information regarding the maintenance task was not communicated with you	Communication
Done a task without the required supervision	Supervision
Had to perform a task you were not trained on	Training/Preparation
Misdiagnosed a situation relating to a maintenance task.	Judgment/Decision-making
Omitted a step when performing a maintenance task	Attention/Memory
Worked on equipment were it was easy to incorrectly install a part	Inadequate Design
Work on equipment with poor Accessibility or layout	Inadequate Design
When reporting at the maintenance site found out that the job was cancelled without it being communicated to you	Communication
Had to perform a task you were not certified to perform	Certification/Qualification

The last 4 questions were used to evaluate the sleep quality and stress levels of the respondents. These 4 questions were optional as it asked for information that could be perceived as being personal and sensitive. The respondents had the opportunity to submit the questionnaire without answering these questions. The questions used in the questionnaire can be found in Appendix B.

4.5.3. Management questionnaire

The goal of the questionnaire was to gather data to facilitate the answering of RQ1 from a management perspective. The questionnaire focused on the management team responsible for the maintenance workers. The maintenance human factors that were identified by the maintenance technicians were used.

The questionnaire was compiled and sent to all Grid, High Voltage Plant/Outdoor Yard Equipment, Control Plant/Secondary Plant and Lines and Servitudes managers in the identified organisation.

The questions were categorised into the following categories:

- general work information,
- ranking of maintenance human factors,
- interest in maintenance human factor measurements, and
- and obtaining data required to measure maintenance human factors.

The first questions of the questionnaire confirmed that the respondents worked in the Electricity Transmission sector. It also established the type and subtype of maintenance that they were responsible to manage. Question 5 to Question 7's purpose was to determine the managers' perspectives of maintenance human factors that have contributed the most to maintenance errors and their rankings. Question 8 to Question 17 were meant to determine the managers' personal interests in a maintenance human factor measurement for their maintenance technician according to the identified most noted maintenance human factors. Personal information (physical measurements or personal perceptions) will be needed to determine a quantitative number for the applicable maintenance human factor measurement. The second last question asked the managers what their preferences would be to obtain this information. The last question was to determine the managers' perspectives of what their staff members would prefer. The questions used in the questionnaire can be found in Appendix C.

4.6. Chapter summary

This chapter addressed the ethical considerations required to perform this study. It briefly discussed the considerations needed to implement the thesis findings practically. Thereafter, the Delphi method was used to identify the data required to answer the research questions linked to the research objective. This was done with a 2-phase survey questionnaire. Concerns regarding the accuracy of self-reporting were addressed and it was found that anonymous questionnaires are an acceptable method. The chapter elaborated on what maintenance human factors were chosen for the survey questionnaire.

The data gathering process and results from the Delphi method will be discussed in Chapter 5. The combined results will then be used in Chapter 6 to perform correlations between literature, the data and the different viewpoint between maintenance technicians and maintenance management.

5. RESULTS: DATA GATHERING

This chapter collected data with regards to the most influential maintenance human factors in both the maintenance technician's perception and the manager's perspective. Although perception and perspective may seem similar, in this thesis the different wording is used intentionally. The maintenance technician's perception was used to indicate their understanding (experiences) of the situation. The maintenance manager's perspective was used to indicate their point of view (attitude towards) of the situation. Additional data, such as maintenance human factors according to frequency, was obtained.

The second part of the chapter collected data of what the preferred measurements are from the maintenance manager's perspective. It also collected data on the maintenance manager's perspective of the willingness of the maintenance technicians to provide data. This data was not necessary for the purpose of this thesis and was collected as additional data.

The data obtained in this chapter was used to determine what maintenance human factors have the most influence on maintenance human errors. These maintenance human factors should be included in the maintenance performance framework.

5.1. Maintenance technicians questionnaire

5.1.1. Data gathering process

Each Transmission Grid is divided into several departments. The three departments, HV plant, secondary plant and lines and servitude, are responsible to operate and maintain those physical assets of the Grid's that forms part of that department's discipline. Figure 5.1 illustrates how a grid structure is laid out in terms of the three disciplines responsible for asset operation and maintenance.

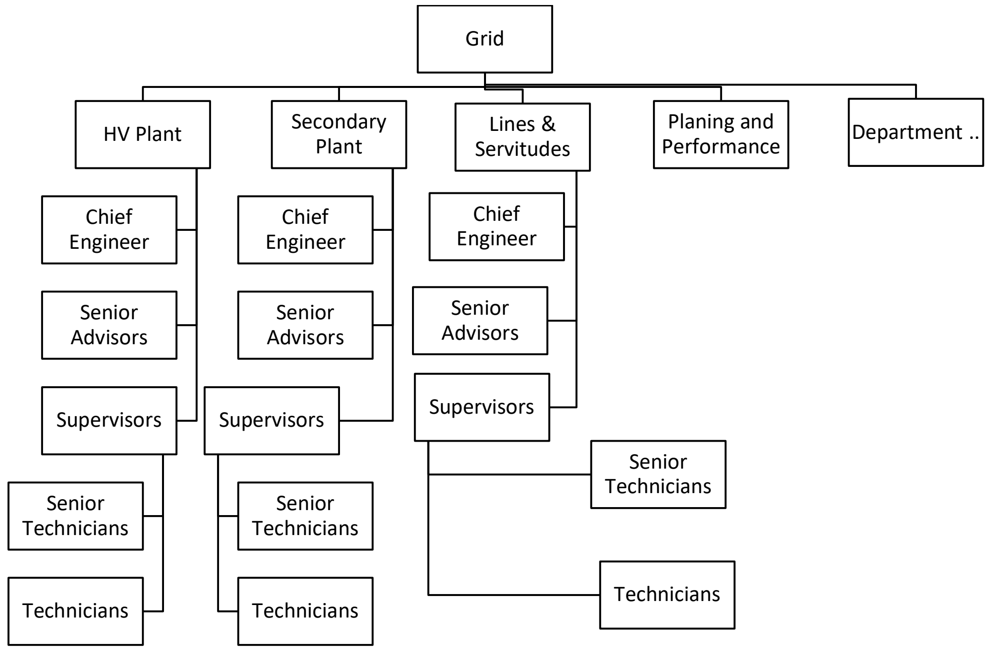

Figure 5.1: Grid structure

The questionnaire was sent out only to Senior Technicians and Technicians, as they are the frontline workers performing maintenance. The questionnaire was sent out to 166 secondary plant, 296 HV plant and 183 lines and servitude technicians internal to the organisation via email. The questionnaire opened on the 18th of October 2019. Reminders of the questionnaire were sent out on the 4th of November 2019 and the 8th of November 2019. The questionnaire was closed on the 11th of November 2019. The 645 contacted staff represent more than 90% of South Africa's Electricity Transmission staff responsible for High Voltage Plant/Outdoor Yard Equipment, Control Plant/Secondary Plant and Lines and Servitudes maintenance.

The email was distributed to the respondents with an introduction of maintenance human factors and a request to participate in the questionnaire. The email contained a hyperlink to the questionnaire which was hosted on www.kwiksurveys.com. The participants were assured that their participation is entirely voluntary and anonymous and that all information obtained from the questionnaire will be strictly confidential. The participants were also informed that they have the right to withdraw at any stage without any penalty or future disadvantage.

The questionnaire consisted of 52 questions with 2 voluntary exits points for the survey. 96 of the 645 contacted staff started the questionnaire, 73 respondents completed the survey until the first exist point, and 61 respondents completed it up to the second voluntary exit point. Some participants exercised their right not to complete the questionnaire by withdrawing from the survey other than at the voluntary exit points.

Data from respondents that did not complete the survey further than question 6 was removed. Data from respondents that completed the survey but did not answer question 7 and question 8 was not removed. No data was removed from respondents that did not complete the survey, but passed question 8. For this reason, each question has a unique number of total responses. After the data clean up, 96 survey responses remained for data processing.

All information gathered through the survey was exported from Kwiksurveys to Microsoft Excel. Graphs and basic statistical calculations provided by Kwiksurveys and calculated with Microsoft Excel and IBM SPSS® were used in this chapter. These graphs and basic statistical calculations can be found in Appendix H.

5.1.2. Data gathered

5.1.2.1. General work information

86 Respondents answered that they worked within the Electricity Transmission sector, 4 in the generation sector and 2 at distribution level. These respondents' responses were not removed from the survey data as the contact list that was used in the survey originated from the organisations staff list. This implies these respondents moved, due to natural staff movement between divisions, from the divisions that formed part of this survey. However, their Electricity Transmission experience was still relevant to the survey.

The responses of the respondents (4) that answered that they do not work for either subdivision of the organisation was analysed. It was found that they were working in the Electricity Transmission sector, but that they listed their respective departments under "other".

40% of the respondents are responsible for High Voltage Plant/Outdoor Yard Equipment maintenance, 33% for Control Plant/Secondary Plant maintenance and 25% for Lines and Servitudes maintenance. 70% are responsible for Major Maintenance activities, 41% for Minor Maintenance and 43% for Inspections. This question was phrased in such a manner that these responses are mutually inclusive.

5.1.2.2. Ranking of maintenance human factors

This section in the questionnaire was to determine the most influential maintenance human factors in the electricity transmission industry from the maintenance technician's perception. High workload, time pressure, fatigue and communication ranked the highest when asked for the factor that contributed the most to a personal maintenance errors made. This question was answered by 88 participant and the results are shown in Figure 5.2.

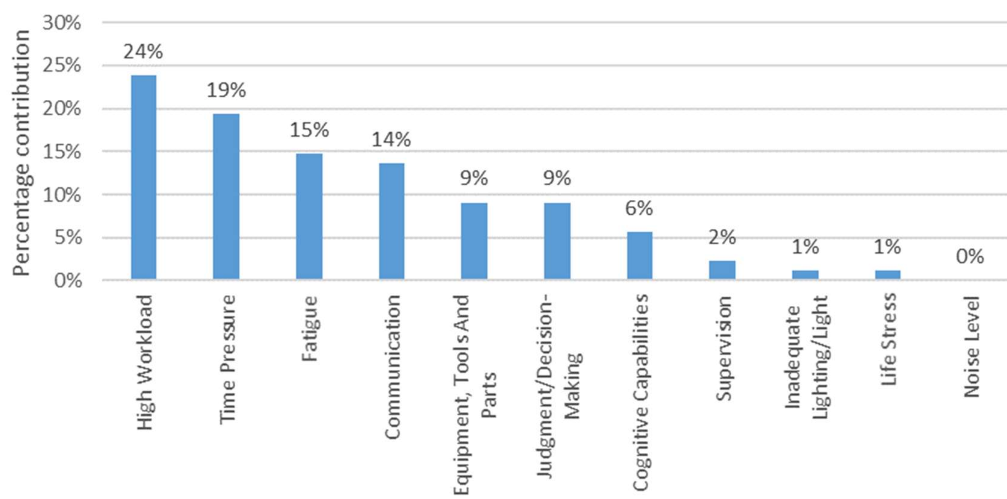

Figure 5.2: Most significant contributing factors to personal maintenance errors made

This is confirmed by the follow-up question that asked what the factor that contributed the second most often to personal maintenance errors made. Communication, high workload, fatigue and time pressure was once again ranked the highest as indicated in Figure 5.3. This question was answered by 90 participants.

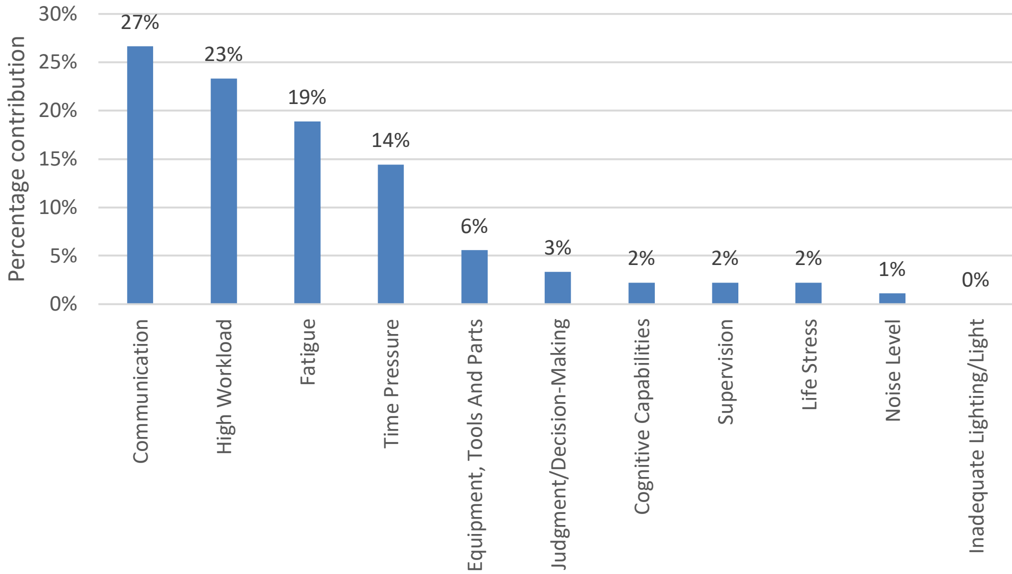

Figure 5.3: Second most significant contributing factors to personal maintenance errors made

For question 9, the respondents were asked to rank the factors that they feel led them to making a maintenance error, this is shown in Table 5.1.

Table 5.1: Ranking of maintenance human factors that contributed to a personal maintenance error

Maintenance human factor	Rank	Median	Mode	Q1	Q2	Q3	IQR
Fatigue	1	1.00	1	1.00	1.00	3.00	2.00
Inadequate Lighting/Light	2	2.00	2	2.00	2.00	9.00	7.00
Communication	3	3.00	3	3.00	3.00	3.75	0.75
High Workload	4	4.00	4	4.00	4.00	4.00	0.00
Cognitive Capabilities	5	5.00	5	5.00	5.00	7.00	2.00
Judgment/Decision-Making	6	6.00	6	6.00	6.00	6.00	0.00
Noise Level	7	7.00	7	7.00	7.00	10.00	3.00
Time Pressure	8	8.00	8	3.00	8.00	8.00	5.00
Supervision	9	9.00	9	7.00	9.00	9.00	2.00
Life Stress	10	10.00	10	8.00	10.00	10.00	2.00
Equipment, Tools And Parts	11	11.00	11	9.00	11.00	11.00	2.00

5.1.2.3. Frequency of maintenance situations

In this section of the questionnaire the frequency of maintenance situations that could lead to a maintenance error was investigated. For each maintenance situation a related maintenance human factor was assigned. This relating factor was not given to the participants in the survey and was only used to code the maintenance situation. Table 5.2 to Table 5.6 indicate the maintenance situations, the relevant maintenance human factors and their rankings.

Analysis from question 16 to question 46 found that the maintenance situation experienced daily was doing a task without the required supervision. Situations related to workload and fatigue rated 3rd and 5th as shown in Table 5.2.

Table 5.2: Maintenance situations experienced by the maintenance workers on a daily basis.

Question	Relating Maintenance Human Factor	Percentage of respondents
Done a task without the required supervision	Supervision	11.29%
Had to perform a task you were not trained on	Training/Preparation	6.45%
Done a job without the correct tool or equipment	Equipment, Tools, And Parts	5.33%
Had trouble concentrating because you were tired.	Fatigue	4.05%
Not made a system safe before working on it, or in its vicinity	Situation Awareness	4.00%
Been interrupted part-way through a task to perform another more urgent task.	Workload	4.00%

Maintenance situations experienced on a weekly basis related to workload, time pressure, fatigue and supervision as shown in Table 5.3. The maintenance situation experienced most on a monthly basis is the same situation as what was experienced daily. However, the percentage of people that feel that they have been asked to work overtime is higher with a monthly frequency. Table 5.4 shows the maintenance situation experienced most often on a monthly basis.

Table 5.3: Maintenance situations experienced by the maintenance workers the most on a weekly basis.

Question	Relating Maintenance Human Factor	Percentage of respondents
Been asked to work overtime to complete the current workload	Workload	12.70%
Been interrupted part-way through a task to perform another more urgent task.	Workload	10.67%
Had to rush a maintenance task due to time pressure	Time Pressure	6.76%
Had trouble concentrating because you were tired.	Fatigue	6.76%
Done a task without the required supervision	Supervision	6.45%

Table 5.4: Maintenance situations experienced by the maintenance workers the most on a monthly basis.

Question	Relating Maintenance Human Factor	Percentage of respondents
Been asked to work overtime to complete the current workload	Workload	30.16%
Had to rush a maintenance task due to time pressure	Time Pressure	29.73%
Had to rush a job to ensure that all your workload gets completed	Workload	26.98%
Had trouble concentrating because you were tired.	Fatigue	24.32%
Been interrupted part-way through a task to perform another more urgent task.	Workload	22.67%

It was found that the maintenance situation experienced most on a yearly basis related to fatigue, equipment, tools, and parts, workload and time pressure as shown in Table 5.5. Maintenance situations that were experienced the least often was that the maintenance technicians started work on the wrong equipment, as shown in Table 5.6.

Table 5.5: Maintenance situations experienced by the maintenance workers the most on a yearly basis.

Question	Relating Maintenance Human Factor	Percentage of respondents
Worked more than 12 hours in a 24-hour period.	Fatigue	47.22%
Been delayed on a task because you could not obtain a major part (for example, a wheel or pump).	Equipment, Tools, And Parts	46.48%
Been asked to work overtime to complete the current workload	Workload	41.27%
Had to rush a maintenance task due to time pressure	Time Pressure	40.54%
Been unable to obtain a special tool or item of maintenance equipment.	Equipment, Tools, And Parts	36.11%

Table 5.6: Maintenance situations experienced by the maintenance workers the most on a never.

Question	Relating Maintenance Human Factor	Percentage of respondents
Started to work on the wrong equipment	Situation Awareness Cognitive Dimensions Attention/Memory	90.67%
Not made a system safe before working on it, or in its vicinity	Situation Awareness	82.67%
Started to do a job the wrong way because you didn't realize that the equipment was different to what you were used to	Skill – based error Cognitive Dimensions Attention/Memory	78.08%
Worked more than two night shifts in a row.	Fatigue	77.03%
Been interrupted part-way through a job and forgotten to return to it	Attention/Memory	76.06%

5.1.2.4. Willingness to provide personal data and management of maintenance human factors

The responses to questions 11, 12, 13 and 15 indicated that most respondents are willing to share data with the organisation if the data was collected by medical professional personnel and if their confidentiality is ensured. This is shown in Table 5.7. The respondents could choose from a scale of 1 (very probably not) to 10 (very probably).

Table 5.7: Willingness to share personal data with the organisation.

Information	N	Median	Mode	Q1	Q2	Q3	IQR
Willingness to share data on your personal fatigue level (Q11)	85	7	5	5	7	9	4
Willingness to share data on your personal life stress level (Q12)	80	6	5	4	6	8	4
Willingness to share data on your work stress level (Q13)	84	8	8	5	8	9	4
Willingness to provide heart rate data to your organization (Q15)	85	7	8	4	7	9	5

From question 10 and question 14, the maintenance workers were asked how well they perceive their supervisors and organisation to be managing these maintenance human factors. This is shown in Table 5.8. The respondents could choose from a scale of 1 (very probably not) to 10 (very probably).

Table 5.8: Management of maintenance human factors

Question	N	Median	Mode	Q1	Q2	Q3	IQR
How well is your supervisor managing human factors (Q10)	85	6	7	4	6	9	5
How well is your organisation managing human factors (Q14)	81	5	4	4	5	7	3

5.1.2.5. Personal sleep and stress levels

This section of the questionnaire contained information that could be perceived as being sensitive or personal and was an addition to the survey. Respondents had the options to submit their survey before this section or to not answer a specific question. 22 Respondents chose to continue with this section of the survey.

It was found that 82% of these 22 respondents sleep between 6 and 8 hours before their shifts or working days start. Only 14% of these 22 respondents had access to their sleep quality information by means of a Fitbit or other wearable device.

Figure 5.4 and Figure 5.5 indicate their perceptions of their personal stress levels and work stress levels. The respondents could choose from a scale of 1 (extremely stressed) to 10 (not stressed).

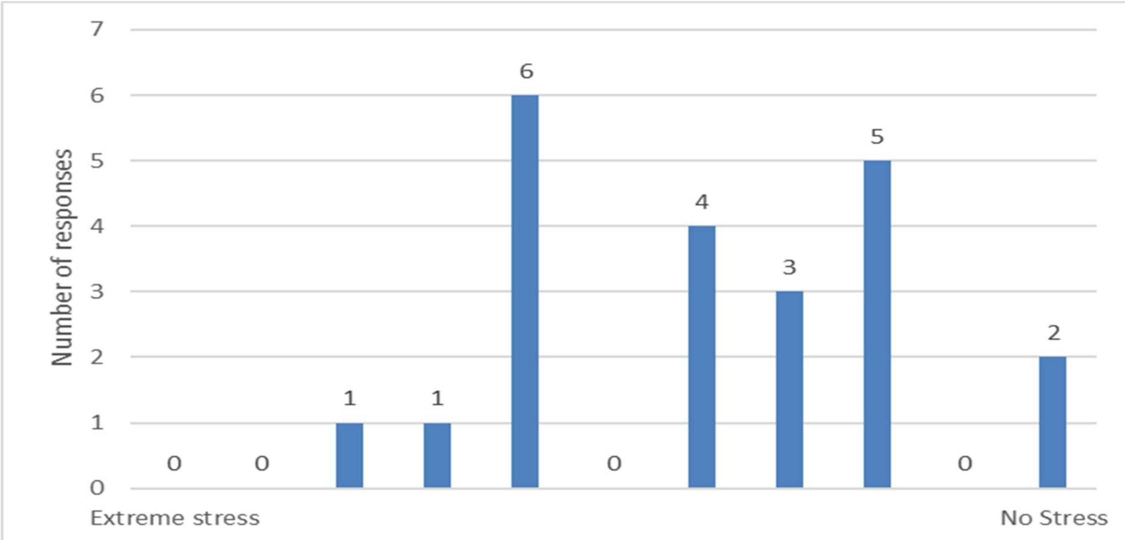

Figure 5.4: Personal stress levels of maintenance technicians

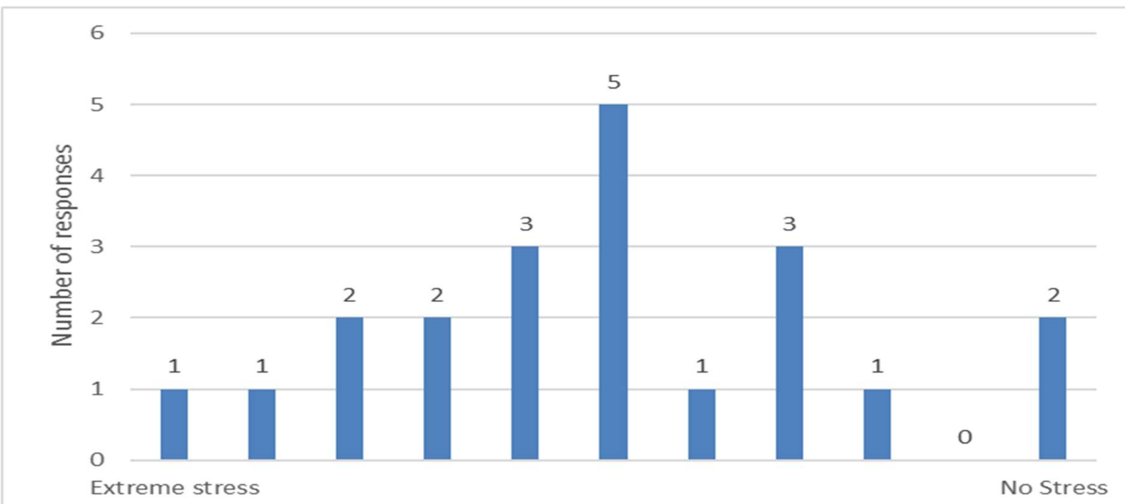

Figure 5.5: Work stress levels of maintenance technicians

5.2. Management questionnaire

5.2.1. Data gathering process

The electricity transmission industry studied in this research forms part of a bigger organisation. The Electricity Transmission division has transmission grids and other sections.

Figure 5.6 illustrates the organogram of the grid structures in terms of the Electricity Transmission division.

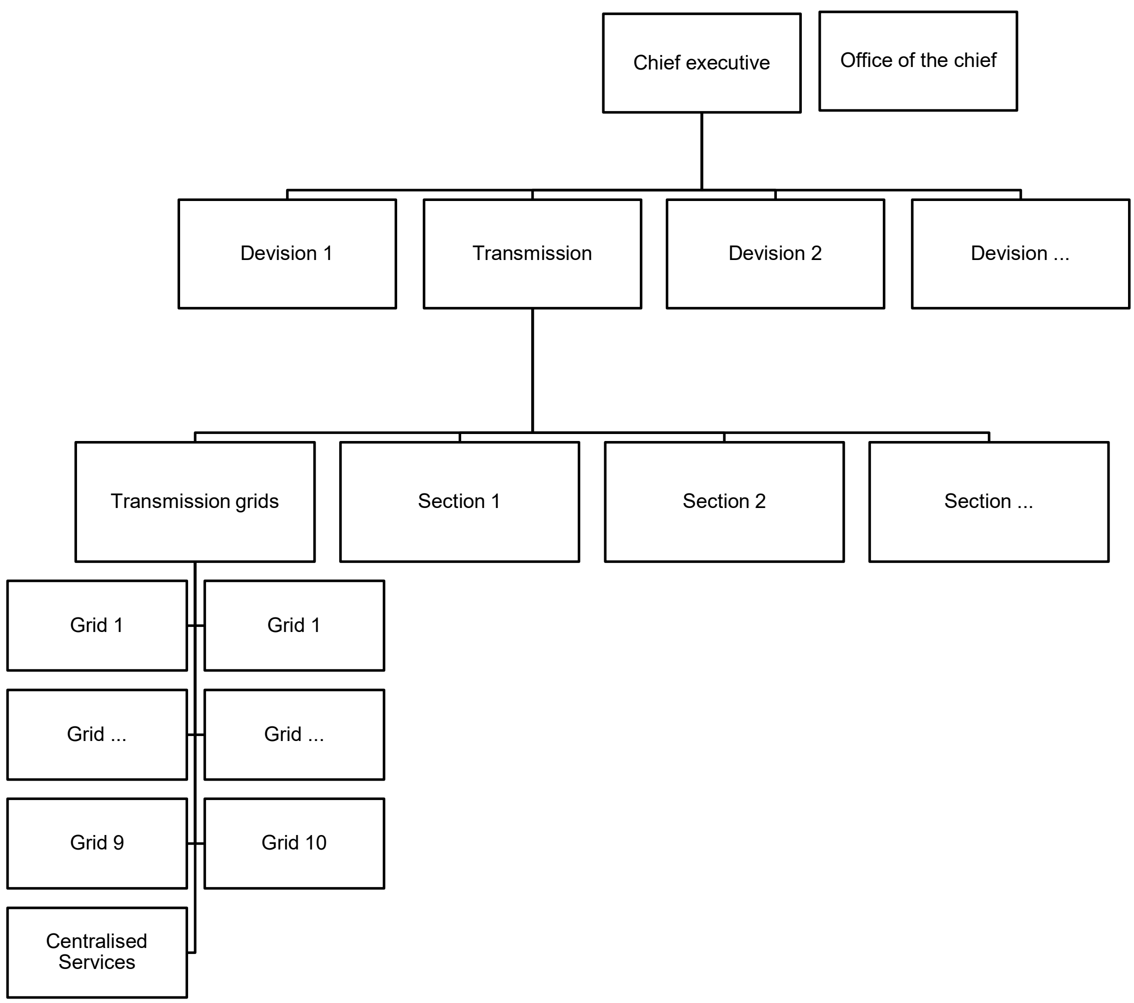

Figure 5.6: Organogram of the Electricity Transmission division

The questionnaire was sent out to 11 senior grid managers, 8 HV Plant managers, 10 Secondary plant managers and 9 lines and servitude managers as per the grid structure mentioned in Figure 5.1. The questionnaire opened on the 23rd of May 2020 and closed on 5 June 2020.

The 38 contacted managers represent more than 90% of South Africa's Electricity Transmission management responsible for High Voltage Plant / Outdoor Yard

Equipment, Control Plant / Secondary Plant and Lines and Servitudes maintenance technicians. These managers are responsible for managing their departments' maintenance performance.

The email was distributed to the respondents with an introduction of maintenance human factors and a request to participate in the questionnaire. The email contained a hyperlink to the questionnaire which was hosted on www.kwiksurveys.com. The participants were assured that their participation is entirely voluntary and anonymous and that all information obtained from the questionnaire will be strictly confidential. The participants were also informed that they have the right to withdraw at any stage without any penalty or future disadvantage.

The questionnaire consisted of 19 questions. 6 of the 38 contacted staff responded to the survey. This equates to a response rate of 15.8 percentage, which is lower than the preferred 20% response rate. It should be noted that the questionnaire was sent out during the international outbreak of the COVID-19 pandemic. Managers were overloaded with crisis management tasks to ensure that the transmission network remained stable and maintained. Therefore, the author did not solicit the managers to reach a higher response rate.

A significant response rate to the technicians' questionnaire was needed as statistical analysis was used to compare the findings with the systematic literature review. The management questionnaire was aimed at identifying the manager's perspective of the maintenance human factors that cause maintenance errors. The management questionnaire is designed to determine if there is alignment between maintenance technician's perception and the manager's perspective.

All information gathered through the survey was exported from Kwiksurveys to Microsoft Excel. Graphs and basic statistical calculations provided by Kwiksurveys and calculated with Microsoft Excel and IBM SPSS® were used in this chapter. These graphs and basic statistical calculations can be found in Appendix H.

5.2.2. Data gathered

5.2.2.1. General work information

All the respondents confirmed that they worked in the Electricity Transmission sector. Figure 5.7 represents the distribution of the number of years that these managers have been in their present position. The managers' education levels are as follows: 50% of the respondents have a postgraduate master's degree, 17% have an undergraduate degree and 33% have a diploma.

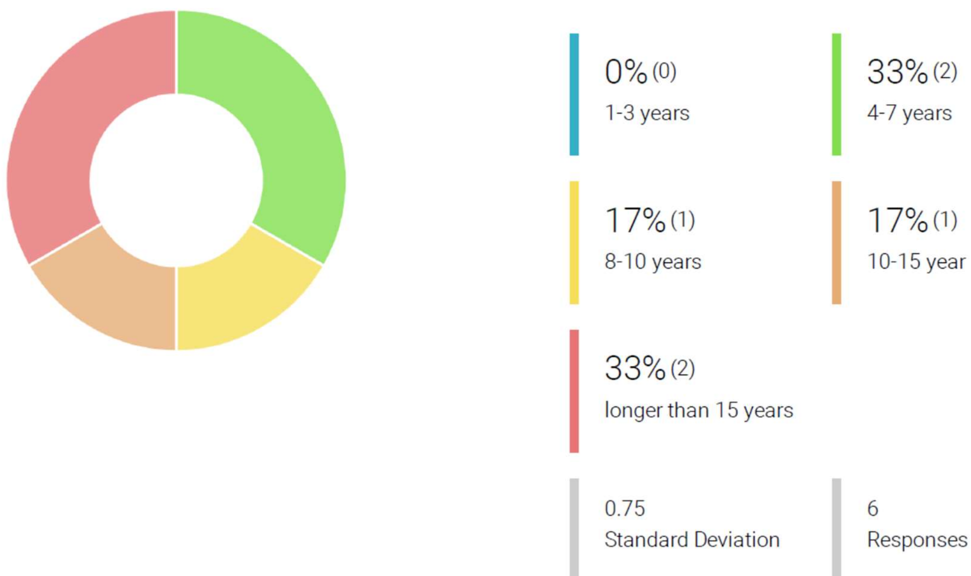

Figure 5.7: Number of years in present position.

5.2.2.2. Ranking of maintenance human factors

This section determined the most influential maintenance human factors in the electricity transmission industry from a manager's perspective. The managers were asked to indicate which maintenance human factors contribute the most to maintenance errors in their departments. The results are that judgment/decision-making ranked the highest with 33%, time pressure, communication, high workload and supervision ranked equal with 17% each.

The responses remained similar when the managers were asked to indicate which maintenance human factors contributed the second most to maintenance errors in their departments. Supervision, that had a 17% contribution, was now at 0% and equipment, tools and parts now had a 17% contribution.

Question 8 of the management questionnaire asked the managers to rank the factors that they feel are causing maintenance errors in their departments. Table 5.9 shows that Judgment/Decision- Making ranked the highest and noise levels ranked the lowest in term of error contributing factors.

Table 5.9: Ranking of maintenance human factors that contributed to maintenance errors in the managers departments

Maintenance human factor	Rank	Median	Mode	Q1	Q2	Q3	IQR
Judgment/ Decision-Making	1	1.50	1	1.00	1.50	2.50	1.50
Time Pressure	2	3.00	3[a]	1.75	3.00	6.00	4.25
Communication	3	4.00	4	2.75	4.00	5.50	2.75
Supervision	4	4.00	4	1.75	4.00	6.50	4.75
High Workload	5	5.50	1[a]	3.25	5.50	7.25	4.00
Equipment, Tools And Parts	6	6.00	5[a]	4.25	6.00	9.00	4.75
Fatigue	8	7.00	8	4.50	7.00	8.25	3.75
Life Stress	7	7.00	7[a]	4.50	7.00	9.00	4.50
Cognitive Capabilities	9	7.50	3[a]	5.25	7.50	9.50	4.25
Inadequate Lighting/ Light	10	10.00	10	9.50	10.00	10.25	0.75
Noise Level	11	11.00	11	10.00	11.00	11.00	1.00

a. Multiple modes exist. The smallest value is shown

5.2.2.3. Interest in maintenance human factor measurements

This section of the questionnaire determined whether managers would be interested to know the status of their maintenance technicians' maintenance human factors. The weighted average and standard deviation for each human factor is indicated in Table 5.10. The respondents could choose from a scale of 1 (very probably not) to 10 (very probably). Question 17 was erroneously a duplicate of Question 13. The results from Question 13 will be used in this thesis as it provides the first impression response of the respondents.

Table 5.10: Managers interest for maintenance technician's perception

Maintenance human factor	Rank	Median	Mode	Q1	Q2	Q3	IQR
Level of workload	1	8.00	8	5.50	8.00	8.50	3.00
Level of effective supervision	2	7.50	7	7.00	7.50	8.50	1.50
Availability to equipment, tools and parts	3	7.50	5[a]	5.75	7.50	9.25	3.50
Level of stress	4	7.00	4[a]	4.00	7.00	8.50	4.50
Level of time pressure	5	6.50	6	5.75	6.50	8.50	2.75
Effective communication	6	6.50	6	5.75	6.50	9.25	3.50
Level of fatigue	7	6.00	5[a]	4.50	6.00	7.75	3.25
Excessive noise levels	8	4.50	5	2.50	4.50	5.25	2.75
Level of inadequate lighting	9	4.00	5	1.75	4.00	5.00	3.25

a. Multiple modes exist. The smallest value is shown

Whether managers were interested in the maintenance technicians' cognitive capabilities or in their judgment/decision-making capabilities was not asked in the questionnaire. Managers have access to personnel files that contain psychometric testing done before employment which can be used to evaluate cognitive capabilities. judgment/decision-making capabilities are a delicate situation within the organization. Even though judgment/decision-making rank the highest in terms of the manager's view on factors leading to maintenance errors, requesting measurements for this can easily trigger conflict in the organisation. Judgment/Decision-Making can be measured under the category of cognitive capabilities as per Section 2.2.3.3: Measurements of cognitive capabilities. This implies that managers could request these measurements to be included in the recruitment processes.

5.2.2.4. Obtaining data required to measure maintenance human factors

The managers were asked what their preference would be to obtain the required data compared to their perspective of the preference of their staff. The results are shown in Table 5.11 and Table 5.12.

Table 5.11: Managers preferred way of obtaining data

Data obtain method	Rank	Median	Mode	Q1	Q2	Q3	IQR
Anonymous checklist / surveys / questionnaire	1	1.00	1	1.00	1.00	2.50	1.50
Anonymous measurable medical data collected by trained medical professionals to summaries the overall status of your department	2	2.00	2	2.00	2.00	2.50	0.50
Named checklist / surveys / questionnaire	3	3.00	3	1.00	3.00	3.00	2.00

Table 5.12: Managers perspective of their staff's preferred way to provide data

Data providing method	Rank	Median	Mode	Q1	Q2	Q3	IQR
Anonymous checklist / surveys / questionnaire	1	1.00	1	1.00	1.00	2.50	1.5
Named checklist / surveys / questionnaire	2	2.00	2	1.50	2.00	3.00	1.5
Measurable medical data collected through a SMART WATCH. The information would be collected by a trained medical professional and their anonymity will be insured.	3	3.00	3	3.00	3.00	4.00	1.0
Measurable medical data collected through a PHYSICAL EXAM. The information would be collected by a trained medical professional and their anonymity will be insured	4	3.00	2[a]	2.00	3.00	3.50	1.5

a. Multiple modes exist. The smallest value is shown

5.3. Chapter summary

This chapter obtained data to answer RQ1: "What maintenance human factors have the most influence on maintenance human errors?" In this chapter the most influential maintenance human factors from the maintenance technician's perception were identified. The maintenance manager's perspective of what the most influential maintenance human factor is was also determined. The second part of this chapter identified the maintenance human factor that managers would prefer most to be measured. The preferred way that the maintenance manager would like to obtain the data was determined. This was compared with the data that the maintenance technicians were willing to provide. Additional data, such as maintenance human factors experienced by maintenance technicians according to frequency, were also obtained.

The combined results will be used in the next chapter to analyse the correlation between the maintenance technicians' perceptions and maintenance management's perspectives. Correlation test will also be done between data obtained for both management and the maintenance technicians to what was found in literature.

6. RESULTS: DATA ANALYSIS AND CORRELATION TESTING

In this chapter, data obtained from the literature review (Chapter 2) and the questionnaire (Chapter 5) was used for correlation testing. This determined if the most noted maintenance human factors from literature corresponds with either the maintenance technicians' perception or with management's perspective. This was done to validate the literature review and perspective of the organisation regarding maintenance human factors. Correlation testing was also done to determine the perceived views regarding maintenance human factors between the maintenance worker and maintenance management. The findings of this chapter were used to determine the answer of RQ1: "What maintenance human factors have the most influence on maintenance human errors?"

6.1. Maintenance technicians questionnaire

6.1.1. Ranking of maintenance human factors according to contribution and influence

This section compared those maintenance human factors that most often contribute to personal maintenance errors, with the most noted and influential human maintenance factors as determined in the systematic and explorative literature reviews.

A combination of the most noted maintenance human factors coded using both the PEAR model and the HFACS-ME framework were tested in the first-round survey questionnaire. These maintenance human factors were:

- Fatigue,
- Inadequate Lighting/Light,
- Communication,
- High Workload,
- Cognitive Capabilities,
- Judgment/Decision-Making,
- Noise Level,
- Time Pressure,
- Supervision,

- Life Stress, and
- Equipment, Tools, And Parts

The combination of the most noted maintenance human factors was tested using 3 questions (Questions 7 – 9) in the survey. The first question determined the factors contributing the most to a person maintenance error as per the maintenance technicians' perception. The second question determined the factors contributing to the second most person maintenance error as per the maintenance technicians' perception. Table 6.1 illustrates the most and second most contributing factors to personal maintenance errors. The third question asked the technicians to rank the given maintenance human factors from most influential to least influential.

Table 6.1: Personal contribution to maintenance errors

Ranking	Contributed the most to a personal maintenance error	Contributed the second most to a personal maintenance error
1	High Workload	Communication
2	Time Pressure	High Workload
3	Fatigue	Fatigue
4	Communication	Time Pressure

Feedback was received from some of the respondents that the Kwiksurvey interface for ranking the maintenance human factors, from most influential to least influential (Question 9), was not user friendly and that it was difficult to order the factors. Because of this feedback, a statistical comparison was made between the answers of Q7, Q8 and Q9 to test the alignment and to validate that the responses to Question 7 should be used.

Table 6.2: Comparison between question 7, 8 and 9

Maintenance Human Factor	Most contributing factors (Q7)	Second contributing factors (Q8)	Ranked by mode (Q9)
High Workload	1	2	4
Time Pressure	2	4	8
Fatigue	3	3	1
Communication	4	1	3
Equipment, Tools, And Parts	5	5	11
Judgment/Decision-Making	6	6	6
Cognitive Capabilities	7	7	5
Supervision	8	8	9
Inadequate Lighting/Light	9	11	2
Life Stress	10	9	10
Noise Level	11	10	7

Table 6.3: Correlation between Q7, Q8 and Q9

			Most contributing factors (Q7)	Second contributing factors (Q8)	Ranked by mode (Q9)
Kendall's tau_b	Most contributing factors (Q7)	Correlation Coefficient	1.000	**0.782****	0.200
		Sig. (2-tailed)		0.001	0.392
		N	11	11	11
	Second contributing factors (Q8)	Correlation Coefficient	**0.782****	1.000	0.200
		Sig. (2-tailed)	0.001		0.392
		N	11	11	11
	Q9	Correlation Coefficient	0.200	0.200	1.000
		Sig. (2-tailed)	0.392	0.392	
		N	11	11	11
Spearman's rho	Most contributing factors (Q7)	Correlation Coefficient	1.000	**0.909****	0.291
		Sig. (2-tailed)		0.000	0.385
		N	11	11	11
	Second contributing factors (Q8)	Correlation Coefficient	**0.909****	1.000	0.273
		Sig. (2-tailed)	0.000		0.417
		N	11	11	11
	Ranked by mode (Q9)	Correlation Coefficient	0.291	0.273	1.000
		Sig. (2-tailed)	0.385	0.417	
		N	11	11	11

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

Kendall's tau_b and Spearman's rho nonparametric correlation tests show a significant correlation between the responses of Q7 and Q8 (Spearman's rho of 0.909). No correlation was found between the responses of Q7 and Q9 or between the responses of Q8 and Q9. This justifies that the responses to Q7, factors that contributed the most to a maintenance error, are used for this thesis.

Additionally, Kendall's tau_b and Spearman's rho nonparametric correlation tests were done to compare the ranking of factors contributing to maintenance errors (Q7) to the ranking factors contributing the most to maintenance human errors according to literature (Table 6.4). The results are shown in Table 6.5 and Table 6.6

Table 6.4: Ranking of factors contributing to maintenance human errors

		Factors found to contribute the most to maintenance human errors			
Maintenance Human Factor	**Most contributing factors (Q7)**	**Hobbs and Williamson (2003)**	**Krulak (2004)**	**Antonovsky et al. (2014)**	**Gordon et al. (2005)**
High Workload	1				
Time Pressure	2	1		14	
Fatigue	3	5			
Communication	4		8	3	2
Equipment, Tools, And Parts	5	2			
Judgment/Decision-Making	6		2	5	
Cognitive Capabilities	7		3	15	9
Supervision	8	7	1	17	10
Inadequate Lighting/Light	9				
Life Stress	10				
Noise Level	11				

Table 6.5: Kendall's tau_b nonparametric correlations between ranking of factors contributing to maintenance errors between maintenance technicians and literature

			Survey Results (Q7)	Hobbs and Williamson (2003)	Krulak (2004)	Antonovsky et al. (2014)	Gordon et al. (2005)
Kendall's tau_b	Survey Results (Q7)	Correlation Coefficient	1.000	0.400	-0.738	0.467	1.000
		Sig. (2-tailed)		0.327	0.077	0.188	
		N	11	5	5	6	3
	Hobbs and Williamson (2003)	Correlation Coefficient	0.400	1.000	-1.000	0.333	
		Sig. (2-tailed)	0.327			0.602	
		N	5	5	2	3	1
	Krulak (2004)	Correlation Coefficient	-0.738	**-1.000****	1.000	-0.527	-1.000
		Sig. (2-tailed)	0.077			0.207	
		N	5	2	5	5	3
	Antonovsky et al. (2014)	Correlation Coefficient	0.467	0.333	-0.527	1.000	1.000
		Sig. (2-tailed)	0.188	0.602	0.207		
		N	6	3	5	6	3
	Gordon et al. (2005)	Correlation Coefficient	**1.000****		**-1.000****	**1.000****	1.000
		Sig. (2-tailed)					
		N	3	1	3	3	3

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

Table 6.6: Spearman's rho nonparametric correlations between ranking of factors contributing to maintenance errors between maintenance technicians and literature

			Survey Results (Q7)	Hobbs and Williamson (2003)	Krulak (2004)	Antonovsky et al. (2014)	Gordon et al. (2005)
Spearman's rho	Survey Results (Q7)	Correlation Coefficient	1.000	0.500	-0.872	0.543	**1.000****
		Sig. (2-tailed)		0.391	0.054	0.266	
		N	11	5	5	6	3
	Hobbs and Williamson (2003)	Correlation Coefficient	0.500	1.000	-1.000	0.500	
		Sig. (2-tailed)	0.391			0.667	
		N	5	5	2	3	1
	Krulak (2004)	Correlation Coefficient	-0.872	**-1.000****	1.000	-0.616	**-1.000****
		Sig. (2-tailed)	0.054			0.269	
		N	5	2	5	5	3
	Antonovsky et al. (2014)	Correlation Coefficient	0.543	0.500	-0.616	1.000	**1.000****
		Sig. (2-tailed)	0.266	0.667	0.269		
		N	6	3	5	6	3
	Gordon et al. (2005)	Correlation Coefficient	**1.000****		**-1.000****	**1.000****	1.000
		Sig. (2-tailed)					
		N	3	1	3	3	3

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

The results show that both Kendall's tau_b and Spearman's nonparametric correlations test returned a direct positive correlation between the contributing factors as reported by Gordon et al. (2005) and the factors contributing most to personal maintenance errors made by the maintenance technicians. The tests returned a significant correlation between the contributing factors reported by Hobbs and Williamson (2003) and the factors contributing most to personal maintenance errors made by the maintenance technicians. The usability of the results need to be is questionable due to the difference in sample sizes. The survey results listed 11 data elements, compared to the 5, 5, 6 and 3 elements identified by the various publications quoted in Table 6.5 and Table 6.6.

By using the results of Question 7, the most influential maintenance human factors, correlation tests were done to determine if there was a correlation between what the maintenance technicians felt was the most influential maintenance human factors and the number of noted maintenance human factors from the systematic literature review.

Table 6.7 illustrates the ranking of the most influential factors compared with the ranking of the number of factors noted using minimal coding, the PEAR model and the HFACS-ME framework. The output of SPSS can be seen in Table 6.8.

Table 6.7: Ranking of survey results compared to cited ranking systematic literature review

		Cited ranked position using		
Maintenance Human Factor	**Most influential from survey**	**minimal coding**	**PEAR Model**	**HFACS-ME framework**
High Workload	1	4	8	7
Time Pressure	2	8	9	24
Fatigue	3	1	6	4
Communication	4	3	1	3
Equipment, Tools, And Parts	5	22	2	22
Judgment/Decision-Making	6	6	26	8
Cognitive Capabilities	7	5	16	14
Supervision	8	12	10	11
Inadequate Lighting/Light	9	2	11	5
Life Stress	10	20	14	10
Noise Level	11	7	17	16

Table 6.8: Kendall's tau_b and Spearman's rho nonparametric correlation tests for Table 6.7

			Survey	Minimal coding	PEAR	HFACS
Kendall's tau_b	Survey	Correlation Coefficient	1.000	0.200	0.418	0.091
		Sig. (2-tailed)		0.392	0.073	0.697
		N	11	11	11	11
	Minimal coding	Correlation Coefficient	0.200	1.000	0.127	**0.600***
		Sig. (2-tailed)	0.392		0.586	0.010
		N	11	11	11	11
	PEAR	Correlation Coefficient	0.418	0.127	1.000	0.236
		Sig. (2-tailed)	0.073	0.586		0.312
		N	11	11	11	11
	HFACS	Correlation Coefficient	0.091	**0.600***	0.236	1.000
		Sig. (2-tailed)	0.697	0.010	0.312	
		N	11	11	11	11
Spearman's rho	Survey	Correlation Coefficient	1.000	0.291	**0.645***	0.164
		Sig. (2-tailed)		0.385	0.032	0.631
		N	11	11	11	11
	Minimal coding	Correlation Coefficient	0.291	1.000	0.155	**0.773****
		Sig. (2-tailed)	0.385		0.650	0.005
		N	11	11	11	11
	PEAR	Correlation Coefficient	**0.645***	0.155	1.000	0.273
		Sig. (2-tailed)	0.032	0.650		0.417
		N	11	11	11	11
	HFACS	Correlation Coefficient	0.164	**0.773****	0.273	1.000
		Sig. (2-tailed)	0.631	0.005	0.417	
		N	11	11	11	11

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

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

The results show that both Kendall's tau_b and Spearman's rho nonparametric correlation tests calculated a positive correlation between what the maintenance technicians perceived as the most influential maintenance human factors and the most noted maintenance human factors using the PEAR model. It also shows positive correlation between the ranking of the number of noted factors using minimal coding and the HFACS-ME framework.

6.1.2. Ranking of maintenance human factors according to frequency

In this section correlation between the identified most influential maintenance human factors' rankings and the frequencies of these maintenance human factors were calculated. Question 7: "Most significant contributing factors to personal maintenance errors made" is compared to Questions 16 to 46 (determine the frequency of occurrences of the maintenance human factors). Table 6.9 illustrates the number of maintenance situations for each of the most influential maintenance human factors. Other maintenance situations were included in the survey as they were frequently cited human factor using minimal coding, the PEAR model or the HFACS-ME framework. These situations relate to: Attention/Memory, Certification/Qualification, Inadequate Design, Procedures/Work Cards, Situation Awareness, Skill-based error and Training/Preparation. Some of the situations were included to test compliance with the organisation's policies. Perceived life stress was not included in in the frequency testing as it was measured under personal sensitive information (Questions 47 and 48). Table 6.10 shows the top ranked maintenance situations experienced, categorised by frequency.

Table 6.9: Influential maintenance human factors compare to the number of maintenance situations tested for the related factor within the survey

Maintenance human factor	Most influential from survey	Number of maintenance situations relating to the maintenance human factor
Workload	1	4
Time Pressure	2	2
Fatigue	3	3
Communication	4	2
Equipment, Tools, And Parts	5	4
Judgment/Decision-Making	6	1
Cognitive Capabilities	7	3
Supervision	8	1
Inadequate Lighting/Light	9	1
Life Stress	10	0
Noise Level	11	1

Table 6.10: Ranked maintenance situations according to frequency.

Maintenance situation	Relating maintenance human factor	Every day	Once a week	Once a month	Once a year	Never
Been interrupted part-way through a job and forgotten to return to it	Attention/Memory					5
Been delayed on a task because you could not obtain a major part (for example, a wheel or pump).	Equipment, Tools, And Parts				2	
Been unable to obtain a special tool or item of maintenance equipment.	Equipment, Tools, And Parts				5	
Done a job without the correct tool or equipment	Equipment, Tools, And Parts	3				
Had trouble concentrating because you were tired.	Fatigue	4	4	4		
Worked more than 12 hours in a 24-hour period.	Fatigue				1	
Worked more than two night shifts in a row.	Fatigue					4
Not made a system safe before working on it, or in its vicinity	Situation Awareness	5				2
Started to work on the wrong equipment	Situation Awareness, Cognitive Dimensions, Attention/Memory					1
Started to do a job the wrong way because you didn't realize that the equipment was different to what you were used to	Skill – based error, Cognitive Dimensions, Attention/Memory					3
Done a task without the required supervision	Supervision	1	5			
Had to rush a maintenance task due to time pressure	Time Pressure		3	2	4	
Had to perform a task you were not trained on	Training/Preparation	2				
Been asked to work overtime to complete the current workload	Workload		1	1	3	
Been interrupted part-way through a task to perform another more urgent task.	Workload	6	2	5		
Had to rush a job to ensure that all your workload gets completed	Workload			3		

Several maintenance situations were removed from the analysis for the reasons shown in Table 6.11. These questions were included to determine whether the organisation's policies were being followed. Compliance with the organisation's policies proved to be true as they either only happen once a year or never. Where there were situations occurring yearly or never ranking combined with daily, weekly and monthly occurrence the question remained for comparison.

Table 6.11: Removed situations from analysis

Maintenance situation	Reason	Frequency ranking
Worked more than 12 hours in a 24-hour period.	According to labour policies staff are not allowed to work more than 60 hours of overtime per month. A normal working day is 8 hours. If the technicians are asked to work overtime, permission is needed from management. This allows for staff to be asked to work overtime, but seldom results in more than 12 hours per 24 hours due to the limit of overtime hours per month.	Once a year: ranking 1
Worked more than two-night shifts in a row.	Most technicians do not work night shift. A designated technician will be on standby for unplanned interruptions. The non-frequent ranking confirms the low rate of unplanned interruptions.	Never: ranking 4
Started to work on the wrong equipment	According to the HV regulations used in the organisation equipment needs to be properly identified and verified by another trained technical. This “buddy system” is in place for safety reasons and to reduce human errors.	Never: ranking 1
Started to do a job the wrong way because you didn’t realize that the equipment was different to what you were used to	The organisation has a relative stable base of similar equipment. This reduces the need for multi-skilling normal technicians. For nonstandard equipment specialist technicians are normally called in to perform the maintenance work.	Never: ranking 3
Been interrupted part-way through a job and forgotten to return to it	Most maintenance is operational outage dependant. Outages are limited. Therefore, maintenance cannot be interrupted as the probability of another outage is small.	Never: ranking 5

There are contradictions in responses to the 3 questions relating to Equipment, Tools and Parts. Therefore, these situations will remain part of the analysed data. This is illustrated in Table 6.12. A possible reason for the contradiction between the low frequency of the situation where maintenance technicians have “Been unable to obtain a special tool or item of maintenance equipment” and the high frequency of the situation where maintenance technicians have “Done a job without the correct tool or equipment” is the organisational culture. The organisational culture has a strong “*’n boer maak n plan*” component. This is an Afrikaans saying that means “to encourage a person who encounters a problem to find a solution.” Therefore, it is instinctive for technicians to perform maintenance without the correct tools or equipment as it is easier to find an alternative solution than to request the correct tool or equipment through the organisation's difficult commercial processes.

Table 6.12: Contradictions with the 3 questions relating to Equipment, Tools, And Parts

Maintenance situation	Relating maintenance human factor	Every day	Once a year
Been delayed on a task because you could not obtain a major part (for example, a wheel or pump).	Equipment, Tools, And Parts		2
Been unable to obtain a special tool or item of maintenance equipment.	Equipment, Tools, And Parts		5
Done a job without the correct tool or equipment	Equipment, Tools, And Parts	3	

The remaining maintenance situation were summated from daily to monthly and from yearly to never. The summated results were ranked. The reason for this that daily to monthly frequencies can be seen as high frequency and yearly to never as low frequency. This is illustrated in Table 6.13.

Table 6.13: Comparison of maintenance situations frequencies

Maintenance situation	Relating maintenance human factor	High frequency maintenance situation	Low frequency maintenance situation
Been delayed on a task because you could not obtain a major part (for example, a wheel or pump).	Equipment, Tools, And Parts	8	1
Been unable to obtain a special tool or item of maintenance equipment.	Equipment, Tools, And Parts	10	4
Done a job without the correct tool or equipment	Equipment, Tools, And Parts	6	9
Had trouble concentrating because you were tired.	Fatigue	4	7
Not made a system safe before working on it, or in its vicinity	Situation Awareness	11	11
Done a task without the required supervision	Supervision	7	10
Had to rush a maintenance task due to time pressure	Time Pressure	5	2
Had to perform a task you were not trained on	Training/Preparation	9	8
Been asked to work overtime to complete the current workload	Workload	3	3
Been interrupted part-way through a task to perform another more urgent task.	Workload	2	5
Had to rush a job to ensure that all your workload gets completed	Workload	1	6

SPSS® was used to perform Kendall's tau_b and Spearman's rho nonparametric correlation tests. This was done to determine if there was correlation between high frequency maintenance situations and low frequency maintenance situations. The output from SPSS can be seen in Table 6.14.

Table 6.14: Correlating testing between high and low frequency maintenance situations

			High	Low
Kendall's tau_b	High	Correlation Coefficient	1.000	0.200
		Sig. (2-tailed)	.	0.392
		N	11	11
	Low	Correlation Coefficient	0.200	1.000
		Sig. (2-tailed)	0.392	.
		N	11	11
Spearman's rho	High	Correlation Coefficient	1.000	0.291
		Sig. (2-tailed)	.	0.385
		N	11	11
	Low	Correlation Coefficient	0.291	1.000
		Sig. (2-tailed)	0.385	.
		N	11	11

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

Kendall's tau_b and Spearman's rho nonparametric correlation tests shows no significant correlation between high and low frequency maintenance situations. Therefore, for the purpose of this study, high frequency maintenance situations will be used to determine the correlation between the frequency of maintenance situations and the most influential maintenance human factors.

To compare the maintenance situations with maintenance human factors, the high frequency maintenance situations with the same maintenance human factors were summated according to the maintenance technician's frequency perception. The number of total responses for those questions were summated and a ranking based on the percentage was calculated as shown in Table 6.15.

Table 6.15: Maintenance human factor ranked by frequency

Maintenance human factor	High frequency maintenance situation	Total number of respondents	Percentage	Ranking
Workload	77	201	38.31%	1
Time Pressure	28	74	37.84%	2
Fatigue	26	74	35.14%	3
Supervision	14	62	22.58%	4
Training/Preparation	11	62	17.74%	5
Equipment, Tools, And Parts	35	218	16.06%	6
Situation Awareness	5	75	6.67%	7

Table 6.16 compares the most influential maintenance human factors' rankings with the frequency of occurrence rankings. Kendall's tau_b and Spearman's rho nonparametric correlation tests were done and the output from SPSS can be seen in Table 6.17.

Table 6.16: Rankings of most influential factors compared with the frequency of maintenance human factor occurrence rankings.

Maintenance Human Factor	Most influential factors	Ranking of high frequency situations
Workload	1	1
Time Pressure	2	2
Fatigue	3	3
Communication	4	-
Equipment, Tools, And Parts	5	6
Cognitive Capabilities	7	-
Supervision	8	4
Training/Preparation	-	5
Situation Awareness	-	7

Table 6.17: Kendall's tau_b and Spearman's rho nonparametric correlation tests for Table 6.16

			Influential	**High Frequency**
Kendall's tau_b	Influential	Correlation Coefficient	1.000	0.800
		Sig. (2-tailed)		0.050
		N	10	5
	High Frequency	Correlation Coefficient	0.800	1.000
		Sig. (2-tailed)	0.050	
		N	5	7
Spearman's rho	Influential	Correlation Coefficient	1.000	**0.900***
		Sig. (2-tailed)		0.037
		N	10	5
	High Frequency	Correlation Coefficient	**0.900***	1.000
		Sig. (2-tailed)	0.037	
		N	5	7

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

From the results it can be seen that Spearman's rho nonparametric correlations test calculated a positive correlation between what the maintenance technicians perceived as the most influential maintenance human factors and the highest occurrences of maintenance human factor situations ranking.

The above indicates that the maintenance technicians' perceptions regarding the most influential maintenance human factors align with the most noted maintenance human factor coded using the PEAR model from the systematic literature review. The maintenance technician's most influential maintenance human factors also correlate with the maintenance human factor situations that they are placed in most often.

6.2. Management questionnaire

Similar to the maintenance technicians' questionnaire, two questions were asked where the maintenance managers gave their perspectives on the maintenance human factors that contributed to maintenance errors. Table 6.18 illustrates the most and second most contributing factors to personal maintenance errors.

Table 6.18: Maintenance manager's perspective of contributing factors to maintenance errors

Ranking	Contributed the most to a personal maintenance error	Contributed the second most to a personal maintenance error
1	Judgment/ Decision-Making	Judgment/ Decision-Making
2	Time Pressure	Time Pressure
3	Communication	Communication
4	High Workload	High Workload
5	Supervision	Equipment, Tools And Parts

The management questionnaire study focussed on:

- verifying the maintenance manager's perspective of the most influential factor to those most noted in the systematic literature review, and
- determining the correlation between the maintenance technician's perception of the most influential maintenance human factor and the managers perspective of it.

The managers were asked to rank the maintenance human factors according to their perspective of the most influential maintenance human factors. This is tabled alongside the most noted maintenance human factors from literature. The rankings are shown in Table 6.19 with the correlation results in Table 6.20.

Table 6.19: Ranking of management survey results compared to cited ranking systematic literature review

		Cited ranked position with		
Maintenance human factor	**Most influential as per management**	**Minimal coding**	**PEAR Model**	**HFACS-ME framework**
Judgment/ Decision-Making	1	6	26	8
Time Pressure	2	8	9	24
Communication	3	3	1	3
Supervision	4	12	10	11
High Workload	5	4	8	7
Equipment, Tools And Parts	6	22	2	22
Fatigue	8	1	6	4
Life Stress	7	20	14	10
Cognitive Capabilities	9	5	16	14
Inadequate Lighting/ Light	10	2	11	5
Noise Level	11	7	17	16

Contrary to the correlation results from the most influential maintenance factors from the maintenance technician's perceptions, there is no significant correlation between the managers' perspectives and the most noted maintenance human factors. The only significant correlation is, as per the previous section, between the ranking of the number of citations using minimal coding and the HFACS-ME framework.

Table 6.20: Kendall's tau_b and Spearman's rho nonparametric correlations test for Table 6-18

			Most influential	Minimal coding	PEAR	HFACS
Kendall's tau_b	Most influential	Correlation Coefficient	1.000	-0.127	0.164	-0.018
		Sig. (2-tailed)		0.586	0.484	0.938
		N	11	11	11	11
	Minimal coding	Correlation Coefficient	-0.127	1.000	0.127	**0.600***
		Sig. (2-tailed)	0.586		0.586	0.010
		N	11	11	11	11
	PEAR	Correlation Coefficient	0.164	0.127	1.000	0.236
		Sig. (2-tailed)	0.484	0.586		0.312
		N	11	11	11	11
	HFACS	Correlation Coefficient	-0.018	**0.600***	0.236	1.000
		Sig. (2-tailed)	0.938	0.010	0.312	
		N	11	11	11	11
Spearman's rho	Most influential	Correlation Coefficient	1.000	-0.264	0.182	-0.045
		Sig. (2-tailed)		0.433	0.593	0.894
		N	11	11	11	11
	Minimal coding	Correlation Coefficient	-0.264	1.000	0.155	**0.773****
		Sig. (2-tailed)	0.433		0.650	0.005
		N	11	11	11	11
	PEAR	Correlation Coefficient	0.182	0.155	1.000	0.273
		Sig. (2-tailed)	0.593	0.650		0.417
		N	11	11	11	11
	HFACS	Correlation Coefficient	-0.045	**0.773****	0.273	1.000
		Sig. (2-tailed)	0.894	0.005	0.417	
		N	11	11	11	11

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

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

The rankings of the most influential maintenance human factors from the maintenance technician's perceptions, and the managers perspectives of the most influential maintenance human factor is illustrated in Table 6.21. Kendall's tau_b and Spearman's rho nonparametric correlation tests were used to determine the correlation between the two points of view. The results are illustrated in Table 6.22.

Table 6.21: Ranking of influential factors according to maintenance technician compared to maintenance management

Maintenance human factor	Most influential as per technician	Most influential as per management
High Workload	1	5
Time Pressure	2	2
Fatigue	3	8
Communication	4	4
Equipment, Tools, And Parts	5	6
Judgment/Decision-Making	6	1
Cognitive Capabilities	7	9
Supervision	8	3
Inadequate Lighting/Light	9	10
Life Stress	10	7
Noise Level	11	11

Table 6.22: Kendall's tau_b and Spearman's rho nonparametric correlations test results for Table 6.21

			Most influential as per technician	Most influential as per management
Kendall's tau_b	Most influential as per technician	Correlation Coefficient	1.000	0.382
		Sig. (2-tailed)		0.102
		N	11	11
	Most influential as per management	Correlation Coefficient	0.382	1.000
		Sig. (2-tailed)	0.102	
		N	11	11
Spearman's rho	Most influential as per technician	Correlation Coefficient	1.000	0.518
		Sig. (2-tailed)		0.102
		N	11	11
	Most influential as per management	Correlation Coefficient	0.518	1.000
		Sig. (2-tailed)	0.102	
		N	11	11

Table 6.22 indicated that there was no statistically significant correlation between the maintenance technician's most influential maintenance human factors and the perspective maintenance managers have of the most influential maintenance human factors.

The managers were asked to rank the maintenance human factors that they would like to measure on a 10-point Likert scale from "Very Probably Not" to "Very Probably." The responses are illustrated in Table 6.23.

Table 6.23: Ranking of influential factors and associated measurement need

Maintenance human factor	Most influential as per management	What management wants
Judgment/Decision-Making	1	
Time Pressure	2	5
Communication	3	4
Supervision	4	1
High Workload	5	3
Equipment, Tools, And Parts	6	2
Life Stress	7	6
Fatigue	8	7
Cognitive Capabilities	9	
Inadequate Lighting/Light	10	9
Noise Level	11	8

Table 6.24: Kendall's tau_b and Spearman's rho nonparametric correlations test results for Table 6.23

			Influential as per management	What management wants
Kendall's tau_b	Influential as per management	Correlation Coefficient	1.000	0.500
		Sig. (2-tailed)		0.061
		N	11	9
	What management wants	Correlation Coefficient	0.500	1.000
		Sig. (2-tailed)	0.061	
		N	9	9
Spearman's rho	Influential as per management	Correlation Coefficient	1.000	**0.700***
		Sig. (2-tailed)		0.036
		N	11	9
	What management wants	Correlation Coefficient	**0.700***	1.000
		Sig. (2-tailed)	0.036	
		N	9	9

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

The results show that Spearman's rho nonparametric correlations test had a positive correlation between what the maintenance manager perceived as the most influential maintenance human factors and the maintenance human factor ranking of the measurement that they would like to have.

6.3. Chapter summary

In this chapter, data obtained from the literature review (Chapter 2) and the questionnaire (Chapter 5) was compared. Various correlation coefficients between data sets were calculated. The human factors tested for this thesis were fatigue, inadequate lighting/light, communication, high workload, cognitive capabilities, judgment/decision-making, noise level, time pressure, supervision, life stress, and equipment, tools and parts. These maintenance human factors were chosen as indicated in Table 4.4. The first part of the chapter focused on the maintenance technician's perception, while the second part focused on the maintenance manager's perspective. Finally, the maintenance technician's perception was compared to the maintenance manager's perspective.

This chapter shows significant correlation between the maintenance technicians' perceptions and literature. There is, however, a disconnection between the maintenance managers' perspectives and both literature and the maintenance technician's perceptions.

Chapter 7 will systematically answer the research question presented in this thesis. RQ2 will be expanded into additional parts. The measurements and measurement methods for the final identified maintenance human factors will then be included into a maintenance performance framework

7. RESULTS: DISCUSSION

The aim of this chapter is to use the analysis and correlation results of the previous chapters to answer the research questions posed in Chapter 1. The research questions are repeated below.

- RQ1: What maintenance human factors have the most influence on maintenance human errors?
- RQ2: How should these maintenance human factors performance indicators and measurements be incorporated into a traditional maintenance performance framework?

Chapter 2 provided human factor measurements and measurement methods and a starting point to determine the most influential maintenance human factors. Chapter 3 outlined a proposed MHFP and TMP scoring methodology with an organisational hierarchical framework used for this thesis. In Chapter 4 the findings of Chapter 2 were used to determine which maintenance human factors should be tested in RQ1. The survey data was displayed in Chapter 5 and analysed in Chapter 6.

The hierarchical maintenance performance framework for the South African electricity transmission industry from this chapter will be validated and finalised by using a Two-round Delphi method. The above process is illustrated in the research roadmap shown in Figure 7.1.

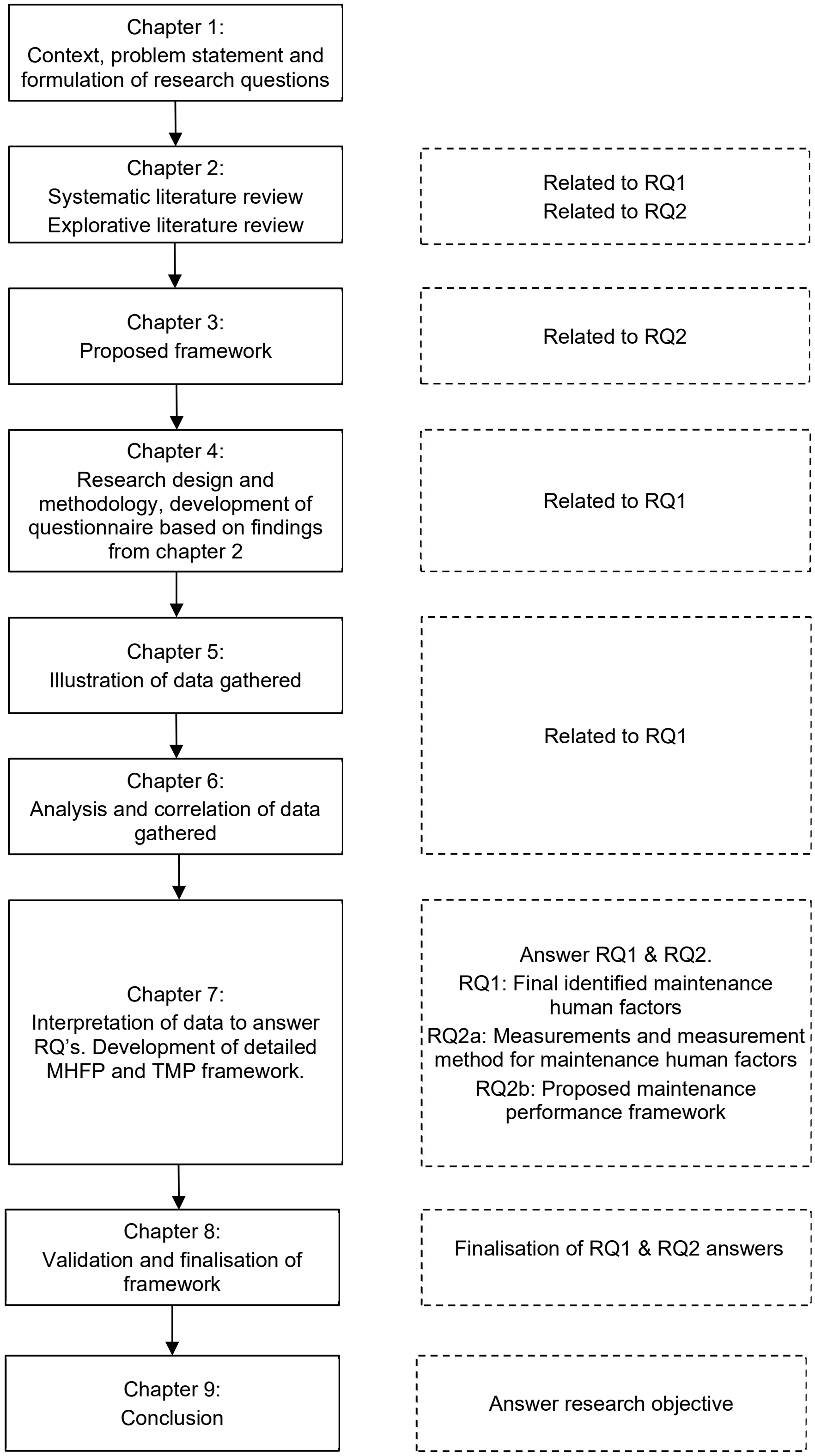

Figure 7.1: Research roadmap

7.1. RQ1: Most influential maintenance human factors

The focus of RQ1 is to determine the most influential (dominant) maintenance human factors that lead to maintenance human errors in the South African electricity transmission industry. The starting point for this was a systematic literature review of the most noted maintenance human factors. Three different coding methods were used, and the results were reported in Figure 2.7, Figure 2.8 and Figure 2.9. Correlation testing between the different coding methods was done, as was correlation testing between the final chosen maintenance human factors to be tested in RQ1. The citation rankings for the chosen survey questions are repeated in Table 7.1.

Table 7.1: Maintenance human factors chosen for the survey

Maintenance Human Factor	Minimal coding	PEAR Model	HFACS-ME framework
Fatigue	1	6	4
Illumination	2	11	5
Communication	3	1	3
Workload	4	8	7
Cognitive Dimensions	5	16	12
Decision Making	6		8
Noise Level	7		16
Time Pressure	8	9	
Supervision	12	10	11
Equipment, Tools, And Parts		2	
Stress		14	10

These most frequently noted maintenance human factors were used to develop the survey questionnaire used in Chapter 4, in order to answer RQ1.

The questionnaires determined the maintenance technicians’ perceptions and the maintenance managers’ perspectives of the most influential (dominant) maintenance human factors. This approach determined if there is alignment or consensus between the two viewpoints.

In Chapter 6 positive correlation was shown between Gordon et al.'s (2005) contributing factors to human errors found in literature and the factors contributing most often to personal maintenance errors made by the maintenance technicians. It was shown that there was significant correlation between the maintenance technicians' perceptions of the most influential maintenance human factors and the most noted maintenance human factors in literature (PEAR model).

The maintenance technicians were asked how often they experience situations where these maintenance human factors are present. The situations were categorised into high frequency and low frequency occurrences. Each maintenance situation had a maintenance human factor related to that situation. This was done to further validate the ranked maintenance human factors from the maintenance technicians' perceptions. The correlation tests showed positive correlation between what the maintenance technicians perceived as the most influential maintenance human factors and the highest occurrences of maintenance human factor situations.

These positive correlation results confirm the findings of Broadbent et al. (1982) and Burdekin (2003) that participants provide consistent and accurate self-assessments of their behaviour. It also aligns with Hobbs and Williamson (2002) where it was found that maintenance personnel demonstrated the willingness to disclose information when their anonymity was protected.

No significant correlation between the maintenance technicians' perceptions and the maintenance managers' perspectives was found. Neither was there significant correlation between the maintenance managers' perspectives and literature. This indicates that the maintenance managers' perspectives may not be aligned to what maintenance technicians experience on shop floor/ground level. It also shows misalignment between what the maintenance managers' perspectives are on the most influential maintenance human factors and academic knowledge found in literature.

The author developed the following propositions to explain the reasons for this misalignment:

- Career paths are very limited for maintenance technicians if they do not obtain a further tertiary education. Most technicians aim to complete bachelor’s or master’s degrees. Retention of these technicians are difficult once they've completed their degrees.
- Very few maintenance managers have started at shop floor level. Therefore, they do not have a reference framework of what the maintenance technicians experience.
- Maintenance technicians report to a maintenance supervisor, who in turn report to the maintenance manager. The maintenance manager seldom experiences the situations on shop floor/ground level as the maintenance supervisor usually manage these situations. The maintenance manager is seen as a more strategic/administrative link, representing his/her department to the higher managerial structures.

The most influential maintenance human factors, as per the maintenance technicians’ perceptions, align with both literature (PEAR Model) and with the frequency of occurrence. This alignment, along with the statistical correlation, indicates that the maintenance technicians’ perception can be trusted. For this reason, Chapter 7 focused on using the influential maintenance human factors as per the maintenance technicians.

The maintenance technicians ranked 11 identified factors in order of most influential to least influential. The top 4 factors, high workload, time pressure, fatigue and communication were chosen to be incorporated into the proposed maintenance performance framework. The 4 identified factors have a cumulative frequency of 72% when the technicians were asked to identify a factor contributed the most to a personal maintenance error.

The chosen maintenance human factors were tested against the principles set out in the theoretic framework of Section 3.1.Table 7.2 illustrates the response to Galar et al.'s (2011b) guidelines and Table 7.3, the response to key aspects before implementing a new measurement systems.

Table 7.2: Galar et al.'s (2011b) guidelines

Guidelines	Authors response
Distinguish measurements that affect human factors	The measurements were determined based on the most noted and most influential maintenance human factors .
Remember the interlinked relationships	The factors in each phase has an interlinked relationship. For example, bad communication can lead to time pressure, where fatigue is a common after effect.
Determine dominant human factors	RQ1 determined the most influential maintenance human factors from both the technician's and management's viewpoint. Even though a ranking correlation could not be found between the two viewpoints; when the top ranked factors where highlighted, there was a communal point of view.
Use already known performance indicators	These maintenance human factors are known with well-defined measurements and measurement methods.

Table 7.3: Key aspect for consideration when implementing new measurement systems.

Source	Aspect	Authors response
Kantowitz (1992)	This process of selecting measurements should be systematic	A systematic process was followed as per research roadmap.
Arca and Prado (2008)	Involve maintenance technicians in selecting relevant factors that will be measured.	The maintenance technicians in this industry participated in the study, identifying their perceptions on the most influential factors.
Kumar et al. (2013)	Measurements should be industry-specific.	This thesis is focused on the electricity transmission industry. As no known framework exist for this specific industry the research roadmap was followed to align measurements to the specific industry.
Woodhouse (2000)	The chosen measurements should have the greatest impact	The 4 identified factors have a cumulative frequency of 72%.

From this, high workload, time pressure, fatigue and communication are used to answer RQ1 "What maintenance human factors have the most influence on maintenance human errors?

7.2. RQ2: Maintenance human factors performance indicators and maintenance performance framework?

The final identified maintenance human factors from RQ1 will be included in the maintenance performance framework that form part of RQ2. These identified maintenance human factors need to be assigned measurements and measurement methods to be incorporated within the maintenance performance framework. Therefore, RQ2 can be divided into two sections:

- RQ2a: Measurements and measurement methods for the chosen maintenance human factors, and
- RQ2b: Incorporation of the measurements into a proposed maintenance performance framework.

7.2.1. RQ2a: Measurements and measurement method for maintenance human factors

Chapter 2 identified measurements and measurement methods for maintenance human factors through an explorative literature review (Table 2.11 to Table 2.13). Table 7.4 condenses this to only show the measurements and measurement methods for the chosen influential maintenance human factors as per RQ1.

In the maintenance technicians' questionnaire, maintenance technicians were asked about their willingness to provide personal data to measure maintenance human factors. Most maintenance technicians answered that they would probably do so, if the data was to be collected by trained medical professional and if their confidentiality would be insured. A median of 7/10 was recorded for willingness to provide data relating to personal fatigue levels and heart rate data. A median of 6/10 shows the probability that maintenance technicians would agree to provide personal life stress data as compared to the median of 8/10 for willingness to provide work stress levels.

Table 7.4: Maintenance human factors aligned with the number of measurements and measurement methods

Indicators	Measurement	Measurement methods	Reference
Workload	National Aeronautics and Space Administration Task Load Index (NASA-TLX) Trier Inventory for the Assessment of Chronic Stress (TICS) Cooper Harper rating scale Subjective Workload Assessment Technique (SWAT) Galvanic Skin Response Parasympathetic/sympathetic ratio, HR, HRV, diastolic pressure, systolic pressure, eye blink frequency and eye blink duration Cortisol responses after wakening Pupil size, average fixation time, fixation frequency, saccade frequency and average saccade velocity changed considerably with mental workload. Air Traffic Workload Input Technique (ATWIT) Instantaneous Self-Assessment (ISA) Impact on Mental Workload (AIM) Rating Scale of Mental Effort (RSME) Primary task performance Secondary task performance Performance and Usability Modelling (PUMA) Physiological measures	Questionnaire, physiological measurement	Guhe et al. (2005) Hwang et al. (2008) Schulz et al. (1998) de Winter (2014) He et al. (2012) Kovesdi et al. (2018) Langan-Fox et al. (2009)
Time Pressure	Roxburgh (2004) time pressure scale Teng et al. (2010) questionnaire Instrument for Stress Oriented Task Analysis (ISTA)	Questionnaire	Roxburgh (2004) Teng et al. (2010) Widmer et al. (2012)
Fatigue	Multidimensional Fatigue Inventory (MFI) Fatigue Severity Scale (FSS) Nottingham Health Profile (NHP) Polio Problem List (PPL) Dutch Short Fatigue Questionnaire (SFQ). Burnout Clinical Subtype Questionnaire (BCSQ-36) Maslach Burnout Inventory-Human Service Scale (MBIHSS) Sleep Quality measurement (nocturnal polysomnography)	Questionnaire, physiological measurement	Smets et al. (1995) Harrington (1994) Horemans et al. (2004) Montero-Marín and García-Campayo (2010) Grunfeld et al. (2000) Maslach and Jackson (1981)

Indicators	Measurement	Measurement methods	Reference
Communication	Roberts and O'reilly 35-item questionnaire Communication Satisfaction Questionnaire (CSQ) Listening characteristics Questionnaire Rosenfeld and Berko (1990) Questionnaire Roberts and O'reilly (1974) Questionnaire	Questionnaire	Roberts and O'reilly (1974) Downs and Hazen (1977) Federal Aviation Administration (2006) Rosenfeld and Berko (1990) Roberts and O'reilly (1974)

This indicates that the maintenance technicians would be willing to provide data to a trained medical professional if their confidentiality would be insured. The organisation has processes and procedures in place to obtain medical data from staff through fitness of duty testing. These tests are performed by medically trained personnel and are sanctioned by labour laws and by the relevant regulatory medical bodies. Therefore, it may be possible to use these regular fitness of duty tests to collect the required data.

7.2.1.1. Proposed measurement methods for high workload

O'Donnell and Eggemeier (1986) provide a complex definition by defining workload as “the portion of the operator's limited capacity required to perform a particular task.” It can be divided into physical workload and mental workload. Hwang et al. (2008) states the generic definition of mental workload as “the amount of resource difference between task demands and capacity provision by an individual.” For high workload 11 questionnaires and 17 physiological measurement are listed in Table 7.4.

Workload measurements, such as planned workload hours (as per maintenance planning), actual planned workload hours (as per the ERP system), overtime worked and staff utilization are heavily critiqued. Some of the critiques on subjective workload are that only face validity has been considered; another concern is that mental workload is not measured. De Winter (2014) argues that (mental) workload is the most used human factor and is easily measured with questionnaires.

The best known assessment of workload is the NASA Task Load Index (NASA-TLX). The NASA-TLX assesses workload within the following dimensions: Mental demand, Physical demand, Temporal demand, Performance effort and Frustration level (Rendon-Velez et al., 2016). de Winter (2014) critiques the excessive use of the NASA-TLX as a measurement tool for workload as specific operational (pragmatic) concerns have not been addressed. The NASA-TLX is orientated to a specific task and not to the overall workload state of personnel.

Most of the remaining measurements list focus on the aviation industry. Based on this, on the fact that mental workload is easily measured with questionnaires and on the shortcomings of the NASA-TLX, the author recommends the use of eight questions from the chronic work overload scale of the Trier Inventory of Chronic Stress (TICS). These questions are (Schulz et al., 1998):

- Too many commitments that I am in charge of.
- The feeling that tasks are too much for me.
- Postponement of urgently needed recreation.
- Too many duties that I have to do.
- Not enough time to fulfil my daily assignments.
- Overload through different duties that I need to take care of.
- Situations with so many difficulties that I cannot deal with all of them.
- The feeling that it is all too much for me.

The original questionnaire used a 5-point Likert scale ranging from never to very frequently. This was changed to a 7-point Likert scale to stay consistent with the other questionnaires.

7.2.1.2. Proposed measurement methods for time pressure

Teng et al. (2010) state that “Time pressure is a psychological urgency attributed to insufficient time for completing required tasks”. Three time pressure questionnaires were mentioned in this thesis: Roxburgh’s (2004) time pressure scale, Teng et al.’s (2010) adapted time pressure scale questionnaire and the Instrument for Stress Oriented Task Analysis (ISTA). To stay consistent with the literature recommendation in Chapter 2 and Chapter 3, methods used to obtain data should be relevant and not time consuming to obtain.

It is recommended that Teng et al.’s (2010) adapted time pressure scale questionnaire be used for its simplicity and fast completion.

The adapted time pressure scale questionnaire has 5, 7-point Likert scale, questions. These are:

- I feel high time pressure at work.
- I feel very busy at work.
- I find that the given time at work is very limited.
- I always feel in a hurry during work hours.
- I do not have sufficient time to finish what I should do at work.

7.2.1.3. Proposed measurement methods for fatigue

The clinical definition for fatigue include: ”an overwhelming sense of tiredness, lack of energy or feelings of exhaustion, difficulty initiating or sustaining voluntary effort, feelings of physical tiredness and lack of energy distinct from sadness or weakness, a subjective lack of physical and/or mental energy” (Mills and Young, 2008). Fatigue can be caused by multiple factors as described in the thesis (high workload, night shifts, sleep deprivation, medical conditions, an unhealthy lifestyle, etc.).

Fatigue can also be a symptom of obstructive sleep apnoea. Sleepiness, fatigue, tiredness and lack of energy are commonly experienced in Obstructive Sleep Apnoea. Obstructive Sleep Apnoea is undiagnosed in at least 80% of men and 90% of women (Chervin, 2000). A polysomnographic test can be done at a sleep centre or in a hospital to record sleep patterns and to diagnose Obstructive Sleep Apnoea (Mayo Clinic, 1998-2020). The maintenance staff indicated that they are willing to provide their personal data to a trained medical professional; it may be worthwhile for the organisation to include polysomnography testing at a 2-yearly interval as part of their fitness of duty testing.

From Table 2.11, there are seven fatigue questionnaires. Most of these questionnaires consist of a large number of questions. When obtaining data (filling in questionnaires) become too cumbersome or time consuming the maintenance staff's cooperation may become obligatory rather than voluntary. The author therefore recommends that the Fatigue Severity Scale (FSS) be used.

The Fatigue Severity Scale (FSS) was developed and copyrighted by Krupp et al. (1988), it is a well-known and an easy to use questionnaire with 9 (7-point Likert scale) questions. The questions are as follows. During the past week, I have found that:

- My motivation is lower when I am fatigued,
- Exercise brings on my fatigue,
- I am easily fatigued,
- Fatigue interferes with my physical functioning,
- Fatigue causes frequent problems for me,
- My fatigue prevents sustained physical functioning,
- Fatigue interferes with carrying out certain duties and responsibilities,
- Fatigue is among my three most disabling symptoms, and
- Fatigue interferes with my work, family, or social life.

7.2.1.4. Proposed measurement methods for communication

Five communication questionnaires are listed in Table 2.11. Roberts and O'reilly's (1974) questionnaire consists of 35 questions. Rosenfeld and Berko (1990) questionnaire consists of 30 questions. The FAA's listening characteristics questionnaire is a self-reporting questionnaire to rate listening characteristics. Questions are for instance: "Do I allow the speaker to express his or her complete thoughts without interrupting?". This questionnaire will therefore not be suitable for the intended purpose of this thesis.

The well-known Downs-Hazen CSQ has been adapted by several authors (Crino and White, 1981; Hamilton, 1987; Greenbaum, 1988; Clampitt and Willihnganz, 1988). Meintjes and Steyn (2006) adapted the CSQ for the South African environment, where only three to four items are used to measure the eight constructs:

- personal feedback,
- corporate perspective,
- organisational integration,
- relationship with supervisor,
- communication climate,

- horizontal communication,
- media quality, and
- relationship with subordinates.

Because Meintjes and Steyn (2006) adapted the CSQ for the South African environment, the author proposes that this questionnaire should be used. Not all 8 constructs are needed for the purpose of determining a communication measurement. Therefore, only 5 constructs were chosen for this purpose. The original questionnaire used a 5-point Likert scale; this will be changed to a 7-point Likert scale to stay consistent with the other questionnaires.

Table 7.5: Maintenance communication questionnaire

Construct	"How satisfied are you with…."
Communication climate	receiving the information needed to do your job on time? conflicts being handled appropriately through proper communication channels?
Supervisor communication	your supervisor listening to you? your supervisor offering guidance for solving job-related problems? your supervisor trusting you? your supervisor being open to ideas?
Organisational integration	information on the requirements of your job?
Media quality	your meetings being well organised?
Personal feedback	information on how you are being evaluated? recognition of your efforts? your superior's understanding of the problems faced by subordinates?

Source: adapted from Meintjes and Steyn (2006)

7.2.2. RQ2b: Proposed maintenance performance framework

Once a company adopted a maintenance performance framework, the maintenance human factors in that framework need to be updated regularly. The author recommends the chosen maintenance human factors included in the maintenance performance framework should be tested against the principles set out in the theoretic framework of Section 3.2, similar to what was done for RQ2a. The author recommends that Kennerley and Neely's (2003) test of relevance be done at regular time intervals to maximize the benefit of the measurement framework. This is to prevent other factors gaining more influence as the original factors may now be actively managed. The test of relevance questions can be asked at monthly operational meetings. For ease of reference, the test of relevance is shown again in Table 7.6.

Table 7.6: Test of relevance for individual performance measures

Test	Question
The truth test	Is the measure definitely measuring what it's meant to measure?
The focus test	Is the measure only measuring what it's meant to measure?
The consistency test	Is the measure consistent whenever or whoever measures?
The access test	Can the data be readily communicated and easily understood?
The clarity test	Is any ambiguity possible in interpretation of the results?
The so what test	Can, and will, the data be acted upon?
The timeliness test	Can the data be analysed soon enough so that action can be taken?
The cost test	Is it worth the cost of collecting and analysing the data?
The gaming test	Does the measure encourage any undesirable behaviours?

Source: Kennerley and Neely (2003)

If a maintenance performance measurement fails the test of relevance, action should be taken to address the aspect of concern. If the measurement repeatedly fails, the following difficult questions should be asked:

- Is the failure caused by a systemic problem in the effectiveness of the maintenance resource management system? In other words, does it highlight shortcomings in management principles?
- Is the failure caused by a systemic problem in the organisation? In other words, does it highlight shortcomings of unwanted truths or misalignment between the maintenance department's goals and strategies and the organisation's goals and strategies?

7.2.2.1. Calculation and examples of a maintenance human factor performance score (MHFP)

By using the chosen MHFP framework, calculation of the MHFP score can start by adapting Visser and Pretorius (2003) TMP scoring formula, the MHFP score can be calculated, as below:

$$MHFP = \sum_{i}^{n} W_i B_i \tag{2}$$

Where B_i is the benefit value, W_i is the weight for factor i, and n is the number of factors.

Table 7.7 and Table 7.8 shows the scoring methodology and calculation method to determine the minimum and maximum value of a MHFP indicator. The minimum and maximum values for the MHFP indicator are based on the indicator's questionnaire scoring methodology. The methodology is based on the questionnaire approach such as: are the questions phrased in a positive or negative way?

Table 7.7: Questionnaires scoring methodology

	Scoring methodology: minimum score	Scoring methodology: maximum score	Preferred score
High workload	Indicates low chronic work overload	Indicates low chronic work overload	As low as possible
Time pressure	Indicates low time pressure	Indicates high time pressure	As low as possible
Fatigue	Indicates low fatigue	Indicates high fatigue	As low as possible
Communication	Indicates dissatisfaction in communication	Indicates satisfaction in communication	As high as possible

For all the questionnaires, a 7-point Liked scale is used. High workload ranges from 1 indicating never and 7 indicating very frequently. For time pressure and fatigue, 1 indicates strongly disagree and 7 indicates strongly agree. For communication, 1 indicates strongly dissatisfied and 7 indicates strongly satisfied. The MHFP value of the indicator is determined by the summation of the respondents' Likert scores for each questionnaire.

Table 7.8: Calculating MHFP minimum and maximum values

Formula	Likert scale	Number of questions	MHFP Min value (# questions)* (min scale)	MHFP Max value (# questions)* (max scale)	Preferred value
High workload	1 - 7	8	8	56	minimum
Time pressure	1 - 7	5	5	35	minimum
Fatigue	1 - 7	9	9	63	minimum
Communication	1 - 7	11	11	77	maximum

In most cases B_i is a normalised valued (0 -1) and can be calculated using a straight line equation. The normalised value is influenced by the minimum and maximum values of the indicator. The benefit value should reflect the benefit added to the organisation. Therefore, there will be a difference in calculation methods, depending on whether the minimum or the maximum value of the indicator is preferred.

Table 7.9 and Table 7.10 shows the calculation methods of the B_i value, based on the preferred minimum or maximum value of the indicator. The table also provides numeric examples. For a preferred maximum value, the minimum value is the normalised 0. For a preferred minimum value, the maximum value is the normalised 0.

Table 7.9: Determining B_i when the maximum value is preferred

Minimum	Maximum	Value	$B_i = \frac{\text{value - minimum}}{\text{maximum– minimum}}$
11	55	48	0.84

Table 7.10: Determining B_i when the minimum value is preferred

Minimum	Maximum	Value	$B_i = \frac{\text{maximum - value}}{\text{maximum– minimum}}$
9	63	15	0.89

Using the above methods, 2 examples for MHFP scores are illustrated. The response percentages of the four identified factors from the maintenance technician's questionnaire are scaled in the same ratio to determine the W_i value.

Table 7.11: Example 1: all maintenance human factors are scoring well

MHFP Indicator	W_i (%)	Min	Max	Value	B_i	B_i*W_i
High Workload	33	8	56	25	0.65	0.21
Time Pressure	26	5	35	13	0.73	0.19
Fatigue	21	9	63	26	0.69	0.14
Communication	19	11	77	68	0.86	0.16
MHFP score						**0.71**

Table 7.12: Example 2: all maintenance human factors are scoring poorly

MHFP Indicator	W_i (%)	Min	Max	Value	B_i	B_i*W_i
High Workload	33	8	56	45	0.23	0.08
Time Pressure	26	5	35	29	0.20	0.05
Fatigue	21	9	63	51	0.22	0.05
Communication	19	11	77	33	0.33	0.06
MHFP score						**0.24**

The MHFP score values calculated for Example 1 (Table 7.11), will be taken as the MHFP score to be included in the calculation of the final TMP score as shown in Table 7.13.

Table 7.13: TMP score inclusive of maintenance human factors

Maintenance Indicator	W_i (%)	Min	Max	Value	B_i	B_i*W_i
System performance	25	0	1.05	0.64	0.61	0.15
Equipment performance	15	0.88	1.05	0.95	0.41	0.06
Maintenance planning	10	0.80	1.20	1.00	0.50	0.05
Maintenance completion %	10	95	100	98.50	0.70	0.07
MHFP	10	0.60	1	0.71	0.28	0.03
Maintenance cost ratio %	10	90	110	96.00	0.70	0.07
Maintenance errors	5	1	20	9.00	0.58	0.03
Personnel cost ratio %	5	90	110	94.00	0.80	0.04
Safety	10	0	0.36	0.15	0.58	0.06
TMP score						**0.56**

As per Section 3.3, the TMP framework and score follows an organisational hierarchical approach, which is shown again in Figure 7.2, to include maintenance human factors in an organisational performance measurement framework.

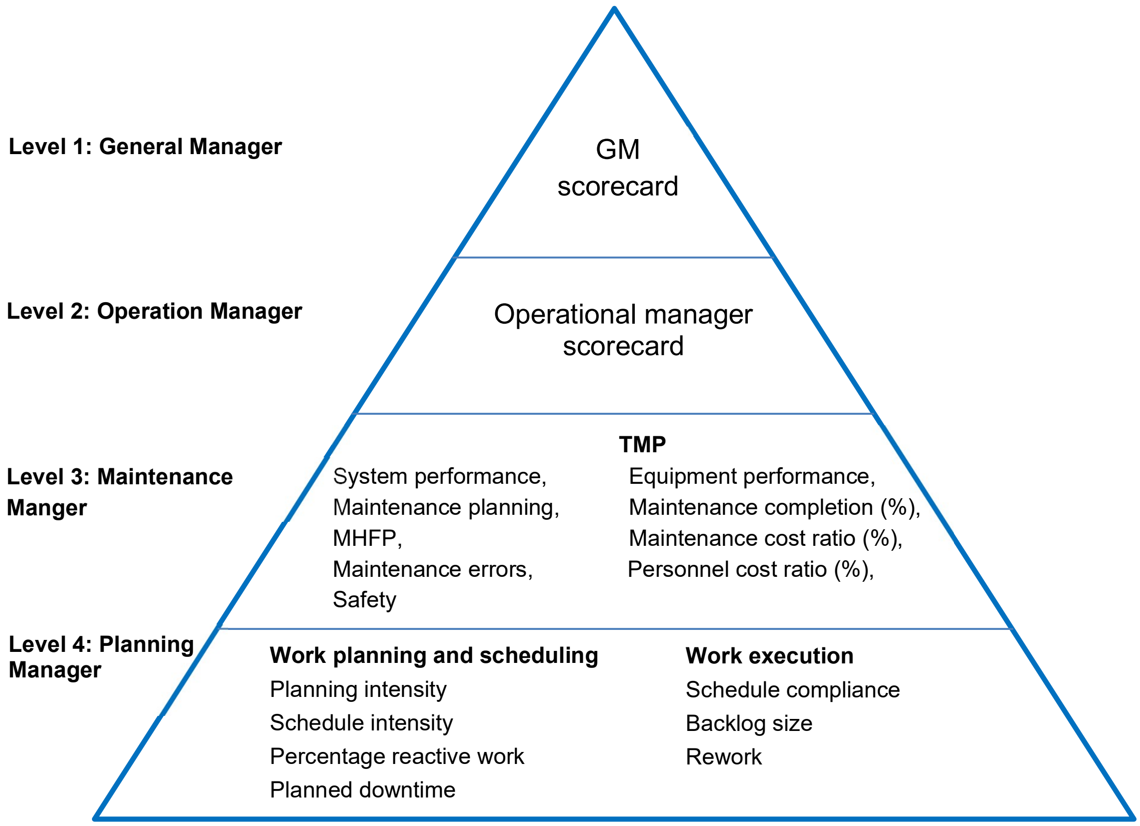

Figure 7.2: Hierarchical maintenance performance framework for the South African electricity transmission industry.

7.3. Chapter summary

In this chapter all the research questions were answered. The most influential maintenance factors within the South African electricity transmission industry were identified (RQ1).

Calculation methods to calculate a MHFP score, as well as the methodology on how these values are derived from the recommended questionnaires, were discussed. In alignment with RQ2 of this thesis, maintenance human factors were included in a TMP framework by establishing an MHFP framework and score. The movement of the maintenance human factor measurement from a planning managers' responsibility to be included in the TMP indicators improves the importance of the contribution that maintenance human factors have on organisations.

The chapter concluded with a hierarchical example of a maintenance performance framework for the South African electricity transmission industry. Chapter 8 will validate and finalise the proposed framework presented in this thesis by using a Two-round Delphi method.

8. VALIDATION OF RESEARCH OUTPUT

This chapter focusses on validating the proposed hierarchical maintenance performance framework for the South African electricity transmission industry inclusive of maintenance human factors using a Two-round Delphi method. The benefits of using a Delphi method is that research outputs that have high uncertainty and speculation can be validated by using a panel of experts (Okoli and Pawlowski, 2004). A small group of experts, between 10 to 15, within a homogeneous sample, should provide adequate results (Skulmoski et al., 2007).

The first three criteria for selecting qualified members was based on recommendations mentioned in Luu et al. (2008):

- top management decision makers who will utilize the outcomes of the Delphi study,
- professional staff members together with their support team, and
- respondents to the Delphi questionnaire whose judgments are being sought.

Two validation questionnaires were distributed. The first to validate the MHFP framework (Appendix D) and the second to validate the TMP framework (Appendix F). Additional criteria for the expert panel selection are described for each separate questionnaire. Each validation questionnaire had different panel members due to the additional criteria. There were panel members that qualified and served on both panel of experts due to their extreme level of expertise on both subjects.

The thesis is structured starting with a systematic literature review to determine a base of maintenance human factors. They were then ranked by maintenance staff and tested against the findings of the systematic literature review. Using a first round structured questionnaire that is founded on an extensive review of literature is therefore adequate (Hsu and Sandford, 2007). This also implies that the recommendation of Skulmoski et al. (2007) to structure the initial questionnaire with broad questions as a purpose of brainstorming is not necessary.

The first round validation questionnaires consisted mostly of questions to be rated using 5 point Likert-type items ranging from strongly disagree to strongly agree. Due to the non-equal-interval characteristics of Likert-type questions, strongly disagree and disagree were combine to determine disagreement. Similarly, agree and strongly agree were combined to determine agreement.

A Two-round Delphi methodology was followed to determine if agreement or disagreement exists within the panel of experts on the statements in the questionnaire. For the first round, strong consensus was defined as when more that 70% of participants either disagreed or agreed, similar to De Villers et al. (2005). For the second round questionnaire consensus and stability were determined through a combination of factors (Holey et al., 2007):

- Percentage analysis and trends
- Comments analysis and trends
- Mode comparisons (movement to central tendency).

Care should be taken in the second round when analysing percentages as non-responders may cause misleading oscillatory movements (Holey et al., 2007). Another limitation of a predefined percentage specification is that items might fall just below the limit. Diamond et al. (2014) critiques that definitions for consensus in Delphi methods vary extensively. From their analysis, percentage agreement thresholds ranged from 50% to 97%, with a median of 75%. They therefore see the threshold limit as “fundamentally an arbitrary cut off”. For this reason they recommend that researches should consider including those items, provided adequate reasons are given.

The results of the Delphi method are illustrated graphically using the frequency response of disagreement and agreement with a dotted line to indicate the required consensus mark. The results are then summarised in tabular form displaying the mode, the disagreement and agreement results and the consensus status. The use of mode when analysing Delphi method data is suitable to avoid instances such as clustering of results around 2 or more points which could cause the median of the results to be misleading (Luu et al., 2008).

For the second round Delphi questionnaires an overall summary of the first round results was provided to the participants. Items that reached consensus in the first round were not re-evaluated. For other questions, such as the weighting of factors in the measuring framework, the weights that had consensus were shown, but the participant could only rate/comment on the factors where no consensus were reached.

Within the first round questionnaire, a significant number of participant chose the mid-point of the Likert-type response (neutral). Most Likert questions have a neutral midpoint, but it is not a requirement (Cooper and Johnson, 2016). In order to combat the reoccurrence of participants not providing definitive opinions, the second round used either a 4 point or a 6 point Likert-type response as given below:

- Strongly disagree (SD)
- Disagree (D)
- Slightly disagree (only for 6 point Likert-type)
- Slightly agree (only for 6 point Likert-type)
- Agree (A)
- Strongly agree (SA)

8.1. MHFP framework: Delphi round 1

8.1.1. Questionnaire construction

The purpose of the first round questionnaire was to confirm RQ1, RQ2, the most significant maintenance human factors identified and the weighting factors used for these factors when calculating the MHFP score.

The questions were categorised into the following categories:

- Identification and area of experience (the identification of participants were coded to ensure anonymity),
- RQ1 confirming the organisational gap, the current state within the organisation and the benefits of answering RQ1,
- significant maintenance human factors identified, and
- the weighting of each indicator within the MHFP score.

8.1.2. Data gathering process

The second criteria for selecting the expert panels members was their area of experience in maintenance human factors. Their expertise had to consist either of one or more of the following:

- Member of the Human Performance Operating Committee.
- Operating error/human error investigations.
- Defence in-depth incident and operational safety analysis.
- Reporting on operating error/human error performance.
- Training on operating error/human error investigations.
- Management.
- Chief engineer.

Once the panel of experts were identified, they were contacted via a individually addressed emails on the 18th of May 2021. The email contained a hyperlink to the questionnaire which was hosted on www.kwiksurveys.com. The participants were assured that their participation is entirely voluntary and anonymous and that all information obtained from the questionnaire will be strictly confidential. The participants were also informed that they have the right to withdraw at any stage without any penalty or future disadvantage.

Personal contact was made close to the end date of the questionnaire to serve as a reminder of the upcoming closing date. The questionnaire was closed on the 1st of June 2021.

Blank respondent data (the participant selected the first continue answer, but did not complete the questionnaire) was removed. Where a respondent started the questionnaire, but did not finish or return later to complete the questionnaire, only the completed data was used. Data from respondents that completed the questionnaire, but did not answer all the questions, was not removed. For this reason, each question has a unique number of total responses. After the data clean up, 18 responses from the panel of experts remained for data processing.

All information gathered through the survey was exported from Kwiksurveys to Microsoft Excel. Graphs and basic statistical calculations provided by Kwiksurveys and calculated with Microsoft Excel. These graphs and basic statistical calculations can be found in Appendix H.

8.1.3. Data gathered

The identities of the participants are treated as confidential and will not be mentioned in the thesis. Where comments were made to certain questions, participant coding will be used.

The 18 participants that formed the panel of experts' areas of expertise are shown in Figure 8.1. The participants were able to select one or more option.

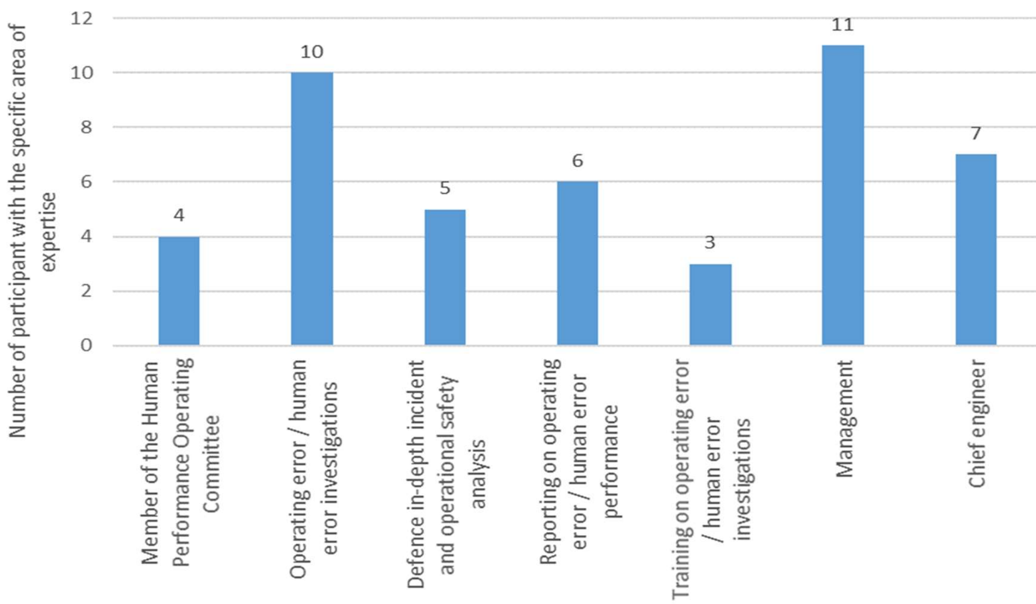

Figure 8.1: Panel of expert's area of expertise

Five questions regarding the most influential maintenance human factors within the organisation were asked. This was to confirm the organisational gap, the current state within the organisation and the benefits of answering RQ1. The results are shown in Figure 8.2.

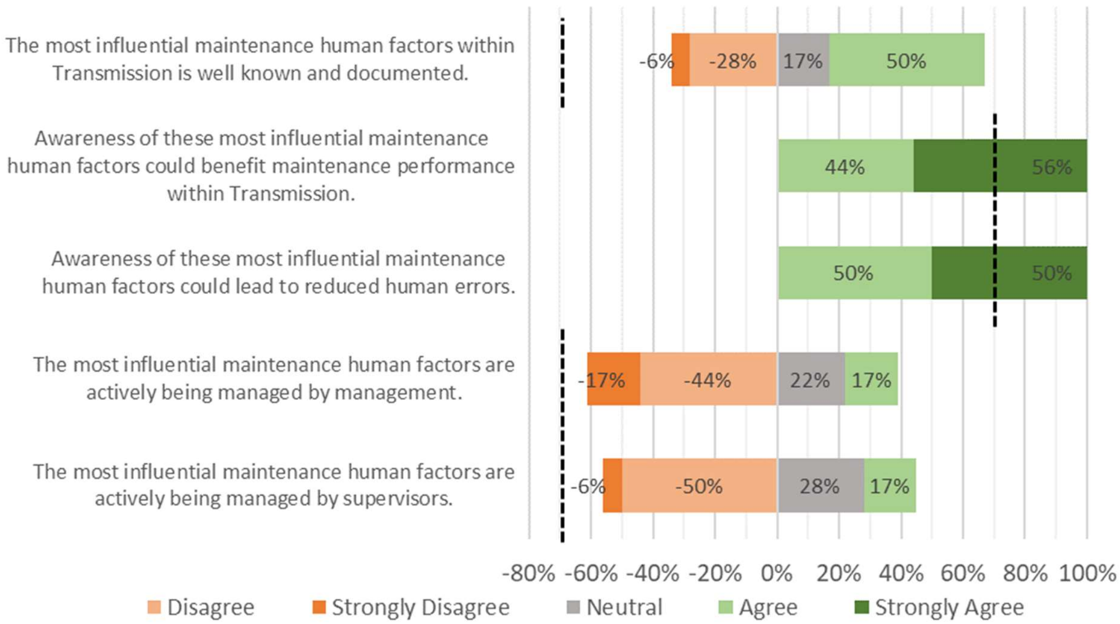

Figure 8.2: Confirmation of organisational gap, current state and benefits of RQ1

Consensus was achieved that awareness of the most influential maintenance factors could have benefits in terms of performance and reduction in human error. Consensus on the identification and documentation, management by management and management by supervisors did not achieve consensus. Whether the most influential maintenance human factors are actively being management by management and management by supervisors had a dominant aspect that they are not being managed.

47% of the respondents agreed that the most influential maintenance human factors are known and well documented. 31% disagreed. Despite the percentage of respondents agreeing being higher, a trend cannot be assumed due to the large number of neutral responses.

Four questions regarding the measurement of the influential maintenance human factors within the organisation were asked. This was to confirm the organisational gap and to confirm the benefits of answering RQ2. The results are shown in Figure 8.3.

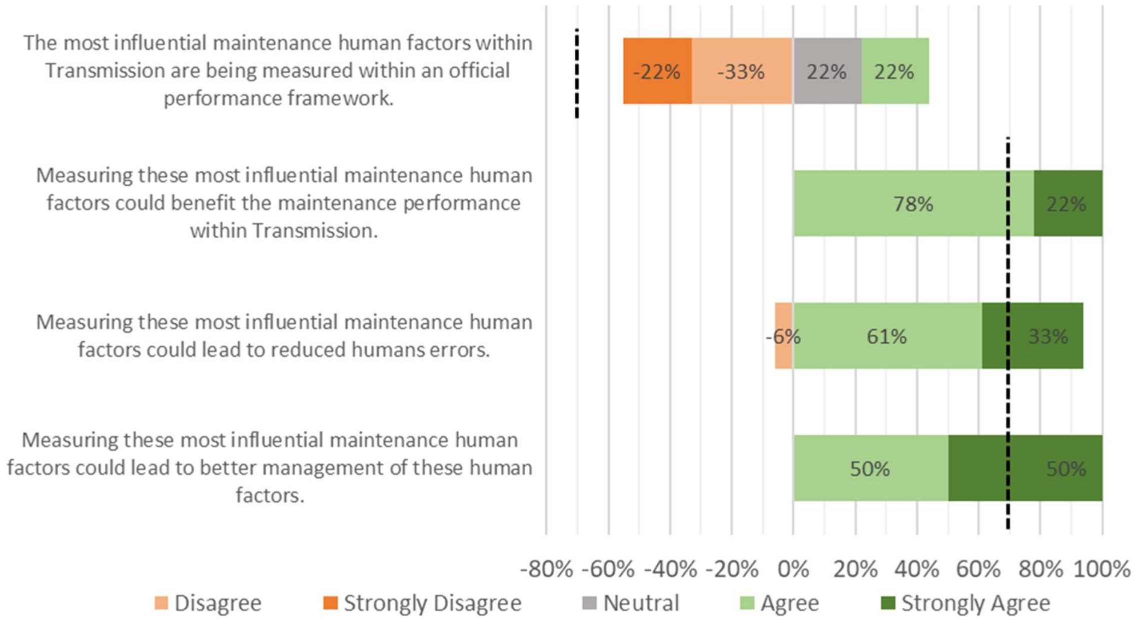

Figure 8.3: Measuring of the influential maintenance human factors within the organisation

Consensus was achieved that measuring the most influential maintenance human factors could have benefits in terms of performance, reduction in human error and better management of these influential maintenance human factors. The results of the question of whether the most influential maintenance human factors are currently being managed show a tendency of disagreement (55%) compared to agreement (22%).

The most influential maintenance human factors identified from the maintenance technicians' questionnaire, which have contributed to a personal maintenance error made, were provided to the panel of experts. They were asked if, in their experience, they would agree or disagree that these factors contribute significantly to human errors. This is shown in Figure 8.4.

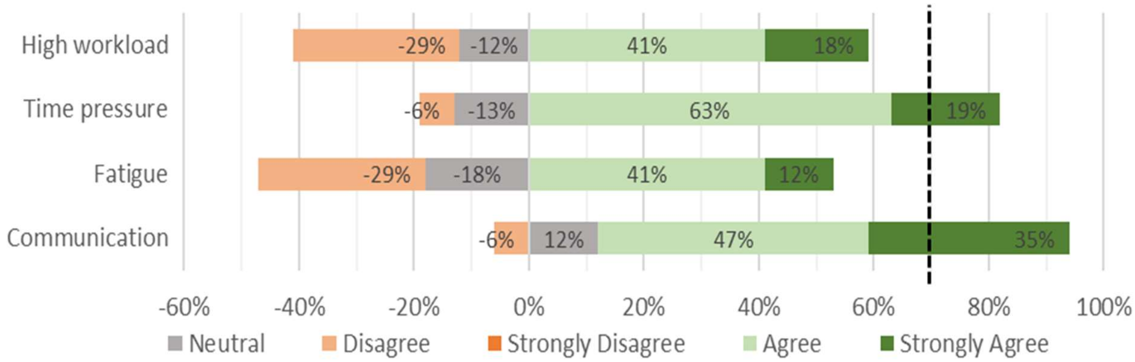

Figure 8.4: Contribution of maintenance human factor on human errors

Consensus were achieved that time pressure and communication significantly contributes to human errors. Consensus on high work load and fatigue was not achieved but had a dominant aspect of agreement.

For the second last question, the panel were asked to confirm the MHFP weighting of each of the identified maintenance human factors (Figure 8.5). The proposed weightings were:

- high workload 33%,
- time pressure 26%,
- fatigue 22%, and
- communication 19%

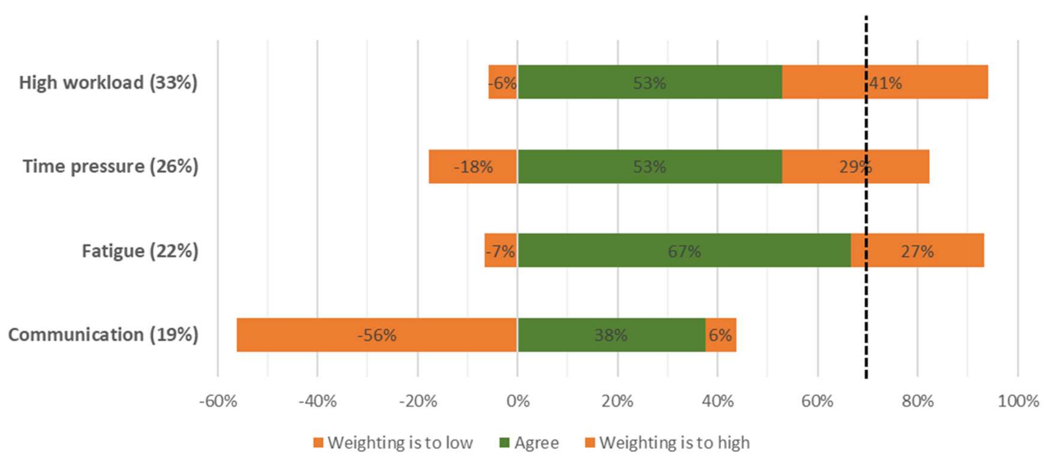

Figure 8.5: Agreement on MHFP weighting of each indicator

Close consensus on the weighting of fatigue were achieved, but overall no consensus were achieved. The feedback if the weight was too low or too high was used to adjust the weighting within the second round Delphi questionnaire.

In the last question, the panel was asked who would be best to calculate or determine these measurements. The participants were allowed to choose more than one option. The results are shown in Figure 8.6. Four possible entities were identified.

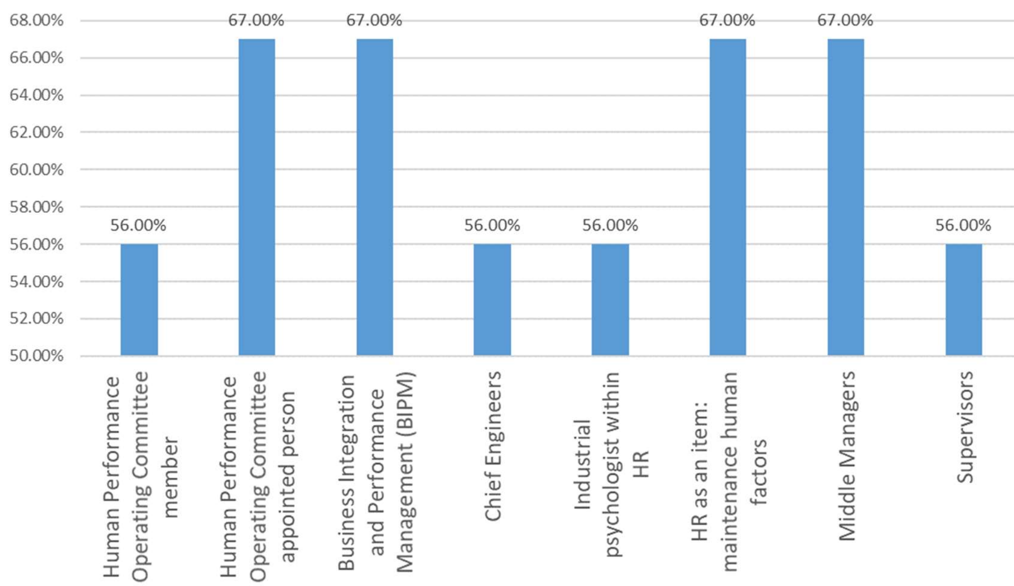

Figure 8.6: Calculation responsibility of MHFP indicators

Table 8.1 provides a summary of maintenance performance framework validation results. 7 of out the 17 statement achieved consensus and 8 of the 17 had leaned towards mutual agreement (50% – 70% of the panel had same opinion).

Table 8.1: Summary of maintenance human factors validation results

Question goal		Question	Mode	Disagreement / Agreement (n, %)	Criteria	Conclusion
RQ1: Maintenance Human Factors	Confirm organisational gap	The most influential maintenance human factors within Transmission is well known and documented.	Agree	6 (34%) / 9 (50%)	>70% disagreement	Dissensus
	Determine current status	The most influential maintenance human factors are actively being managed by management.	Disagree	11 (61%) / 3 (17%)	>70% disagreement	Dissensus
	Determine current status	The most influential maintenance human factors are actively being managed by supervisors.	Disagree	10 (56%) / 3 (17%)	>70% disagreement	Dissensus
	Confirm benefit	Awareness of these most influential maintenance human factors could benefit maintenance performance within Transmission.	Strongly agree	0 (0%) / 18 (100%)	>70% agreement	Consensus
	Confirm benefit	Awareness of these most influential maintenance human factors could lead to reduced human errors.	Strongly agree	0 (0%) / 18 (100%)	>70% agreement	Consensus
RQ2a: Measurements and measurement method for the chosen maintenance human factors	Confirm organisational gap	The most influential maintenance human factors within Transmission are being measured within an official performance framework.	Disagree	10 (55%) / 4 (22%)	>70% disagreement	Dissensus
	Confirm benefit	Measuring these most influential maintenance human factors could benefit the maintenance performance within Transmission.	Agree	0 (0%) / 18 (100%)	>70% agreement	Consensus
	Confirm benefit	Measuring these most influential maintenance human factors could lead to reduced humans errors.	Agree	1 (6%) / 17 (94%)	>70% agreement	Consensus
	Confirm benefit	Measuring these most influential maintenance human factors could lead to better management of these human factors.	Agree	0 (0%) / 18 (100%)	>70% agreement	Consensus
Significance of maintenance human factor		High workload	Agree	5 (29%) / 10 (59%)	>70% agreement	Dissensus
		Time pressure	Agree	1 (6%) /13 (82%)	>70% agreement	Consensus
		Fatigue	Agree	5 (29%) / 9 (53%)	>70% agreement	Dissensus
		Communication	Agree	1 (6%) / 14 (82%)	>70% agreement	Consensus
MHFP weighting of each of the identified maintenance human factors		High workload 33%	Agree	8 (47%) / 9 (53%)	>70% agreement	Dissensus
		Time pressure 26%	Agree	8 (47%) / 9 (53%)	>70% agreement	Dissensus
		Fatigue 22%	Agree	5 (33%) / 10 (67%)	>70% agreement	Dissensus
		Communication 19%	Weighting is to low	10 (63%) /6 (38%)	>70% agreement	Dissensus

8.2. MHFP framework: Delphi round 2

The results of the first round questionnaire were the basis for the second round questionnaire. Additional expansion questions were added where the first responses to the first round's questions were inconsistent. These additional questions aimed at determining the reason for the inconsistency of the results.

8.2.1. Questionnaire construction

In the second questionnaire (Appendix E) only the participant's name and email address were asked for as the information was already obtained. The participants received feedback on questions that have reached consensus and were only asked to answer question were consensus was not achieved.

The responses to the questions for RQ1, the current status of managing maintenance human factors, did not achieve consensus. Within the first round questionnaire 58% of participants disagreed/strongly disagreed with the below statements, 26% of the participants remained neutral and only 16% agreed/strongly agreed with the original statements. The statements were rephrased to:

- The most influential maintenance human factors are NOT actively being managed by management.
- The most influential maintenance human factors are NOT actively being managed by supervisors.

To understand the inconsistent responses from the participants in the first round, 4 statements were added to the questionnaire:

- Knowledge of human error causes are based on work experience
- Knowledge of human error causes are based on record keeping, historical data and mathematical calculations.
- Knowledge of the **underlying human factor** that lead to the human errors are based on work experience.
- Knowledge of the **underlying human factor** that lead to the human errors record keeping, historical data and mathematical calculations.

The participants were asked to evaluate (or indicate their level of agreement according to the Likert scale) the original statements again. The statement was divided into two parts:

- The most influential maintenance human factors within Transmission are well known.
- The most influential maintenance human factors within Transmission are well documented.

The results of the questions meant to confirm whether there is an organisational gap (RQ2) did not achieve consensus. Therefore, the participants were given the first round results (55% strongly disagree & disagree, 22% neutral, and 22% agreed & strongly agreed) and asked to indicate their level of agreement with the statement below:

- The most influential maintenance human factors within Transmission are NOT being measured within an official performance framework.

Two of the most influential maintenance human factors identified (time pressure and communication) did not achieve consensus that they contribute significantly to maintenance human errors. The results of the first round were presented to the panel. They were asked to confirm if the statements below are valid:

- High workload contributes significantly to maintenance human errors.
- Fatigue contributes significantly to maintenance human errors.

The weightings of the MHFP indictors were adjusted based on the feedback received from participants and they were asked to re-evaluate the new, proposed weightings. The changes are shown below in Table 8.2.

Table 8.2: Round 2 MHFP indicator weightings

	Weighing (Round 1)	Suggested weighting (Round 2)
High workload	33%	28%
Time pressure	26%	24%
Fatigue	22%	22%
Communication	19%	26%

In the last question the participants were asked to indicate, from the 4 identified entities, who they think would be best suited to calculate/determine the MHFP score.

- Human Performance Operating Committee appointed person.
- Business Integration and Performance Management.
- HR as an item: maintenance human factors.
- Middle Managers.

8.2.2. Data gathering process

The panel of experts from the first round were individually addressed per email on the 14th of June 2021. The email thanked them for their participation in the first round and requested them to participate in the follow-up round. The email contained a hyperlink to the questionnaire which was hosted on www.kwiksurveys.com.

Personal contact was made close to the end date of the questionnaire to serve as a reminder of the upcoming closing date. The questionnaire was closed on the 24th of June 2021. 83% (15) of the first round panel members participated in the second round.

Blank respondent data (the participant selected the first continue answer) but did not completed the questionnaire was removed. All information gathered through the survey was exported from Kwiksurveys to Microsoft Excel. Graphs and basic statistical calculations provided by Kwiksurveys and calculated with Microsoft Excel were used in this chapter. These graphs and basic statistical calculations can be found in Appendix H.

8.2.3. Data gathered

With the first question the current state of managing maintenance human factor within the organisation regarding RQ1 was revaluated. The results are shown in Figure 8.7. An increase in percentage consensus is seen, although due to the neutral option no longer being available an increase is disagreement is also seen. It should be noted that the statement is now phrased in the opposite manner as in Round 2.

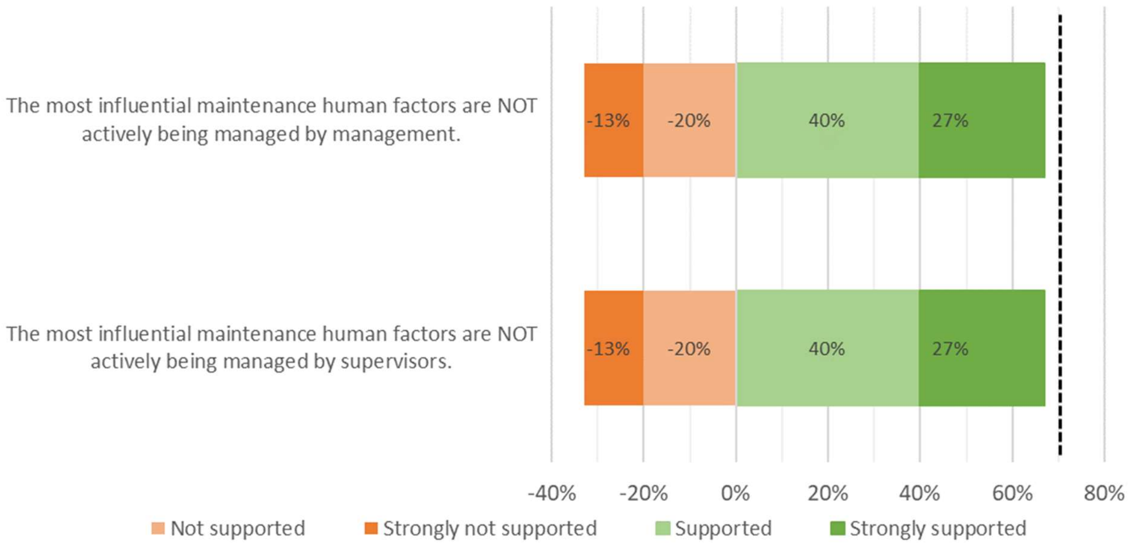

Figure 8.7: Management (current state) of the influential maintenance human factors within the organisation (round 2)

The ratio of responses supporting the statement in terms of management managing maintenance human factors changed from 11 (61%) / 3 (17%) to 10 (67%) / 5 (33%). Two participants withdrawing their support offset the additional support of the statement received from the opinion change from the round 1 neutral responses. The ratio of consensus in terms of supervisor managing maintenance human factors changed from 10 (56%) / 3 (17%) to 10 (67%) / 5 (33%).

The ratio of responses supporting and not supporting the statements is relatively stable across the two rounds. The percentage increase is due to the reduced number of participants. The mode of the responses to the statements, in both rounds, indicate that maintenance human factors are not actively being managed..

The five participants that disagreed with the statements are from Occupational Hygiene and Safety, Chief Advisor Human performance, Senior Advisor Safety Risk Management, Senior Technologist Electric and Middle Manager - Grid Operations.

Only one participant provided a comment on the questions and is shown as a verbatim quote below.

"The practice of integrating human factors into day to day work and operating processes are not demonstrated through the use of the incident investigation processes. This process is triggered by a human and organisational event. We do not always listen to the human when they tell us that they are about to make an error and stop the work. There have been situations when people have been successful in exercising their right to refuse unsafe work."

The participants that agreed to the statements where five Chief Engineers, a Senior Supervisor experienced in human performance training in a nuclear transmission grid environment, three Middle Managers and a Senior Manager. It can be seen that the participants that deal with day to day operations agreed to the statement compared to the non-operational participant. An exception is the Grid Operations Middle Manager, who, from the author's knowledge, is responsible for reporting and strategic planning rather than experiencing day to day operational challenges. This is confirmed by the responses to the second question where close to 70% of the participants agreed that their knowledge is based on work experience and not record keeping, historical data or mathematical calculations (Figure 8.8).

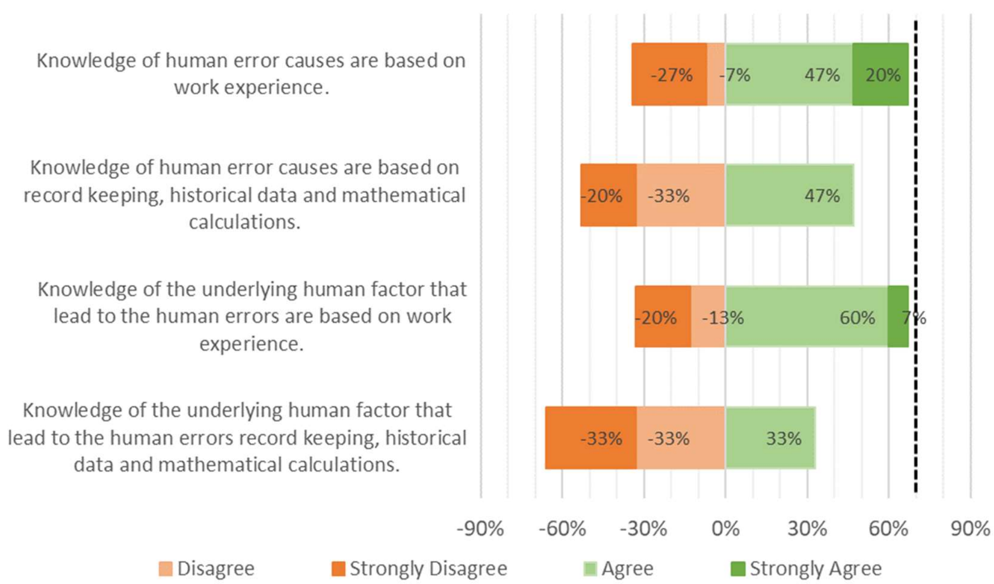

Figure 8.8: Additional questions with regards to the organisational gap

The second question aimed to gain more knowledge regarding the underlying opinions that lead to the results of the first round question "The most influential maintenance human factors within Transmission are well known and documented."

The participants were then asked to answer the original question again. The question was divided into two parts as seen in Figure 8.9. Consensus that the most influential maintenance human factors within Transmission are not documented has been achieved as expected from the additional questions. Dissensus on if the most influential maintenance human factors within Transmission is well known still remains. The ratio of agreement to disagreement remained relatively stable in comparison to the Round 1 question, considering that the neutral option was no longer available.

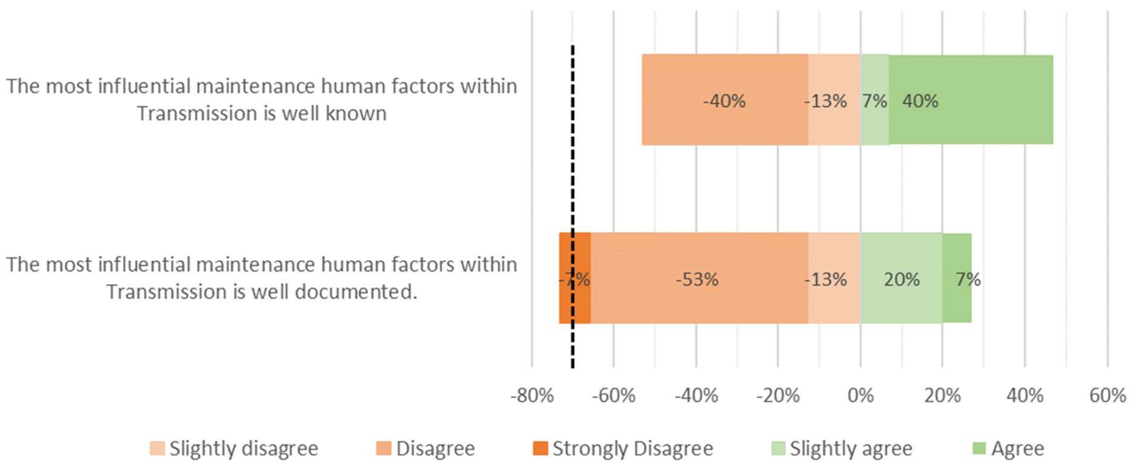

Figure 8.9: Confirmation of organisational gap (round 2)

In the first round 10 (55%) respondents agreed that the most influential maintenance human factors within Transmission are **NOT** being measured within an official performance framework. Within the second round the number increased to 14 (93%) participants indicating a strong movement of opinions and consensus (Figure 8.10).

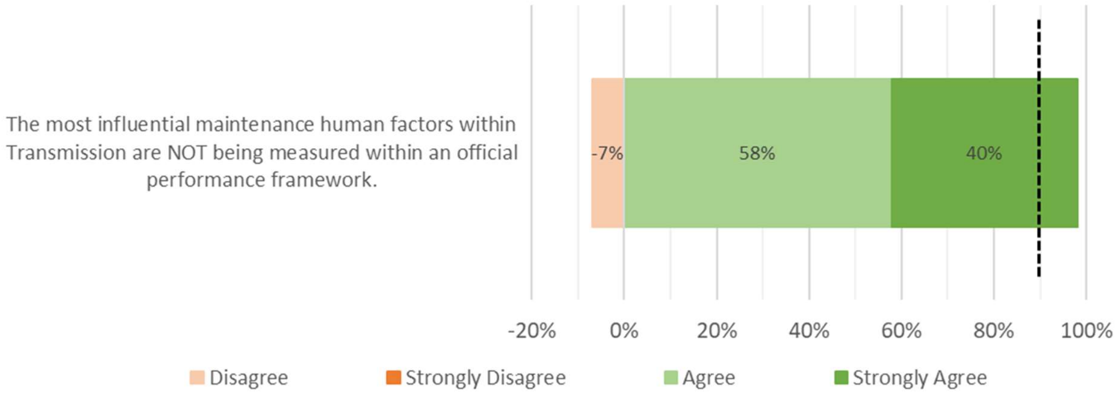

Figure 8.10: Measuring of the influential maintenance human factors within the organisation (round 2)

Two human factors (high workload and fatigue) were retested to determine whether they have a significant influence on maintenance errors (Figure 8.11). When high work load was evaluated in the first round, 5 (29%) of the 17 participants did not agree with the statement and 10 (59%) agreed. In the second round, 6 participants still did not agree and 9 participants agreed.

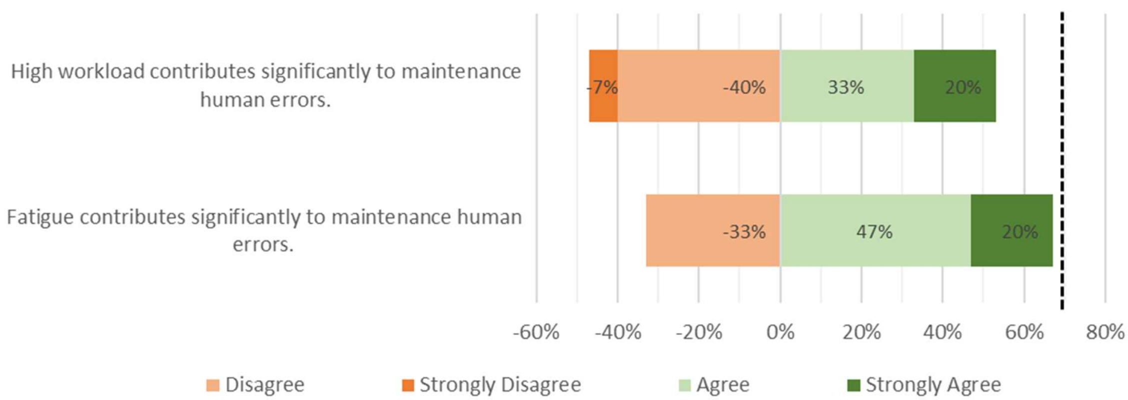

Figure 8.11: Contribution of maintenance human factor on human errors

When fatigue was evaluated in the first round, 5 (29%) of the 17 participants did not agree with the statement and 9 (52%) agreed. In the second round, 5 participants still did not agree and 10 participants agreed.

The ratio of opinions is relatively stable across the two rounds with little shift of opinions. The percentage increase is due to the reduced number of participants. The mode for fatigue remained favourable towards significantly contributing to maintenance errors, where the mode for high workload changed unfavourably toward high workload significantly contributing to maintenance errors.

A higher percentage of participants disagreed with the statement that high workload does not significantly contribute to maintenance human errors than for the statement's counterpart concerning fatigue. One of the Senior Managers commented on the human factors: "The above factors do contribute to human errors but I disagree with contributing significantly to it." Another comment stated that maintenance human errors are more related to skill levels. Four of the participants that did not agree with the statement that high workload significantly contributes to maintenance human errors are Chief Engineers.

The weightings of the MHFP indictors were adjusted based on the feedback received from participants in Round 1. The participants were asked to re-evaluate the new proposed weightings. Figure 8.12 indicates a significant shift to a strong consensus for the new weightings.

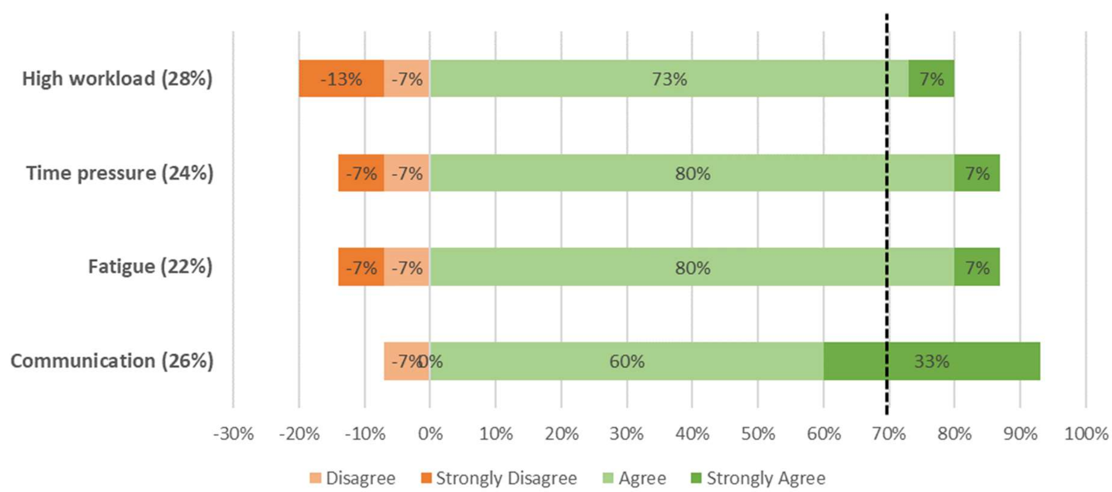

Figure 8.12: Agreement on MHFP weighting of each indicator (round 2)

For the last question consensus (11/15 respondents) indicated that Business Integration and Performance Management would be best suited to calculate/determine these measurements, as indicated in Figure 8.13.

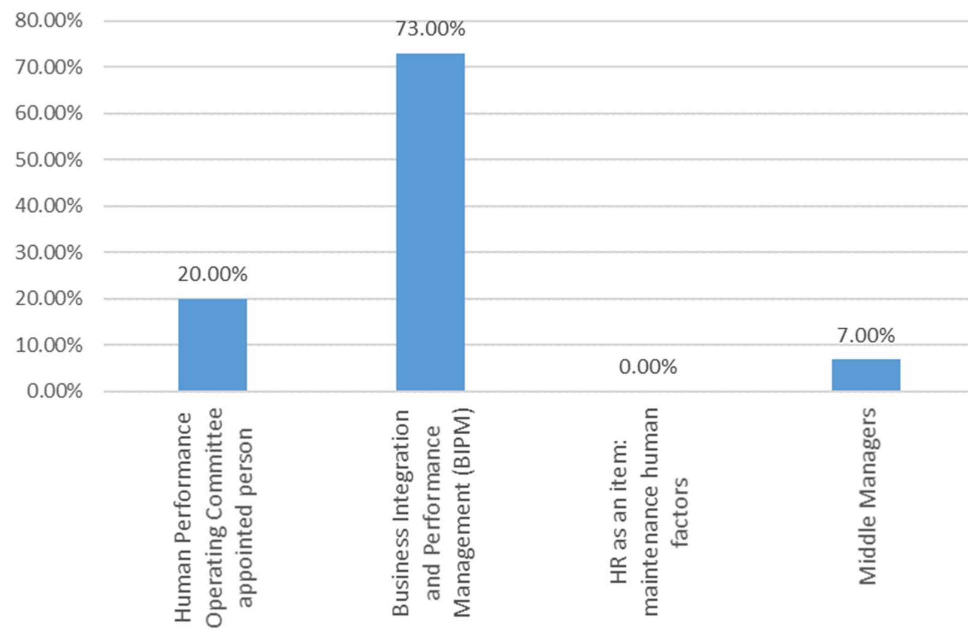

Figure 8.13: Calculation responsibility of MHFP indicators (round 2)

Table 8.3: Summary of maintenance human factors validation results (round 2)

Question goal		Question	Mode	Disagreement / Agreement (n, %)	Criteria	Conclusion
RQ1: Maintenance Human Factors	Confirm organisational gap	The most influential maintenance human factors within Transmission is well known	Disagree	8 (53%) / 7 (47%)	>70% disagreement	Dissensus
	Confirm organisational gap	The most influential maintenance human factors within Transmission is well documented.	Disagree	11 (73%) / 4 (27%)	>70% disagreement	Consensus
	Additional	Knowledge of human error causes are based on work experience.	Agree	5 (33%) / 10 (67%)	Information only	
	Additional	Knowledge of human error causes are based on record keeping, historical data and mathematical calculations.	Agree	8(53%) / 7 (47%)		
	Additional	Knowledge of the underlying human factor that lead to the human errors are based on work experience.	Agree	5 (33%) / 10 (67%)		
	Additional	Knowledge of the underlying human factor that lead to the human errors record keeping, historical data and mathematical calculations.	Strongly Disagree	10 (67%) / 5 (33%)		
	Determine current status	The most influential maintenance human factors are NOT actively being managed by management.	Supported	5 (33%) / 10 (67%)	>70% agreement	Dissensus
	Determine current status	The most influential maintenance human factors are NOT actively being managed by supervisors.	Supported	5 (33%) / 10 (67%)	>70% agreement	Dissensus
RQ2a: Measurements and measurement method for the chosen maintenance human factors	Confirm organisational gap	The most influential maintenance human factors within Transmission are NOT being measured within an official performance framework.	Agree	1 (7%) / 14 (93%)	>70% agreement	Consensus
Significance of maintenance human factor		High workload	Disagree	7 (47%) / 8 (53%)	>70% agreement	Dissensus with contradictions
		Fatigue	Agree	5 (33%) / 10 (67%)	>70% agreement	Dissensus
MHFP weighting of each of the identified maintenance human factors		High workload 28%	Agree	3 (20%) / 12 (80%)	>70% agreement	Consensus
		Time pressure 24%	Agree	2 (14%) / 13 (87%)	>70% agreement	Consensus
		Fatigue 22%	Agree	2 (14%) / 13 (87%)	>70% agreement	Consensus
		Communication 26%	Agree	1 (7%) /14 (93%)	>70% agreement	Consensus

Table 8.3 provides a summary of maintenance performance framework validation results. Statements were no clear consensus could be achieved adds value to this study. It indicates the areas where there are diverse opinions and should be the main focus point for change management for the framework to be implemented. Transmission consist of different geographical areas that are termed Transmission Grids. Each grid has its own manager and from the comments on the questions, it is clear that the diverse opinions can be accounted for by the different management approaches for each grid. Dissensus should be acknowledged as the diverse opinions highlights where problems could be hidden and where more information might be needed (Birko et al., 2015). Dissensus also indicated the clusters of the experts with different views.

8.2.3.1. Dissensus that the most influential maintenance human factors within Transmission is well known

Two questions were asked to determine if an organisational gap exists within the organisation. This was to determine the validity of the contribution that this thesis will make to the South African electricity transmission industry. Dissensus on whether the most influential maintenance human factors within Transmission is well known was determined. This is a result of participants having knowledge based on work experience and not from record keeping, historical data and mathematical calculations. This is reaffirmed by the consensus that the most influential maintenance human factors within Transmission are not well documented.

By providing a research output that identified the most significant maintenance human factors that lead to maintenance errors, a way of measuring these maintenance human factors and incorporating it into an overall TMP framework this thesis will contribute to the South African electricity transmission industry.

8.2.3.2. Dissensus current status of management of most influential maintenance human factors

Dissensus on whether the most influential maintenance human factors are actively being managed by management and supervisors still remain. It is the author’s opinion that this is due to different management styles between management and supervisors.

The author advises that maintenance human factor training be provided within all the Transmission Grids. Dissensus on this question does not invalidate the research gap identified and addressed in this thesis.

8.2.3.3. Dissensus on high workload being a significant contributor that leads to maintenance human errors

The responses to high workload being a significant contributor were split relatively equal between participants agreeing and participants disagreeing with the statement. This relatively equal split is thought-provoking.

- High workload was ranked as the most significant contributing factors to personal maintenance errors made by the maintenance technicians.
- In the responses to the maintenance managers' questionnaire, high workload was ranked as one of the top four elements that contributed the most and the second most to maintenance errors according to the maintenance managers' perspectives. The number of participants in the Delphi study are, however, larger than that of the maintenance managers' questionnaire and thus carries more statistical weight.
- The weighting for high workload within the MHFP score is the highest (28%) of all the factors.

The points listed above contradicts those respondents who claimed that high workload is not a significant contributor that leads to maintenance human errors. For this reason, high workload will be regarded as a significant contributor that leads to maintenance human errors and will still be included in the calculation of the MHFP score.

8.2.3.4. Dissensus on fatigue being a significant contributor that leads to maintenance human errors

The mode for fatigue remained favourable towards significantly contributing to maintenance errors in the first and in the second round. It ranked third (15% || 13 out of 88 participants) in the list of most significant contributing factors to personal maintenance errors made from the maintenance technicians questionnaire, but scored the lowest (22%) on the weighting for the MHFP score. With the maintenance managers' questionnaire fatigue was not one of the top four elements that contributed the most and second most to maintenance errors according to the maintenance managers' perspectives. In the systematic literature review fatigue ranked first when using minimal coding, 6th when using the PEAR model and 4th using coding based on the HFACS-ME framework.

The author proposes that fatigue is a contributing factor to maintenance errors and should be included in the calculation of the MHFP score. Re-evaluation on whether fatigue is a significant contributor that leads to maintenance human errors within the electricity transmission industry is needed.

8.3. TMP framework: Delphi round 1

8.3.1. Questionnaire construction

The first round questionnaire aimed to confirm the TMP indictors and the weightings used for these indicators when calculating the TMP score. The hierarchical maintenance performance framework for the South African electricity transmission industry as proposed in Chapter 7 (Figure 7.2) was given to the panel of experts. The questionnaire can be found in Appendix G.

The questions were categorised into the following categories:

- obtaining agreement on the TMP indicators chosen,
- obtaining agreement on the weighting of each indicator within the TMP score,
- confirmation of the research objective and the research output.

8.3.2. Data gathering process

The second criteria for selecting the expert panel's members was their area of experience in maintenance human factors. Their expertise had to consist either of one or more of the following:

- Business Integration and Performance Management
- Developing yearly performance measurements

- Reporting on performance measurements
- Reporting on maintenance performance
- Reporting on technical performance
- Grid management
- Grid middle management
- Chief engineer

Once the panel of experts was identified, they were contacted per individually addressed emails on the 18th of May 2021. Each email contained a hyperlink to the questionnaire which was hosted on www.kwiksurveys.com. The participants were assured that their participation is entirely voluntary and anonymous and that all information obtained from the questionnaire will be strictly confidential. The participants were also informed that they have the right to withdraw at any stage without any penalty or future disadvantage.

Personal contact was made close to the end date of the questionnaire to serve as a reminder of the upcoming closing date. The questionnaire was closed on the 1st of June 2021.

Blank data, where the participant selected the first continue answer, but did not completed the questionnaire was removed. Where a respondent started the questionnaire, but did not finish or return later to complete the questionnaire, only the completed data was used. Data from respondents that completed the questionnaire but did not answer all the questions was not removed. For this reason, each question has a unique number of total responses. After the data clean-up, 16 questionnaires remained for data processing.

All information gathered through the survey was exported from Kwiksurveys to Microsoft Excel. Graphs and basic statistical calculations provided by Kwiksurveys and calculated with Microsoft Excel were used in this chapter. These graphs and basic statistical calculations can be found in Appendix H.

8.3.3. Data gathered

The identities of the participants are treated as confidential and will not be mentioned in the thesis. Where comments were made to certain questions, participant coding is used.

The areas of expertise of the 16 participants that formed the panel of experts are shown in Figure 8.14. The participants were able to select one or more option.

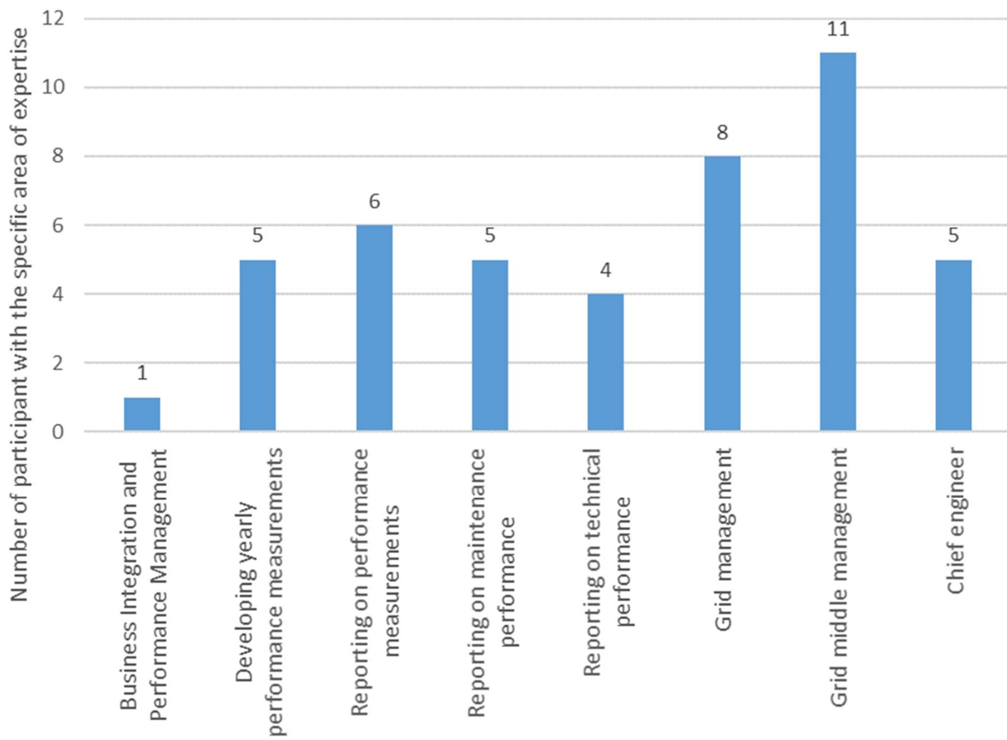

Figure 8.14: Panel of experts' areas of expertise

The panel of experts formed consensus on 8 out of the 9 proposed TMP indicators as shown in Figure 8.15. Personnel cost ratio had 63% agreement and 13% disagreement.

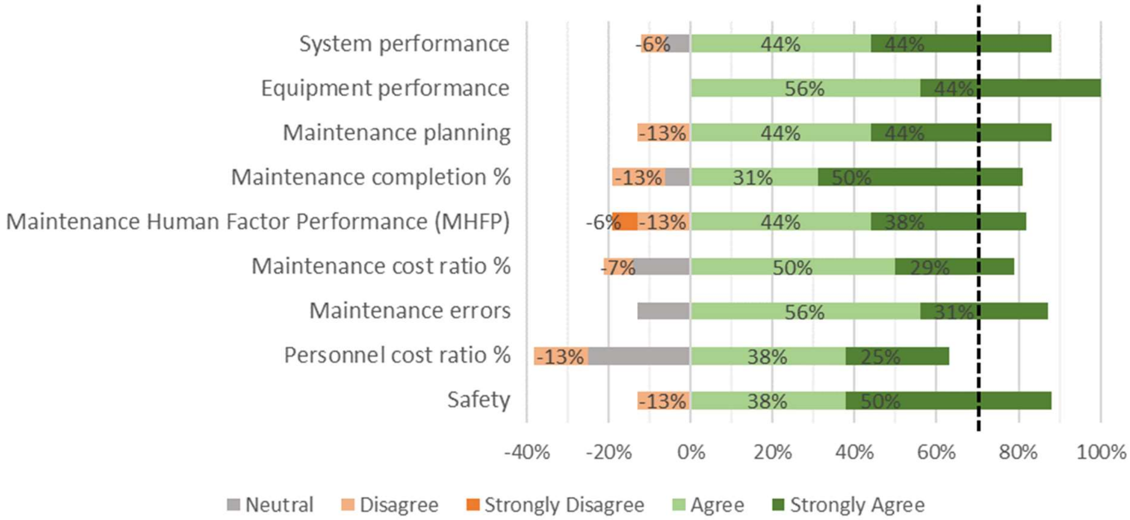

Figure 8.15: Agreement on TMP indicators

In the second question, the panel was asked to confirm the TMP weighting of each of the identified indicators (Figure 8.16). Consensus between the panel members' responses to the TMP weightings were in support of the following weightings:

- Maintenance completion (85 %),
- Safety (10 %), and
- Personnel cost ratio (5 %).

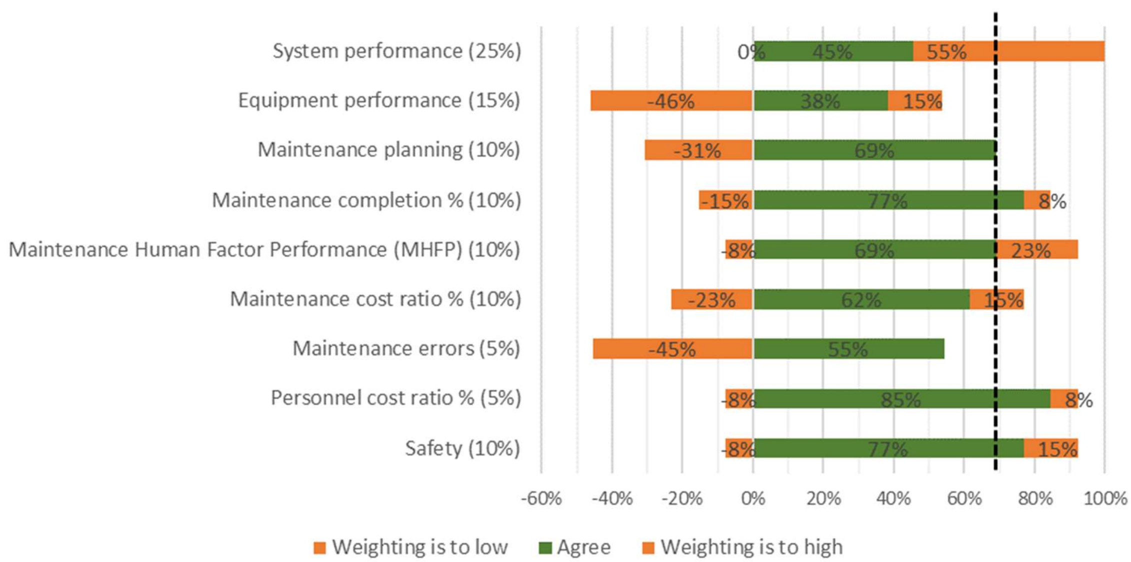

Figure 8.16: Agreement on MHFP weighting of each indicator

The last question aimed at validating the research objective and research outputs. The 3 statements, as per Figure 8.17, achieved consensus within the first round.

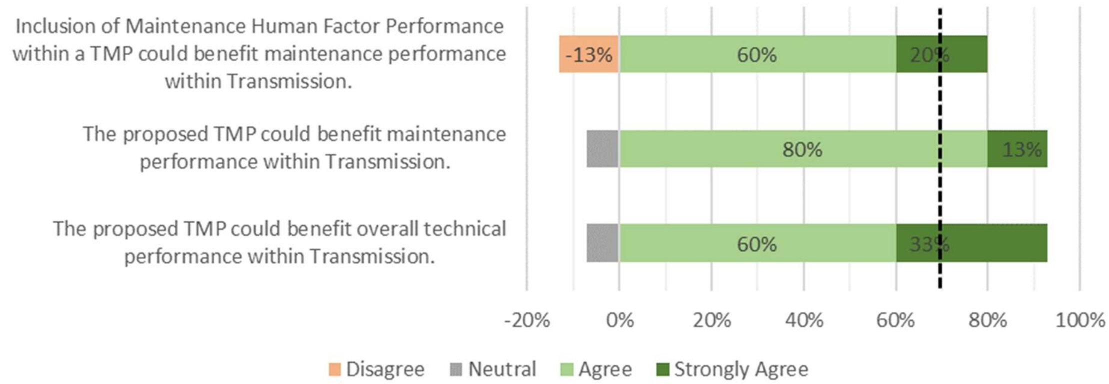

Figure 8.17: Validation of research objective and research output

14 of the 20 statements achieved consensus and 5 of the 20 leaned towards mutual agreement (50% – 70% of the panel members had the same opinions). Table 8.4 provides a summary of maintenance performance framework validation results.

Table 8.4: Summary of maintenance performance framework validation results

Question goal		Question	Mode	Disagreement / Agreement (n, %)	Criteria	Conclusion
TMP Indicators		System performance	Strongly agree	1 (6%) /14 (88%)	>70% agreement	Consensus
		Equipment performance	Agree	0 (0%)/16 (100%)	>70% agreement	Consensus
		Maintenance planning	Strongly agree	2 (13%) /14 (88%)	>70% agreement	Consensus
		Maintenance completion %	Strongly agree	2(13%) /13 (81%)	>70% agreement	Consensus
		Maintenance Human Factor Performance (MHFP)	Agree	3(19%) /13 (81%)	>70% agreement	Consensus
		Maintenance cost ratio %	Agree	1(7%)/11 (79%)	>70% agreement	Consensus
		Maintenance errors	Agree	0 (0%)/14 (87%)	>70% agreement	Consensus
		Personnel cost ratio %	Agree	2(13%) /10 (63%)	>70% agreement	Dissensus
		Safety	Strongly agree	2(13%) /14 (88%)	>70% agreement	Consensus
Scaling / weighting TMP indicators		System performance (25%)	Weighting is to high	6 55 /5 45%	>70% agreement	Dissensus
		Equipment performance (15%)	Agree	8 62/5 38%	>70% agreement	Dissensus
		Maintenance planning (10%)	Agree	4 31/9 69 %	>70% agreement	Dissensus
		Maintenance completion % (10%)	Agree	3 23/10 77%	>70% agreement	Consensus
		Maintenance Human Factor Performance (MHFP) (10%)	Agree	4 31 /9 69%	>70% agreement	Dissensus
		Maintenance cost ratio % (10%)	Agree	5 38 /8 62%	>70% agreement	Dissensus
		Maintenance errors (5%)	Agree	5 45 /6 55%	>70% agreement	Dissensus
		Personnel cost ratio % (5%)	Agree	2 15 /11 85%	>70% agreement	Consensus
		Safety (10%)	Agree	3 23 /10 77%	>70% agreement	Consensus
RQ2b: Incorporation of the measurements into a proposed maintenance performance framework.	Confirm research objective	Inclusion of Maintenance Human Factor Performance within a TMP framework could benefit maintenance performance within Transmission.	Agree	2 (13%) / 13 (87%)	>70% agreement	Consensus
	Confirm research output	The proposed TMP framework could benefit maintenance performance within Transmission.	Agree	0 (0%) / 14 (93%)	>70% agreement	Consensus
	Confirm research output	The proposed TMP framework could benefit overall technical performance within Transmission.	Agree	0 (0%) / 14 (93%)	>70% agreement	Consensus

8.4. TMP framework: Delphi round 2

8.4.1. Questionnaire construction

The results of the first round questionnaire formed the basis of the second round questionnaire. The results were provided to the participants as feedback within the second questionnaire.

In the first question of Round 1, more than 70% of the participants agreed/strongly agreed with the inclusion of the identified TMP indicators, except for “personnel cost ratio%”. The participants’ responses to the inclusion of “personnel cost ratio%” were: 13% strongly disagree & disagree, 25% neutral, and 63% agreed & strongly agreed. In the second round the participants were asked if they would support the validity of including “personnel cost ratio%” as a TMP indicator.

The weightings of the TMP indictors were adjusted based on the feedback received from participants in Round 1 and they were asked to re-evaluate the new, proposed weightings. The changes are shown below in Table 8.5. Where more than 70% of the participants agreed to a weighting in Round 1, support of the weighting was not asked for again.

Table 8.5: Round 2 TMP indicator weightings

Maintenance Indicator	Round 1 Weighing	Round 2 suggested weights
System performance	25%	15%
Equipment performance	15%	20%
Maintenance planning	10%	10%
Maintenance completion %	10%	Consensus in Round 1
Maintenance Human Factor Performance (MHFP)	10%	10%
Maintenance cost ratio %	10%	10%
Maintenance errors	5%	10%
Personnel cost ratio %	5%	Consensus in Round 1
Safety	10%	Consensus in Round 1

8.4.2. Data gathering process

Each of the members of the panel of experts from Round 1 were individually addressed by email on the 14th of June 2021. The email thanked them for their participation in the first round and requested them to participate in the follow-up round. Each email contained a hyperlink to the questionnaire which was hosted on www.kwiksurveys.com.

Personal contact was made close to the end date of the questionnaire to serve as a reminder of the upcoming closing date. The questionnaire was closed on the 24th of June 2021.

Blank data (the participant selected the first continue answer but did not complete the questionnaire) was removed. Blank respondent data (the participant filled in their personal information, but did not complete the questionnaire) was removed. After the data clean-up, 75% (12) of the first round panel members participated in the second round.

All information gathered through the survey was exported from Kwiksurveys to Microsoft Excel. Graphs and basic statistical calculations provided by Kwiksurveys and calculated with Microsoft Excel were used in this chapter. These graphs and basic statistical calculations can be found in Appendix H.

8.4.3. Data gathered

In the first round the agreement to disagreement ratio was 10 (63%) to 2 (13%). In the second round the agreement to disagreement ratio was 9 (75%) to 3 (25%) (Figure 8.18). The ratio of responses supporting and not supporting the statements is relatively stable across the two rounds. The percentage increase is due to the reduced number of participants. The mode of the responses to the statements, in both rounds, indicate that “Personnel cost ratio” should be included. It will be concluded that consensus is reached that “Personnel cost ratio” should be included.

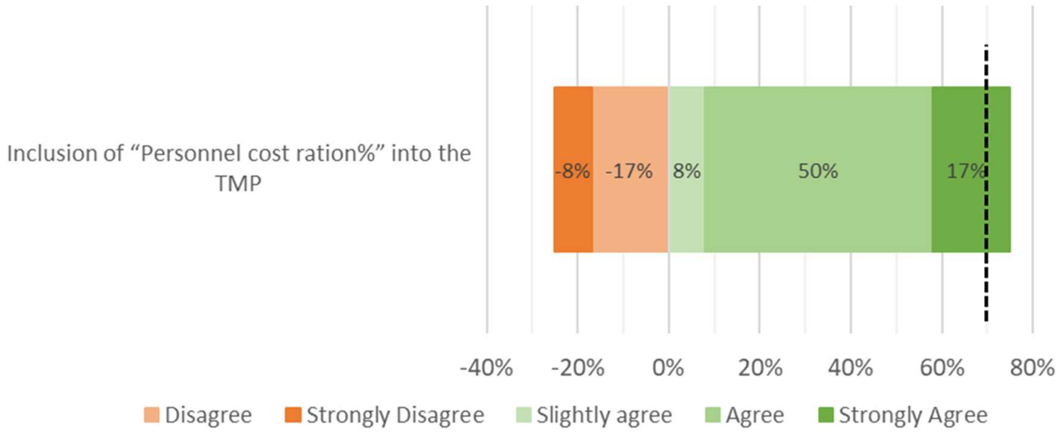

Figure 8.18: Agreement on TMP indicators (Round 2)

The weightings of the TMP indictors were adjusted based on the feedback received from participants in Round 1. They were asked to re-evaluate the new, proposed weightings. In Figure 8.19 a significant shift to a strong consensus for the new weightings can be seen.

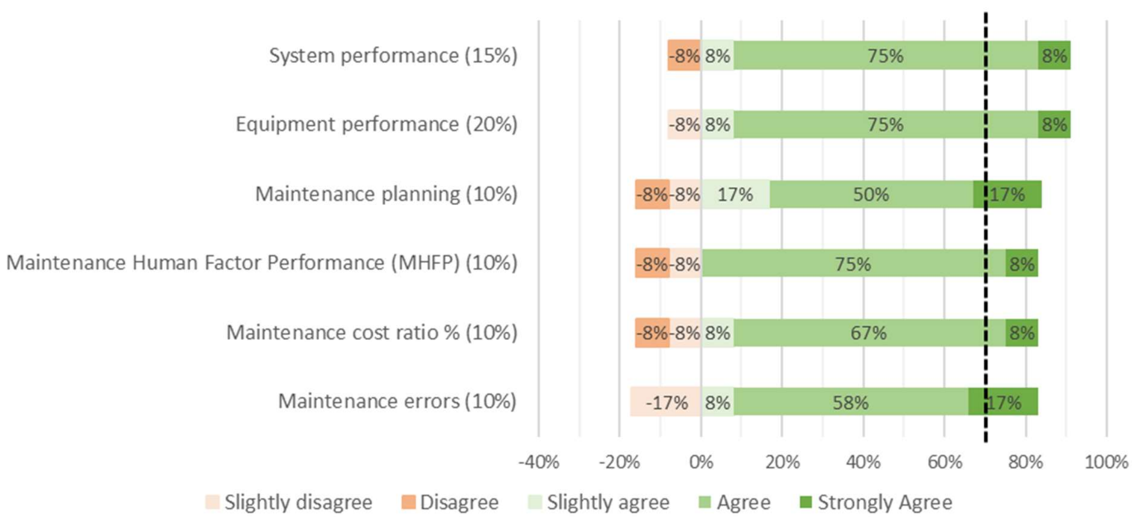

Figure 8.19: Agreement on TMP weighting of each indicator (Round 2)

After round two, the panel of experts reached consensus as indicated in Table 8.6 for each of the factors tested.

Table 8.6: Summary of maintenance performance framework validation results (Round 2)

Question goal	Question	Mode	Disagreement / Agreement (n, %)	Criteria	Conclusion
TMP Indicators	Personnel cost ratio %	Agree	3(25%) /9 (75%)	>70% agreement	Consensus
Scaling / weighting TMP indicators	System performance (15%)	Agree	1 (8.5%) /11 (91.5%)	>70% agreement	Consensus
	Equipment performance (20%)	Agree	1 (8.5%) /11 (91.5%)	>70% agreement	Consensus
	Maintenance planning (10%)	Agree	2 (17%) /10 (83%)	>70% agreement	Consensus
	Maintenance Human Factor Performance (MHFP) (10%)	Agree	2 (17%) /10 (83%)	>70% agreement	Consensus
	Maintenance cost ratio % (10%)	Agree	2 (17%) /10 (83%)	>70% agreement	Consensus
	Maintenance errors (10%)	Agree	2 (17%) /10 (83%)	>70% agreement	Consensus

8.5. Chapter summary

This chapter validated the proposed hierarchical maintenance performance framework for the South African electricity transmission industry inclusive of maintenance human factors using a Two-round Delphi method. It served as validation of the contribution that this thesis will make to the South African electricity transmission industry.

Three significant maintenance human factors (high workload, time pressure and communication) that lead to maintenance errors were validated (RQ1). The weighting of each MHFP indicator was validated through the MHFP framework questionnaire (RQ2a). The organisational hierarchical performance framework, inclusive of maintenance human factors, was validated through the TMP framework questionnaire (RQ2b).

Additional questions were asked of the panel of experts in the Delphi questionnaire. It was validated that the most influential maintenance human factors within Transmission are not being measured within an official performance framework. The benefits of implementing the research output was validated.

- Awareness of the most influential maintenance factors could have benefits in terms of performance and reduction in human error.
- Measuring the most influential maintenance human factors could have benefits in terms of performance, reduction in human error and better management of these influential maintenance human factors.
- Inclusion of Maintenance Human Factor Performance within a TMP framework could benefit maintenance performance within Transmission.
- The proposed TMP framework could benefit maintenance performance and technical performance within Transmission.

Chapter 9 will serve as closure for this thesis. It will link how the research questions have provided answers to the research objective. It will remark on the contributions made to literature, recommendations for future work and provide a short self-assessment.

9. THESIS CONCLUSION

This doctoral thesis was written to contribute to the domain of maintenance management. This was done by addressing a critical literature gap: “What are some of the most influential maintenance human factors and how to include them in a maintenance performance system.” This thesis focused on answering these questions within the South African electricity transmission industry.

The first chapters provided a brief summary of the research objectives and research questions; an explorative literature review; a systematic literature review and the research methodology used in this thesis.

The systematic literature review was used as the starting point to determine the most noted maintenance human factors. This was then used to determine the most significant maintenance human factors within the electricity transmission industry through an organisational survey.

Chapter 7 provided a systematic approach to interpret the data from previous chapters, in order to provide answers to the RQ’s posed in this thesis. The RQ’s were developed to assist in answering the main thesis objective, by dividing it into tangible questions that were answered systematically.

In Chapter 8, the answers to the research questions were validated through a Two-round Delphi method. The Delphi questionnaire also served to validate the benefits of implementing the research output in the organisation.

9.1. Research questions

9.1.1. RQ1: What maintenance human factors have the most influence on maintenance human errors?

Four significant maintenance human factors were identified from the maintenance technicians’ questionnaire that have the most influence on maintenance human errors: high workload, time pressure, fatigue and communication. From the validation of these factors in the Delphi questionnaire consensus on time pressure and communication was achieved. Time pressure and communication were validated with the Delphi questionnaire.

High workload was not validated in the Delphi questionnaire as there was no clear consensus achieved. There were, however, contradictions between the responses from the various questionnaire target groups, the prevailing opinion in literature and the prior findings of this thesis. In Section 8.2.3.3 the contradictions were discussed and it was concluded that high workload will remain as a significant contributor that leads to maintenance human errors.

The Delphi questionnaire could not validate fatigue as a significant maintenance human factor that has an impact on maintenance human errors as the responses by the panel of experts were not predominantly in support of it or not in support of it. The mode of the responses was in support of fatigue as a significant maintenance human factor. The author propose that fatigue remain as an MHFP indicator, but that re-evaluation should be done through an in-depth analysis.

9.1.2. RQ2: How should these maintenance human factors performance indicators and measurements be incorporated into a traditional maintenance performance framework?

RQ2 was be divided into two sections:

- RQ2a: Measurements and measurement method for the chosen maintenance human factors, and
- RQ2b: Incorporation of the measurements into a proposed maintenance performance framework.

Chapter 2 identified measurements and measurement methods for maintenance human factors through an explorative literature review (Table 2.11 to Table 2.13 with additional information in Appendix A). Using the findings of the explorative literature review, measurements and measurement method (Section 7.2.1) were determined to calculate a maintenance human factor performance (MHFP) framework and score. By providing tangible measurements with a calculation method, it ensures that the most influential maintenance human factors can be measured and included in an organisation's performance system.

In Section 3.3 nine total maintenance performance (TMP) indicators for the South African electricity transmission industry were identified, along with weightings for each factor. The TMP framework is inclusive of the MHFP score, thus incorporating the measurements into a proposed maintenance performance framework.

In Chapter 8 the MHFP and TMP indicators were verified through the Delphi questionnaire. The weightings were adapted after Round 1 and consensus on the weightings of each indicator was achieved in Round 2.

9.2. Thesis Objectives

The research objective was proposed to provide recommendations in solving the problem statement in Section 1.4. Maintenance human factors should be aligned to the specific industry they are being measured in. The gap in literature in regards to maintenance human factors to be used in the electricity transmission industry, as well a lack of an implementation strategy or framework, hinders solving the research problem. The research objective is therefore restated below:

"The objective of this research was to determine the most influential maintenance human factors and corresponding measurements that have a positive impact to reduce maintenance human error and that could be included in an organisation's performance system for the maintenance department".

The RQ's were answered using systematic thinking, assisted by literature verification and industry validation. The most influential maintenance human factors chosen for the South African electricity transmission industry correlated statistically to literature and were validated through a Delphi method questionnaire (RQ1). The organisational hierarchical performance framework proposed in Chapter 3 of the thesis was used to integrate RQ1 and proved to be a usable performance system for an organisation (RQ2).

Figure 9.1: Final hierarchical maintenance performance framework for the South African electricity transmission industry, as a graphical summary of the research output.

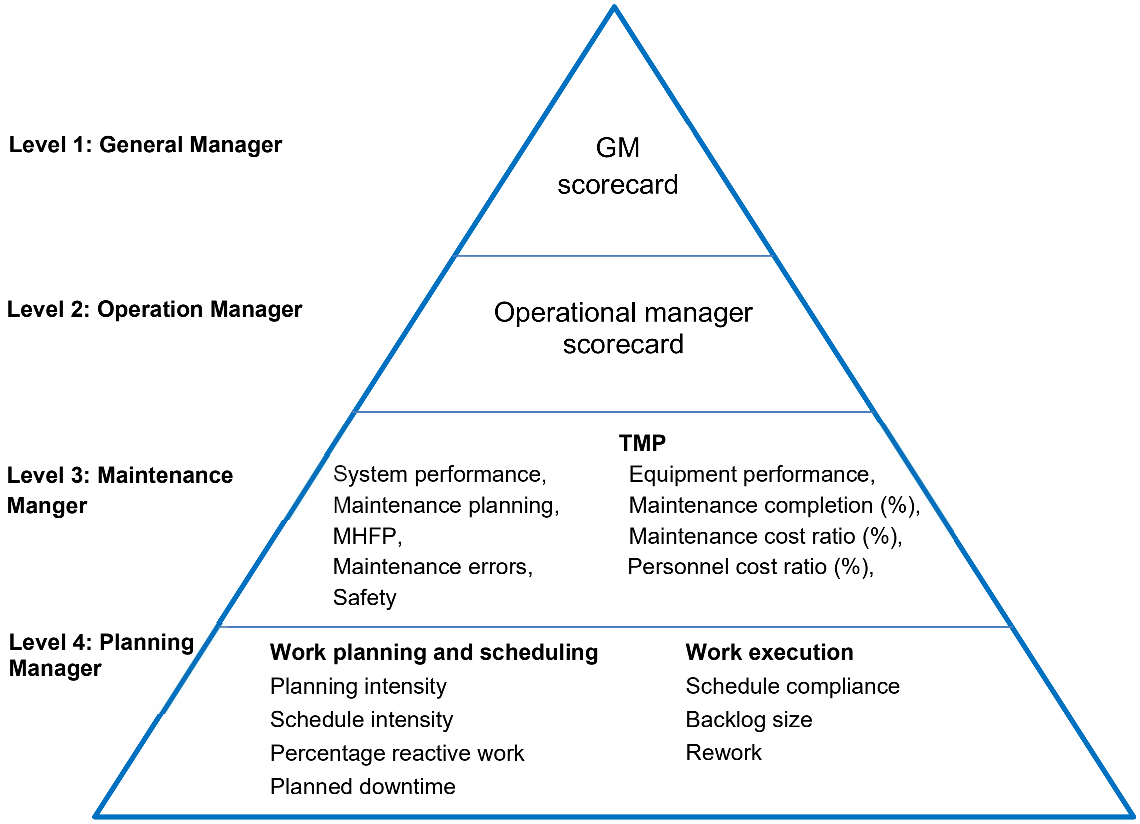

Figure 9.1: Final hierarchical maintenance performance framework for the South African electricity transmission industry

The final level 3 TMP score for the maintenance manager can be calculated using the TMP score and the formula:

$$TMP = \sum_{i}^{n} W_i \cdot B_i$$

where B_i is the benefit value, W_i is the weight for factor i, and n is the number of factors.

The concluded TMP framework, with weightings, for this thesis is shown in Table 9.1. Exact minimums, maximums and values cannot be provided in this thesis due to confidentiality, but the values are realistic within the electricity transmission industry and therefore remain as an example.

Table 9.1: Concluded TMP indicators and weightings

Maintenance Indicator	W_i (%)	Min	Max	Value	B_i	B_i*W_i
System performance	15	0.00	1.05	0.64	0.61	0.09
Equipment performance	20	0.88	1.05	0.95	0.41	0.08
Maintenance planning	10	0.80	1.20	1.00	0.50	0.05
Maintenance completion %	10	95.00	100.00	98.50	0.70	0.07
Maintenance human factor performance (MHFP)	10	0.60	1.00	0.73	0.33	0.03
Maintenance cost ratio %	10	90.00	110.00	96.00	0.70	0.07
Maintenance errors	10	1.00	20.00	9.00	0.58	0.06
Personnel cost ratio %	5	90.00	110.00	94.00	0.80	0.04
Safety	10	0.00	0.36	0.15	0.58	0.06
TMP score						**0.55**

Calculation of an MHFP score, which is needed for the calculation of the TMP score, can be done through the formula:

$$MHFP = \sum_{i}^{n} W_i B_i$$

where B_i is the benefit value, W_i is the weight for factor i, and n is the number of factors. The concluded MHFP framework, with weightings, for this thesis is shown in Table 9.2. The minimum and maximum values were determined by the questionnaires chosen to measure the MHFP indicator. Exact minimums, maximums and values cannot be provided in this thesis and therefore remain as example values.

Table 9.2: Concluded MHFP indicators and weightings

MHFP Indicator	W_i (%)	Min	Max	Value	B_i	B_i*W_i
High Workload	28	8	56	25	0.65	0.18
Time Pressure	24	5	35	13	0.73	0.18
Fatigue	22	9	63	26	0.69	0.15
Communication	26	11	77	68	0.86	0.22
MHFP score						**0.73**

The Delphi questionnaire posed to a panel of experts, that included top management decision makers who can utilize the outcomes of the Delphi study, confirmed that:

- Measuring the most influential maintenance human factors could have benefits in terms of performance, reduction in human error and better management of these influential maintenance human factors.

This validates part of the thesis objective that finding "*the most influential maintenance human factors and corresponding measurements that have a positive impact to reduce maintenance human error"* will have benefits to the organisation.

Additional to the second part of the thesis objective, that the maintenance human factors "*be included in an organisation's performance system for the maintenance department"*, consensus was achieved that:

- Inclusion of Maintenance Human Factor Performance within a TMP framework could benefit maintenance performance within Transmission.

The panel of experts were in support that the proposed TMP framework for Transmission (Table 9.1) could benefit maintenance performance and technical performance within Transmission, therefore validating the final research output.

9.3. Implications and contributions to theory and practise

Answering the research objective provided a significant contribution to literature by including maintenance human factors in a higher hierarchy of the electricity transmission performance system. This shift in mind-set will be of a critical necessity for performance measurements 4.0. Without this, successful implementation of Industry 4.0 in the maintenance department would become a cumbersome or even impossible task.

Identifying the most significant maintenance human factors that lead to maintenance human errors within the electricity transmission industry will provide a contribution to academic knowledge as research in this field is limited.

Incorporation of measurements of these factors into an organisational performance measurement frameworks is uncommon in industry. It is reiterated that performance measurement frameworks needs to be industry specific. This research output contributes to academic knowledge by providing a method of doing this within the South African electricity transmission industry.

A practical, implementable contribution is made with the thesis providing a calculation methodology to calculate an exact total maintenance performance score for both maintenance and maintenance human factors.

9.4. Recommendations

The most significant maintenance human factors are not only dependent on the person himself, but also on the way that the person is managed. This is evident by the misalignment between the maintenance technicians' perceptions and the maintenance managers' perspectives. The thesis is based on the relationship between maintenance performance, maintenance performance measurements, maintenance human factors and maintenance resource management, as illustrated in Figure 9.2.

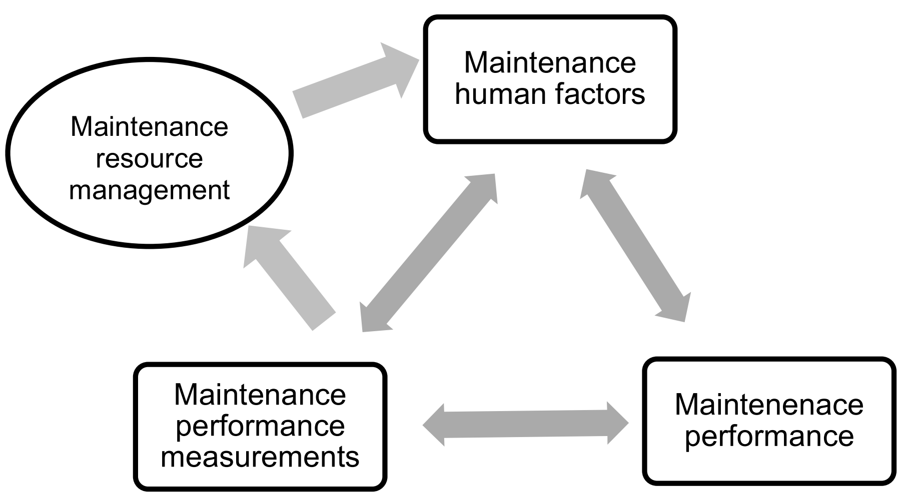

Figure 9.2: The relationship between maintenance performance, maintenance performance measurements and maintenance human factors

Source: Peach (2014)

The results of this thesis reiterates the importance of maintenance resource management. Maintenance management include human aspects as a prequel component of maintenance resource management (Jonsson (1997). The improvement of incorporating maintenance resource management into organisational operations is documented in literature (Reynolds et al., 2010; Shanmugam and Paul Robert, 2015a). Maintenance resource management can be managed by the maintenance manager himself. The scope of the maintenance manager in this particular organisation is limited. His span of control normally ends with administration and accountability of maintenance execution. The other factors identified in literature falls under the human resources domain of the organisation.

It is recommended that both maintenance managers, human resource personnel and management should receive maintenance human factor training. Should a working relationship not be formed between maintenance and human resources resulting in a united maintenance resource management strategy the implementation of maintenance human factor could fail. This concept is stated by (Fixsen and Blase, 2009): “An effective intervention is one thing, implementation of an effective intervention is a very different thing.”

Secondly, it is recommended that once managers have received maintenance human factor training, effective maintenance human factor investigations should be done. The most frequently identified factors from the investigations can then receive additional attention by maintenance resource management. Thereafter, a database with this information should be created and kept up to date. This will address the lack of documented information of influential human factors that lead to human error and hinders actionable turnaround plans to reduce human errors. Once a database is implemented, identification and analysis of significant maintenance factor studies should be done with tangible data instead of relying on surveys.

Finally, it is recommended that fatigue as a possible significant contributor that leads to maintenance human errors in the electricity transmission industry be re-evaluated.

9.5. Limitations of the research

Accurate classification of the root causes of human errors are not recorded in the organisation. Causes for faults, failures and negative impacts on performance measurements caused by human errors will only be recorded as human error. Investigation will in some cases reveal the real cause of the human error, but the investigations are mostly superficial and will end there. In-depth analysis of the reasons for these errors are not studied, nor recorded in a system where trends can be analysed and allow improvement/preventative strategies to be put in place.

Caution should be taken in the planning of the timeframes of measuring and calculating the MHFP score. Within the organisation, official performance measurements are only used biannually for performance and organisational reporting. Selective TMP indicators are reported on, on a monthly basis to track performance, but only the biannual results are taken as organisational compacted values. This will ease the burden of calculating monthly MHFP scores. The author recommends that quarterly MHFP scores are calculated so that progress can be tracked.

9.6. Suggestions for future research

The author proposed that fatigue is a contributing factor to maintenance errors and should be included in the calculation of the MHFP score. Future research is required to re-evaluate whether fatigue is a significant contributor that leads to maintenance human errors in the electricity transmission industry.

Further studies, using the methodology used in this thesis, are required for the South African generation, nuclear generation and distribution industries. This will add value in determining the significant contributors to maintenance errors in those industries. The results will also be valuable for use in comparative studies between the subsections of the overall South African electricity industry.

The methodology used in this thesis could also be used for future research in other industries where maintenance errors have high consequences.

For future research it is recommended that a long term study to document information of influential human factors that lead to maintenance human error be done. This will address the lack of quantitative data on human factors in maintenance departments.

9.7. Thesis conclusion

Maintenance human factor measurements were researched. The most influential maintenance human factors in the electricity transmission industry were determined: high workload, time pressure and communication. Measurement methods and a calculation method to calculate an MHFP score was provided and validated. Maintenance human factors were incorporated in to an organisational performance measurement framework (TMP) consisting of 9 indicators: system performance, equipment performance, maintenance planning, maintenance completion %, maintenance human factor performance (MHFP), maintenance cost ratio %, maintenance errors, personnel cost ratio % and safety.

Benefits of the research objective were validated through a panel of organisational experts:

- Measuring the most influential maintenance human factors could have benefits in terms of performance, reduction in human error and better management of these influential maintenance human factors.
- Inclusion of Maintenance Human Factor Performance within a TMP framework could benefit maintenance performance within Transmission.

The research from this thesis also address literature gaps within academia relating to maintenance human factors and maintenance performance measurements in the electricity transmission industry.

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APPENDIX A. ADDITIONAL LITERATURE ON HUMAN FACTOR MEASUREMENTS

A.1. Human factor measurements: people

A.1.1. Measurements of workload

De Waard (1996) provided a simplistic definition of workload as ”a demand placed upon humans.” O'Donnell and Eggemeier (1986) provided a more complex definition by defining workload as “the portion of the operator's limited capacity required to perform a particular task.” It can be divided into physical workload and mental workload. Hwang et al. (2008) states the generic definition of mental workload as “the amount of resource difference between task demands and capacity provision by an individual.”

Some measurements for workload have been summarized by Guhe et al. (2005). They classified these measurements as subjective measurements, performance measurements, and physiological measurements. Psychological measurements of workload provides real-time, continuous data with a high sensitivity of the cognitive requirements (Hwang et al., 2008). The different measures used in these three categories include the National Aeronautics and Space Administration Task Load Index (NASA-TLX), Multiple Resource Theory and Galvanic Skin Response (Guhe et al., 2005).

Hwang et al. (2008) used eye blink duration, eye blink frequency, systolic- and diastolic blood pressure, heart rate (HR), heart rate variability (HRV) and the parasympathetic/sympathetic ratio to predict nuclear power plant operators’ work performance.

Schulz et al. (1998) investigated the correlation between cortisol responses after wakening with work overload, as an aspect of chronic stress. The study found that there was a higher early morning cortisol increase after awakening in the work overload group than in the low workload group. He cites that work overload is “everyday tasks which are so demanding that coping is only possible with very high effort. Frequent experience of coping with too many demands is perceived as chronic work overload.”

The “Trier Inventory for the Assessment of Chronic Stress” (TICS) was used to determine the respondent’s workload levels as seen in Table A.1.

Schulz et al. (1998) observed correlation between work overload and chronic fatigue, and correlation between work overload and chronic exhaustion.

Table A.1: TICS Questions relating to chronic work overload

Question no.	Texts
5	Too many commitments that I am in charge of
12	The feeling that tasks are too much for me
10	Postponement of urgently needed recreation
18	Too many duties that I have to do
23	Not enough time to fulfil my daily assignments
28	Overload through different duties that I need to take care of
32	Situations with so many difficulties that I cannot deal with all of them
35	The feeling that it is all too much for me

Source: Schulz et al. (1998)

Other measurements that can be used for workload are planned workload hours (as per maintenance planning), actual planned workload hours (as per the ERP system), overtime worked and staff utilization.

Some critique exists with measuring workload as mentioned by Kantowitz (1992) and Nygren (1991). One of the critiques on subjective workload is that only face validity has been considered and that other vital measurement issues have been ignored. Another concern is the general lack of explanation of the hypothetical construct of mental workload.

de Winter (2014) argues that (mental) workload is the most used human factor and is easily measured with questionnaires. He critiques the excessive use of the NASA-TLX as a measurement tool for workload. He compares, amongst others, the NASA-TLX, Cooper Harper rating scale, and the Subjective Workload Assessment Technique (SWAT) with each other. He argues that the increase use of the NASA-TLX as a measurement questionnaire is based on the Matthew effect as it has reached sufficient escape velocity and is now the easiest available choice. According to de Winter specific operational (pragmatic) concerns have not been addressed since the first publication of the NASA-TLX.

He et al. (2012) researched the relationship between a pilot's mental workload and eye activity measurements. They ran nine experimental trials and conducted a subjective survey on time pressure and mental workload experienced by the pilots. They found that pupil size, average fixation time, fixation frequency, saccade frequency and average saccade velocity changed considerably with mental workload.

This is reiterated by Kovesdi et al. (2018) that states that eye tracking can provide a valid, reliable and sensitive measurement in control room settings for visual attention, situation awareness and workload. In their study they showed a positive relation between fixation duration and pupil diameter, and the workload.

Langan-Fox et al. (2009) summarizes human factor measurements for air traffic control systems. Under workload they mention the following measuring methods:

- National Aeronautics and Space Administration Task Load Index (NASA–TLX),
- Air Traffic Workload Input Technique (ATWIT),
- Instantaneous Self-Assessment (ISA),
- Impact on Mental Workload (AIM),
- Rating Scale of Mental Effort (RSME),
- Primary task performance,
- Secondary task performance,
- Performance and Usability Modelling (PUMA), and
- Phycological measures (e.g. Electrocardiograph (ECG), eye-movement tracking (EMT), electromyography (EMG) and (EEG)).

A.1.2. Measurements of fatigue

DeLuca (2005) states that fatigue can be both a symptom and a disease. Sleep deprivation, medical conditions, insults to the brain, psychiatric disorders and an unhealthy lifestyle can all cause fatigue as a symptom. Neurasthenia, DeCosta syndrome and chronic fatigue syndrome can be diseases where fatigue from a part of the illness (DeLuca, 2005). He claims there is no clear definition for fatigue as there is no universal definition. He suggests the following as a definition for fatigue: “Fatigue is the reduction in performance with either prolonged or unusual exertion. Fatigue can be sensory, motor, cognitive or subjective.”

The clinical definition for fatigue in patients with multiple sclerosis include: ”an overwhelming sense of tiredness, lack of energy or feelings of exhaustion, difficulty initiating or sustaining voluntary effort, feelings of physical tiredness and lack of energy distinct from sadness or weakness, a subjective lack of physical and/or mental energy” (Mills and Young, 2008).

The FAA list the effects of fatigue as (Federal Aviation Administration, 2006):

- increased anxiety,
- decreased short-term memory,
- slowed reaction time,
- decreased work efficiency,
- reduced motivation,
- decreased vigilance,
- increased variability in work performance,
- increased errors of omission, including forgetting or ignoring normal procedures,
- increased risk tolerance, and
- reduced problem-solving ability.

Harrington (1994) states that bad-quality sleep and insufficient recovery can lead to impaired performance, decreased alertness and increased fatigue. This can also relate to shift workers with reduced opportunity for sleep and with reduced sleep quality.

Dawson and Reid (1997) did a study to compare the effects sleep deprivation has on performance. They found that 24 hours of sleep deprivation has performance effects similar to a blood alcohol content of 0.1%.

Chalder et al. (1993) developed a rating scale to measure fatigue using 14 questions. Smets et al. (1995) published a Multidimensional Fatigue Inventory (MFI) designed to measure fatigue. The MFI measures: reduced activity, reduced motivation, mental fatigue, physical fatigue, and general fatigue.

Horemans et al. (2004) compared 4 measurement questionnaires of fatigue: the Dutch Short Fatigue Questionnaire (SFQ), the Nottingham Health Profile (NHP) energy category, the Fatigue Severity Scale (FSS) and the Polio Problem List (PPL) fatigue item.

Extreme and consistent fatigue can sometimes lead to burnout. A lack of energy and emotions for work is generally referred to as "burnout." This has the effect that inadequate energy and emotions are available in the workplace (Teng et al., 2010).

Montero-Marín and García-Campayo (2010) defines burnout as: "a prolonged response to chronic emotional and interpersonal stressors on the job, determined by the dimensions of exhaustion, cynicism, and inefficacy". They measured this with a Burnout Clinical Subtype Questionnaire (BCSQ-36). Work burnout has also been extensively measured by modifying the 22-item Maslach Burnout Inventory-Human Service Scale (MBIHSS) (Grunfeld et al., 2000; Maslach and Jackson, 1981).

A.1.3. Measurements of cognitive capabilities

Gottfredson ((1997), as cited in Ispas and Borman (2015)) defines cognitive capabilities as: "a general mental capability involving reasoning, problem solving, planning, abstract thinking, complex idea comprehension, and learning from experience."

Gottfredson ((1997), as cited in Lubinski (2004)) comments on general intelligence:

"It is not merely book learning, a narrow academic skill, or test-taking smarts. Rather, it reflects a broader and deeper capability for comprehending our surroundings—"catching on," "making sense" of things, or "figuring out" what to do."

Baltes (1987 cited in Motta and Joseph (2000)) states that cognitive development can be dived into two conceptual levels: mechanics (the humans' biologically based information-processing systems) and pragmatics (knowledge and skills acquired through learning and experience).

Murphy (1989) provides critique on the model of Schmidt et al. (1986) that stated that job performance is impacted the most by cognitive ability. According to Murphy this is mostly based on correlational evidence and not all variables were catered for. He states that job performance is affected not only by cognitive ability but also by factors such as substance abuse, absenteeism and interpersonal relations.

Murphy (1989) does agree with Schmidt et al. (1986) that measures of cognitive ability can predict job performance and that the validity of cognitive test are consistently greater or equal to other options such as interviews. This agrees with Marin et al. (2011) that examined the relationship between chronic stress, cognitive function and mental health.

Kantowitz (1992) relates cognitive capabilities to human factors through his information processing model as shown in Figure A.1.

Gottfredson (1997) states that personnel selection research has provided much evidence on the significance of intelligence as a predictor of performance, particularly for high level work. He agrees with this, as intelligence is fundamentally the ability to deal with complexity and information processing. According to Gottfredson, intelligence also effects everyday life such as social life and economic undertakings. He presents evidence that the advantages of higher intelligence, even if not significantly higher, contributes to influence the overall life likelihood of individuals at different ranges of the IQ bell curve.

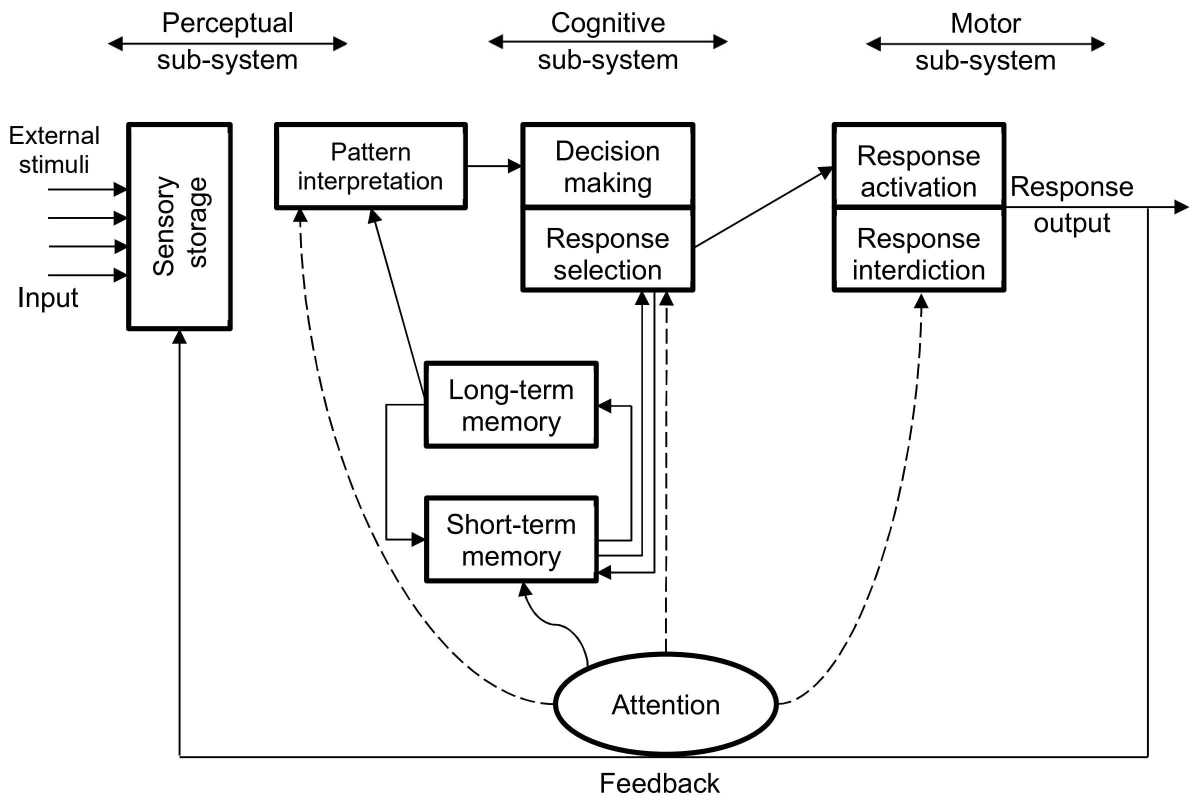


Figure A.1: Human information processing model

Source: Kantowitz (1992)

Reynolds (1998) states that intelligence testing is one of the oldest types of test used by psychologist and is most frequently used to determine intellectual giftedness, learning disabilities and intellectual disabilities in children. The Stanford-Binet Intelligence Scale are widely used for school children in the Unites States. For adults intelligence and aptitude tests are used mostly for administrative purposes. The most frequently used tests include the Kaufman scales, the Wechsler scales and the Stanford-Binet Intelligence Scale (Reynolds, 1998).

According to Motta and Joseph (2000) different tests yield different results such as the Cognitive Abilities Test (CogAT) that measures quantitative, verbal and nonverbal abilities. The Differential Aptitude Tests (DAT) measures 9 different subcategories.

Ivnik et al. (2001) test the diagnostic competences of cognitive tests frequently used in clinical practices using the Mayo Cognitive Factor Scale Scores (MCFS).

The Wechsler Adult Intelligence Scale - Fourth Edition (WAIS-IV) represents the latest revision of cognitive ability measures. Wechsler (2008) defines intelligence testing as: ”a highly sophisticated technical enterprise for measuring human cognitive diversity…” and requires 60 – 90 minutes for respondents to complete (Wechsler, 2008; Weiss et al., 2010). Some of the aspects that the Wechsler Adult Intelligence Scale (WAIS) tests are illustrated in Table A.2.

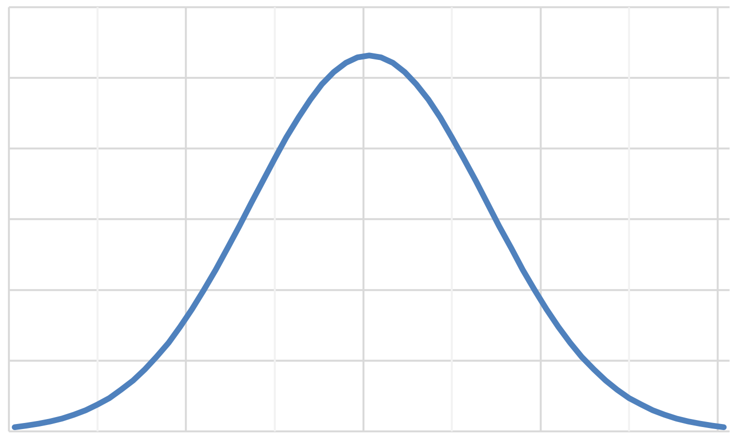
Table A.2: WAIS test and assessment activity

Test	Assessment activity
Information	Recall of factual knowledge.
Comprehension	Explanation of practical circumstances.
Vocabulary	Free definition.
Coding	Identification of symbol-number pairings.
Arithmetic	Mental calculation of problems presented verbally.
Similarities	Explanation of likenesses between objects or concepts.
Digit span	Recall of spans of digits presented aurally, both forwards and backwards.
Picture completion	Identification of parts missing in pictures of common objects.
Block design	Reproduction of 2-dimensional designs using 3-dimensional blocks.
Picture arrangement	Chronological sequencing of pictures.
Object assembly	Reassembly of cut-up figures.

Source: Johnson and Bouchard Jr (2011)

Johnson and Bouchard Jr (2011) combined 42 mental ability tests into three batteries. These tests were a combination of the following three testing methods: the Comprehensive Ability Battery; the Hawaii Battery with Raven; and the Wechsler Adult Intelligence Scale

An Intelligence Quotient (IQ) score is a subset of most intelligence test results. IQ scores follow a normal distribution and scores drop of quickly in both directions from the median of the curve. The median for the Wechsler’s IQ Score is 100 and shown in Figure A.2 (AllPsych, 2018; de la Jara, 2018; Mind Ware, 2020; Sternberg, 2015).



Standard Deviations	-3	-2	-1	0	1	2	3
Wechsler IQ	55	70	85	100	115	130	145
Stanford-Binet IQ	52	68	84	100	116	132	148
Cumulative %	0.003%	0.135%	2.275%	50.000%	84.134%	97.725%	99.865%

Figure A.2: IQ normal curve

Source: de la Jara (2018)

Formal assessments are a critical criterion for the selection of new soldiers in the U.S. Army. These assessments include (National Research Council, 2015):

- basic education attainment,
- moral character screens,
- Armed Services Vocational Aptitude Battery (ASVAB), and
- cognitive knowledge, skill and ability.

The cognitive tests include tests such as verbal and mathematical tests (Armed Forces Qualifying Test (AFQT)). The National Research Council (2015) was tasked to identify possible new measurements for the U.S. Army. They concluded that inhibition control, fluid intelligence, executive attention and working memory capacity should also be tested.

Under skill acquisition, training and recruitment, and selection Langan-Fox et al. (2009) listed the following measuring methods:

- Controller Aptitude (CONAPT) battery,
- Air Traffic Selection and Training (AT_SAT) battery,
- Air Traffic Controller Performance Model (ATC-PM), and
- Air Traffic Controller Specialist Performance Ecole Nationale d'Aviation Civile (ATC STP ENAC).

Alternative measures for cognition are gaining traction. Nucci et al. (2011) developed a Cognitive Reserve Index questionnaire (CRIq). They define cognitive reserve as "the ability to optimize and maximize performance through two mechanisms: recruitment of brain networks, and/or compensation by alternative cognitive strategies."

The ability of good judgment and decision-making relates to cognitive capabilities. Frederick (2005) states that a decision involves deliberation, planning and strategizing; which agrees with the definition of cognitive capabilities of Gottfredson (1997). This is verified by Del Missier et al. (2012) that shows that general cognitive abilities (e.g. fluid intelligence and numeracy) are positively correlated with decision-making performance.

A.1.4. Measurements of situation awareness

Baumgartner et al. (2010) defines a lack of situation awareness as "a lack of awareness of the available information's overall meaning." He remarks that this results in the prevention of pre-emptive situations, as well-timed and precise solutions are obstructed by this lack.

Endsley (1988) defines situation awareness as "the detection of the elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future". Endsley comments that situation awareness becomes even more important in team settings, as both the individual and the group's decision determine performance (Endsley, 1989). He defines team situation awareness as "the degree to which every team member possesses the situation awareness required for his or her responsibilities" (Endsley, 1989).

Endsley and M. Robertson (2000) states that situation awareness is of great significance to performance and error prevention. Some environments where situation awareness is especially important are military operations, maintenance operations, aviation domains, aeronautics and space domains, and road traffic management (Baumgartner et al., 2010; Endsley and M. Robertson, 2000; Langan-Fox et al., 2009; Sarter and Woods, 1991).

In their summary of human factor measurements for air traffic control systems, Langan-Fox et al. (2009) listed several measuring methods for situation awareness. These methods are:

- Situation Awareness Global Assessment Technique (SAGAT),
- Situation Awareness Rating Technique (SART),
- Situation Awareness SHAPE[1] Questionnaire (SASHA_Q),
- Measuring Situation Awareness of Area Controllers within the Context of Automation (in its German translation) (SALSA),
- Situation Present Assessment Method (SPAM),
- Situation Awareness Verification and Analysis Tool (SAVANT),
- Situation Awareness SHAPE Online (SASHA_L), and
- physiological measurements (e.g. EMT).

A.1.5. Measurements of distraction

Distractions have been measured in office, aviation and automotive environments using self-reports and observational methods (Banbury and Berry, 2005; Burns et al., 2005; Healey et al., 2006; Jett and George, 2003; Latorella, 1996; Loukopoulos et al., 2001). Healey et al. (2006) concluded that pilot performance can be negatively affected by distractions and interruptions.

[1] Solutions for Human-Automation Partnership in European ATM* (SHAPE)
* Air Traffic Management (ATM)

The HFACS-ME framework lists distraction/interruption under attention/memory as causes of incidents. This could be related to cognitive abilities such as fluid intelligence, working memory capacity, executive attention and inhibition control (National Research Council, 2015).

Casner and Schooler (2015), states that there are three different types of distractions: depletion, external distractions and internal distractions. They measured the effects of distractions in pilots by the number of callouts missed. Their results are tabulated in Table A.3.

Table A.3: Effects of distractions on pilots per category

Total missed callouts	35
Depletion	0 (0%)
External distractions	9 (26%)
Internal distractions	8 (23%)
Both external and internal distractions	6 (17%)
Total explained	23 (66%)
Total unexplained	12 (34%)

Source: Casner and Schooler (2015)

Noise levels, measured in decibel (dB), can affect the annoyance level of employees. Variable noise has a bigger influence than constant noise (Kjellberg et al., 1996). Studies have found that there is correlation between noise and the thermal condition of the workplace and on an employee's health and performance. Noise and thermal conditions do not have the same effects on employees. It was found that noise decreased concentration and the work rate and that noise increased fatigue. Employees whom experienced increased heat made 56% more errors (Witterseh et al., 2002).

Failure to prevent distraction can decrease work rate and increase errors. Studies on dual-tasking (doing two or more tasks at once) have shown that performance decreases when working memory overlaps and conflicts with attention processes of the task (Kim et al., 2005).

Somervell et al. (2001) studied the effects of peripheral displays on task performance. Their intention was to define the effects of increasing peripheral displays on user performance. These peripheral displays could be load monitors, e-mail monitors, systems clocks, stock tickers or others. They have found that simple tasks take significantly longer when these displays are being used. A similar study has been done using Microsoft Instant Messenger as a distraction while performing a task. The study concluded that these interruptions and distractions have a negative effect on performance (Czerwinski et al. within Somervell et al. (2001)).

In the health industry, measurements for distractions and interruptions have gained momentum in operating theatres. The observational tools aim to record interference during surgery and correlate it to the surgical team's performance (Healey et al., 2006). The observational tool classified the following as interferences:

- phone – any phone in theatre or next to theatre,
- bleeper – any bleeper activated in theatre,
- radio – action or response to the radio causing distraction,
- case irrelevant communication – any conversation irrelevant to the case,
- communication difficulties – e.g. lack of response to request,
- external staff – anyone not part of the team in theatre (except the observer),
- equipment – any item of equipment or provision not at hand or failing,
- work environment – workspace and human–interface problems,
- procedural – events intrinsic to the case work, and
- movement in front of or behind video monitors – laparoscopic cases only.

Langan-Fox et al. (2009) classified inattentiveness or distraction as being the opposite of vigilance. They listed the following measuring methods for boredom, monotony and vigilance:

- physiological measures (e.g. heart rate, heart rate variability, galvanic skin response, eye-movement tracking),
- deviations noticed,
- error detection,
- Dundee Stress State Questionnaire (DSSQ),
- standard SSI, and
- other subjective rating scales.

A.1.6. Measurements of stress

In the INPO (2006) Human Performance Reference Manual, stress is defined as “the body’s mental and physical response to a perceived threat in the environment.” They emphasize the word “perceived” as this varies between individuals as their ability to handle the threats varies. The Yerkes-Dodson law describes the relationship of how the level of stress affects performance (Calabrese, 2008). An elaborated illustration of this can be seen in Figure A.3 (Bayer-Hohenwarter, 2009). Feign death is the plying dead behaviour of animals in extreme stress, as a defence mechanism. For humans this is also known as tonic immobility, a temporary state of motor inhibition. The definition of eustress is known as “a form of stress after which a person’s adaptive capacity increases” (Kupriyanov and Zhdanov, 2014).

Stress can inhibit one’s ability to sense, perceive, recall, think, or act. If the individual is unable to respond to the situation, anxiety and fear will follow. Further symptoms, together with anxiety and fear, are memory lapses, lapses in critical thinking and the loss of the ability to accurately perform physical acts. Active fatigue and stress management can lead to better performance and fewer individual errors (Park et al. (2012), as cited in Sheikhalishahi et al. (2016)).

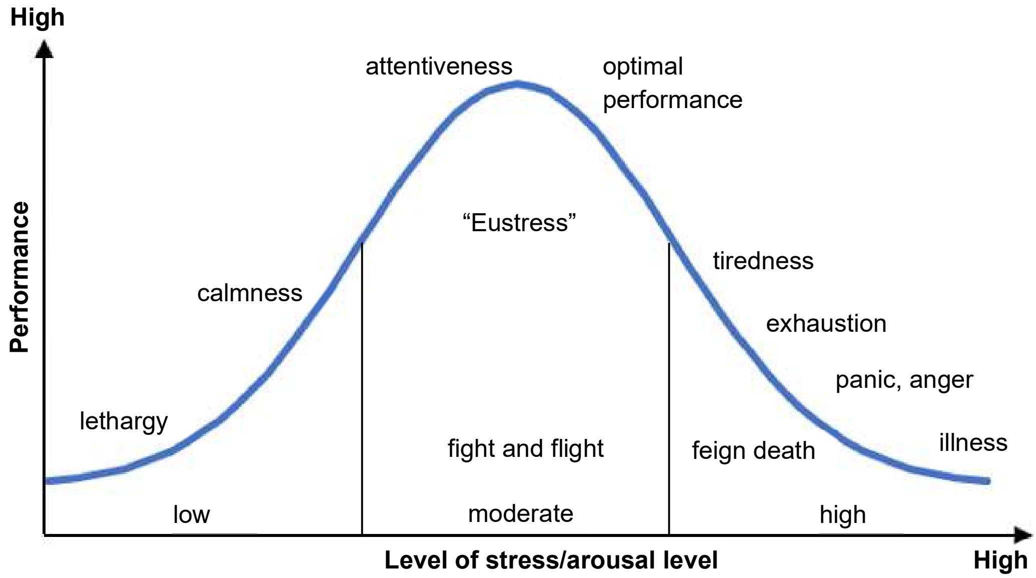


Figure A.3: Stress Curve

Source: Bayer-Hohenwarter (2009)

Cohen et al. (1983) published a global perceived stress measure within the psychological domain. The Perceived Stress Scale (PSS) measures the point to 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 domain (Levenstein et al., 1993), and the Copenhagen Psychosocial Questionnaire (COPSOQ) (Kristensen et al., 2005). The COPSOQ assesses psychosocial factors at work, the well-being of employees, stress and some personality factors. The State-and-Trait Anxiety Inventory could also be used to measure an individual's level to stress (Bayer-Hohenwarter, 2009).

Another tool is the Stress-oriented job analysis instrument (ISTA) that measures the correlation between stressors and psychological dysfunction. The result can be used to determine areas that need better management. The elements measured are listed below (Zapf, 1993):

- resources (control over time and control at work),
- stressors (social stressors, concentration necessities, interruptions, organisational problems and time pressure), and
- work content (variety and complexity of work).

In response to stress the human body releases hormones. Severe stress can lead to high levels of cortisol, as cortisol is a metabolite of the primary stress hormone cortisone (MedicineNet, 2018). Cortisol is associated with the ‘feigning death reaction’ (Bayer-Hohenwarter, 2009). Measuring stress through salivary cortisol levels as a biomarker of psychological stress is common practise in the medical and psychological fields (Bayer-Hohenwarter, 2009; Hellhammer et al., 2009).

Bayer-Hohenwarter (2009) critiques that salivary cortisol is only one element of the bigger picture. Catecholamines from the “fight-and-flight” reaction is also released with moderate levels of stress and react different than salivary cortisol in the same stimuli. The Clinical Stress Assessment method developed by renowned stress researcher, Sepp Porta, relies on a detailed blood analysis, measuring noradrenaline, adrenaline, magnesium and other metabolic parameters (Bayer-Hohenwarter, 2009).

The time lag of approximately 30 minutes, between a stressful stimuli and measurable salivary cortisol level is problematic. Therefore, the source or cause of the cortisol release cannot be clearly determined. This is illustrated in Figure A.4.

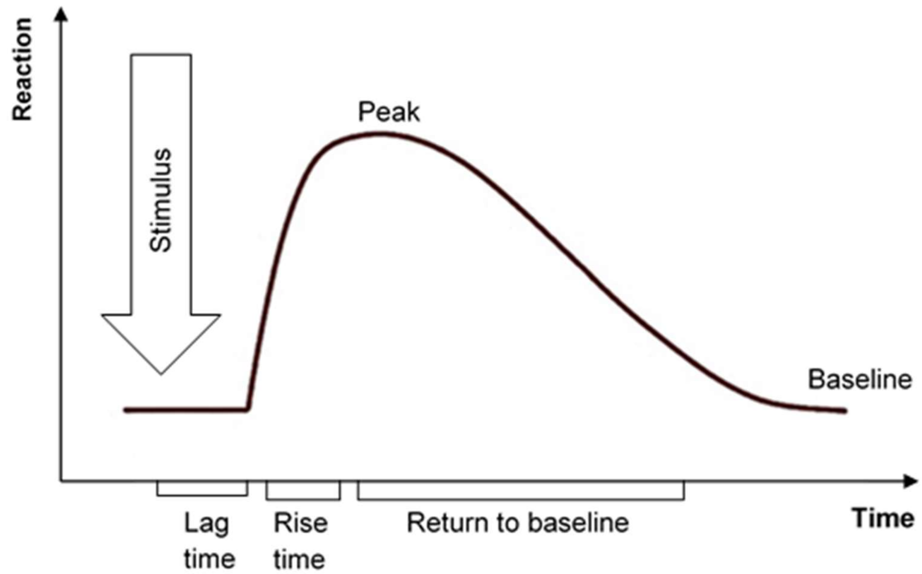


Figure A.4: Time lag between stress and cortisol

Source: Bayer-Hohenwarter (2009)

According to Hellhammer et al. (2009), there are circumstances where there is a dissociation between salivary cortisol and the hypothalamic–pituitary–adrenal axis (HPAA) related endocrine signals. This and the time lag between stress and cortisol level rise are the two main concerns with using salivary cortisol levels as a measure for stress. There is a correlation between free cortisol levels in saliva and free cortisol levels in blood, making the collection and processing of cortisol levels easy. Therefore, this method is the preferred method in stress research.

As mentioned, Langan-Fox et al. (2009) summarizes human factor measurements for air traffic control systems. Under motivation and stress they mentions the following measuring methods:

- Dundee Stress State Questionnaire (DSSQ),
- Scale of Feelings (SOF),
- Copenhagen Psychosocial Questionnaire (CPQ),
- observable behaviour,
- physiological measures (e.g. blood pressure / cortisol / heart rate, S-IGA), and
- other subjective rating scales.

A.1.7. Measurements of vagal tone/heart rate variability

Kantowitz (1992) has foreseen the necessity to include physiological measures in human factor measurements. He noted that heart rate measurements are one off those favourable measurements as it will be easy to obtain relative to other measurements. Kantowitz's prediction was correct. Heart rate monitors have become easy to obtain and are available even in the form of wrist bands. These wrist band hart rate monitors are mass-produced for the consumer market. This type of measurement collection is non-invasive, pain free and relatively affordable. Heart rate variability measurements in the physiological domain has also become more prevalent in the last 20 years. Cardiac vagal tone can be indexed by HRV. HRV have been linked to health levels, social, emotional and self-regulation at the cognitive level (Laborde et al., 2017).

A.1.8. Measurements of motivation/moral and work satisfaction

Motivation is defined by Robbins (2001) as "the processes that account for an individual's intensity, direction and persistence of effort toward attaining a goal. Intensity has to do with how hard a person tries. Direction defines what the effort is applied to. Persistence is a measure of how long a person can maintain the effort".

Absenteeism can be used to measure staff moral (Galar et al., 2011b; Peach et al., 2016). Peach et al. (2016) used "number of personal interventions / numbers of maintenance staff" as a measurement of motivation and performance feedback in their maintenance performance framework.

Izvercian et al. (2016) studied various articles and papers. They found that these studies agreed that work satisfaction and work performance influence each other. Some authors state that satisfied workers are creative and more productive; other authors state that work satisfaction reduce staff turnover and increase performance. Work satisfaction can be promoted through successful implementation of motivational theory such as job rotation, autonomous work groups, etc. However, it needs to be stressed that there are multiple variables that influence work satisfaction (Izvercian et al., 2016).

Steijn (2004, as cited in Izvercian et al. (2016)) suggested 5 main variables that influence work satisfaction. These variables are quoted in Table A.4.

Table A.4: Work satisfaction variables

Individual characteristics	Work characteristics	Work environment	Personnel management practices	Overall satisfaction
• Age • Gender • Ethnicity • Education level	• Income • Supervisory position • Working full time • Permanent job • Skill utilization • Sector of work	• Task autonomy • Satisfaction with management • Pay and workload	-	-

Source: Izvercian et al. (2016)

A.2. Human factor measurements: environment

A.2.1. Measurements of communication

The Federal Aviation Administration (2006) developed a visual method to illustrate appropriate communication channels for various types of information as shown in Table A.5.

Table A.5: Communication channels

	Appropriate communication channels				
Type of information	**Face-to-Face conversation or group meeting**	**Radio or telephone**	**Instant messaging, texting, or non-video chat**	**Email or web browser**	**Video teleconference/ chat**
Facts not requiring interpretation	✓	✓	✓	✓	✓
Information requiring interpretation or discussion	✓	✓			✓
Time sensitive information or questions	✓	✓	✓		✓
Visual information	✓				✓
Information requiring handling of a component or tool	✓				
Information requiring demonstration	✓				✓
On-the-job training	✓				

Source: Federal Aviation Administration (2006)

The FAA has also compiled a self-reporting questionnaire to rate listening characteristics on a 4-point Likert scale, as indicated in Table A.6.

Table A.6: Listening characteristics questionnaire

Number	Questions
1	Do I allow the speaker to express his or her complete thoughts without interrupting?
2	Do I listen between the lines, especially when conversing with individuals who frequently use hidden meanings?
3	Do I actively try to develop retention ability to remember important facts?
4	Do I write down the most important details of a message?
5	In recording a message, do I concentrate on writing the major facts and key phrases?
6	Do I read essential details back to the speaker before the conversation ends to insure correct understanding?
7	Do I refrain from turning off the speaker because the message is dull or boring, or because I do not personally know or like the speaker?
8	Do I avoid becoming hostile or excited when a speaker's views differ from my own?
9	Do I ignore distractions when listening?
10	Do I express a genuine interest in the other individual's conversation?

Source: Federal Aviation Administration (2006)

Rosenfeld and Berko (1990) developed a 30-question questionnaire.

Based on their responses, participants are categorized into the following categories:

- communicates skilfully all or most of time,
- often communicates skilfully,
- sometimes communicates skilfully,
- rarely communicates skilfully, and
- never or almost never communicates skilfully.

Roberts and O'reilly (1974) developed a 35-item questionnaire to measure 16 facets of organisational communication. These facets are:

- trust,
- influence,
- mobility,
- lateral directionality,
- downward directionality,
- upward directionality,
- desire for interaction,
- satisfaction,
- gatekeeping,
- overload,
- accuracy,
- summarization, and
- 4 modalities (written, face-to-face, telephonic, and other communication).

Downs and Hazen (1977) developed a Communication Satisfaction Questionnaire (CSQ) that measures 10 factors. By using the CSQ, Clampitt and Downs (1993), indicated that, for the two companies in their study, communication is perceived to have a significant impact on productivity. They concluded that the impact of communication on productivity is dependent on job design. This CSQ has been used and adapted in other academic studies (Meintjes and Steyn, 2006). These questionnaires can be used to measure communication from the maintenance worker's perspective in terms of team communication and organisational communication.

A.2.2. Measurements of supervision

Clarke (1999), in the field of psychiatry, views supervision as an apprentice–master relationship and the foundation in psychiatric training. He states that it is an essential method to transfer skills, knowledge and attitude, and an incorporation method for practical, theoretical and personal elements. He states that good interaction by a supervisor provides warmth, respect, understanding and trust. This is also true in the maintenance management domain.

The FAA states that the role of supervisors is to provide guidance, training opportunities, leadership, motivation and to be proper role models. This is to ensure that the trainee/worker will succeed (Federal Aviation Administration, 2006).

The Maintenance Error Decision Aid (MEDA) lists contributing factors under supervision that can lead to maintenance system failures (Federal Aviation Administration, 2006). These are:

- planning,
- organizing,
- prioritizing,
- delegation,
- instructing,
- feedback,
- performance management, and
- team building.

Raouf and Ben-Daya (1995) states that improved maintenance productivity and work quality can be obtained through correctly applied supervision. They also state that a maintenance supervisor should focus on maintenance management through supervision and that supervision should be on job sites. They advised that a maintenance planner should take over most of the planning/scheduling functions for the maintenance supervisor to achieve this.

Inaba and Butler noted in their Transportation Research Board Special Report that the selection criteria for supervisors are problematic. They list two scenarios.

- Technicians are promoted based on technical skills even when they lack management skills.
- Supervisors have the required managerial skills but lack technical skills.

Kantowitz (1992) mentions that, management administration, supervisory ratio (ratio of supervisors to supervised as a proxy for supervisory intensity) can be a measurement of supervision (Flin et al., 2000). This method by does not account for all variables, such as span of control (Flin et al., 2000).

Mearns et al. (1997), as cited in (Flin et al., 2000) investigated the role of supervision with a 52 attitude item test. Flin et al. (2000) states that employee supervision is mostly measured by satisfaction and perception questionnaires relating to the supervisors' attitudes and actions.

Clarke (1999) aimed to develop an evaluation method (questionnaire) whereby supervision and training experience can by evaluated by trainees. The aim of the model is to identify precise shortcomings in training and supervision. In his questionnaire in the field of psychiatry, he tested for structural and qualitative aspects of supervision. These are:

- amount of supervision,
- punctuality and reliability,
- availability,
- observed interview,
- demonstrated interview,
- constructive critical feedback,
- encouragement,
- educational value,
- clinical guidance, and
- support.

In the related field of psychotherapy, 37 genetic counsellors were tested with the Psychotherapy Supervisor Development Scale (PSDS) before a one day supervision training conference. After the conference their PSDS scores significantly increased (Atzinger et al., 2016). The PSDS included questions relating to:

- demographic information,
- supervision experience,
- number of students supervised per year,
- learning objectives,
- supervisor competencies, and
- development scale.

The Clinical Outcomes in Routine Evaluation - Outcome Measure (CORE-OM) is a measurement method for supervision used throughout the United Kingdom (Ögren et al., 2014). Ögren et al. (2014) continued with a systematic literature review to find 49 test instruments. These instruments are either for the supervisee or for the supervisor. Some of these identified tests may be adaptable to maintenance supervision, such as the:

- Competencies of Supervisors (Borders and Leddick, 1987),
- Supervision Outcomes Survey (Worthen and Isakson, 2000),
- Supervisee Satisfaction Questionnaire – SSQ (Larsen, Attkisson, Hargreaves, and Nguyen, 1979),
- Supervisor perception form (Heppner and Handley, 1982), and
- Supervisory Relationship Questionnaire (Farber, 2003).

The Maintenance Resource Management Technical Operations Questionnaire (MRM/TOQ), developed in 1991, is a self-report questionnaire regarding human factors within aviation maintenance (Taylor and Thomas Iii, 2003). This has been adapted by Taylor and Thomas Iii (2003) to simplify the 34 item MRM/TOQ to 27, 18 and 15 item questionnaires This was done by using multiple factor analyses. Of the 4 questions relating to supervision in the original MRM/TOQ, 3 remained in the adapted

15 item questionnaire. This demonstrates the importance of supervision within maintenance. The questions and their adaptions can be seen in Table A.7.

Table A.7: MRM/TOQ adaptations

Original phrasing	Simplified phrasing	34 item	27 item	18 item	15 item
My supervisor can be trusted	My supervisor can be trusted	✓	✓	✓	✓
My supervisor protects confidential or sensitive information	My supervisor protects confidential information	✓	✓	✓	✓
My suggestions about safety would be acted on if I expressed them to my lead or supervisor	My safety suggestions would be acted upon if I reported them	✓	✓	✓	✓
Supervisor makes realistic promises and keeps them	-	✓	✓	×	×

Source: Adapted from Taylor and Thomas Iii (2003)

A.2.3. Time pressure

Zur and Breznitz (1981), in context of their study, defined time pressure as “in terms of the amount of information that has to be considered and processed during one time unit or in terms of the time allotted for processing a fixed amount of information”. This is confirmed by (Teng et al., 2010) when they state that “Time pressure is a psychological urgency attributed to insufficient time for completing required tasks”.

Roxburgh (2004) developed a 9 item time pressure scale based on the work of Dapkus (1985) and other sources. The time pressure scale uses a Likert scale from "strongly agree" to "strongly disagree". The time pressure scale asked the participant to rate the questions below based on the question “In the last twelve months how often have you felt”:

- You never seem to have enough time to get everything done.
- You feel pressed for time.
- You are often in a hurry.
- You feel rushed to do the things that you have to do.
- You have enough time for yourself.
- You feel that too much is expected of you.
- You worry about how you are using your time.

- You are always running out of time.
- There just don't seem to be enough hours in the day.

Teng et al. (2010) expanded on Putrevu and Ratchford's (1997) questionnaire by adapting applicable questions into the context of work, by replacing the original wording with the wording "at work". This resulted in a 5 item questionnaire with a 7-point Likert scale by asking the participant to rate the time pressure they experience.

- I feel high time pressure at work.
- I feel very busy at work.
- I find that the given time at work is very limited.
- I always feel in a hurry during work hours.
- I do not have sufficient time to finish what I should do at work.

Widmer et al. (2012) measured time pressure using questions from the Instrument for Stress Oriented Task Analysis (ISTA). The questions use a 5-point Likert scale ranging from "very seldom/never" to "very often/always. Examples of these questions are:

- "How often do you have to work faster than normal in order to complete your work?", and
- "How often does it happen that you go home late because of too much work?"

Time pressure can be a trigger by other human factors as shown in Table A.8. This has the implication that time pressure does not specifically have to be measured, but that the presence of the mentioned human factors in can give an indication of the presence of time pressure.

Table A.8: Human factors triggered by time pressure

Human factors triggered by time pressure	Source
Fatigue Burnout Exhaustion	Teng et al. (2010) Gelsema et al. (2006) Demerouti et al. (2000)
Stress	Roxburgh (2004) Zur and Breznitz (1981) Rendon-Velez et al. (2016) Bayer-Hohenwarter (2009) Maule and Hockey (1993)
Cognitive abilities Decision quality Judgment accuracy Information processing	Teng et al. (2010) Hahn et al. (1992) Zur and Breznitz (1981) Rendon-Velez et al. (2016) Ahituv et al. (1998) Maule and Hockey (1993)

A.2.4. Measurements of teamwork

As cited by Rosen et al. (2008), measuring team performance can:

- determine the causes of current performance,
- provide feedback on present individual and team competencies targeted for training, and
- identify future training requirements for the team or an individual.

Valentine et al. (2015) cites teamwork is affected by psychological safety, mutual respect, coordination and communication.

Generally, either self-reports or observational methods are used to measure teamwork. Observational methods are normally costly, thus limiting the number of observations. Self-reporting is a subjective method of evaluating competencies within oneself, your team members and the interaction between them. Self-reporting has the limitation of systematic bias and response bias. Therefore, one barrier to effective measuring of team performance is reliable, valid and practical tools for these measurements (Rosen et al., 2014).

Despite the above mentioned limitations of self-reporting, self-reporting of teamwork is cost effective, easily distributed, effortless and provide data to observe relationships between teamwork characteristics (Valentine et al., 2015). Valentine et al. (2015) reviewed 35 surveys that measure teamwork and found that the majority of surveys measure communication, coordination and respect. The authors tested the surveys for psychometric validity as this ads confidence in the survey results.

Ulloa and Adams (2004) continued the work of Adams et al. (2002) by using the Team Effectiveness Questions to measure the constructs identified by Adams et al. (2002). Adams et al. (2002) identified the following constructs for team effectiveness: psychological safety, role clarity, common purpose, clearly defined goals, accountable interdependence, mature communication and productive conflict resolution.

Within the aviation industry the NOTECHS (Non-Technical Skills Evaluation System) is used for training and assessment of teamwork. The NOTECHS is based on 4 dimensions namely co-operation, leadership and managerial skills, situation awareness and decision making, Table A.9 (Flin et al., 2003). In the NOTECHS, team building falls in the category of co-operation as per Table 2.20.

Table A.9: Categories and elements of NOTECHS

Category	Elements
Co-operation	• Team-building and maintaining • Considering others • Supporting others • Conflict solving
Leadership and Managerial Skills	• Use of authority and assertiveness • Providing and maintaining standards • Planning and co-ordination • Workload management
Situation Awareness	• Awareness of aircraft systems • Awareness of external environment • Awareness of time
Decision Making	• Problem definition and diagnosis • Option generation • Risk assessment and option selection • Outcome review

Source: Flin et al. (2003)

Table A.10: NOTECHS Co-operation category

Element	Good practice	Poor practice
Team building and maintaining	• Establishes atmosphere for open communication • Encourages inputs and feedback from others • Does not compete with other	• Blocks open communication • Keeps barriers between crewmembers • Competes with others
Considering others	• Takes notice of the suggestions of other crewmembers even if s/he does not agree • Takes condition of other crewmembers into account • Gives personal feedback	• Ignores suggestions of other crewmembers • Does not take account of the condition of other crewmembers • Shows no reaction to other crewmembers
Supporting others	• Helps other crewmembers in demanding situations • Offers assistance	• Hesitates to help other crewmembers in demanding situations • Does not offer assistance
Conflict solving	• Keeps calm in interpersonal conflicts • Suggests conflict solution • Concentrates on what is right rather than who is wrong	• Overreacts in interpersonal conflicts • Sticks to own position without considering a compromise • Accuses other crewmembers of making errors

Source: Flin et al. (2003)

Rosen et al. (2008) provides a summary of methods used for team performance measurements in simulation-based training (SBT), Table A.11.

Table A.11: Method for team performance measurement used in SBT

Method	Description	Advantages	Disadvantages
Event-based measurement	A general method that generates behavioral checklists that are linked to scenario events and KSAs being trained	Maintains explicit connections between measurement opportunities (ie, scenario events), acceptable behaviors, and KSAs being trained Focuses observers' attention on predefined events Reduces amount of judgment a rater has to make by focusing on observable behaviors	Development of measures can be time consuming relative to other approaches Measurement tools must be developed for each scenario
Behaviorally-anchored rating scales (BARS)	Provides brief descriptions of behaviors as anchors associated with each particular rating	Amendable to modification Facilitates accurate ratings by providing concrete examples of behaviors	When behavioral anchors contain specific types of behavior, observers tend to focus on these isolated behaviors and miss
Behavioral observation scales (BOS)	Generally uses a Likert type scale to rate the frequency of certain team processes	Avoids potential problems with BARS (rating exceptional or isolated performance) by focusing on typical performance	Requires raters to estimate frequencies and consequently ratings may be influenced by recency and primacy effects
Self-report measures	Questionnaires administered to each team member individually	Well suited to capture affective factors that influence team performance (e.g. collective efficacy, trust, collective orientation, psychological safety)	Does not capture dynamic performance, translating individual scores to team level scores can be problematic

Source: Rosen et al. (2008)

A.3. Human factor measurements: resources

A.3.1. Measurements of equipment, tools and parts

In the PEAR model resources are defined as “anything that the maintenance engineer (or anyone else) needs to get the job done” (CASA, 2013). These resources are both tangible and intangible. Below is a list of possible resources as identified in the PEAR model.

Table A.12: Resources as identified in the PEAR model

• Procedures/work cards	• Task lighting
• Technical manuals	• Training
• Other people	• Quality systems
• Test equipment	• Time
• Tools	• Personnel
• Computers/software	• Budget
• Paperwork/signoffs	• Consumables
• Ground-handling equipment	• Repairable
• Work stands and lifts	• Spares
• Fixtures	• PPE
• Materials	• Data

Source: CASA (2013)

The HFACS-ME model identifies inadequate resources as: part unavailable, manning shortfall and funding constraints (Krulak, 2004). Therefore, equipment, tools and parts can be regarded as part of the management and measurement of overall resources.

The HFACS-ME model lists three states for equipment, with corresponding Level 4 factors. Examples of these states and their corresponding factors are:

- Damaged/Unserviced: Defective test sets or equipment failures,
- Unavailable/Inappropriate: Starting a job because the equipment was not available, and
- Dated/Uncertified: Working from old manuals or procedures.

The HFACS-MEDA Organizational Influences related to equipment/facility resources identifies the following factors that should be considered (Federal Aviation Administration, 2006):

- proper equipment, tools or part unavailable, and
- tool or equipment cannot be used in the intended environment.

The use of the HFACS-ME data from investigation of incidents is a reactive way of identifying shortfalls under equipment. The findings can be used for trend analysis to implement intervention strategies. It would be advisable to formulate a questionnaire based on this to form a pro-active approach.

The authors of CASA (2013) supports that the most important resource element is to focus on identifying areas where resources are deficient. They state that, by asking question that identify shortage of equipment, tools and parts can often lead to alternative solutions.

The following questions are extracted from the Human Factors Guide for Aviation Maintenance and Inspection (Federal Aviation Administration, 2006) that can be used to determine required resources.

- How many workers are required to perform this task?
- How much time does the overall task require?
- What tools are required for each step?
- Where must workers go to obtain tools?
- How do they obtain tools?

The following questions are extracted from Hobbs and Williamson's (2002) Maintenance Behaviour Questionnaire (MBQ) that determined frequency of occurrences related to equipment, tools and parts.

How often have you performed each of the actions below in the last year?

- left a tool or a torch behind in an aircraft,
- been misled by confusing documentation,
- installed a part the wrong way,
- done a job without the correct tool or equipment,
- not referred to the maintenance manual or other approved documentation on a familiar job,
- not referred to the maintenance manual or other approved documentation on an unfamiliar job,
- not referred to the parts catalogue when selecting a part,
- done a job a better way than that in the manual,
- adjusted or rigged a system incorrectly because the documentation was unclear or misleading,
- selected the wrong part to install,

- found a part (e.g. in your pocket) after a job was completed,
- disconnected part or system to make a job easier, but not documented the disconnection,
- manufactured a component without formal drawings or approval,
- dropped an object into a hard-to-reach area,
- lost a component part-way through a job, and
- assembled a component or system incorrectly because the documentation was unclear or misleading.

One of the negative consequences of not managing equipment, tools and parts correctly are store robbery. This leads to the removal of equipment from one machine to be installed in another. Unfortunately store robbery is a frequent solution to unavailability of parts (Ford et al., 2015).

APPENDIX B. MAINTENANCE TECHNICIANS QUESTIONNAIRE

Maintenance Human Factor Survey

Dear Participant,

You are invited to complete a survey questionnaire that forms part of my formal PhD Engineering Management studies, titled “Maintenance Human Factors”.

Maintenance human factors are characteristics which define the way in which a person behaves. These behaviours influence the way the maintenance department operates and performs. This Survey is conducted to understand human factor influence within the Electricity Transmission industry from the maintenance staff’s prospective.

Your participation in this study is entirely voluntary and **ANONYMOUS**. You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. You don’t even have to provide the reason/s for your decision. Your withdrawal will in no way influence your continued relationship with the research team. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes. NO information will be shared to management with the intend of prosecution, disciplinary actions or punishment.

In this regards I would be very grateful if you could complete the on-line questionnaire, available at:

You will be asked to respond to questions as honestly as possible and it should not take more than 15 minutes to complete the survey. The closing date for the survey will be xxxx

Your participation in the study will be greatly appreciated.

Student: Rina Peach (072 3838 746, RINA@IEEE.ORG)
Study leader: Professor Krige Visser (Krige.Visser@up.ac.za)

Should you wish to receive the final thesis of this study, you may request it through email (RINA@IEEE.ORG).

Student declaration:
The student wishes to declare that she is a full time employee within an Electricity Transmission Organisation. The particular organization did grant her permission to conduct this study.

Informed consent

By clicking continue you agree that:

I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach.

The nature, objective, possible safety and health implications have been explained to me and I understand them.

I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

Questions

Part A: Personal Information

2. For which Company do you work for	*"Organisation"* Generation *"Organisation"* Transmission *"Organisation"* Distribution Other: Please specify
3. For which type of maintenance are you responsible	High Voltage Plant / Outdoor Yard Equipment Control Plant / Secondary Plant Lines and Servitudes Other: Please specify
4. How long, in years, have you been in your present position?	a 1-3y b 4-7y c 8-10y d 10-15y e >=15y
5. For which subtype of maintenance are you responsible	Inspections Minor Maintenance Major Maintenance
6. What is the highest level of education you have completed?	No formal education Matriculated from high school Vocational training Diploma BTech University Degree Postgraduate degree Other: Please specify

Part B: Maintenance Human Factors

Maintenance human factors are characteristics which define the way in which maintenance staff behave and perform maintenance. These behaviours influence maintenance errors and maintenance performance. Maintenance human factors span across both the behavioural domain (motivation, stress) and the physical domain (work environment, heat, noise). These factors include factors such as (but are not limited to): Communication, High Workload, Noise Levels, Time Pressures, Fatigue, etc

The aim of this survey is determine the most influential maintenance human factors within the Electricity Transmission industry from the maintenance staff's prospective.

This survey is ANONYMOUS and it is requested that you answers as honestly and accurately as possible.

7. When you think of a maintenance error you have made, which of the following do you think contributed **the most** to it.	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision Life Stress Equipment, Tools, And Parts
8. When you think of a maintenance error you have made, which of the following do you think contributed **the second most** to it.	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision Life Stress Equipment, Tools, And Parts
9. Please rank the following factors that you feel led to you making the maintenance error	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision

	Life Stress Equipment, Tools, And Parts

Would you be willing to fill in a checklist or surveys at work that would measure the following:

10. How well your ***supervisor*** is managing human factors. These checklists would rate how well some of the factors in question 8 and 9 are managed by your ***supervisor.***	Very Probably Not Probably Not Possibly Probably Very Probably
11. Your personal fatigue level.	Very Probably Not Probably Not Possibly Probably Very Probably
12. Your personal life stress level.	Very Probably Not Probably Not Possibly Probably Very Probably
13. Your work life stress level.	Very Probably Not Probably Not Possibly Probably Very Probably
14. How well your ***organisation*** is managing human factors. These checklists would rate how well some of the factors in question 7 to 9 are managed by your ***organisation.***	Very Probably Not Probably Not Possibly Probably Very Probably
15. Would you be willing to provide heart rate data to your organization? This could be done through a heart rate monitor watch. The information will be collected by trained medical professionals and your confidentiality will be insured.	Very Probably Not Probably Not Possibly Probably Very Probably

<u>At work in the last year, on average, how often have you”:</u>

	Relating Factors **(Not to be given to participants – used for coding only)**

16. Done a job without the correct tool or equipment	Every day, Once a week, once a month, once a year, never, not relevant	Equipment, Tools, And Parts
17. Not made a system safe before working on it, or in its vicinity	Every day, Once a week, once a month, once a year, never, not relevant	Situation Awareness
18. Found a part (e.g. in your pocket) after a job was completed	Every day, Once a week, once a month, once a year, never, not relevant	Skill – based error Cognitive Dimensions Attention/Memory
19. Started to work on the wrong equipment	Every day, Once a week, once a month, once a year, never, not relevant	Situation Awareness Cognitive Dimensions Attention/Memory
20. Been interrupted part-way through a job and forgotten to return to it	Every day, Once a week, once a month, once a year, never, not relevant	Attention/Memory
21. Been interrupted part-way through a task to perform another more urgent task.	Every day, Once a week, once a month, once a year, never, not relevant	Workload
22. Had to rush an inspection.	Every day, Once a week, once a month, once a year, never, not relevant	Time Pressure
23. Had to rush an maintenance task due to time pressure	Every day, Once a week, once a month, once a year, never, not relevant	Time Pressure
24. Been delayed on a task because you could not obtain a consumable part (for example, an 'O' ring, oil, etc).	Every day, Once a week, once a month, once a year, never, not relevant	Equipment, Tools, And Parts
25. Had trouble concentrating because you were tired.	Every day, Once a week, once a month, once a year, never, not relevant	Fatigue
26. Found an error in a maintenance document.	Every day, Once a week, once a month, once a year, never, not relevant	Procedures/Work Cards
27. Worked more than 12 hours in a 24-hour period.	Every day, Once a week, once a month, once a year, never, not relevant	Fatigue

28. Been delayed on a task because you could not obtain a major part (for example, a wheel or pump).	Every day, Once a week, once a month, once a year, never, not relevant	Equipment, Tools, And Parts
29. Worked more than two night shifts in a row.	Every day, Once a week, once a month, once a year, never, not relevant	Fatigue
30. Been unable to obtain a special tool or item of maintenance equipment.	Every day, Once a week, once a month, once a year, never, not relevant	Equipment, Tools, And Parts
31. Started to do a job the wrong way because you didn't realize that the equipment was different to what you were used to	Every day, Once a week, once a month, once a year, never, not relevant	Skill – based error Cognitive Dimensions Attention/Memory
32. Done a task without the correct lighting / illumination	Every day, Once a week, once a month, once a year, never, not relevant	Illumination
33. Voluntary Survey exit point: 32 / 46 Completed :) You are almost done with the survey ;) Just hang in there! Do you want to continue?		
34. Been asked to work overtime to complete the current workload	Every day, Once a week, once a month, once a year, never, not relevant	Workload
35. Had to rush a job to ensure that all your workload gets completed	Every day, Once a week, once a month, once a year, never, not relevant	Workload
36. Had to reduce maintenance activities on jobs to ensure that all your workload gets completed	Every day, Once a week, once a month, once a year, never, not relevant	Workload
37. Done a task without in a high noise level environment	Every day, Once a week, once a month, once a year, never, not relevant	Noise Level
38. Felt that important information regarding the maintenance task was not communicated with you	Every day, Once a week, once a month, once a year, never, not relevant	Communication
39. Done a task without the required supervision	Every day, Once a week, once a month, once a year, never, not relevant	Supervision

40. Had to perform a task you were not trained on	Every day, Once a week, once a month, once a year, never, not relevant	Training/Preparation
41. Misdiagnosed a situation relating to a maintenance task.	Every day, Once a week, once a month, once a year, never, not relevant	Judgment/Decision-making
42. Omitted a step when performing a maintenance task	Every day, Once a week, once a month, once a year, never, not relevant	Attention/Memory
43. Worked on equipment were it was easy to incorrectly install a part	Every day, Once a week, once a month, once a year, never, not relevant	Inadequate Design
44. Work on equipment with poor Accessibility or layout	Every day, Once a week, once a month, once a year, never, not relevant	Inadequate Design
45. When reporting at the maintenance site found out that the job was cancelled without it being communicated to you	Every day, Once a week, once a month, once a year, never, not relevant	Communication
46. Had to perform a task you were not certified to perform	Every day, Once a week, once a month, once a year, never, not relevant	Certification/Qualification

Part C: Sensitive Information

The following section may be seen as sensitive personal information. Should you not wish to answer these questions, you may submit the survey as is. Alternatively, you may select the "Do not wish to answer" option if it is only applicable to one particular question.

47. Voluntary Survey exit point: Thank you for getting so far. You can now choose to submit - or hold on a little bit longer.	
48. How much time do you usually sleep before shifts or your working day?	Less than 6 hours 6-8 hours 9-11 hours more than 12 hours Do not wish to answer
49. Do you have access to your own sleep quality information, such as a Fitbit or other wearable device?	Yes No Do not wish to answer

50. If yes: how much deep sleep do you get on average:
    Less than 1 hour a night
    Between 1 and 2 hours
    Between 2 and 3 hours
    Between 3 and 4 hours
    More than 4 hours

51. How would you rate your own personal stress level?	No stress Mild stress Moderate stress Much stress Extreme stress Do not wish to answer
52. How would you rate your own work stress level?	No stress Mild stress Moderate stress Much stress Extreme stress Do not wish to answer

APPENDIX C. MANAGEMENT QUESTIONNAIRE

Maintenance Human Factors: Management Survey

Dear Manager,

You are invited to complete an online survey questionnaire that forms part of my formal PhD Engineering Management studies, titled “Maintenance Human Factors”.

The survey can be done using a cell phone, tablet or computer.

Maintenance human factors are characteristics which define the way in which a person behaves. These behaviours influence the way the maintenance department operates and performs. This Survey is conducted to understand human factor influence within the Electricity Transmission industry from the maintenance staff’s prospective.

This questionnaire is aimed at managers responsible for maintenance staff / field workers. The questions asked within this questionnaire are based on the results from a questionnaire sent to maintenance staff / field workers at the end of 2019.

Your participation in this study is entirely voluntary and **ANONYMOUS**. You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. You don’t even have to provide the reason/s for your decision. Your withdrawal will in no way influence your continued relationship with the research team. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes.

In this regards I would be very grateful if you could complete the on-line questionnaire, available at:

https://kwiksurveys.com/s/lIHgfJSp

You will be asked to respond to questions as honestly as possible and it should not take more than 10 minutes to complete the survey. The closing date for the survey will be *Friday 5 June 2020.*

Your participation in the study will be greatly appreciated.

Student: Rina Peach (072 3838 746, RINA@IEEE.ORG)
Study leader: Professor Krige Visser (Krige.Visser@up.ac.za)

Should you wish to receive the final thesis of this study, you may request it through email (RINA@IEEE.ORG).

Student declaration:
The student wishes to declare that she is a full time employee within an Electricity Transmission Organisation. The particular organization did grant her permission to conduct this study.

Informed consent

By clicking continue you agree that:
I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach.

The nature, objective, possible safety and health implications have been explained to me and I understand them. I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

Questions

Part A: Personal Information

2.	For which Company do you work for	*"Organisation"* Generation *"Organisation"* Transmission *"Organisation"* Distribution Other: Please specify
3.	How long, in years, have you been in your present position?	a 1-3y b 4-7y c 8-10y d 10-15y e >=15y
4.	For which discipline are your currently responsible for to manage maintenance staff:	High Voltage Plant / Outdoor Yard Equipment Control Plant / Secondary Plant Lines and Servitudes Other: Please specify
5.	What is the highest level of education you have completed?	No formal education Matriculated from high school Vocational training Diploma BTech University Degree (under graduate) Postgraduate degree: Masters Postgraduate degree: PhD Other: Please specify

Part B: Maintenance Human Factors

The following questions are aimed to determine the alignment between manager's perspectives on maintenance human factors and the maintenance staff / field workers perspectives. The questions asked within this questionnaire are based on the results from a questionnaire sent to maintenance staff / field workers at the end of 2019.

Maintenance human factors are characteristics which define the way in which maintenance staff behave and perform maintenance. These behaviours influence maintenance errors and maintenance performance. Maintenance human factors span across both the behavioural domain (motivation, stress) and the physical domain (work environment, heat, noise). These factors include factors such as (but are not limited to): Communication, High Workload, Noise Levels, Time Pressures, Fatigue, etc

This survey is ANONYMOUS and it is requested that you answers as honestly and accurately as possible.

6. When you think of maintenance errors that occurred in your department, which of the following do you think contributed **the most** to it.	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision Life Stress Equipment, Tools, And Parts
7. When you think of maintenance errors that occurred in your department, which of the following do you think contributed **the second most** to it.	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision Life Stress Equipment, Tools, And Parts
8. Please rank the following factors that you feel are causing maintenance errors in your department. From 1 causing the most, to 11 causing the least number of errors.	Fatigue Inadequate Lighting/Light Communication High Workload Cognitive Capabilities Judgment/Decision-Making Noise Level Time Pressure Supervision Life Stress Equipment, Tools, And Parts

Would you, as manager, be interested in a measurement for you maintenance staff's:

9. perception of the level of **workload** they experience	Very Probably Not Probably Not Possibly Probably Very Probably
10. perception of the level of **time pressure** they experience	Very Probably Not Probably Not Possibly Probably Very Probably
11. perception of the level of **fatigue** they experience	Very Probably Not Probably Not Possibly Probably Very Probably
12. perception of the level of effective **communication** they experience	Very Probably Not Probably Not Possibly Probably Very Probably
13. perception of the level of availability to **equipment, tools and parts**	Very Probably Not Probably Not Possibly Probably Very Probably
14. perception of the level of effective **supervision** they experience	Very Probably Not Probably Not Possibly Probably Very Probably
15. perception of the level of **stress** they experience	Very Probably Not Probably Not Possibly Probably Very Probably
16. perception of the level of **inadequate lighting** they experience	Very Probably Not Probably Not Possibly Probably Very Probably

17. perception of the level of availability to **equipment, tools and parts**	Very Probably Not Probably Not Possibly Probably Very Probably
18. perception of the level of **excessive noise levels** they experience	Very Probably Not Probably Not Possibly Probably Very Probably

Part C: Sensitivity of Information

The above mentioned factors might be seen as sensitive information for maintenance staff.

Please rank:

19. Which of the following ways would **YOU** feel more comfortable with, to obtain the information:	Named checklist / surveys / questionnaire Anonymous checklist / surveys / questionnaire Anonymous measurable medical data collected by trained medical professionals to summaries the overall status of your department
20. Which of the following ways do you think would your **STAFF** feel more comfortable with to provide the information:	Named checklist / surveys / questionnaire Anonymous checklist / surveys / questionnaire Measurable medical data collected through a **SMART WATCH**. The information would be collected by a trained medical professionals and their anonymity will be insured. Measurable medical data collected through a **PHYSICAL EXAM**. The information would be collected by a trained medical professionals and their anonymity will be insured

APPENDIX D. MHFP FRAMEWORK ROUND 1

Dear xxxx,

You are invited to complete an online survey questionnaire that forms part of my formal PhD Engineering Management studies, titled “Maintenance Human Factors in the South African Electricity Transmission Industry”. The purpose of this questionnaire is to determine the validity of my research model based on the survey results sent to maintenance staff / field workers at the end of 2019.

In this regards I would be very grateful if you could complete the on-line questionnaire, before xxxx, available at:

https://kwiksurveys.com/s/xxxx

The survey can be done using a cell phone, tablet or computer.

Kind regards,
Student: Rina Peach (072 3838 746, RINA@IEEE.ORG)
Study leader: Professor Krige Visser (Krige.Visser@up.ac.za)

Declaration:
The student does have an *“Organisation”* permission letter (attached) stating that she has permission to conduct research within the *“Organisation”* environment. Should you wish to receive the final thesis of this study, you may request it through email (RINA@IEEE.ORG).

Informed consent

Your participation in this study is entirely voluntary. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes. Your comments and opinions will not be shared with any other participant.

A declaration is also made that your comments and opinions shall in no way influence your continued relationship with the research team. It is therefore asked that you respond to the questions as honestly as possible.

You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. Your withdrawal will in no way influence your continued relationship with the research team.

By clicking continue you agree that:

I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach.

I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

Questions

Part A: Personal Information

The aim of this questionnaire is to determine your expert opinion, on the measurement model proposed by the researcher. This model is based on the results from a questionnaire sent to maintenance staff / field workers within Transmission at the end of 2019.

Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

- Email address
- Name and surname
- Applicable area of experience in maintenance human factors (more than one option can be selected)
    a. Member of the Human Performance Operating Committee
    b. Operating error / human error investigations
    c. Defence in-depth incident and operational safety analysis
    d. Reporting on operating error / human error performance
    e. Training on operating error / human error investigations
    f. Management
    g. Chief engineer
    h. Other, please specify in as much detail as possible:
        i. Example: Academic researcher (Switzerland), focusing on human factors with in power transmission.

Part B: Research Question 1

The first identified research question within this study is “What maintenance human factors have the most influence on maintenance human errors?” Maintenance human factors are “factors external and internal that either positively or negatively affect the maintenance technician’s ability to perform maintenance tasks”.

The primary goal of knowing these factors are to manage these human factors to reduce maintenance human errors, hence maintenance errors due to human factors or behaviours.

In you experience would you agree to the following research statements:

	Strongly disagree, disagree, I don’t know, agree and strongly agree
The most influential maintenance human factors within Transmission is well known and documented.	
Awareness of these most influential maintenance human factors could benefit maintenance performance within Transmission.	
Awareness of these most influential maintenance human factors could lead to reduced humans errors.	
The most influential maintenance human factors are actively being managed by management.	
The most influential maintenance human factors are actively being managed by supervisors.	

Part C: Research Question 2

The second identified research question relates to how these maintenance human factor can be included a maintenance performance framework. This is to actively know the measurable state of the human factor in order to effectively manage them.

	Strongly disagree, disagree, I don’t know, agree and strongly agree
The most influential maintenance human factors within Transmission are being measured within an official performance framework.	
Measuring these most influential maintenance human factors could benefit the maintenance performance within Transmission.	
Measuring these most influential maintenance human factors could lead to reduced humans errors.	
Measuring these most influential maintenance human factors could lead to better management of these human factors.	

Comments/ personal views and opinions (optional):

Part D: Most influential maintenance human factors

From the survey the following factors were identified as the most influential maintenance human factors, that have contributed to a personal maintenance error made by the technician:

- High workload,
- time pressure,
- fatigue, and
- communication.

In you experience would you agree that these factors contribute significantly to maintenance human errors considering some situational examples that are given.

High workload,

- Too many commitments that I am in charge of.
- The feeling that tasks are too much for me.
- Postponement of urgently needed recreation.
- Too many duties that I have to do.
- Not enough time to fulfil my daily assignments.
- Overload through different duties that I need to take care of.
- Situations with so many difficulties that I cannot deal with all of them.
- The feeling that it is all too much for me.

	Strongly disagree, disagree, I don't know, agree and strongly agree
High workload	

Time pressure,

- I feel high time pressure at work.
- I feel very busy at work.
- I find that the given time at work is very limited.
- I always feel in a hurry during work hours.
- I do not have sufficient time to finish what I should do at work.

	Strongly disagree, disagree, I don't know, agree and strongly agree
Time pressure	

Fatigue

- My motivation is lower when I am fatigued,
- Exercise brings on my fatigue,
- I am easily fatigued,
- Fatigue interferes with my physical functioning,

- Fatigue causes frequent problems for me,
- My fatigue prevents sustained physical functioning,
- Fatigue interferes with carrying out certain duties and responsibilities,
- Fatigue is among my three most disabling symptoms, and
- Fatigue interferes with my work, family, or social life.

	Strongly disagree, disagree, I don't know, agree and strongly agree
Fatigue	

Communication

Communication climate	receiving the information needed to do your job on time? conflicts being handled appropriately through proper communication channels?
Supervisor communication	your supervisor listening to you? your supervisor offering guidance for solving job-related problems? your supervisor trusting you? your supervisor being open to ideas?
Organisational integration	information on the requirements of your job?
Media quality	your meetings being well organised?
Personal feedback	information on how you are being evaluated? recognition of your efforts? your superior's understanding of the problems faced by subordinates?

	Strongly disagree, disagree, I don't know, agree and strongly agree
Communication	

Comments/ personal views and opinions (optional):

Part E: Measuring the most influential maintenance human factors

The table below illustrates the percentage of resonance that ranked each factor as the most influential:

Maintenance Human Factor	
High Workload	24%
Time Pressure	19%
Fatigue	15%
Communication	14%

If weighting of these factors were to be normalized to a 100 as illustrated below, what would your opinion be on the weight of each factor:

	Weigh	**It is too low, in agreement, it is to high**	**If you are not in agreement, what would you suggest the weighting should be**
High workload	33%		
time pressure	26%		
fatigue	22%		
communication	19%		

In your opinion, if these factor were to be measure, who would be best suited to calculate / determine these measurements. These measurements of these factor will be done though academic and industry validated surveys. More than one option can be chosen

- Human Performance Operating Committee member
- Human Performance Operating Committee appointed person
- Business Integration and Performance Management
- Chief Engineers
- Industrial psychologist within HR
- HR as an item: maintenance human factors
- Middle Managers
- Supervisors

Comments/ personal views and opinions (optional):

APPENDIX E. MHFP framework round 2

Dear xxxx,

Thank you for completing the first round of my thesis model validity survey ☺ There were allot of aspects that have now been validated, however there are still some uncertainty about other elements.

I would therefore kindly ask to complete a second survey. *THIS QUESTIONNAIRE CONSIST OF ONLY A FEW QUESTIONS AND WOULD NOT TAKE MORE THAT 5 MINUTES TO COMPLETE.*

The second survey is to provide the results from the first survey, then provide you an opportunity to support / not support the statements made from the first round results.

I would be very grateful if you could complete the on-line questionnaire, before xxxx, available at:

https://kwiksurveys.com/s/xxxx

The survey can be done using a cell phone, tablet or computer.

Kind regards,
Student: Rina Peach (072 3838 746, RINA@IEEE.ORG)
Study leader: Professor Krige Visser (Krige.Visser@up.ac.za)

Declaration:
The student does have an *"Organisation"* permission letter (attached) stating that she has permission to conduct research within the *"Organisation"* environment. Should you wish to receive the final thesis of this study, you may request it through email (RINA@IEEE.ORG).

Informed consent
Your participation in this study is entirely voluntary. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes. Your comments and opinions will not be shared with any other participant.

A declaration is also made that your comments and opinions shall in no way influence your continued relationship with the research team. It is therefore asked that you respond to the questions as honestly as possible.

You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. Your withdrawal will in no way influence your continued relationship with the research team.

By clicking continue you agree that:

I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach.

I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

Questions

Part A: Personal Information

The aim of this questionnaire is provide feedback on the first round questionnaire and validate statements made for the first questionnaire data analysis.

Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

- Email address
- Name and surname

Part B: Research Question 1

Maintenance human factors are the softer human root causes that lead up to a human error being made. Some examples are high workload, fatigue, working under extreme time pressure and a breakdown of communication. Not all maintenance human factors cause human error; however, the cause of human error share similar factors with maintenance human factors.

From the first round questionnaire, all participants agreed/strongly agreed to the below statements:

- Awareness of these most influential maintenance human factors could benefit maintenance performance within Transmission.

- Awareness of these most influential maintenance human factors could lead to reduced human errors.

From the first round questionnaire, 58% of participants disagreed/strongly disagreed with the below statements (26% of the participant remained neutral and only 16% agreed/strongly agreed):

- The most influential maintenance human factors are actively being managed by management.
- The most influential maintenance human factors are actively being managed by supervisors.

Would you therefore support that these statements are valid:

	Strongly not supported, not supported, supported and strongly supported
The most influential maintenance human factors are **NOT** actively being managed by management.	
The most influential maintenance human factors are **NOT** actively being managed by supervisors.	

Participants response to the statement "The most influential maintenance human factors within Transmission is well known and documented." Were:

- 31% disagreed/strongly disagreed,
- 21% neutral, and
- 47% agreed/strongly agreed

To understand the different responses from the participants, please answer the following questions.

In you experience

	Strongly disagree, disagree, agree and strongly agree
Knowledge of human error causes are based on work experience	
Knowledge of human error causes are based on record keeping, historical data and mathematical calculations	
Knowledge of the **underlying human factor** that lead to the human errors are based on work experience	
Knowledge of the **underlying human factor** that lead to the human errors record keeping, historical data and mathematical calculations	

Based on the above questions kindly re-answer the original question (now split into two parts), taking in to consideration that maintenance human factors are the softer human root causes that lead up to a human error being made.

	Strongly disagree, disagree, agree and strongly agree
"The most influential maintenance human factors within Transmission is well known"	
"The most influential maintenance human factors within Transmission is well documented."	

Comments/ personal views and opinions (optional):

Part C: Research Question 2

From the first round questionnaire, more than 90% of all participants agreed/strongly agreed to the below statements:

- Measuring these most influential maintenance human factors could benefit the maintenance performance within Transmission.
- Measuring these most influential maintenance human factors could lead to reduced humans errors.
- Measuring these most influential maintenance human factors could lead to better management of these human factors.

Participant's response to the statement "The most influential maintenance human factors within Transmission are being measured within an official performance framework." Were:

- 55% strongly disagree & disagree, 22% neutral, and 22% agreed & strongly agreed

Would you therefore support that the below statement is valid:

	Strongly disagree, disagree, agree and strongly agree
"The most influential maintenance human factors within Transmission are **NOT** being measured within an official performance framework."	

Comments/ personal views and opinions (optional):

Part D: Most influential maintenance human factors

From the first round questionnaire, more than 80% of all participants agreed/strongly agreed that **time pressure** and **communication** contribute significantly to maintenance human errors.

Participant's response that high workload contributes significantly to maintenance human errors were: 29% strongly disagree & disagree, 12% neutral, and 59% agreed & strongly agreed.

Would you therefore support that the below statement is valid:

	Strongly disagree, disagree, agree and strongly agree
High workload contributes significantly to maintenance human errors.	

Participant's response that fatigue contributes significantly to maintenance human errors were: 29% strongly disagree & disagree, 18% neutral, and 53% agreed & strongly agreed.

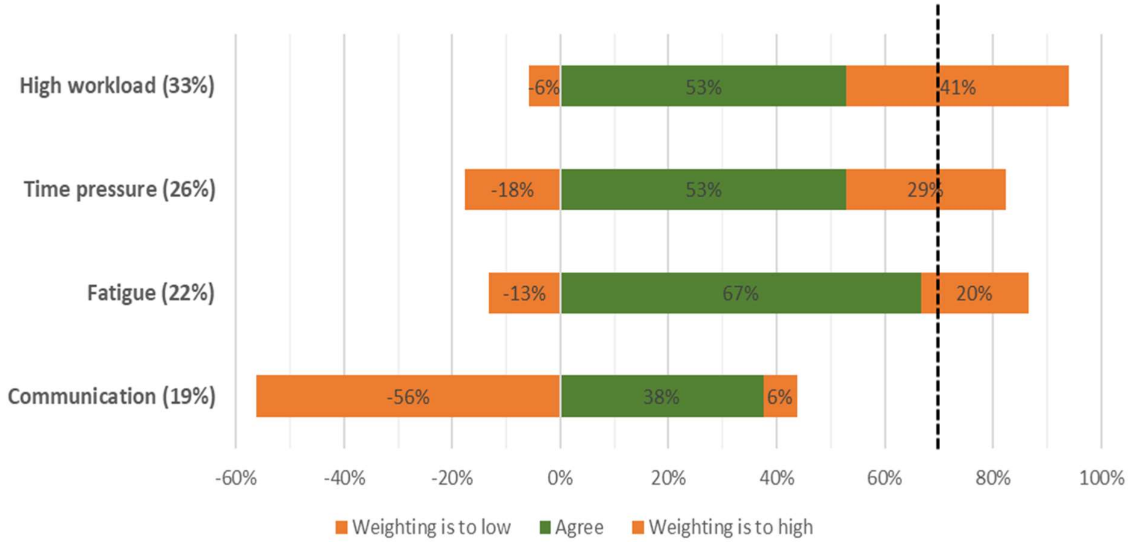
Would you therefore support that the below statement is valid:

	Strongly disagree, disagree, agree and strongly agree
Fatigue contributes significantly to maintenance human errors.	

Comments/ personal views and opinions (optional):

Part E: Measuring the most influential maintenance human factors

Feedback regarding weightings to measure each element are shown below.



Taking the results into consideration the weighting were changed as below

	Weigh (Round 1)	**Round 2 suggested weights**
High workload	33%	28%
Time pressure	26%	24%
Fatigue	22%	22%
Communication	19%	26%

Would you therefore support the adjusted weightings?

	Weigh	**It is too low, in agreement, it is to high**
High workload	28%	
Time pressure	24%	
Fatigue	22%	
Communication	26%	

From the first round questionnaire the below 4 options received equally the highest rating when it was asked would be best suited to calculate / determine these measurements.

Kindly indicate from these 4 options who you think would be best suited to calculate / determine these measurements.

- Human Performance Operating Committee appointed person
- Business Integration and Performance Management
- HR as an item: maintenance human factors
- Middle Managers

Comments/ personal views and opinions (optional):

APPENDIX F. TMP FRAMEWORK ROUND 1

Dear xxxx,

You are invited to complete an online survey questionnaire that forms part of my formal PhD Engineering Management studies, titled "Maintenance Human Factors in the South African Electricity Transmission Industry". The purpose of this questionnaire is to determine the validity of my research model based on the survey results sent to maintenance staff / field workers at the end of 2019.

In this regards I would be very grateful if you could complete the on-line questionnaire, before xxxx, available at:

https://kwiksurveys.com/s/ xxxx

The survey can be done using a cell phone, tablet or computer.

Kind regards,
Student: Rina Peach (072 3838 746, RINA@IEEE.ORG)
Study leader: Professor Krige Visser (Krige.Visser@up.ac.za)

Declaration:
The student does have an *"Organisation"* permission letter (attached) stating that she has permission to conduct research within the *"Organisation"* environment. Should you wish to receive the final thesis of this study, you may request it through email (RINA@IEEE.ORG).

Informed consent
Your participation in this study is entirely voluntary. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes. Your comments and opinions will not be shared with any other participant.

A declaration is also made that your comments and opinions shall in no way influence your continued relationship with the research team. It is therefore asked that you respond to the questions as honestly as possible.

You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. Your withdrawal will in no way influence your continued relationship with the research team.

By clicking continue you agree that:

I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach.

I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

Questions

Part A: Personal Information

The aim of this questionnaire is to determine your expert opinion, on the maintenance performance measurement/framework proposed by the researcher. This model is based on the results from a questionnaire sent to maintenance staff / field workers within Transmission at the end of 2019.

Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

- Email address
- Name and surname
- Applicable area of experience in maintenance performance measurements/frameworks (more than one option can be selected)
    - i. Business Integration and Performance Management
    - j. Developing yearly performance measurements
    - k. Reporting on performance measurements
    - l. Reporting on maintenance performance
    - m. Reporting on technical performance
    - n. Grid management
    - o. Grid middle management
    - p. Chief engineer
    - q. Other, please specify in as much detail as possible:

i. Example: Academic researcher (Switzerland), focusing on maintenance performance measurements/frameworks with in power transmission.

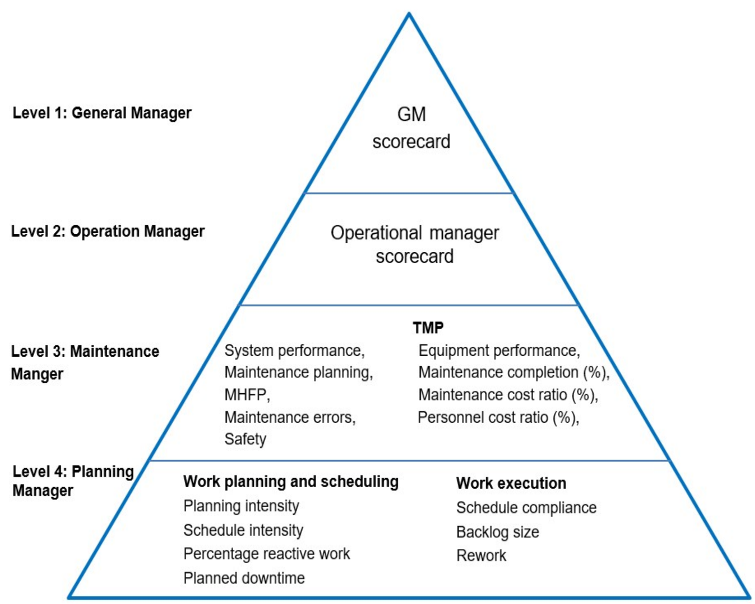
Definitions:
Maintenance human factors are "factors external and internal that either positively or negatively affect the maintenance technician's ability to perform maintenance tasks".

Part B: Research Question

Maintenance performance frameworks can be used to quantitatively measure and track key performance factors to ensure management of these factors. From the questionnaire sent to maintenance staff / field workers within Transmission the following maintenance human factors were identified as the most influential maintenance human factors, that have contributed to a personal maintenance error made by the technician: high workload, time pressure, fatigue and communication.

By including the most significant maintenance human factors with corresponding measurements in a maintenance performance framework, proactive action can be taken to reduce maintenance human errors, identify performance gaps, achieve higher operational reliability and improve the overall performance of the maintenance department

The model below is proposed by the researcher as a maintenance performance measurements/frameworks within Transmission.



Titles for responsible persons at each level were generically chosen as multiple managers could be responsible at each level. It can therefor form part of their individual, section, division or grid performance framework.

In you experience, would you agree that the following level 3 elements should be included in a Total Maintenance Performance (TMP) measurement framework:

	Strongly disagree, disagree, I don't know, agree and strongly agree
System performance	
Equipment performance	
Maintenance planning	
Maintenance completion %	
Maintenance Human Factor Performance (MHFP)	
Maintenance cost ratio %	
Maintenance errors	
Personnel cost ratio %	
Safety	

Comments/ personal views and opinions (optional):

Part C: Weighting of TMP elements

If weighting of these factors were to be normalized to a 100 as illustrated below, what would your opinion be on the weight of each factor:

Maintenance Indicator	Wi (%)	**It is too low, in agreement, it is to high**	**If you are not in agreement, what would you suggest the weighting should be**
System performance	25		
Equipment performance	15		
Maintenance planning	10		
Maintenance completion %	10		
Maintenance Human Factor Performance (MHFP)	10		
Maintenance cost ratio %	10		
Maintenance errors	5		
Personnel cost ratio %	5		
Safety	10		

Comments/ personal views and opinions (optional):

Part D: Benefits of the proposed TMP

In you experience would you agree to the following research statements:

	Strongly disagree, disagree, I don't know, agree and strongly agree
Inclusion of Maintenance Human Factor Performance within a TMP could benefit maintenance performance within Transmission.	
The proposed TMP could benefit maintenance performance within Transmission.	
The proposed TMP could benefit overall technical performance within Transmission.	

Comments/ personal views and opinions (optional):

APPENDIX G.TMP FRAMEWORK ROUND 2

Dear xxxx,

Thank you for completing the first round of my thesis model validity survey ☺ There were allot of aspects that have now been validated, however there are still some uncertainty about other elements.

I would therefore kindly ask to complete a second survey. *THIS QUESTIONNAIRE CONSIST OF ONLY A FEW QUESTIONS, AND WOULD NOT TAKE MORE THAT 5 MINUTES TO COMPLETE.*

The second survey is to provide the results from the first survey, then provide you an opportunity to support / not support the statements made from the first round results.

I would be very grateful if you could complete the on-line questionnaire, before xxxx, available at:

https://kwiksurveys.com/s/ xxxx

The survey can be done using a cell phone, tablet or computer.

Kind regards,
Student: Rina Peach (072 3838 746, RINA@IEEE.ORG)
Study leader: Professor Krige Visser (Krige.Visser@up.ac.za)

Declaration:
The student does have an *"Organisation"* permission letter (attached) stating that she has permission to conduct research within the *"Organisation"* environment. Should you wish to receive the final thesis of this study, you may request it through email (RINA@IEEE.ORG).

Informed consent
Your participation in this study is entirely voluntary. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes. Your comments and opinions will not be shared with any other participant.

A declaration is also made that your comments and opinions shall in no way influence your continued relationship with the research team. It is therefore asked that you respond to the questions as honestly as possible.

You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. Your withdrawal will in no way influence your continued relationship with the research team.

By clicking continue you agree that:

I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach.

I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

Questions

Part A: Personal Information

The aim of this questionnaire is provide feedback on the first round questionnaire and validate statements made for the first questionnaire data analysis.

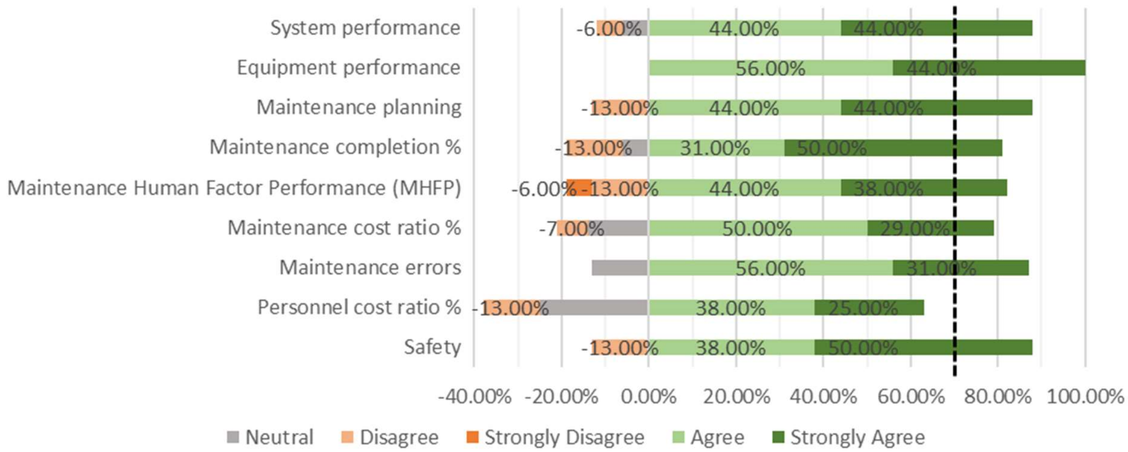
Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

- Email address
- Name and surname

Part B: TMP Element
From the first round questionnaire, more than 80% of all participants agreed/strongly agreed to the below statements regarding the benefits of the proposed TMP :

- Inclusion of Maintenance Human Factor Performance within a TMP could benefit maintenance performance within Transmission.
- The proposed TMP could benefit maintenance performance within Transmission.
- The proposed TMP could benefit overall technical performance within Transmission.

In the first questionnaire, 9 elements were proposed to be included in a Total Maintenance Performance (TMP) measurement framework. More than 70% of all participants agreed/strongly agreed that 8 of the 9 elements should be included in the TMP as per the graph below.



Participant's response to include "personnel cost ratio%", were:

- 13% strongly disagree & disagree, 25% neutral, and 63% agreed & strongly agreed

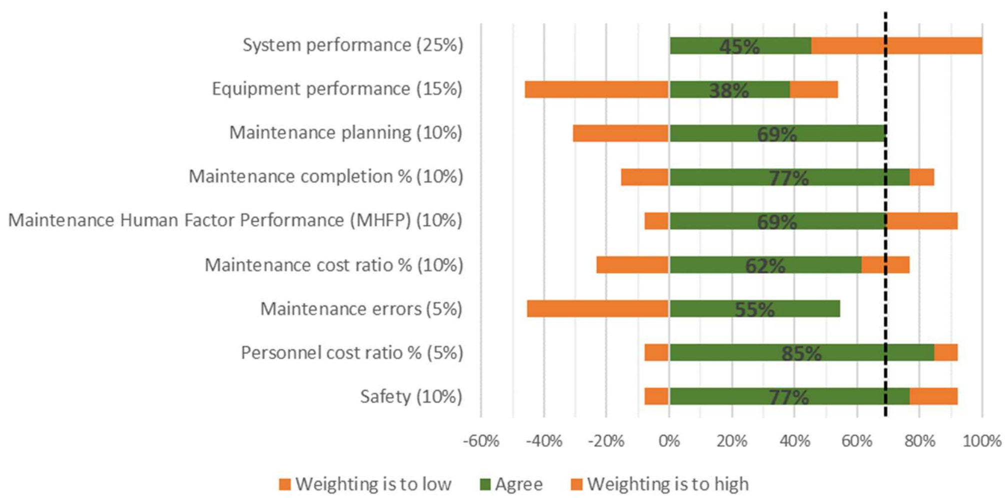
Would you therefore support that including "personnel cost ration%" into the TMP is valid:

- Strongly disagree, disagree, slightly disagrees, slightly agree, agree and strongly agree

Comments/ personal views and opinions (optional):

Part C: Weighting of TMP elements

In the first round weightings to measure each element were proposed. The responses to the weightings are shown below.



Taking the results into consideration the weighting were changed as below. Were more than 70% of the participant agreed to the weighting (round 1), support of the weighting was not asked for again.

Maintenance Indicator	Round 1 Weighing	Round 2 suggested weights
System performance	25%	15%
Equipment performance	15%	20%
Maintenance planning	10%	10%
Maintenance completion %	10%	10%
Maintenance Human Factor Performance (MHFP)	10%	10%
Maintenance cost ratio %	10%	10%
Maintenance errors	5%	10%
Personnel cost ratio %	5%	5%
Safety	10%	10%

Would you therefore support the adjusted weightings?

Maintenance Indicator	Round 2 suggested weights	Strongly disagree, disagree, slightly disagrees, slightly agree, agree and strongly agree
System performance	15%	
Equipment performance	20%	
Maintenance planning	10%	
Maintenance Human Factor Performance (MHFP)	10%	
Maintenance cost ratio %	10%	
Maintenance errors	10%	

Comments/ personal views and opinions (optional):

APPENDIX H. SURVEY REPORTS GENERATED BY KWIKSURVEYS

H.1. Maintenance technicians questionnaire

H.2. Management questionnaire

H.3. MHFP Framework Round 1

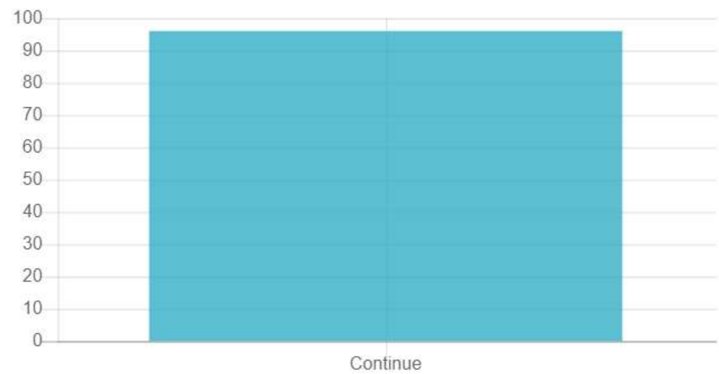
H.4. MHFP Framework Round 2

H.5. TMP Framework Round 1

H.6. TMP Framework Round 2

H.1. Maintenance technicians questionnaire

1 By clicking continue you agree that: I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach. The nature, objective, possible safety and health implications have been explained to me and I understand them. I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.



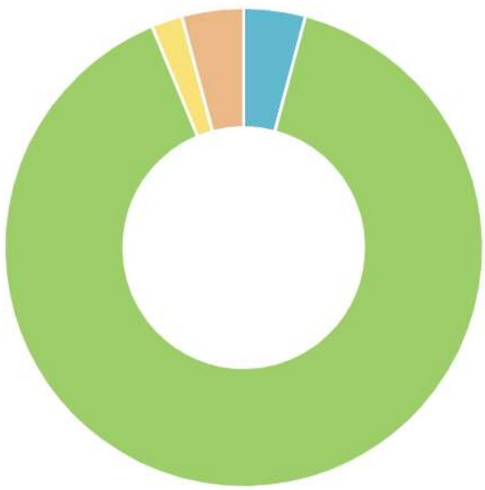
100% (96)
Continue

96
Responses

Part A

Personal Information

2 For which Company do you work for?



4% (4)
[redacted]Generation

90% (86)
[redacted]Transmission

2% (2)
[redacted]Distribution

4% (4)
Other (Please Specify)

35.81
Standard Deviation

96
Responses

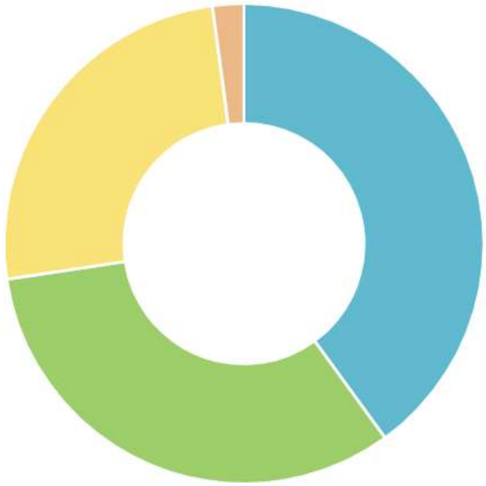
technology

PTM

central Grid

HV plant Technical Support

3 For which type of maintenance are you responsible?



40% (38)
High Voltage Plant / Outdoor Yard Equipment

33% (31)
Control Plant / Secondary Plant

25% (24)
Lines and Servitudes

2% (2)
Other (Please Specify)

13.5
Standard Deviation

95
Responses

High voltage and Secondary plant

Transformers

4 How long, in years, have you been in your present position?

14% (13)
1-3 years

40% (38)
4-7 years

18% (17)
8-10 years

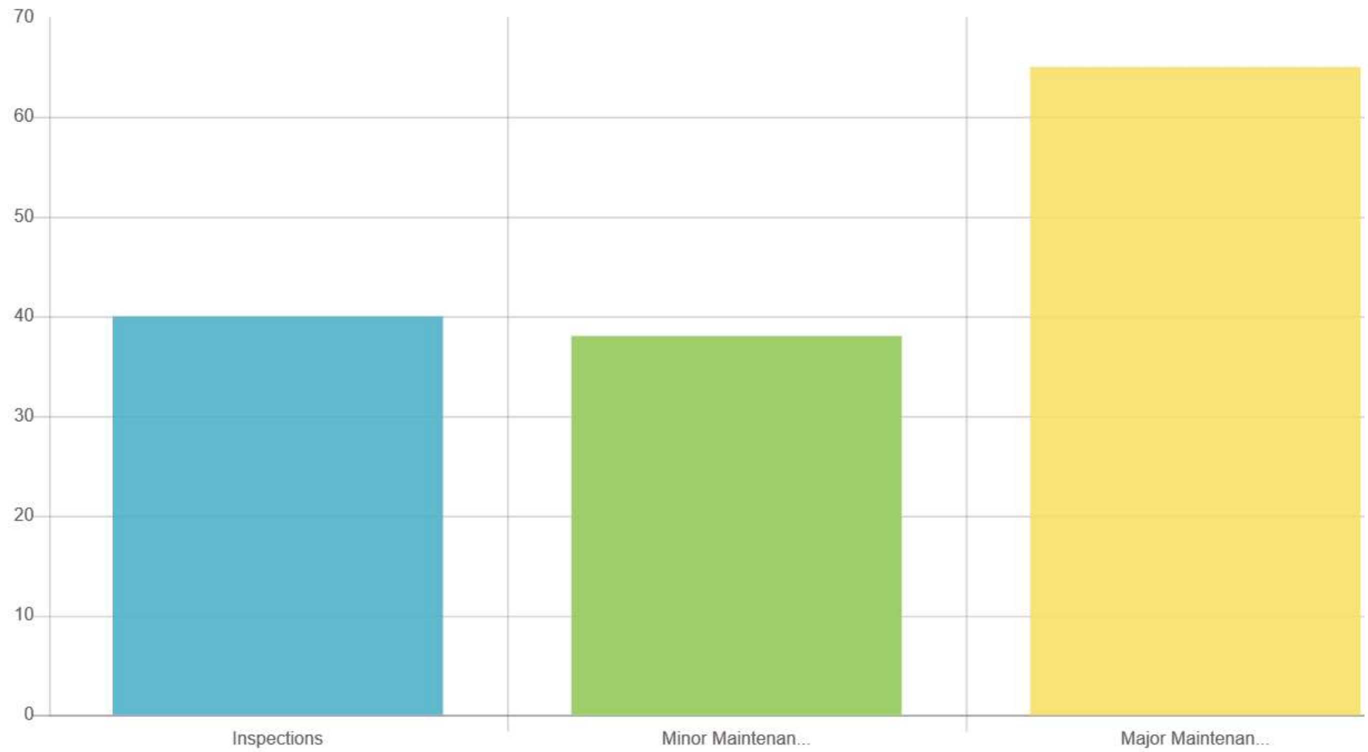
14% (13)
10-15 year

16% (15)
longer than 15 years

9.52
Standard Deviation

96
Responses

5 For which subtype of maintenance are you responsible?



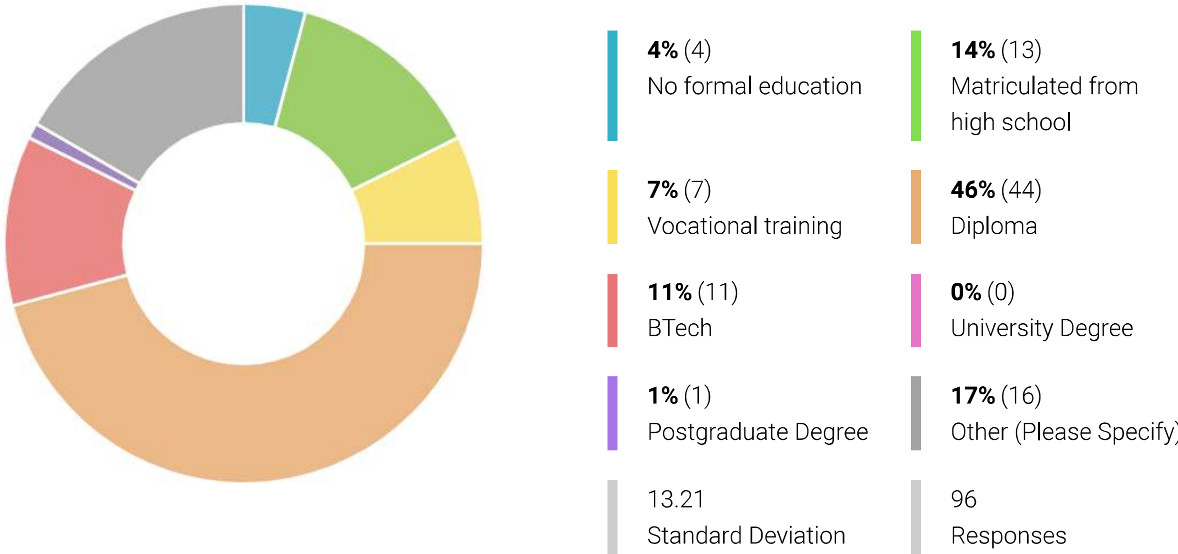
43% (40)
Inspections

41% (38)
Minor Maintenance

70% (65)
Major Maintenance

143
Responses

6 What is the highest level of education you have completed?



Electrician

N4 electrical certificate

Electrical trade

N4 with Trade Test

N4 (Electrical Certificate) & Artisan in Electrical

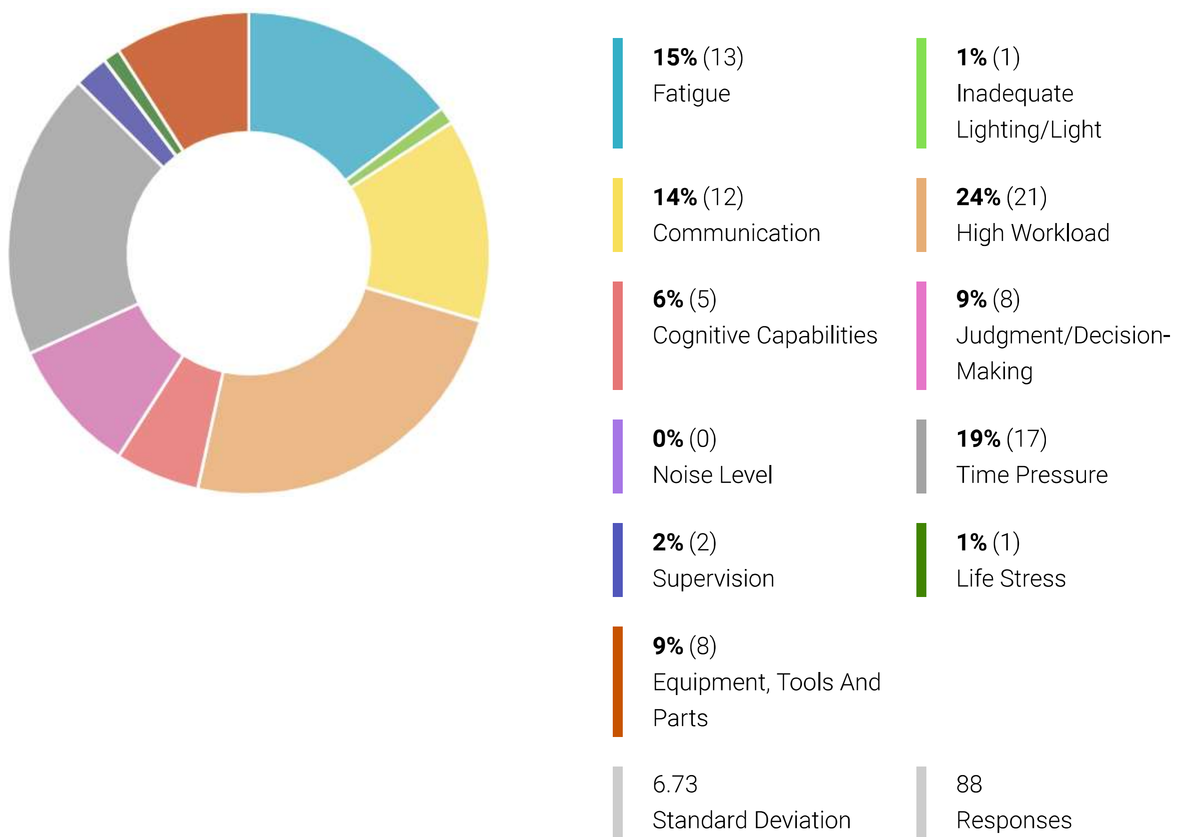
Part B

Maintenance human factors are characteristics which define the way in which maintenance staff behave and perform maintenance. These behaviours influence maintenance errors and maintenance performance. Maintenance human factors span across both the behavioural domain (motivation, stress) and the physical domain (work environment, heat, noise). These factors include factors such as (but are not limited to): Communication, High Workload, Noise Levels, Time Pressures, Fatigue, etc

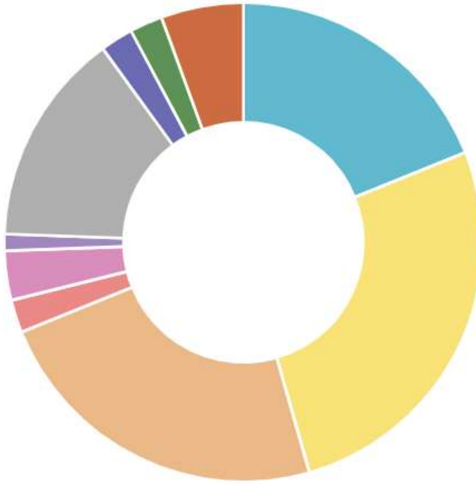
The aim of this survey is determine the most influential maintenance human factors within the Electricity Transmission industry from the maintenance staff's prospective.

This survey is ANONYMOUS and it is requested that you answers as honestly and accurately as possible.

7 When you think of a maintenance error you have made, which of the following do you think contributed the most to it?



8 When you think of a maintenance error you have made, which of the following do you think contributed the second most to it?



19% (17) Fatigue

0% (0) Inadequate Lighting/Light

27% (24) Communication

23% (21) High Workload

2% (2) Cognitive Capabilities

3% (3) Judgment/Decision-Making

1% (1) Noise Level

14% (13) Time Pressure

2% (2) Supervision

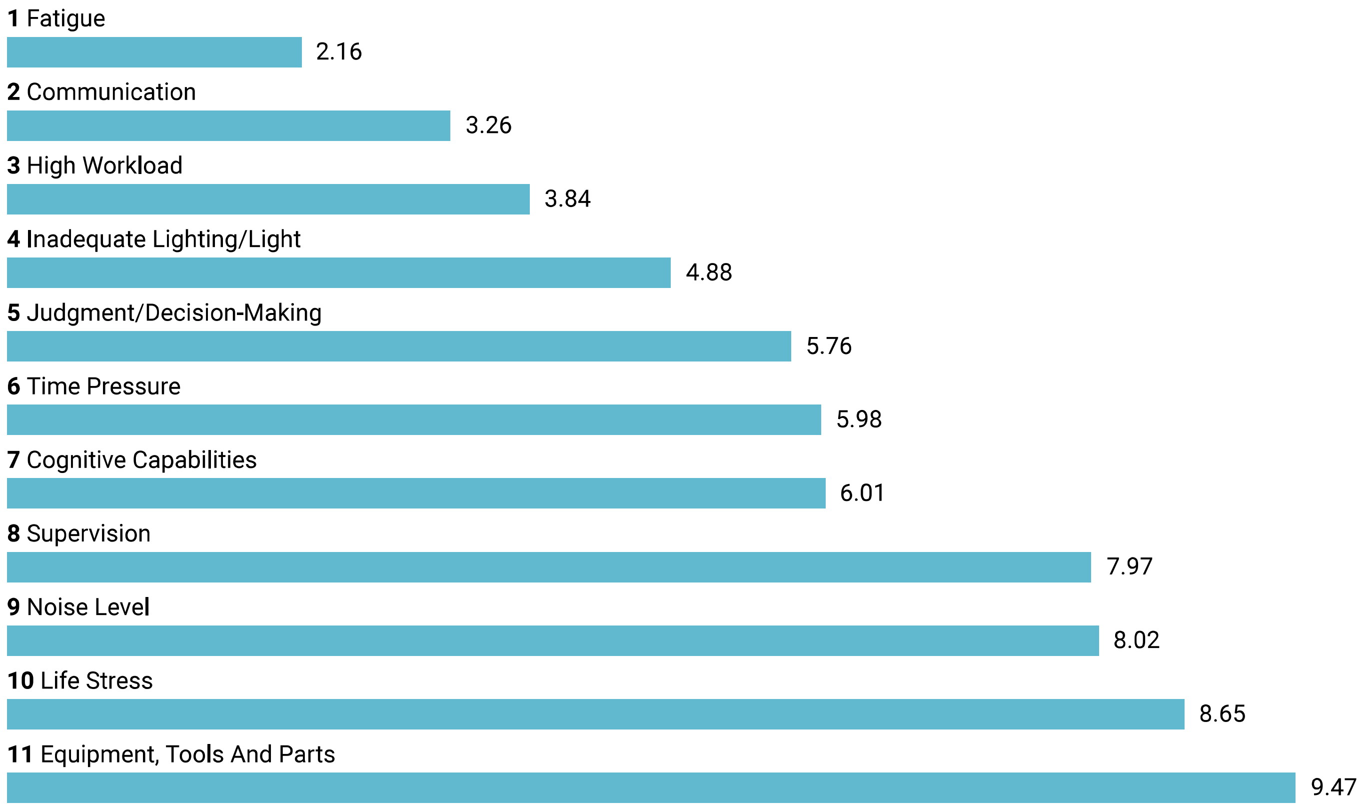
2% (2) Life Stress

6% (5) Equipment, Tools And Parts

8.45 Standard Deviation

90 Responses

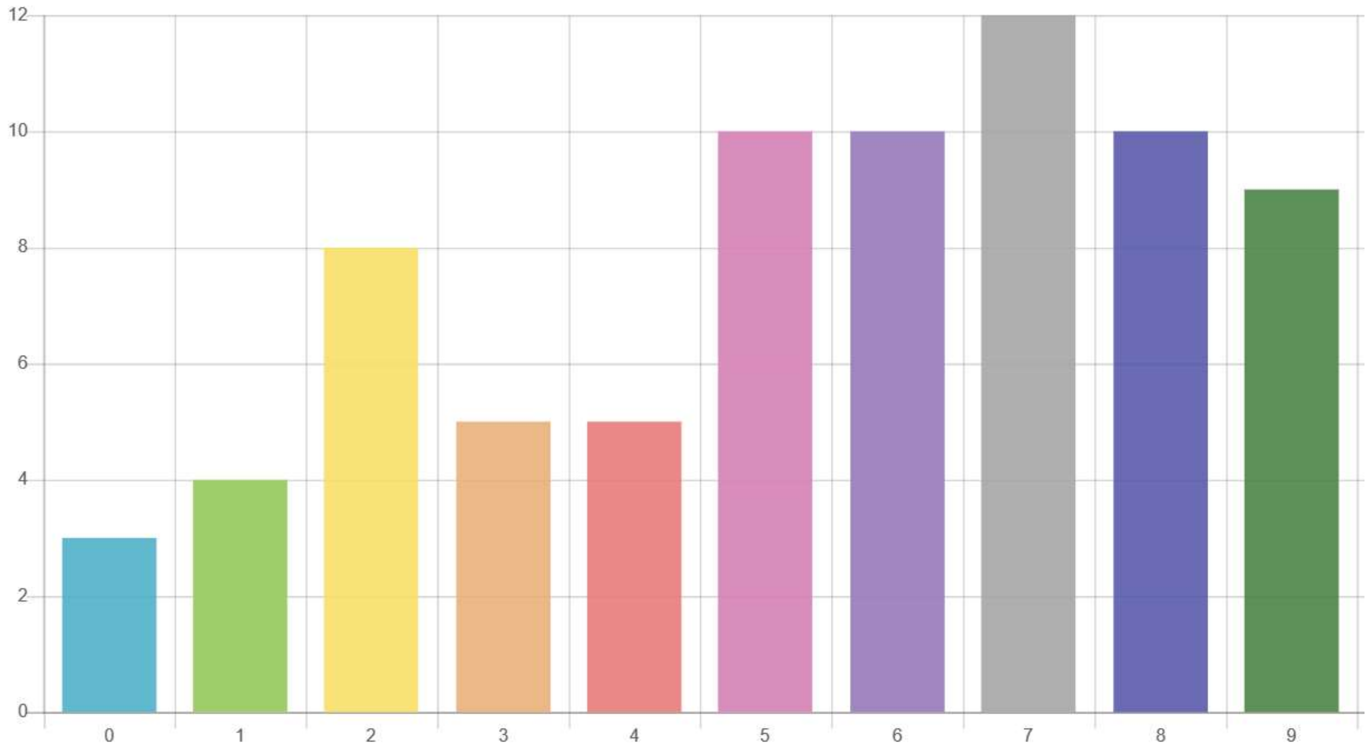
9 Please rank the following factors that you feel led to you making the maintenance error.



Part B

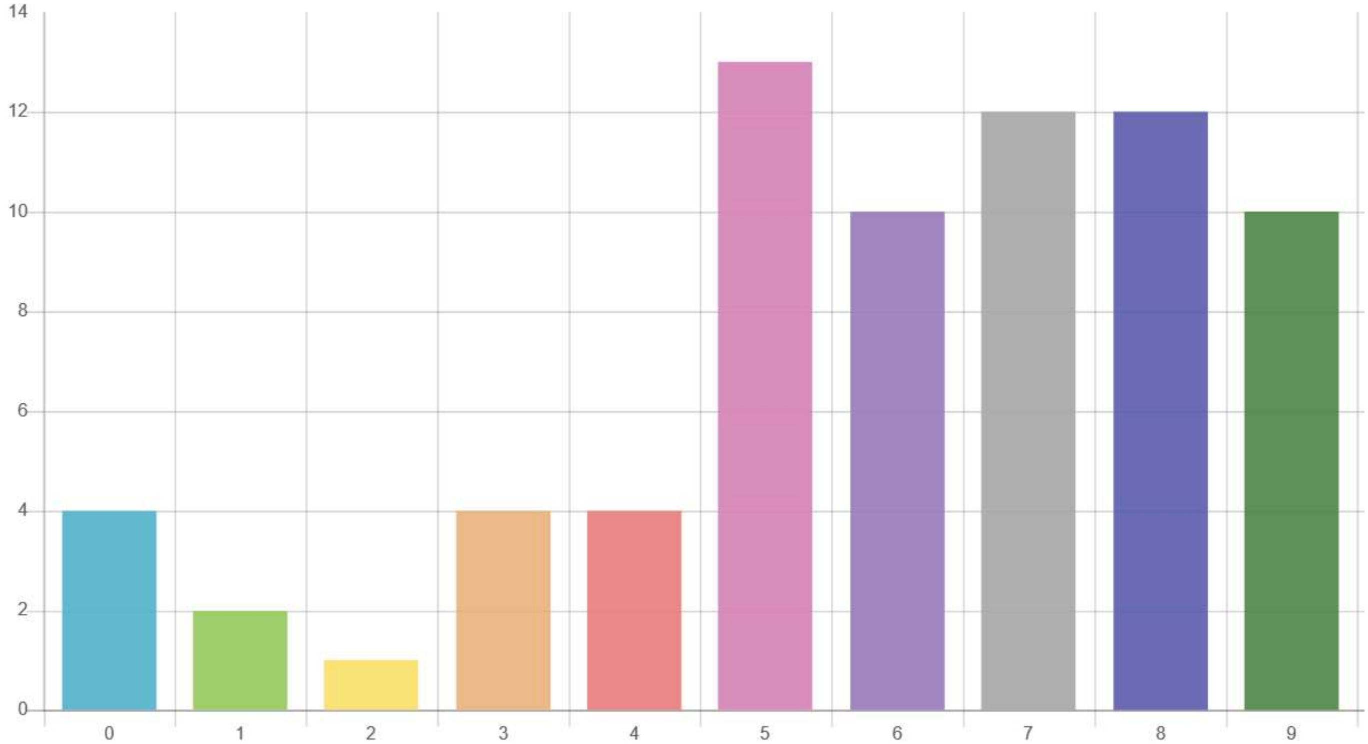
Would you be willing to fill in a checklist or surveys at work that would measure the following:

10 How well your supervisor is managing human factors. These checklists would rate how well some of the factors in question 7 to 9 are managed by your supervisor.



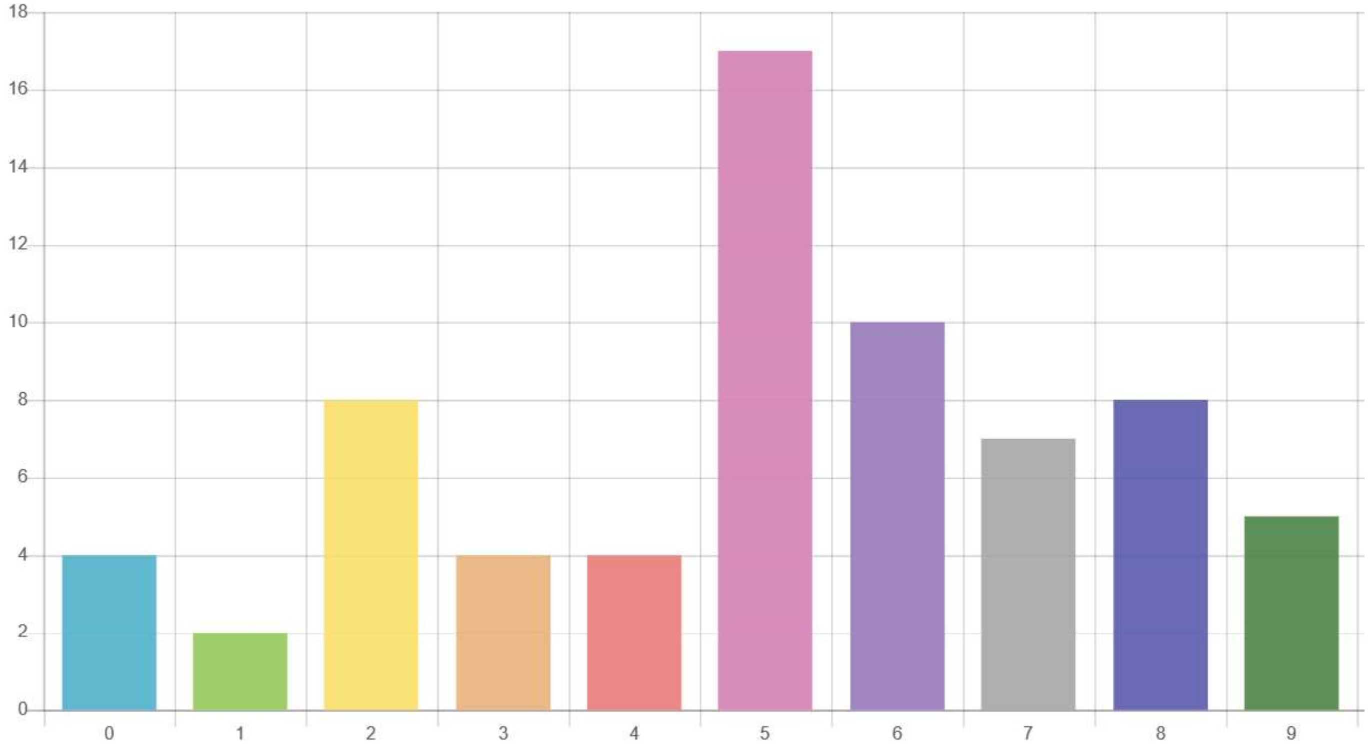
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	3 (4%)	4 (5%)	8 (9%)	5 (6%)	5 (6%)	10 (12%)	10 (12%)	**12 (14%)**	10 (12%)	9 (11%)	9 (11%)	2.83	85	5.88 / 10
														5.88 / 10

11 Would you be willing share data on your personal fatigue level?



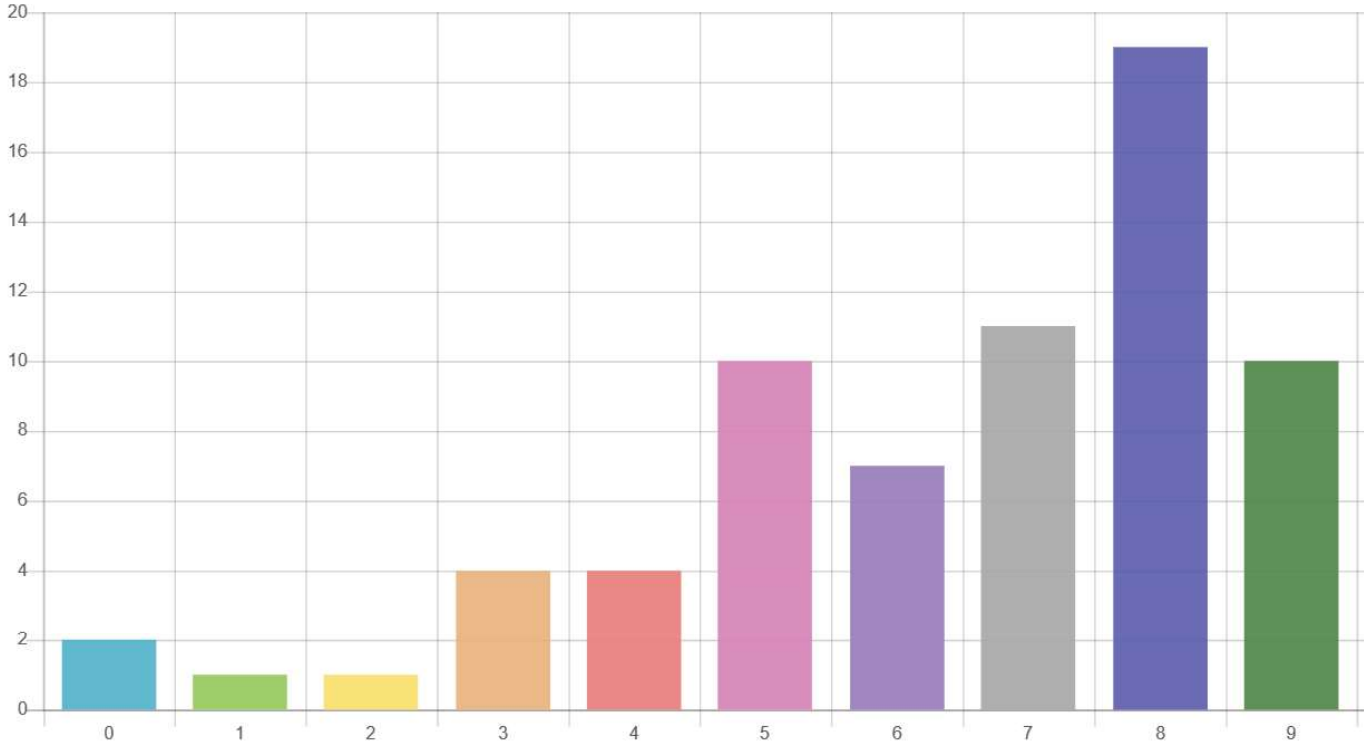
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	4 (5%)	2 (2%)	1 (1%)	4 (5%)	4 (5%)	**13 (15%)**	10 (12%)	12 (14%)	12 (14%)	10 (12%)	13 (15%)	4.49	85	6.55 / 10
														6.55 / 10

12 Would you be willing share data on your personal life stress level?



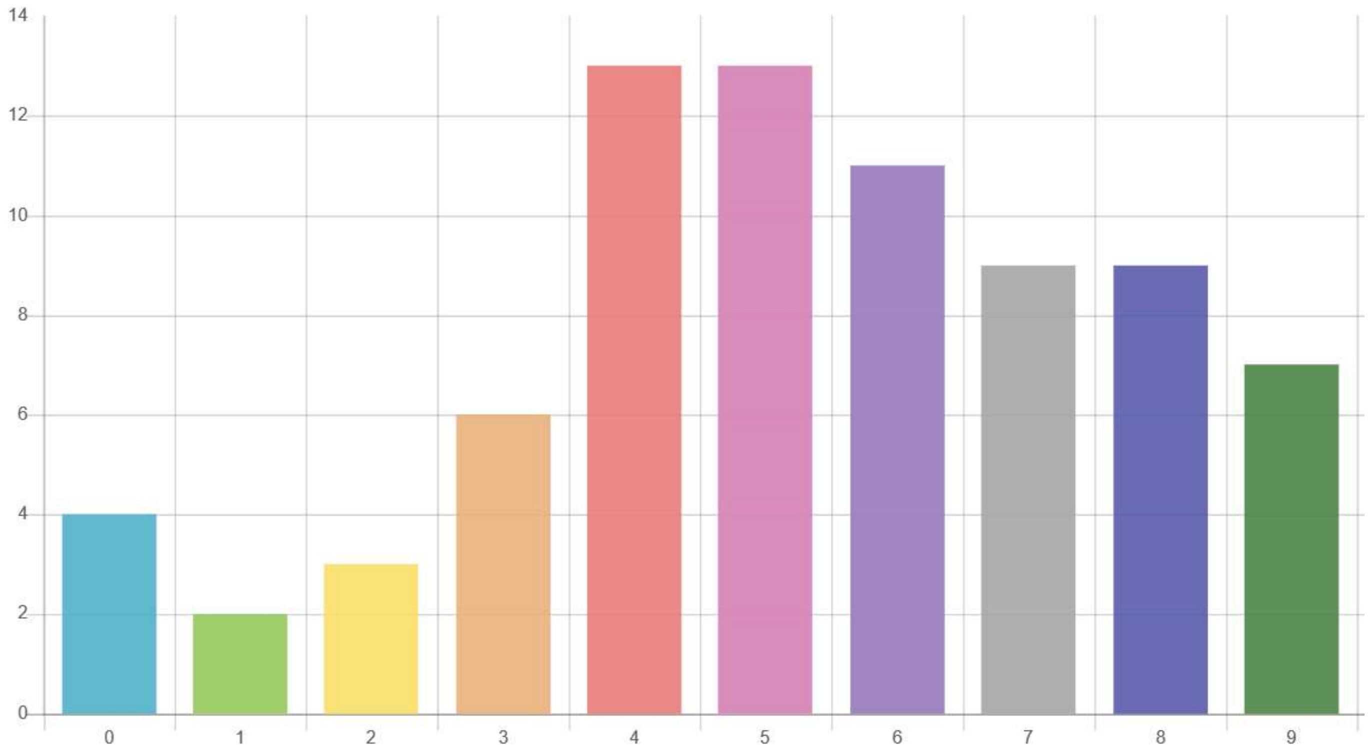
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	4 (5%)	2 (3%)	8 (10%)	4 (5%)	4 (5%)	**17 (21%)**	10 (13%)	7 (9%)	8 (10%)	5 (6%)	11 (14%)	4.07	80	5.74 / 10
														5.74 / 10

13 Would you be willing share data on your work stress level?



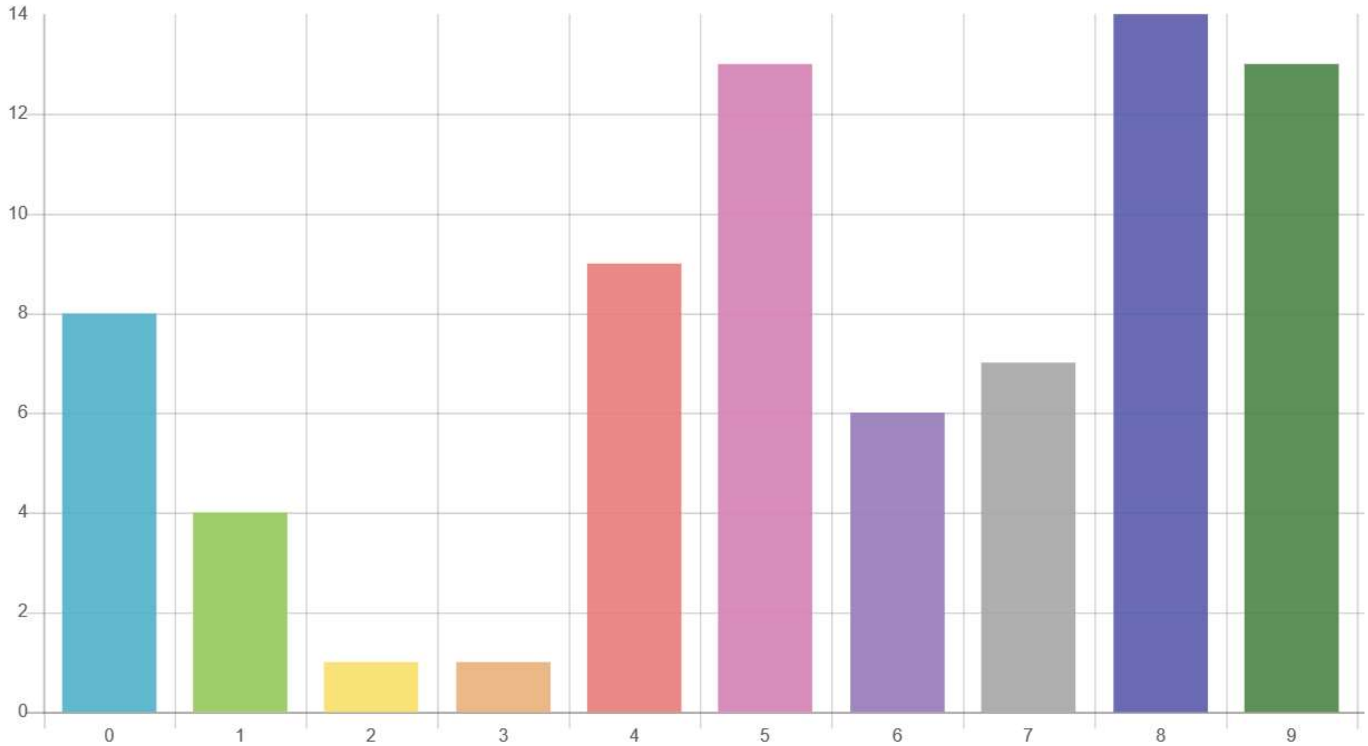
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	2 (2%)	1 (1%)	1 (1%)	4 (5%)	4 (5%)	10 (12%)	7 (8%)	11 (13%)	**19 (23%)**	10 (12%)	15 (18%)	5.66	84	7.05 / 10
														7.05 / 10

14 How well your organisation is managing human factors. These checklists would rate how well some of the factors in question 7 to 9 are managed by your organisation.



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	4 (5%)	2 (2%)	3 (4%)	6 (7%)	**13 (16%)**	13 (16%)	11 (14%)	9 (11%)	9 (11%)	7 (9%)	4 (5%)	3.75	81	5.52 / 10
														5.52 / 10

15 Would you be willing to provide heart rate data to your organization? This could be done through a heart rate monitor watch. The information will be collected by trained medical professionals and your confidentiality will be insured.

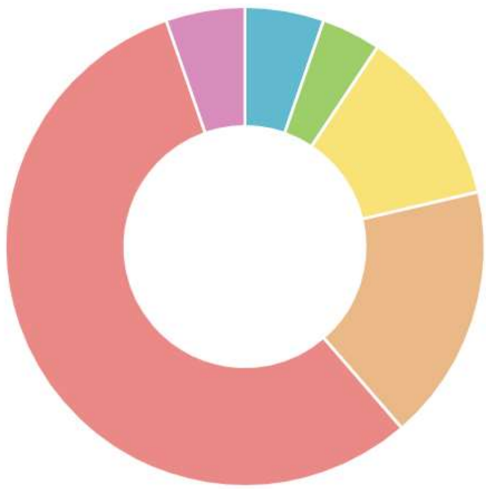


	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	8 (9%)	4 (5%)	1 (1%)	1 (1%)	9 (11%)	13 (15%)	6 (7%)	7 (8%)	**14 (16%)**	13 (15%)	9 (11%)	4.33	85	6.05 / 10
														6.05 / 10

Part B

At work in the last year, on average, how often have you:

16 Done a job without the correct tool or equipment.



5% (4) Every day

4% (3) Once a week

12% (9) Once a month

17% (13) Once a year

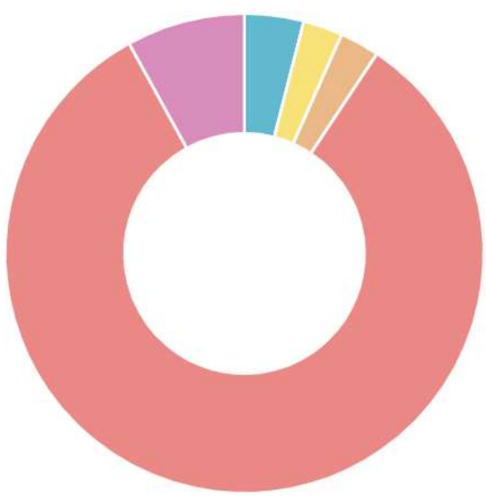
56% (42) Never

5% (4) N/A

13.65 Standard Deviation

75 Responses

17 Not made a system safe before working on it, or in its vicinity.



4% (3) Every day

0% (0) Once a week

3% (2) Once a month

3% (2) Once a year

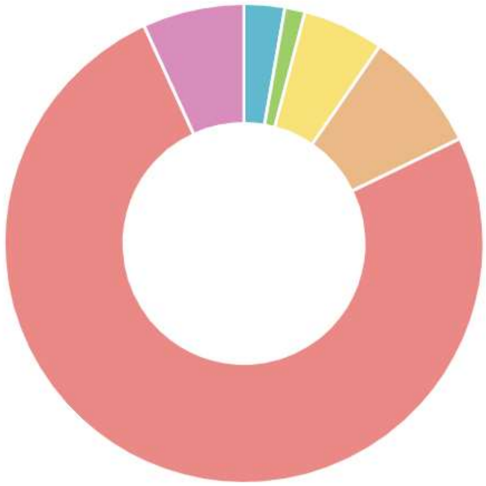
83% (62) Never

8% (6) N/A

22.21 Standard Deviation

75 Responses

18 Found a part (e.g. in your pocket) after a job was completed.



3% (2) Every day

1% (1) Once a week

5% (4) Once a month

8% (6) Once a year

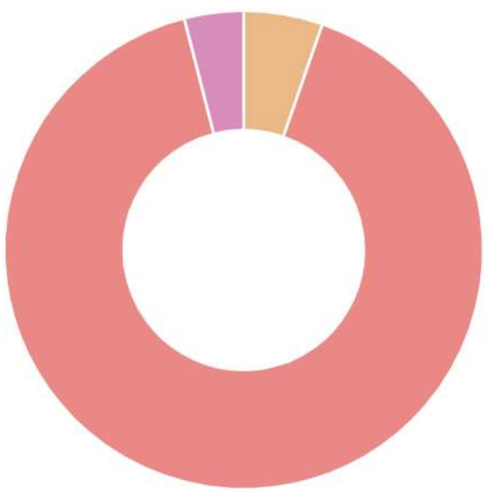
75% (55) Never

7% (5) N/A

19.23 Standard Deviation

73 Responses

19 Started to work on the wrong equipment.



0% (0) Every day

0% (0) Once a week

0% (0) Once a month

5% (4) Once a year

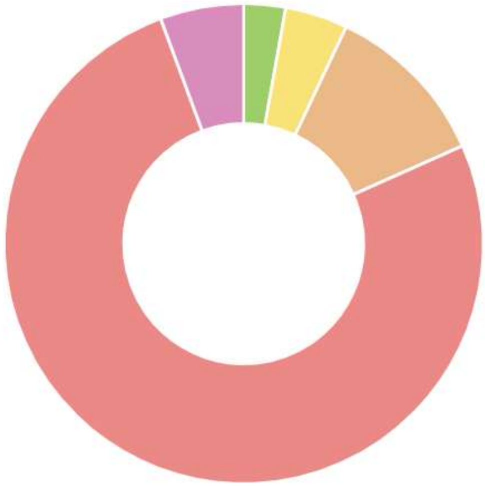
91% (68) Never

4% (3) N/A

24.87 Standard Deviation

75 Responses

20 Been interrupted part-way through a job and forgotten to return to it.



0% (0)
Every day

3% (2)
Once a week

4% (3)
Once a month

11% (8)
Once a year

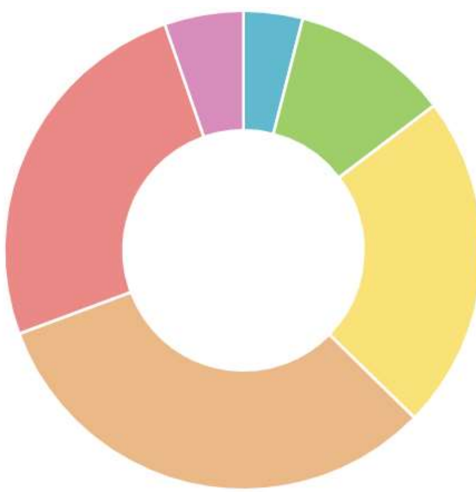
76% (54)
Never

6% (4)
N/A

19.01
Standard Deviation

71
Responses

21 Been interrupted part-way through a task to perform another more urgent task.



4% (3)
Every day

11% (8)
Once a week

23% (17)
Once a month

32% (24)
Once a year

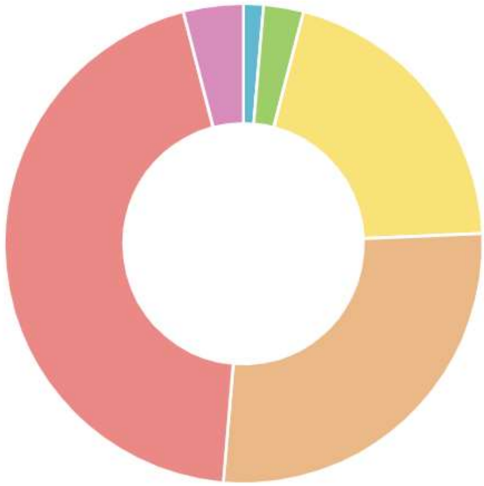
25% (19)
Never

5% (4)
N/A

7.93
Standard Deviation

75
Responses

22 Had to rush an inspection.



1% (1)
Every day

3% (2)
Once a week

20% (15)
Once a month

27% (20)
Once a year

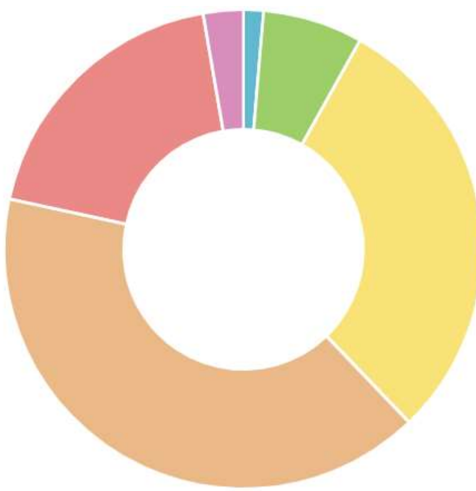
45% (33)
Never

4% (3)
N/A

11.66
Standard Deviation

74
Responses

23 Had to rush an maintenance task due to time pressure.



1% (1)
Every day

7% (5)
Once a week

30% (22)
Once a month

41% (30)
Once a year

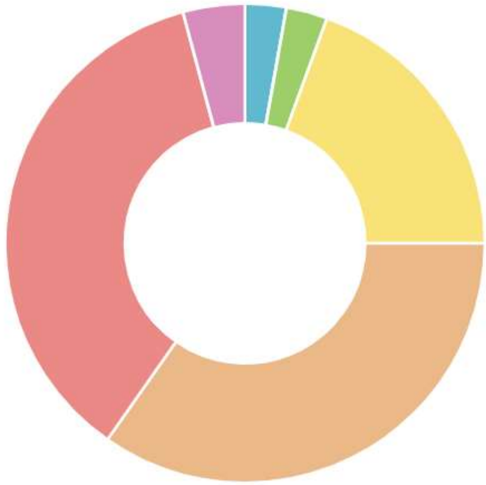
19% (14)
Never

3% (2)
N/A

10.78
Standard Deviation

74
Responses

24 Been delayed on a task because you could not obtain a consumable part (for example, an 'O' ring, oil, etc).



3% (2)
Every day

3% (2)
Once a week

19% (14)
Once a month

35% (25)
Once a year

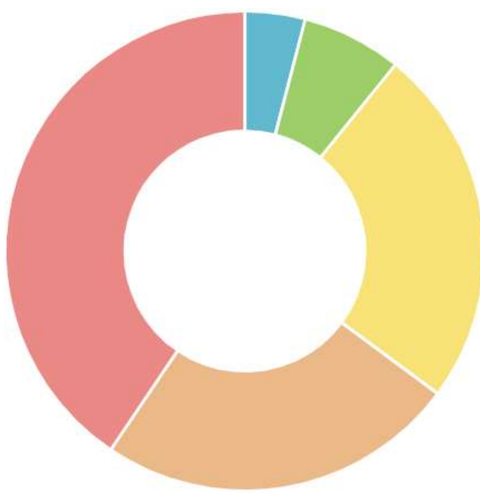
36% (26)
Never

4% (3)
N/A

10.41
Standard Deviation

72
Responses

25 Had trouble concentrating because you were tired.



4% (3)
Every day

7% (5)
Once a week

24% (18)
Once a month

24% (18)
Once a year

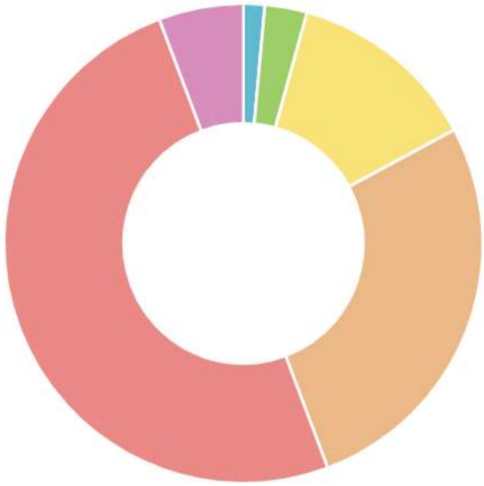
41% (30)
Never

0% (0)
N/A

10.56
Standard Deviation

74
Responses

26 Found an error in a maintenance document.



1% (1) Every day

3% (2) Once a week

13% (9) Once a month

27% (19) Once a year

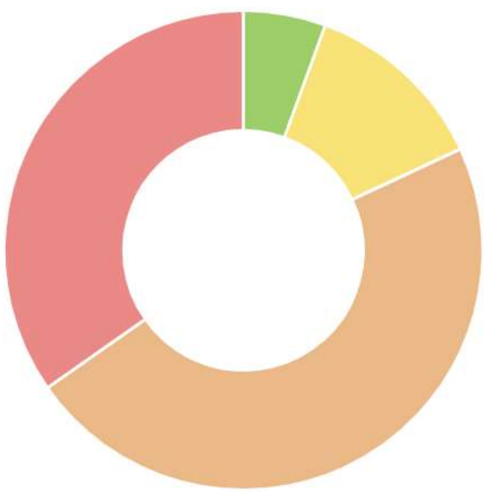
50% (35) Never

6% (4) N/A

12.05 Standard Deviation

70 Responses

27 Worked more than 12 hours in a 24-hour period.



0% (0) Every day

6% (4) Once a week

13% (9) Once a month

47% (34) Once a year

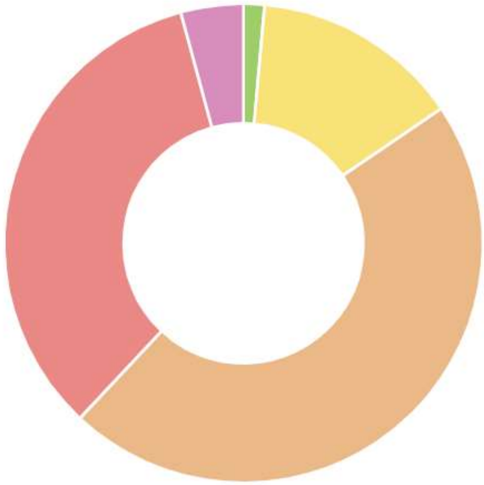
35% (25) Never

0% (0) N/A

13 Standard Deviation

72 Responses

28 Been delayed on a task because you could not obtain a major part (for example, a wheel or pump).



0% (0) Every day

1% (1) Once a week

14% (10) Once a month

46% (33) Once a year

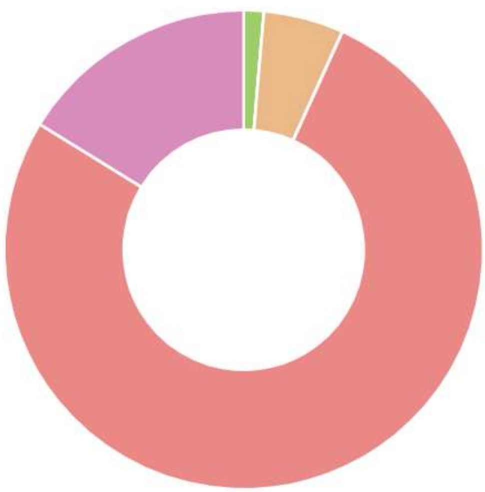
34% (24) Never

4% (3) N/A

12.48 Standard Deviation

71 Responses

29 Worked more than two night shifts in a row.



0% (0) Every day

1% (1) Once a week

0% (0) Once a month

5% (4) Once a year

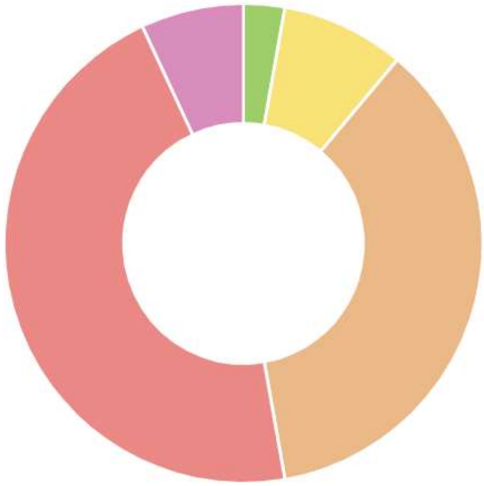
77% (57) Never

16% (12) N/A

20.4 Standard Deviation

74 Responses

30 Been unable to obtain a special tool or item of maintenance equipment.



0% (0) Every day

3% (2) Once a week

8% (6) Once a month

36% (26) Once a year

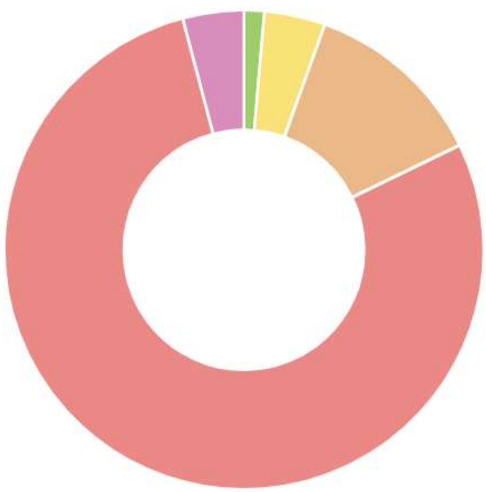
46% (33) Never

7% (5) N/A

12.69 Standard Deviation

72 Responses

31 Started to do a job the wrong way because you didn't realize that the equipment was different to what you were used to.



0% (0) Every day

1% (1) Once a week

4% (3) Once a month

12% (9) Once a year

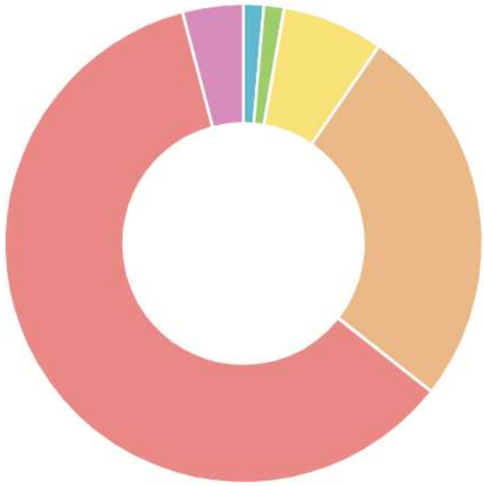
78% (57) Never

4% (3) N/A

20.25 Standard Deviation

73 Responses

32 Done a task without the correct lighting / illumination.



1% (1) Every day

1% (1) Once a week

7% (5) Once a month

26% (19) Once a year

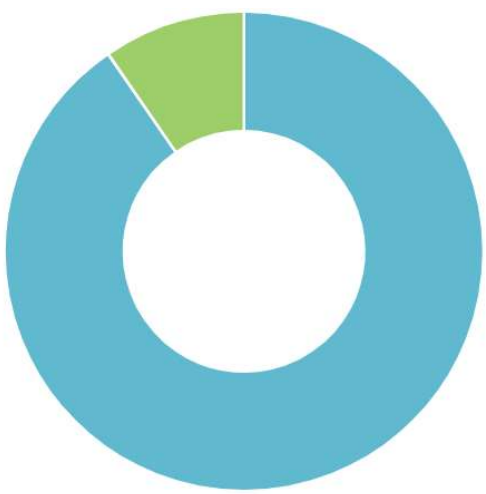
60% (44) Never

4% (3) N/A

15.52 Standard Deviation

73 Responses

33 32 / 46 Completed :) You are allmost done with the survey ;) Just hang in there! Do you want to continue?



90% (66) Continue - (Thank you)

10% (7) Submit - (Please give me one more chance!)

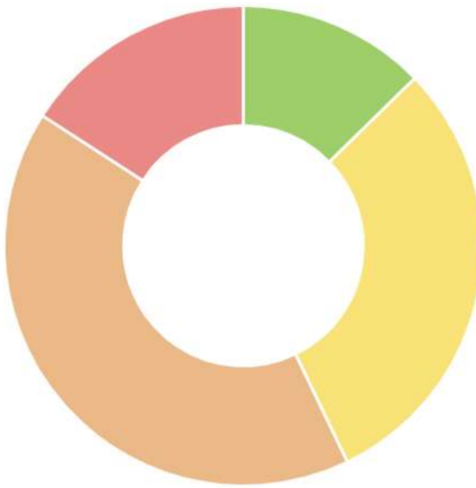
29.5 Standard Deviation

73 Responses

Part B

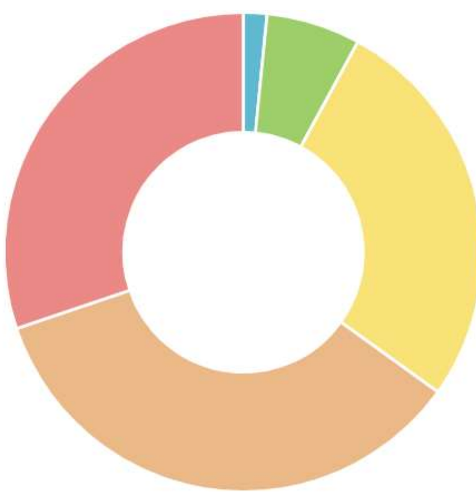
At work in the last year, on average, how often have you:

34 Been asked to work overtime to complete the current workload.



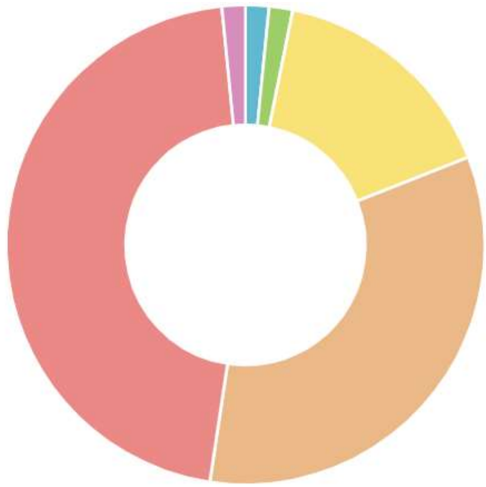
0% (0) Every day	13% (8) Once a week
30% (19) Once a month	41% (26) Once a year
16% (10) Never	0% (0) N/A
9.48 Standard Deviation	63 Responses

35 Had to rush a job to ensure that all your workload gets completed.



2% (1) Every day	6% (4) Once a week
27% (17) Once a month	35% (22) Once a year
30% (19) Never	0% (0) N/A
9.03 Standard Deviation	63 Responses

36 Had to reduce maintenance activities on jobs to ensure that all your workload gets completed.



2% (1)
Every day

2% (1)
Once a week

16% (10)
Once a month

33% (21)
Once a year

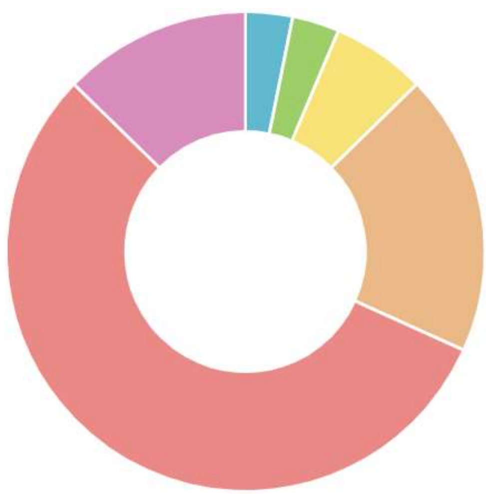
46% (29)
Never

2% (1)
N/A

10.98
Standard Deviation

63
Responses

37 Done a task without in a high noise level environment.



3% (2)
Every day

3% (2)
Once a week

6% (4)
Once a month

19% (12)
Once a year

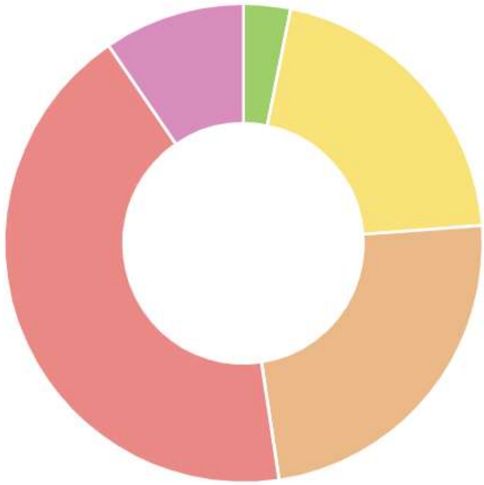
56% (35)
Never

13% (8)
N/A

11.51
Standard Deviation

63
Responses

38 Felt that important information regarding the maintenance task was not communicated with you.



0% (0)
Every day

3% (2)
Once a week

21% (13)
Once a month

24% (15)
Once a year

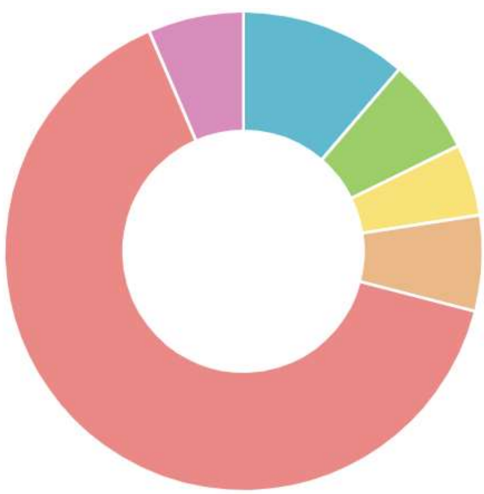
43% (27)
Never

10% (6)
N/A

9.14
Standard Deviation

63
Responses

39 Done a task without the required supervision.



11% (7)
Every day

6% (4)
Once a week

5% (3)
Once a month

6% (4)
Once a year

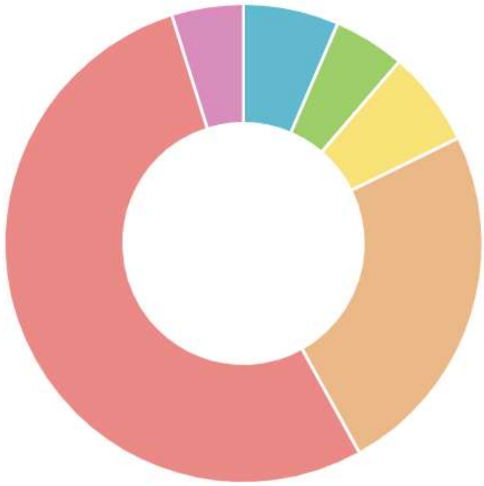
65% (40)
Never

6% (4)
N/A

13.32
Standard Deviation

62
Responses

40 Had to perform a task you were not trained on.



6% (4) Every day

5% (3) Once a week

6% (4) Once a month

24% (15) Once a year

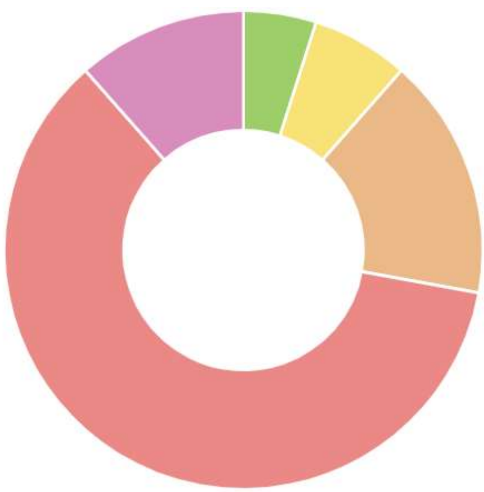
53% (33) Never

5% (3) N/A

10.98 Standard Deviation

62 Responses

41 Misdiagnosed a situation relating to a maintenance task.



0% (0) Every day

5% (3) Once a week

7% (4) Once a month

16% (10) Once a year

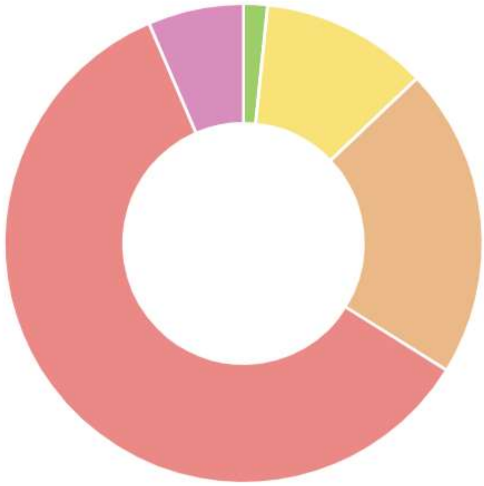
61% (37) Never

11% (7) N/A

12.4 Standard Deviation

61 Responses

42 Omitted a step when performing a maintenance task.



0% (0) Every day

2% (1) Once a week

11% (7) Once a month

21% (13) Once a year

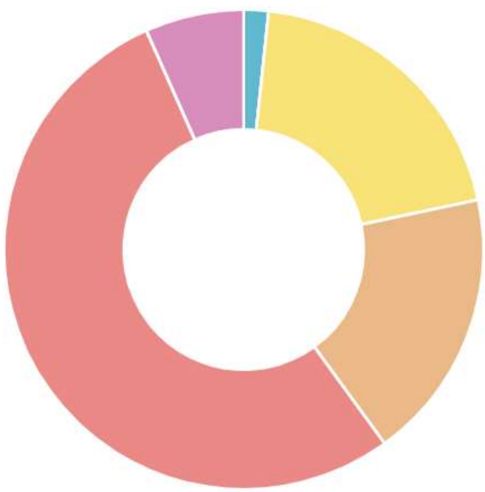
60% (37) Never

6% (4) N/A

12.67 Standard Deviation

62 Responses

43 Worked on equipment were it was easy to incorrectly install a part.



2% (1) Every day

0% (0) Once a week

20% (12) Once a month

18% (11) Once a year

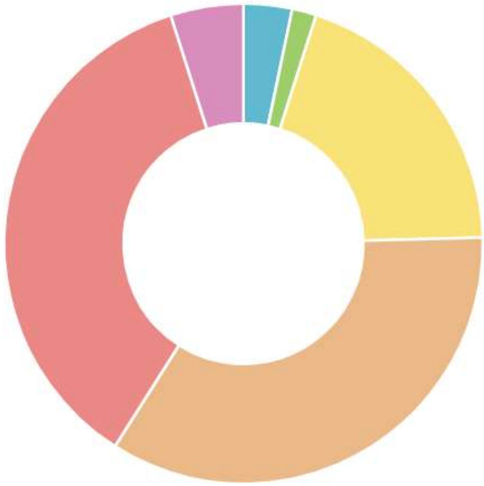
53% (32) Never

7% (4) N/A

10.85 Standard Deviation

60 Responses

44 Work on equipment with poor Accessibility or layout.



3% (2)
Every day

2% (1)
Once a week

20% (12)
Once a month

34% (21)
Once a year

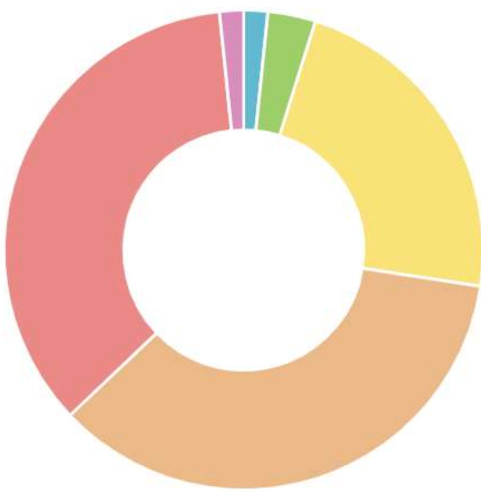
36% (22)
Never

5% (3)
N/A

8.78
Standard Deviation

61
Responses

45 When reporting at the maintenance site found out that the job was cancelled without it being communicated to you.



2% (1)
Every day

3% (2)
Once a week

23% (14)
Once a month

35% (22)
Once a year

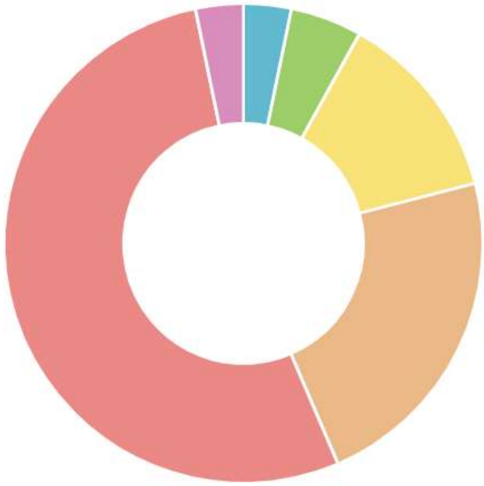
35% (22)
Never

2% (1)
N/A

9.39
Standard Deviation

62
Responses

46 Had to perform a task you were not certified to perform.



3% (2)
Every day

5% (3)
Once a week

13% (8)
Once a month

23% (14)
Once a year

53% (33)
Never

3% (2)
N/A

10.99
Standard Deviation

62
Responses

47 Thank you for getting so far. You can now choose to submit - or hold on a little bit longer.

66% (40)
Submit

34% (21)
4 more questions

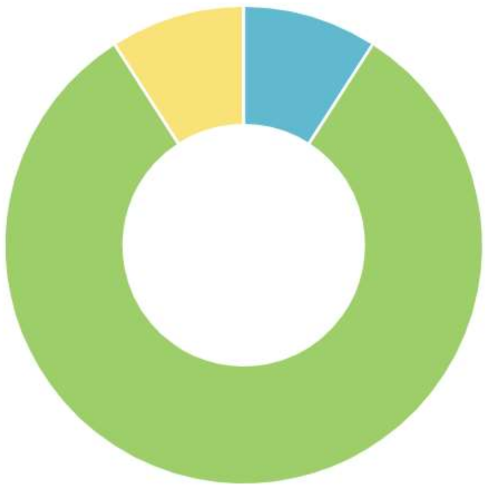
9.5
Standard Deviation

61
Responses

Part C

The following section may be seen as sensitive personal information. Should you not wish to answer these questions, you may submit the survey as is. Alternatively, you may select the “Do not wish to answer” option if it is only applicable to one particular question.

48 How much time do you usually sleep before shifts or your working day?



9% (2)
Less than 6 hours

82% (18)
6-8 hours

9% (2)
9-11 hours

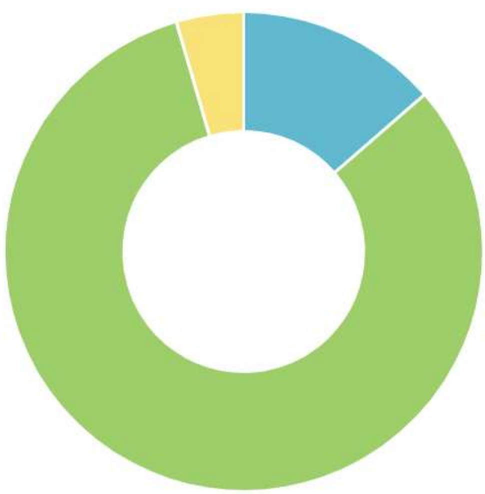
0% (0)
more than 12 hours

0% (0)
Do not wish to answer

6.86
Standard Deviation

22
Responses

49 Do you have access to your own sleep quality information, such as a Fitbit or other wearable device?



14% (3)
Yes

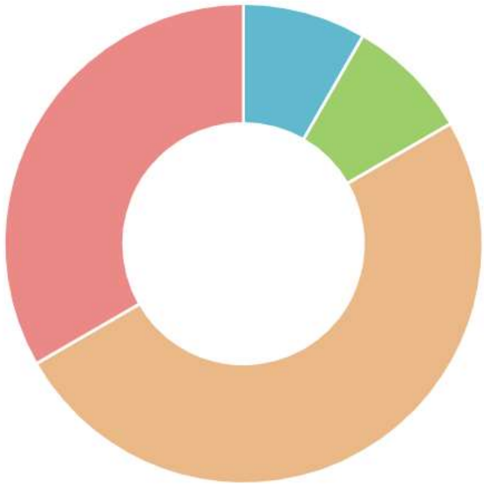
82% (18)
No

5% (1)
Do not wish to answer

7.59
Standard Deviation

22
Responses

50 If yes (question 50): How much DEEP sleep do you get on average:



8% (1)
Less than 1 hour a night

8% (1)
Between 1 and 2 hours

0% (0)
Between 2 and 3 hours

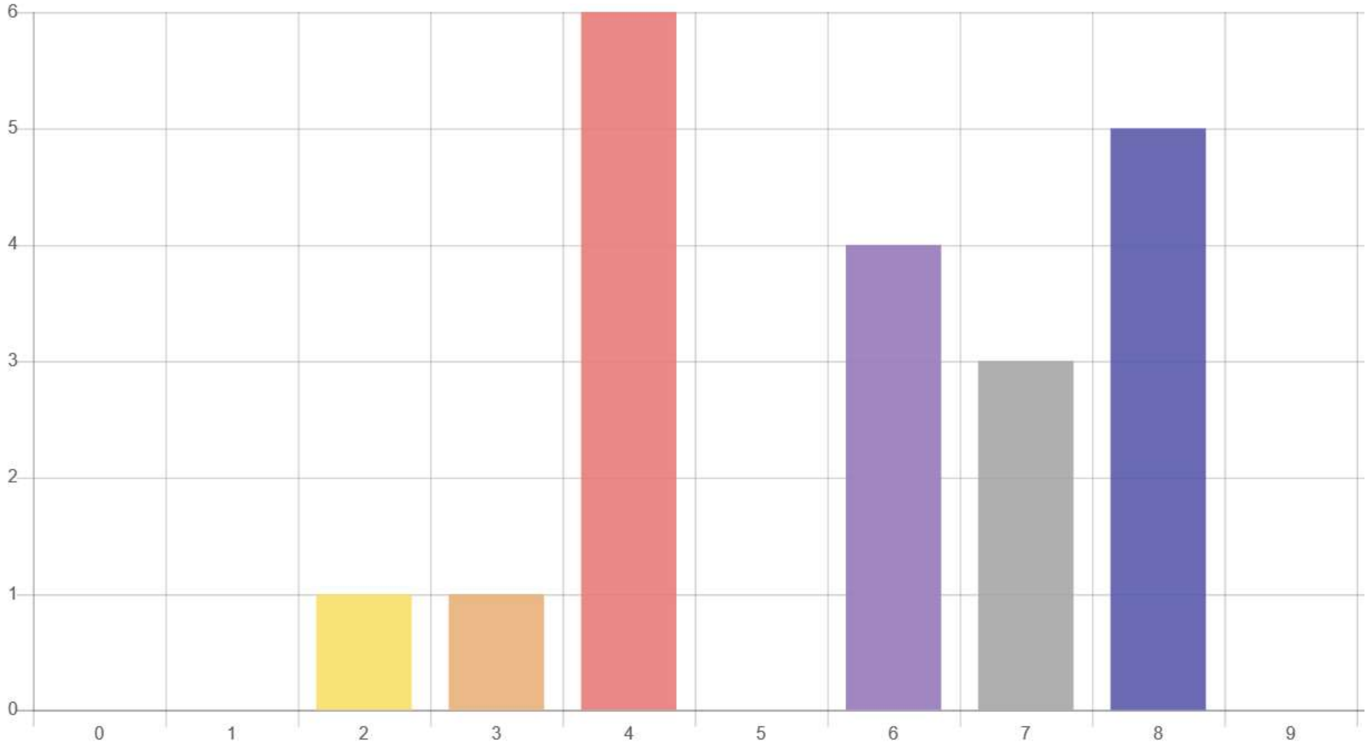
50% (6)
Between 3 and 4 hours

33% (4)
More than 4 hours

2.24
Standard Deviation

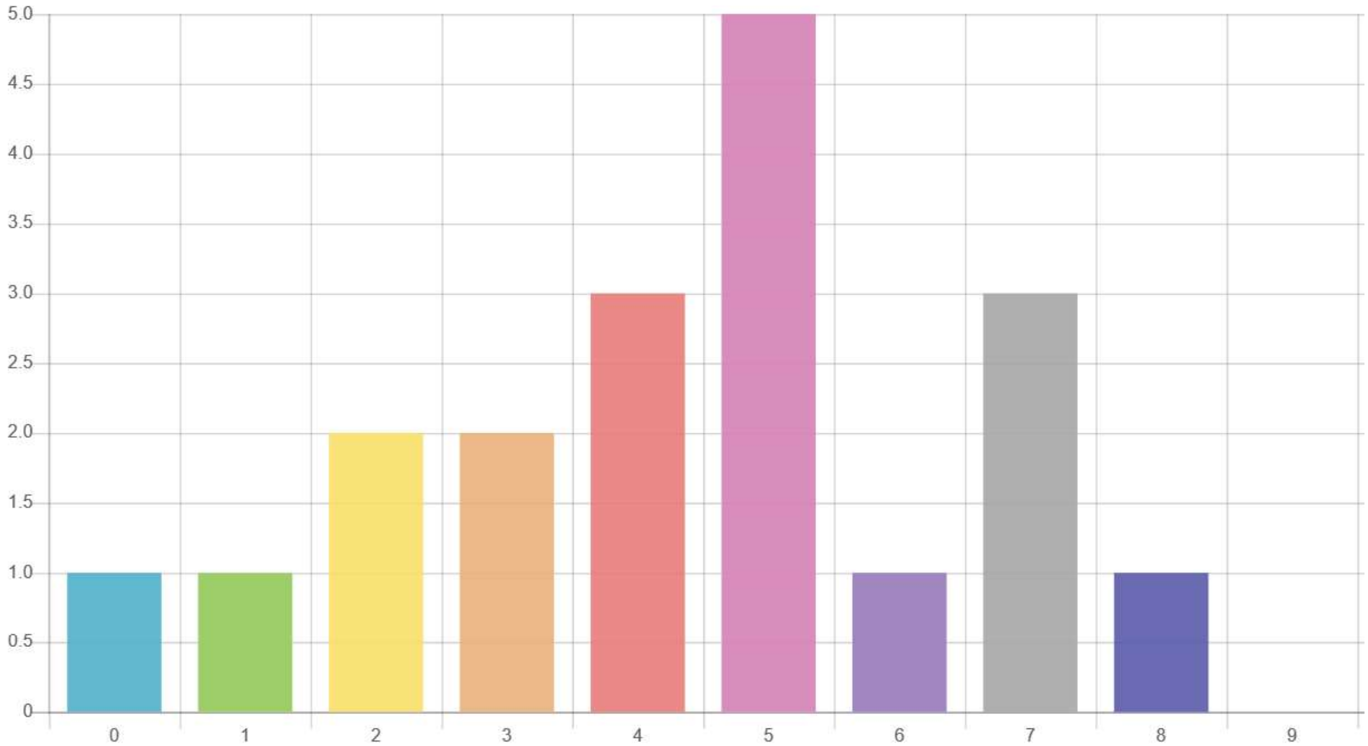
12
Responses

51 How would you rate your own personal stress level?



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Extreme stress - No stress	0 (0%)	0 (0%)	1 (5%)	1 (5%)	**6 (27%)**	0 (0%)	4 (18%)	3 (14%)	5 (23%)	0 (0%)	2 (9%)	2.09	22	6.09 / 10
														6.09 / 10

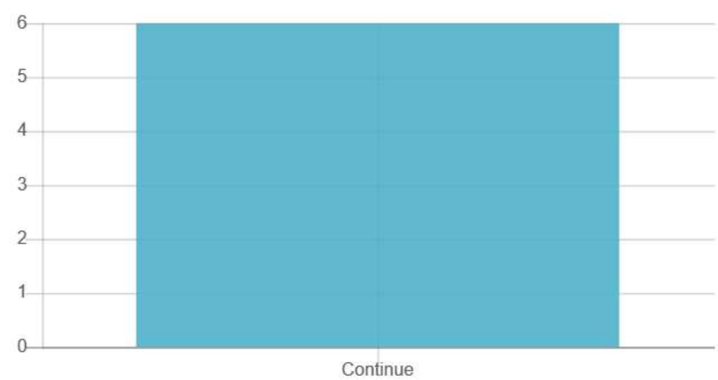
52 How would you rate your own work stress level?



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Extreme stress - No stress	1 (5%)	1 (5%)	2 (10%)	2 (10%)	3 (14%)	**5 (24%)**	1 (5%)	3 (14%)	1 (5%)	0 (0%)	2 (10%)	1.31	21	4.9 / 10
														4.9 / 10

H.2. Management questionnaire

1 By clicking continue you agree that: I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach. The nature, objective, possible safety and health implications have been explained to me and I understand them. I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.



100% (6)
Continue

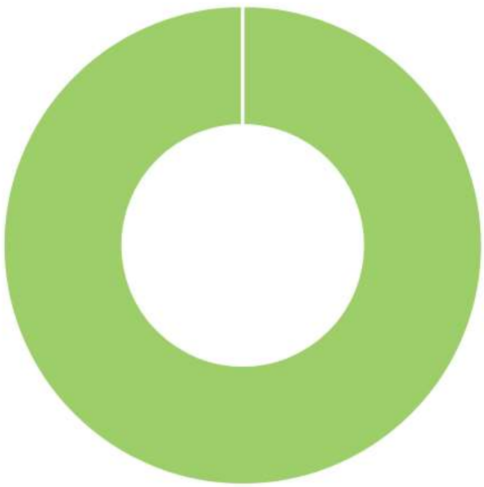
6
Responses

Part A

Personal Information

(Page 1/5)

2 For which Company do you work for?



0% (0)
[redacted]Generation

100% (6)
[redacted]Transmission

0% (0)
[redacted]Distribution

0% (0)
Other (Please Specify)

2.6
Standard Deviation

6
Responses

3 How long, in years, have you been in your present position?

0% (0)
1-3 years

33% (2)
4-7 years

17% (1)
8-10 years

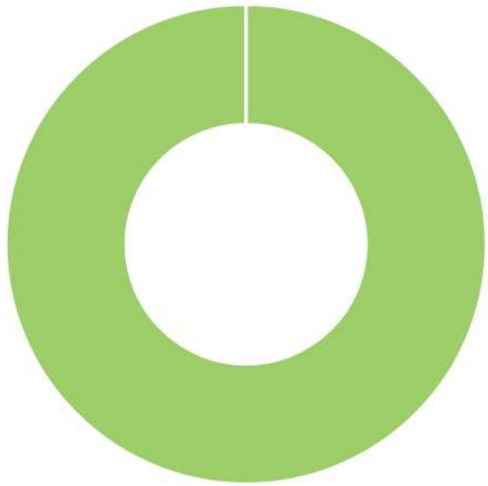
17% (1)
10-15 year

33% (2)
longer than 15 years

0.75
Standard Deviation

6
Responses

4 For which discipline are your currently responsible for to manage maintenance staff:



0% (0)
High Voltage Plant / Outdoor Yard Equipment

100% (1)
Control Plant / Secondary Plant

0% (0)
Lines and Servitudes

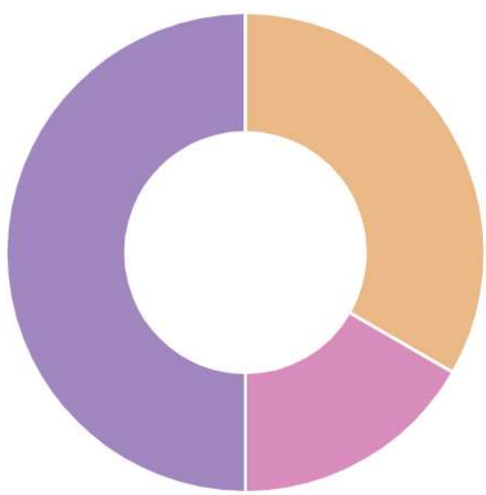
0% (0)
Grid Manager

0% (0)
Other (Please Specify)

0.4
Standard Deviation

1
Responses

5 What is the highest level of education you have completed?



0% (0)
No formal education

0% (0)
Matriculated from high school

0% (0)
Vocational training

33% (2)
Diploma

0% (0)
BTech

17% (1)
University Degree (undergraduate)

50% (3)
Postgraduate Degree: Masters

0% (0)
Postgraduate degree: PhD

0% (0)
Other (Please Specify)

1.05
Standard Deviation

6
Responses

Part B

The following questions are aimed to determine the alignment between manager's perspectives on maintenance human factors and the maintenance staff / field workers perspectives. The questions asked within this questionnaire are based on the results from a questionnaire sent to maintenance staff / field workers at the end of 2019.

Maintenance human factors are characteristics which define the way in which maintenance staff behave and perform maintenance. These behaviours influence maintenance errors and maintenance performance. Maintenance human factors span across both the behavioural domain (motivation, stress) and the physical domain (work environment, heat, noise). These factors include factors such as (but are not limited to): Communication, High Workload, Noise Levels, Time Pressures, Fatigue, etc

This survey is ANONYMOUS and it is requested that you answers as honestly and accurately as possible.

(Page 2/5)

6 When you think of maintenance errors that occurred in your department, which of the following do you think contributed the most to it.

0% (0)
Fatigue

0% (0)
Inadequate Lighting/Light

17% (1)
Communication

17% (1)
High Workload

0% (0)
Cognitive Capabilities

33% (2)
Judgment/Decision-Making

0% (0)
Noise Level

17% (1)
Time Pressure

17% (1)
Supervision

0% (0)
Life Stress

0% (0)
Equipment, Tools And Parts

0.66
Standard Deviation

6
Responses

7 When you think of maintenance errors that occurred in your department, which of the following do you think contributed the second most to it.

0% (0)
Fatigue

0% (0)
Inadequate Lighting/Light

17% (1)
Communication

17% (1)
High Workload

0% (0)
Cognitive Capabilities

33% (2)
Judgment/Decision-Making

0% (0)
Noise Level

17% (1)
Time Pressure

0% (0)
Supervision

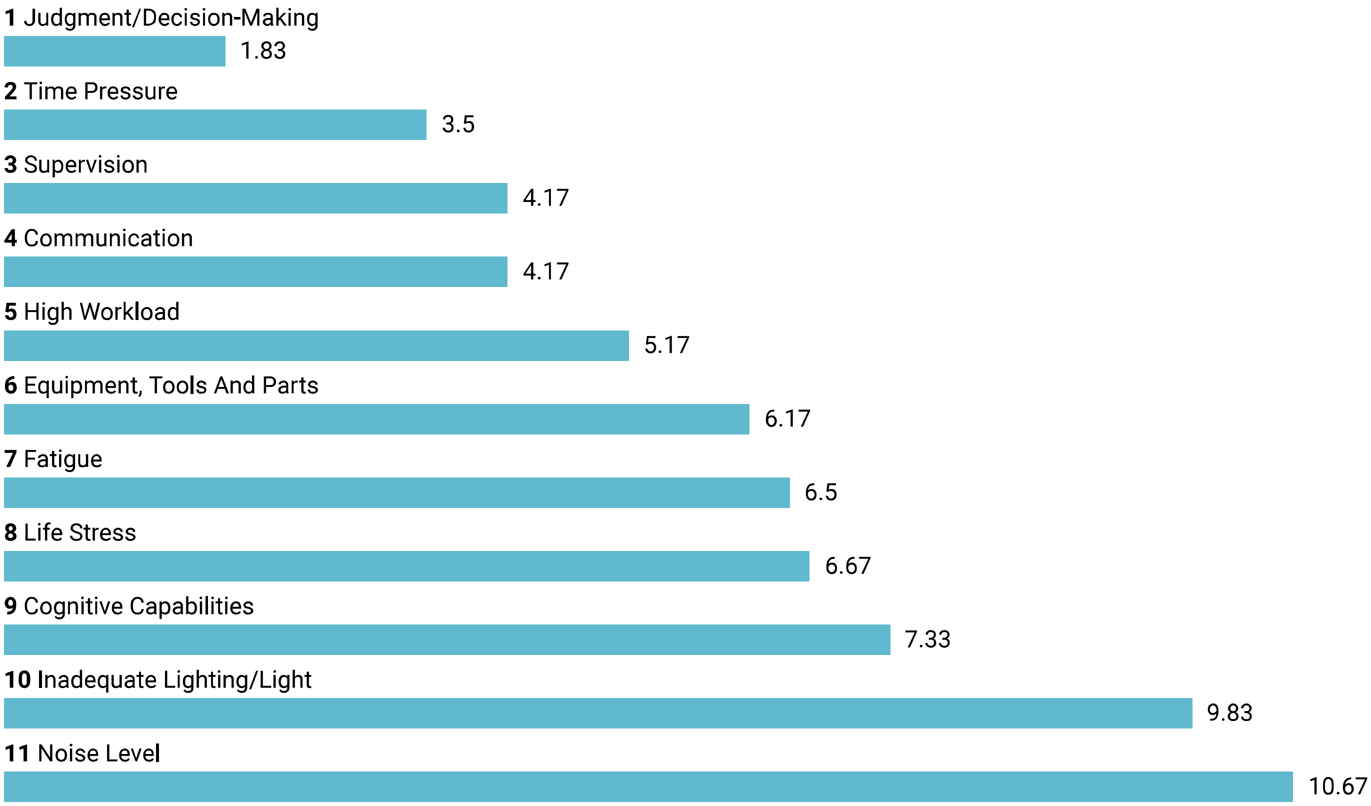
0% (0)
Life Stress

17% (1)
Equipment, Tools And Parts

0.66
Standard Deviation

6
Responses

8 Please rank the following factors that you feel are causing maintenance errors in your department. From 1 causing the most, to 11 causing the least number of errors. Hold and drag the factor to change the order.

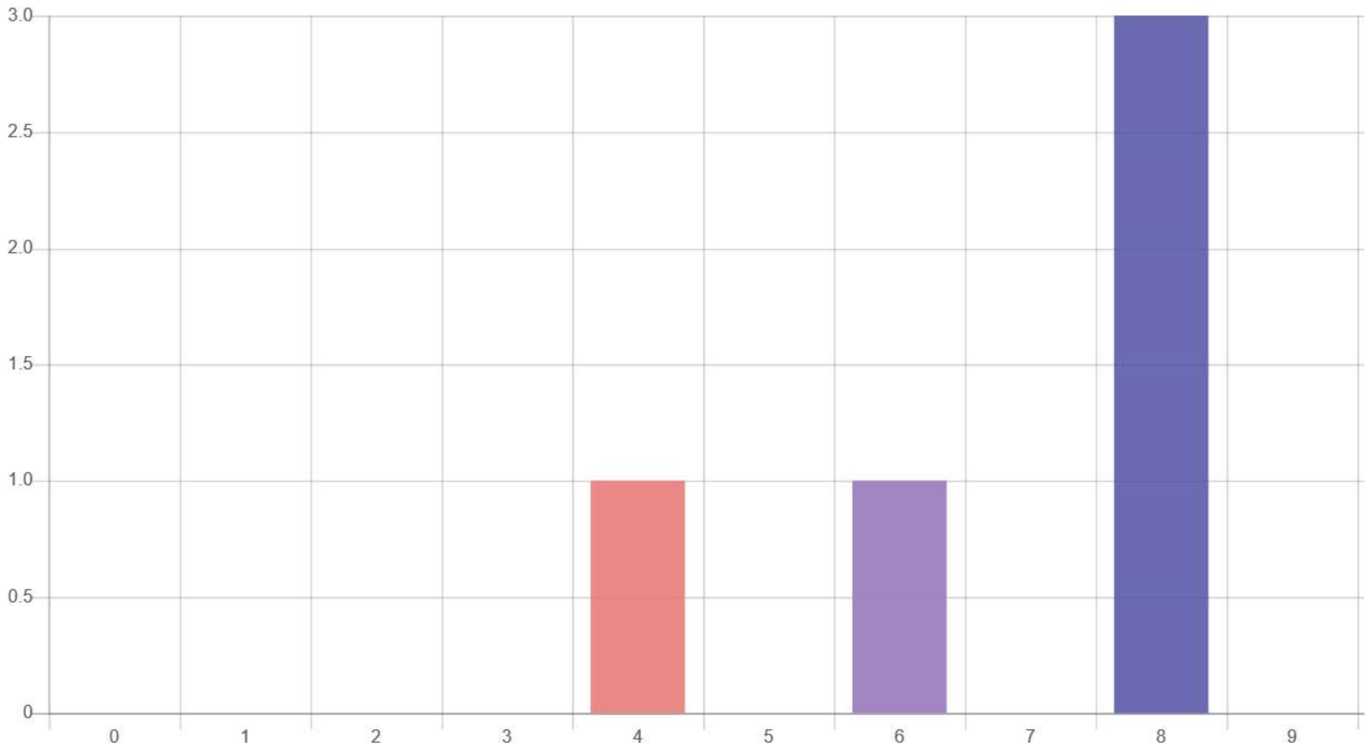


Part B

Would you, as manager, be interested in a measurement for you maintenance staff's:

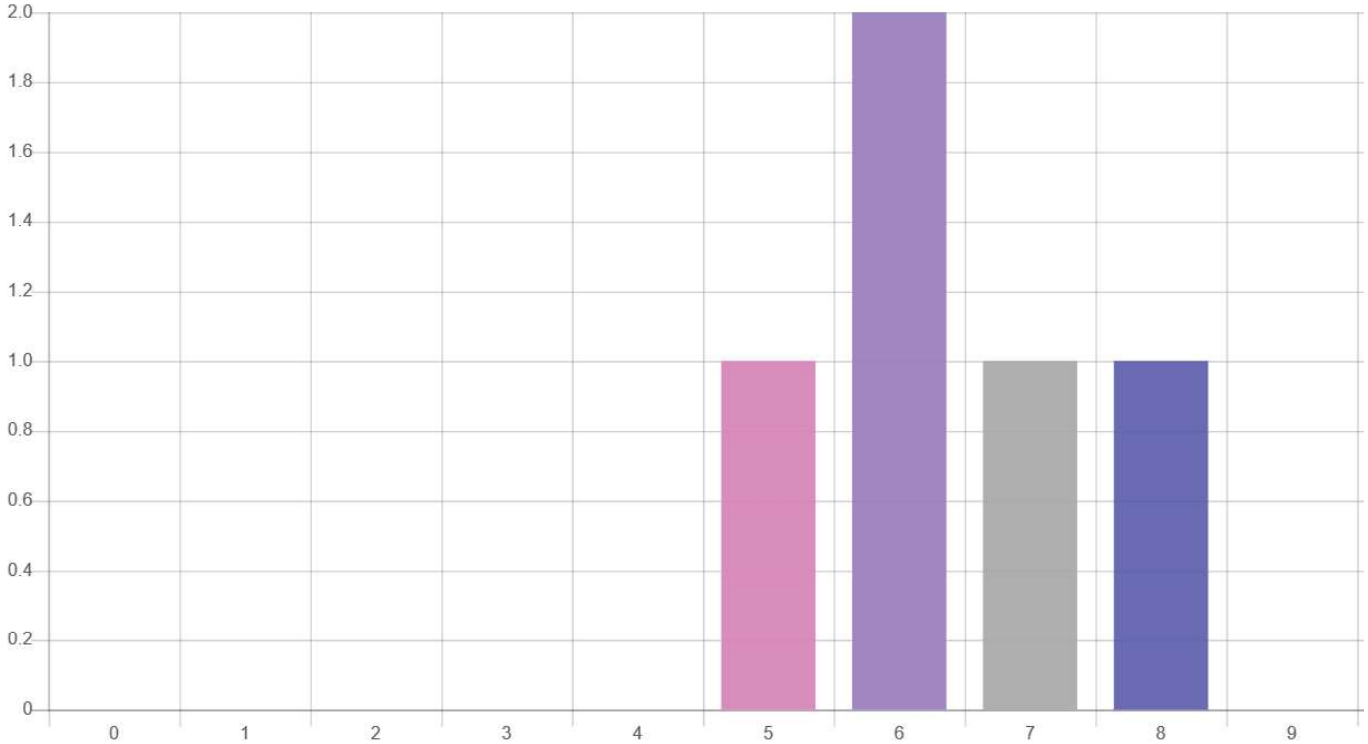
(Page 3/5)

9 perception of the level of workload they experience



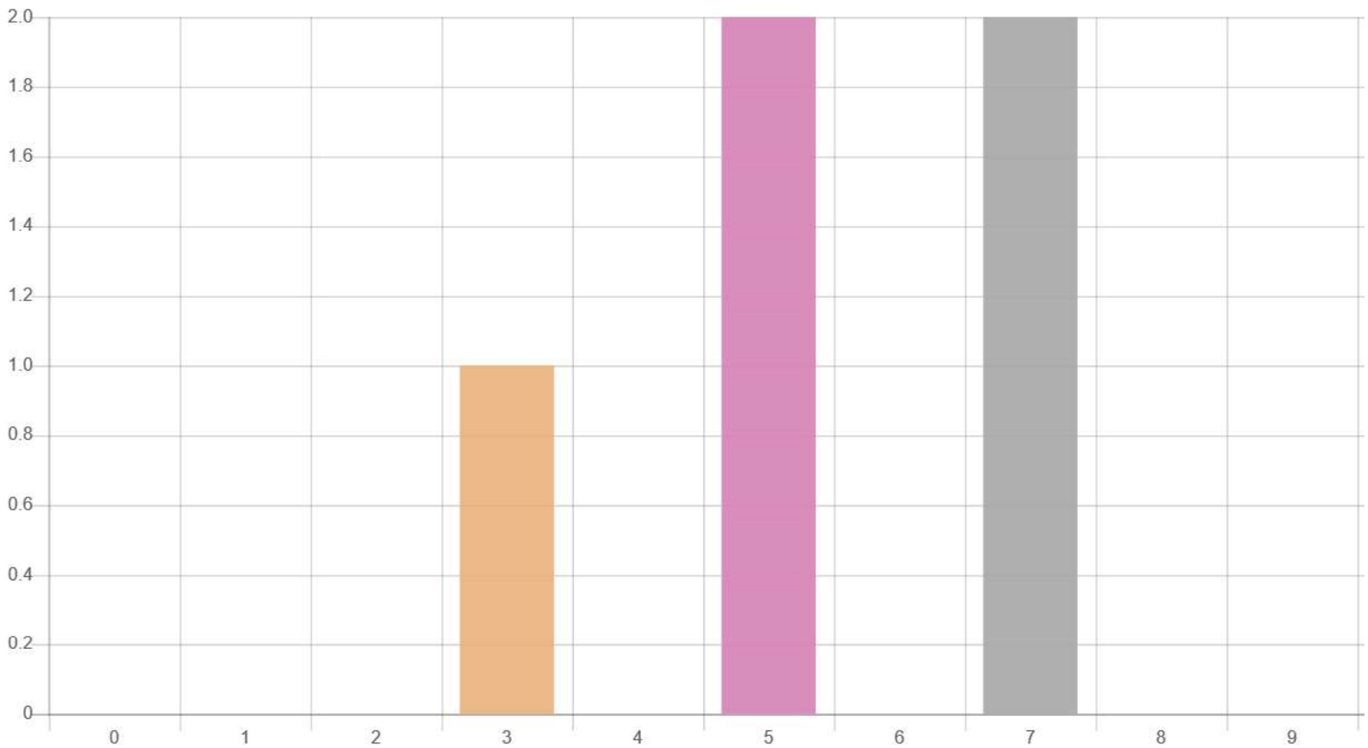
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (17%)	0 (0%)	1 (17%)	0 (0%)	**3 (50%)**	0 (0%)	1 (17%)	0.89	6	7.33 / 10
														7.33 / 10

10 perception of the level of time pressure they experience



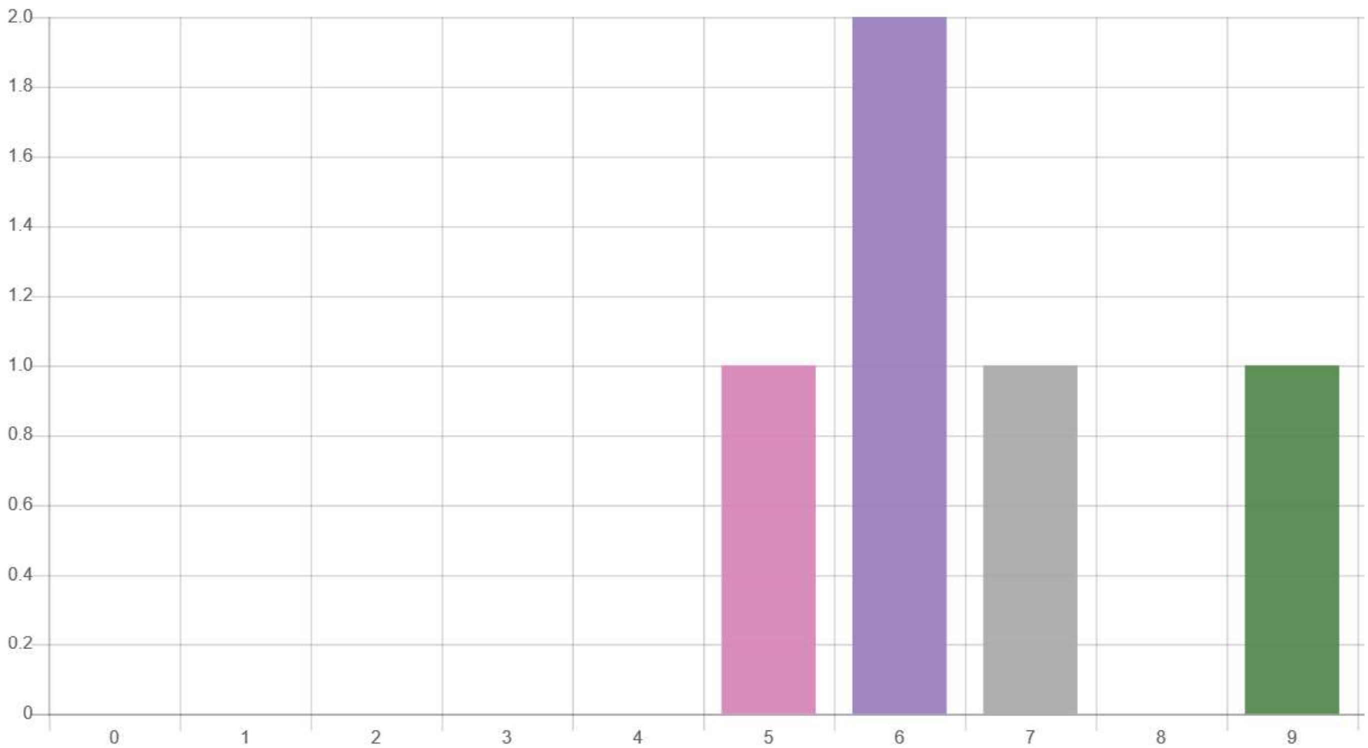
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (17%)	**2 (33%)**	1 (17%)	1 (17%)	0 (0%)	1 (17%)	0.66	6	7 / 10
														7 / 10

11 perception of the level of fatigue they experience



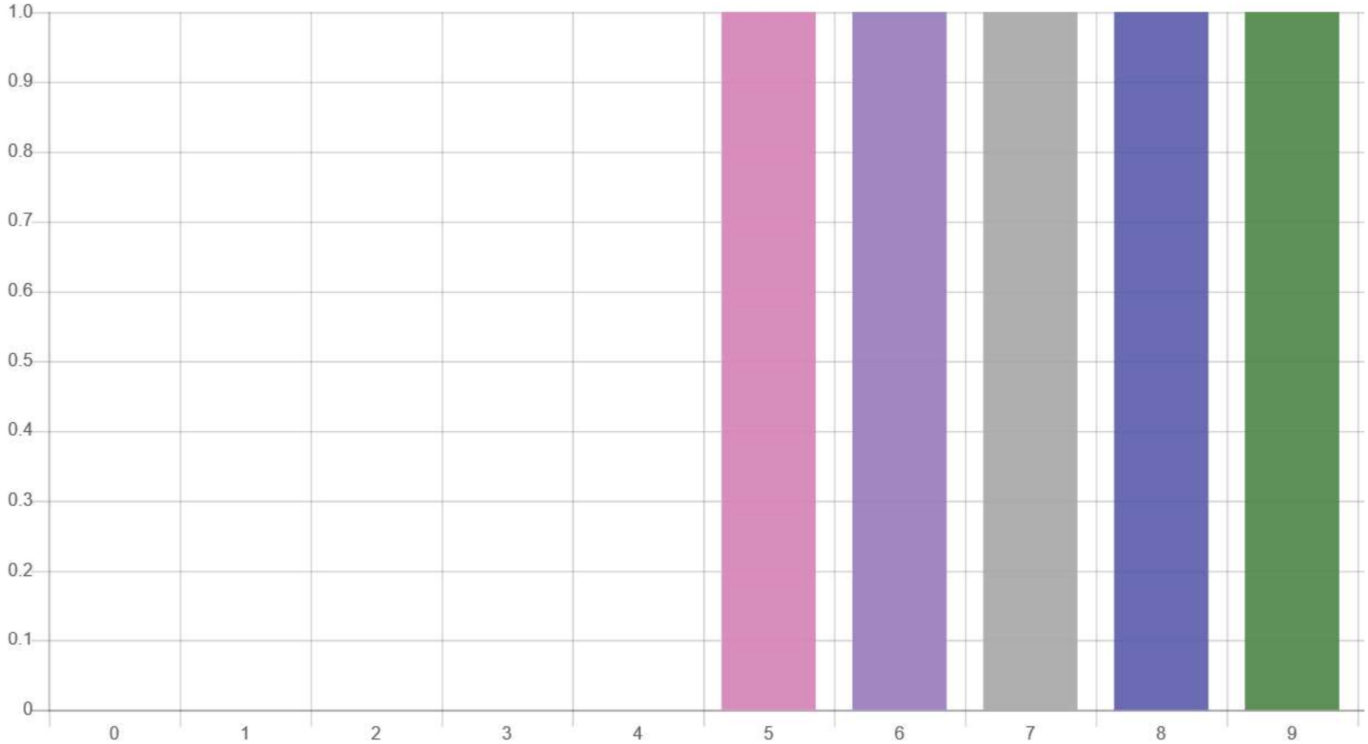
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	0 (0%)	0 (0%)	1 (17%)	0 (0%)	**2 (33%)**	0 (0%)	2 (33%)	0 (0%)	0 (0%)	1 (17%)	0.78	6	6.17 / 10
														6.17 / 10

12 perception of the level of effective communication they experience



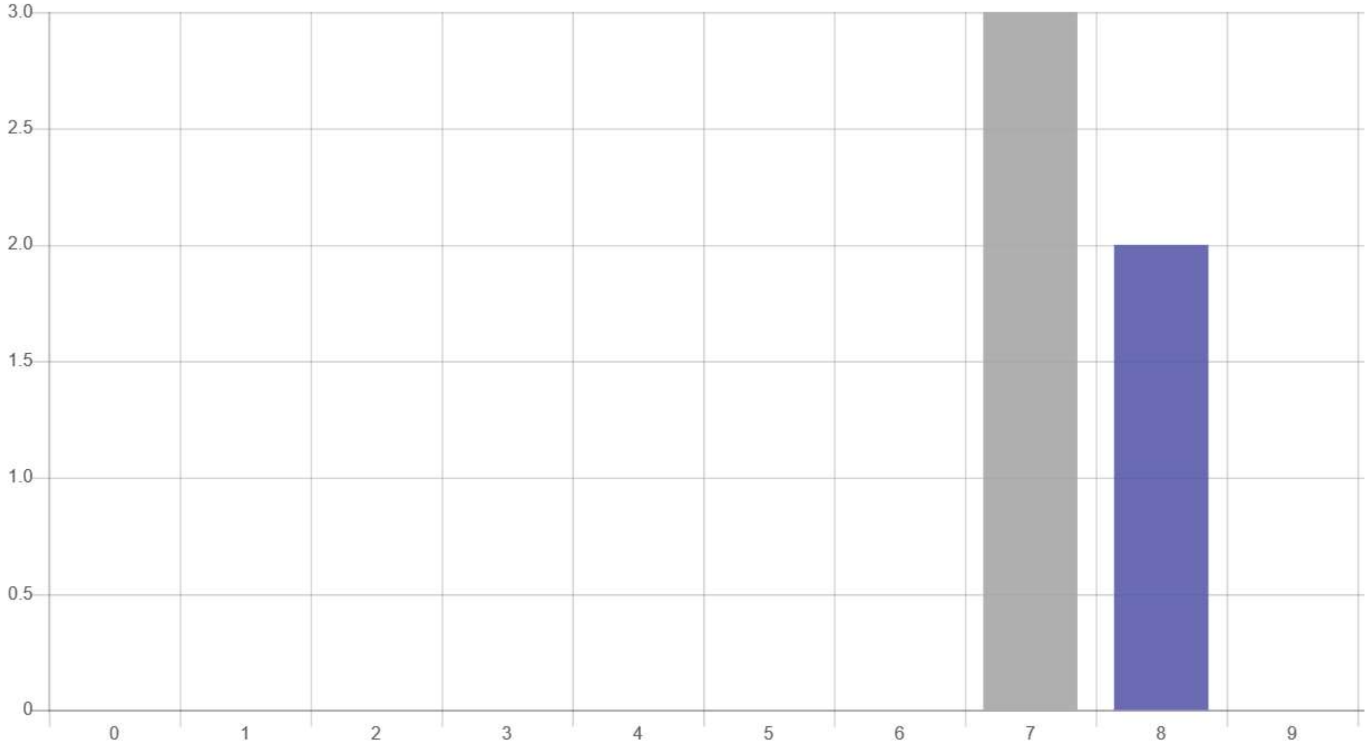
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (17%)	**2 (33%)**	1 (17%)	0 (0%)	1 (17%)	1 (17%)	0.66	6	7.17 / 10
														7.17 / 10

13 perception of the level of availability to equipment, tools and parts



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	**1 (17%)**	1 (17%)	1 (17%)	1 (17%)	1 (17%)	1 (17%)	0.5	6	7.5 / 10
														7.5 / 10

14 perception of the level of effective supervision they experience



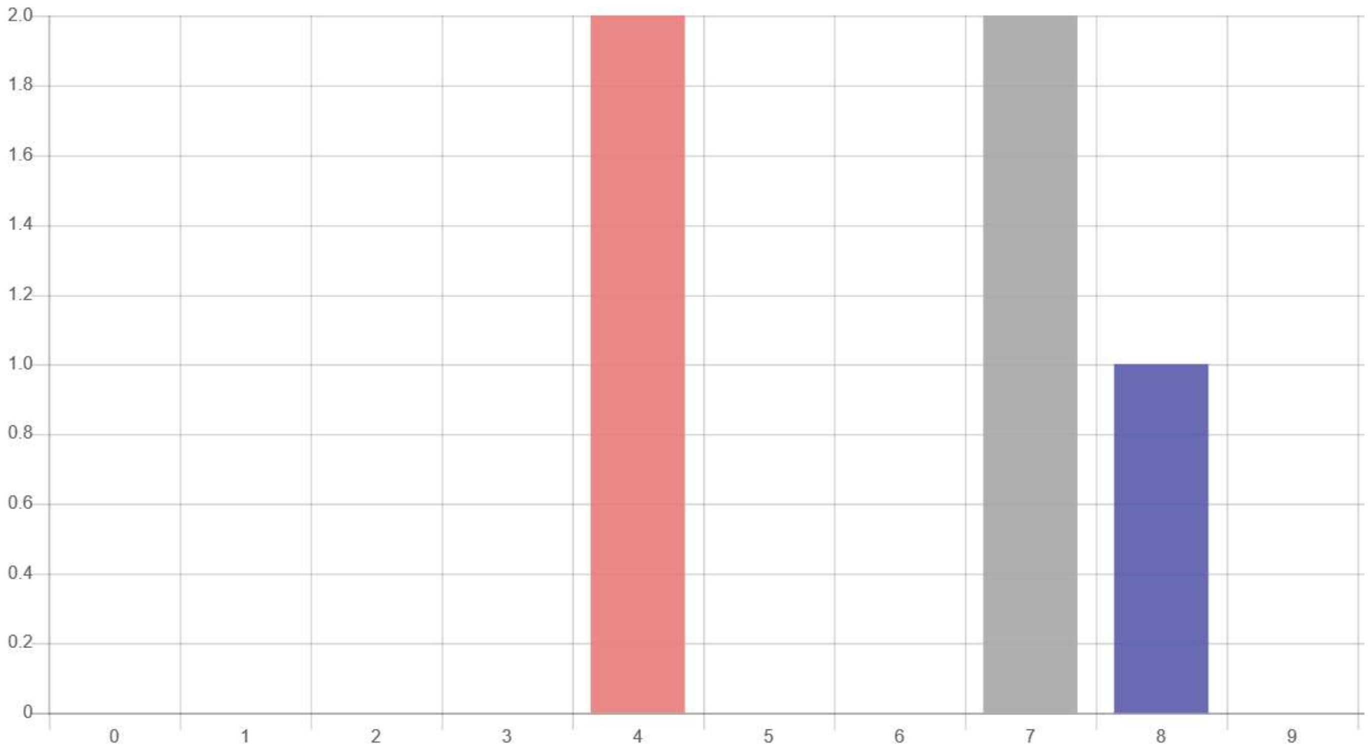
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	**3 (50%)**	2 (33%)	0 (0%)	1 (17%)	0.99	6	7.83 / 10
														7.83 / 10

Part B

Would you, as manager, be interested in a measurement for you maintenance staff's:

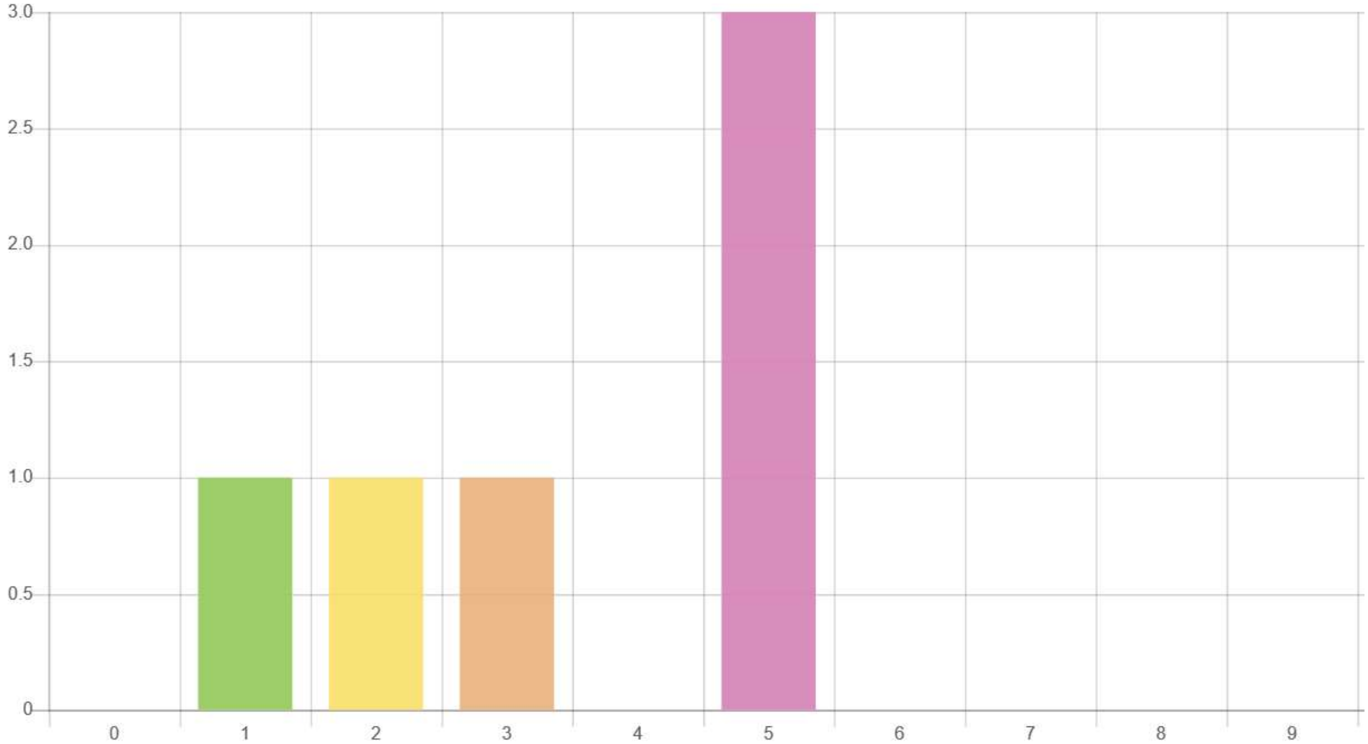
(Page 4/5)

15 perception of the level of stress they experience



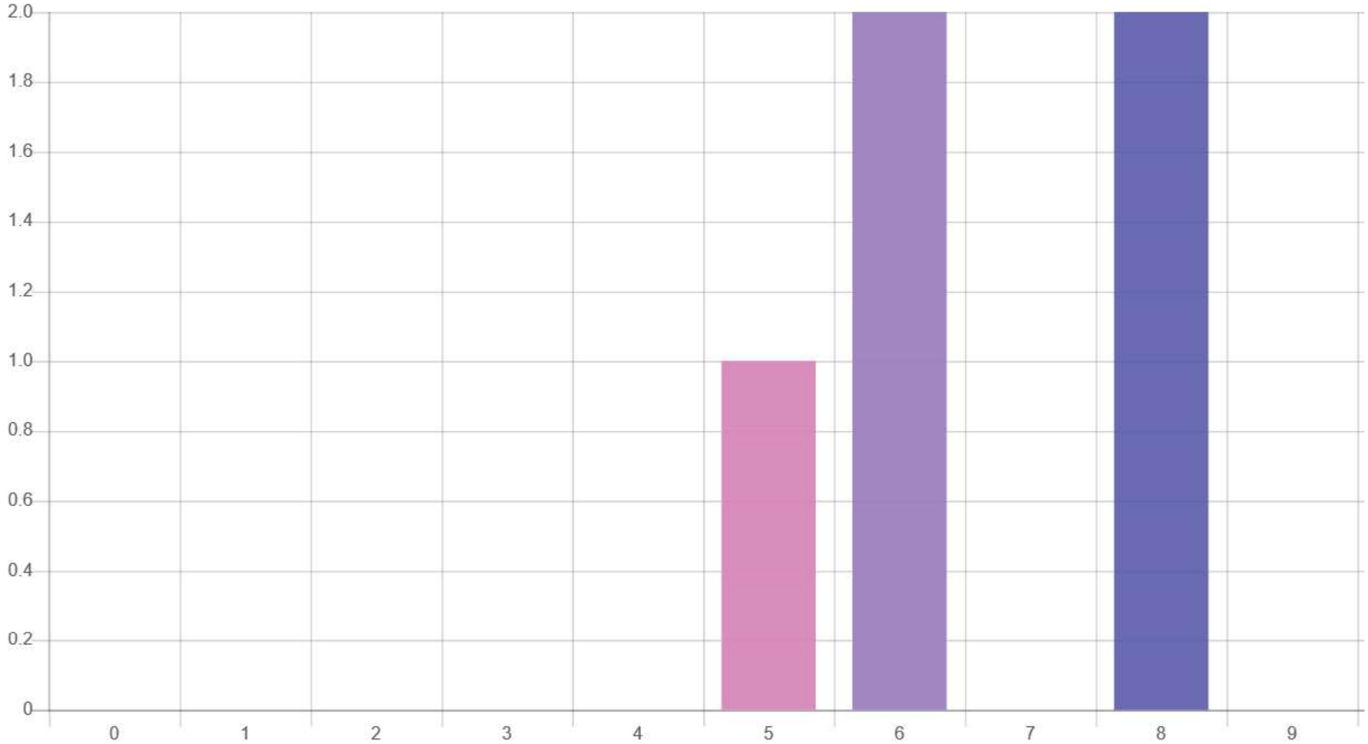
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	0 (0%)	0 (0%)	0 (0%)	**2 (33%)**	0 (0%)	0 (0%)	2 (33%)	1 (17%)	0 (0%)	1 (17%)	0.78	6	6.67 / 10
														6.67 / 10

16 perception of the level of inadequate lighting they experience



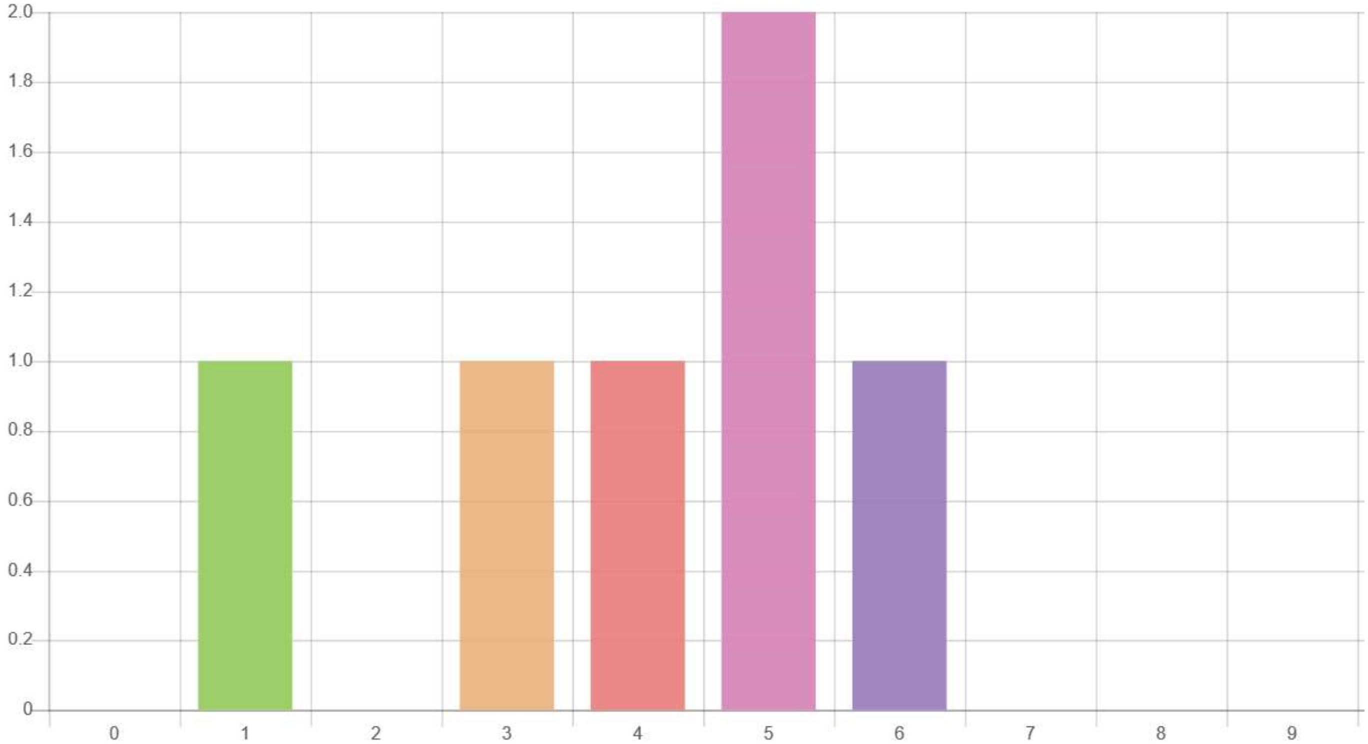
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	1 (17%)	1 (17%)	1 (17%)	0 (0%)	**3 (50%)**	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0.89	6	3.5 / 10
														3.5 / 10

17 perception of the level of availability to equipment, tools and part



	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (17%)	**2 (33%)**	0 (0%)	2 (33%)	0 (0%)	1 (17%)	0.78	6	7.17 / 10
														7.17 / 10

18 perception of the level of excessive noise levels they experience



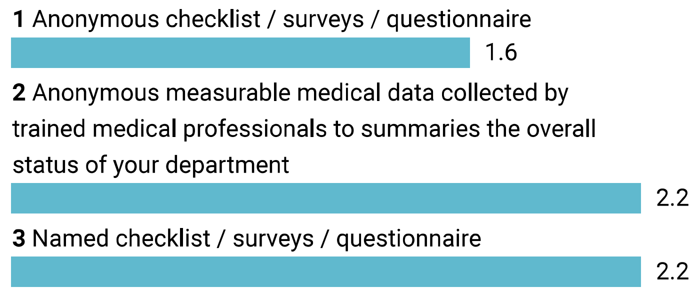
	0	1	2	3	4	5	6	7	8	9	10	Standard Deviation	Responses	Weighted Average
Very Probably Not - Very Probably	0 (0%)	1 (17%)	0 (0%)	1 (17%)	1 (17%)	**2 (33%)**	1 (17%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0.66	6	4 / 10
														4 / 10

Part C

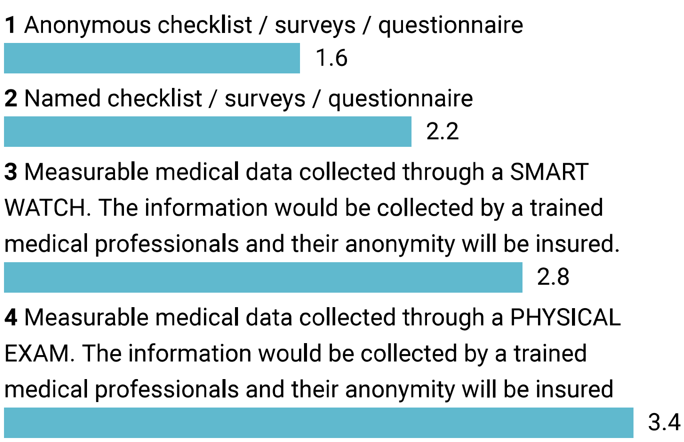
The mentioned maintenance human factors might be seen as sensitive information for maintenance staff. Please rank the following in order of preference. (Hold and drag the factor to change the order.)

(Page 5/5)

19 Which of the following ways would YOU feel more comfortable with, to obtain the information:



20 Which of the following ways do you think would your STAFF feel more comfortable with to provide the information:



Maintenance Human Factors Validation **(H.3. Round 1)**

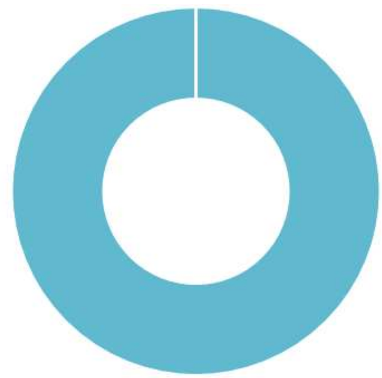
Informed consent

Your participation in this study is entirely voluntary. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes. Your comments and opinions will not be shared with any other participant.

A declaration is also made that your comments and opinions shall in no way influence your continued relationship with the research team. It is therefore asked that you respond to the questions as honestly as possible.

You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. Your withdrawal will in no way influence your continued relationship with the research team.

1 By clicking continue you agree that: I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach. I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.



100% (18)
Continue

0% (0)
Cancel

9
Standard Deviation

18
Responses

Personal Information

The aim of this questionnaire is to determine your expert opinion, on the measurement model proposed by the researcher. This model is based on the results from a questionnaire sent to maintenance staff / field workers within Transmission at the end of 2019.

Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

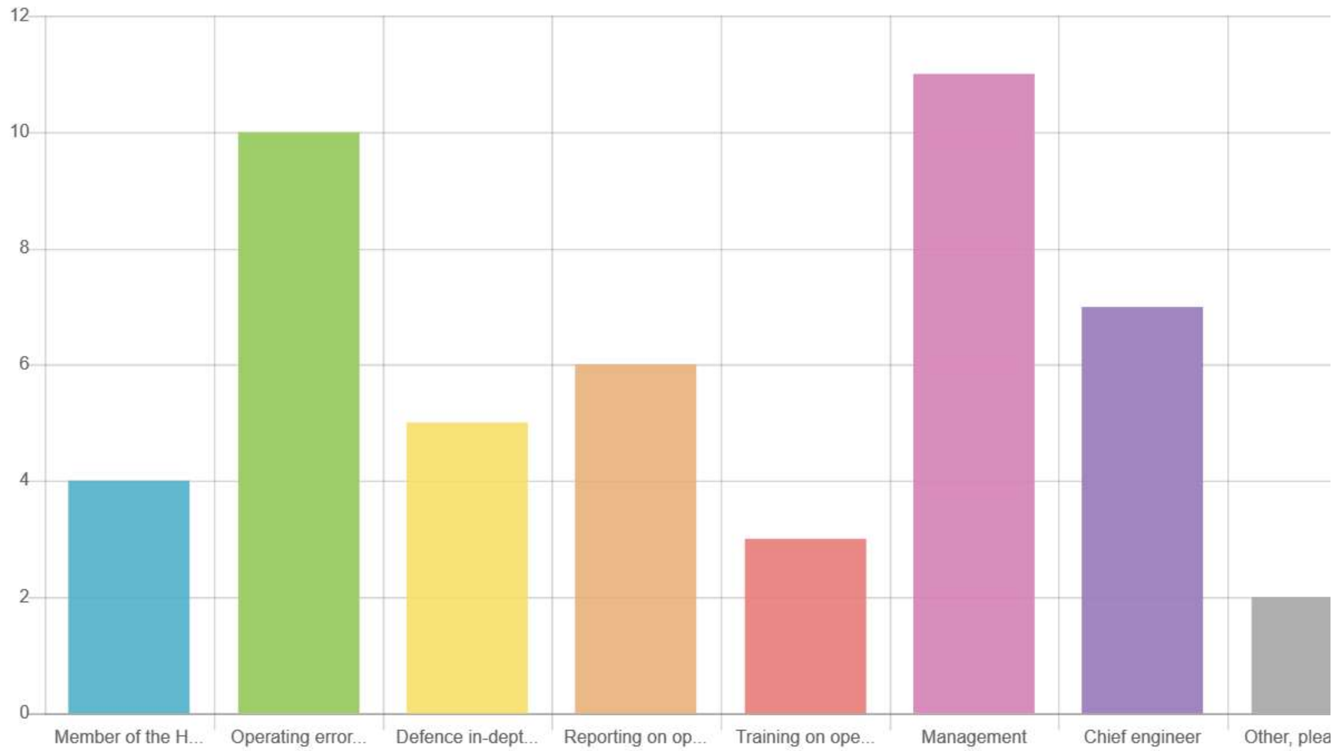
2 Email address

Censored for confidentiality

3 Name and surname

Censored for confidentiality

4 Applicable area of experience in maintenance human factors (more than one option can be selected)



22% (4)
Member of the Human Performance Operating Committee

56% (10)
Operating error / human error investigations

28% (5)
Defence in-depth incident and operational safety analysis

33% (6)
Reporting on operating error / human error performance

17% (3)
Training on operating error / human error investigations

61% (11)
Management

39% (7)
Chief engineer

11% (2)
Other, please specify in as much detail as possible. Example: Academic researcher (Switzerland), focusing on human factors with in power transmission.

48
Responses

I am on the Human performance operating committee. I do training in human error investigations and report on operating errors. I do all of the above but i am not an engineer. I am the corporate human performance subject matter expert

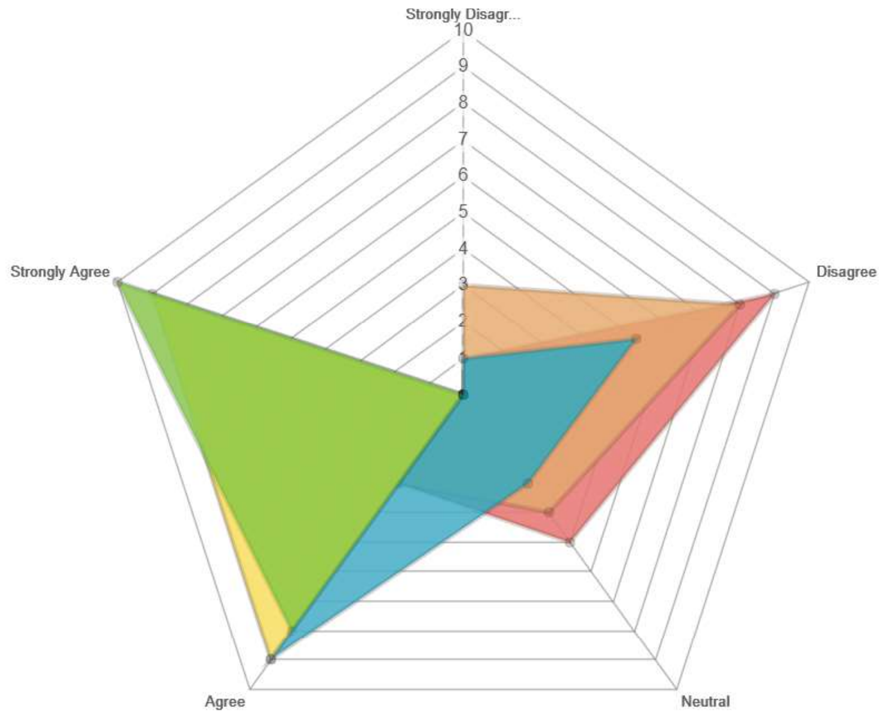
I am a Senior Supervisor in the High Voltage Transmission environment and work in the nuclear transmission grid environment. I was involved with the creation of the current human performance training material and is also a human performance trainer. I have been in the human performance training environment for the last 7 years, but also actively involved to ensure that it gets practically implemented daily by the team that reports to me directly.

Research Question 1

The first identified research question within this study is “What maintenance human factors have the most influence on maintenance human errors?” Maintenance human factors are “factors external and internal that either positively or negatively affect the maintenance technician’s ability to perform maintenance tasks”.

The primary goal of knowing these factors are to manage these human factors to reduce maintenance human errors, hence maintenance errors due to human factors or behaviours.

5 In you experience would you agree to the following research statements:



	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Standard Deviation	Responses	Weighted Average
The most influential maintenance human factors within Transmission is well known and documented.	1 (6%)	5 (28%)	3 (17%)	**9 (50%)**	0 (0%)	3.2	18	3.11 / 5
Awareness of these most influential maintenance human factors could benefit maintenance performance within Transmission.	0 (0%)	0 (0%)	0 (0%)	8 (44%)	**10 (56%)**	4.45	18	4.56 / 5
Awareness of these most influential maintenance human factors could lead to reduced human errors.	0 (0%)	0 (0%)	0 (0%)	**9 (50%)**	9 (50%)	4.41	18	4.5 / 5
The most influential maintenance human factors are actively being managed by management.	3 (17%)	**8 (44%)**	4 (22%)	3 (17%)	0 (0%)	2.58	18	2.39 / 5
The most influential maintenance human factors are actively being managed by supervisors.	1 (6%)	**9 (50%)**	5 (28%)	3 (17%)	0 (0%)	3.2	18	2.56 / 5
								3.42 / 5

6 Comments, personal views and opinions (optional):

Supervisors as the foot-soldiers should be even more involved on HP and Error reduction proactively

In the main currently, only Human Errors resulting in trips / interruptions / operating errors are investigated and records kept. Maintenance errors are seldom identified by others, except the coal face staff, and not investigated in order to reduce the frequency of such errors.

Although factors are known, supervisors and/or manager's execution plans are often overruled through the expectations from Executive level

Operating error focus supercedes human error focus because of the safety factor. More alignment with WANO practice at all levels would assist - staff, supervisory and management accountability

From the investigation conducted, the root causes have been established and the information is available, however there is a need to deep dive of the issues picked and continuous improvement strategies to be put in place

basically i do not believe that Tx has the political will to implement a human factor programme. there is great contentment to focus on the error done by the human but not the system that induces the errors. on many occassions we have asked HPOC to pay attention to reinforcing mechanisms, human error analysis methodologies and machanisms of actions but there seems discomfort to work on systemic organisational issues and organisational failure that impact errors. we focus on the person who inherits the error likely situations and go against best practice.

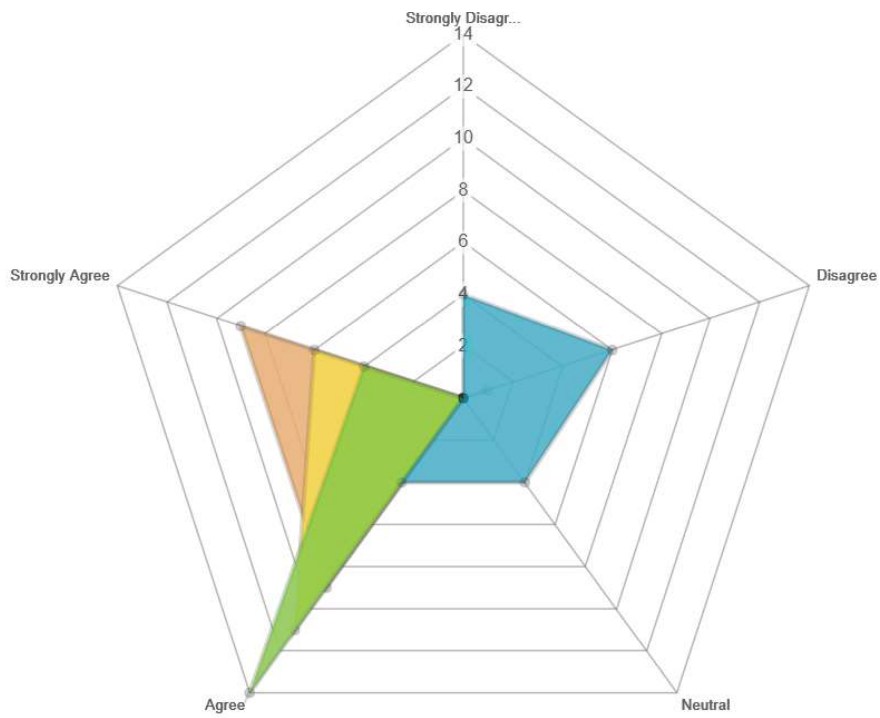
One will notice in areas where there is less human performance errors, the risk perception is better by the workers because they are more aware of the error likely situations. Planning in that area is done better and communication channels are actively used by all involved. This together with a questioning attitude of the workers and the persons leading the teams assists in identifying the potential hazards / error likely situations upfront and actively addressing these concerns. This leads to a proactive approach towards safety, personal wellbeing and sustained production.

some supervisors are hands on while others are not proactive and sometimes absent during performance of an activity

Research Question 2

The second identified research question relates to how these maintenance human factor can be included a maintenance performance framework. This is to actively know the measurable state of the human factor in order to effectively manage them.

7 In you experience would you agree to the following research statements:



	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Standard Deviation	Responses	Weighted Average
The most influential maintenance human factors within Transmission are being measured within an official performance framework.	4 (22%)	**6 (33%)**	4 (22%)	4 (22%)	0 (0%)	1.96	18	2.44 / 5
Measuring these most influential maintenance human factors could benefit the maintenance performance within Transmission.	0 (0%)	0 (0%)	0 (0%)	**14 (78%)**	4 (22%)	5.43	18	4.22 / 5
Measuring these most influential maintenance human factors could lead to reduced humans errors.	0 (0%)	1 (6%)	0 (0%)	**11 (61%)**	6 (33%)	4.32	18	4.22 / 5
Measuring these most influential maintenance human factors could lead to better management of these human factors.	0 (0%)	0 (0%)	0 (0%)	**9 (50%)**	9 (50%)	4.41	18	4.5 / 5
								3.85 / 5

8 Comments, personal views and opinions (optional):

Current records only reflect percentage of maintenance tasks completed, performance of plant and investigated human errors (Trips/ Interruptions/ operating errors only). Errors occurring during maintenance is seldom recorded, therefore seldom investigated and recorded.

The age old sayings: "Show me how you measure me, and I'll show you how I react" / "What gets measured, gets done", state it all.

More focus on learning as opposed to stigmatizing of errors would be a big advantage

The operating error KPI is one of the KPI's with a heavy weight, that translates to leadership strong message on the elimination of operating error. More focus is needed as well on the human errors as those are not highly measures and the impact might also be severe

We need management support to understand systemic safety

Most influential maintenance human factors

From the survey the following factors were identified as the most influential maintenance human factors, that have contributed to a personal maintenance error made by the technician:

• High workload,

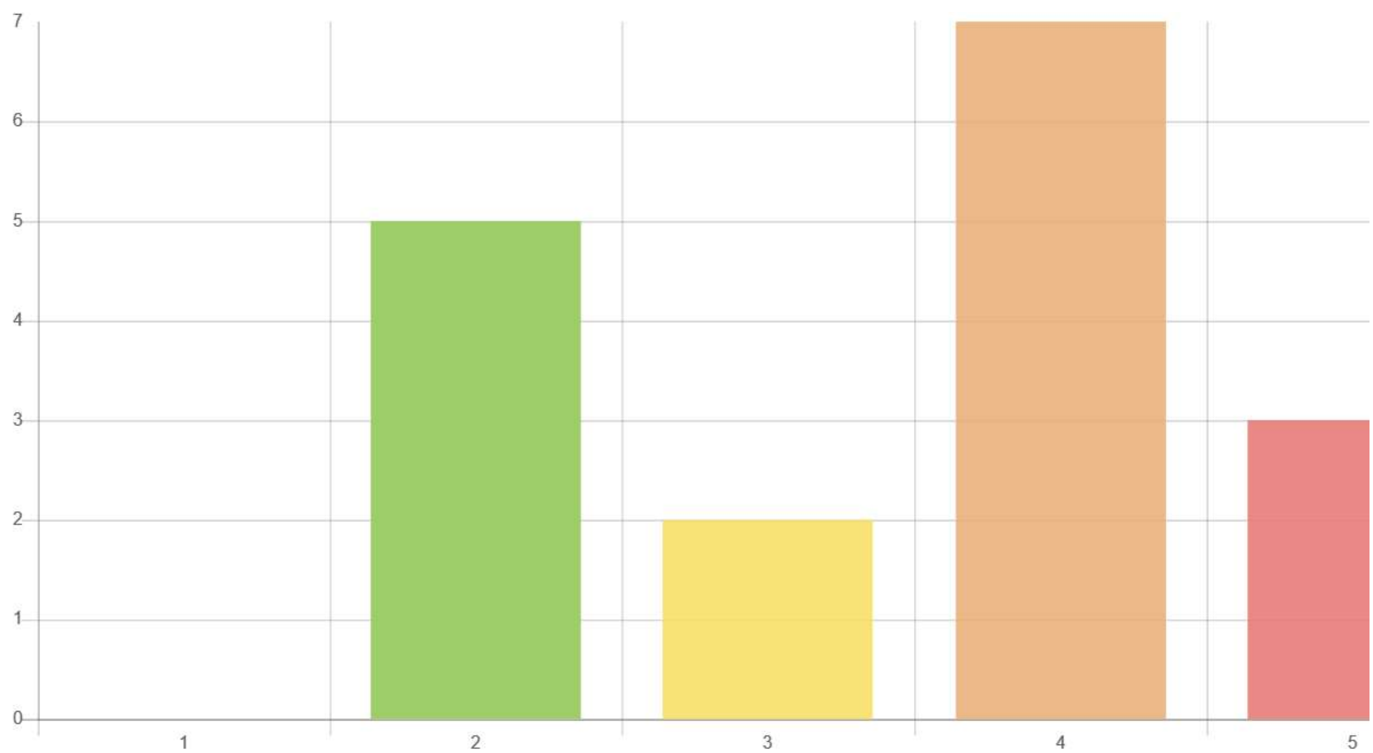
• time pressure,

• fatigue, and

• communication.

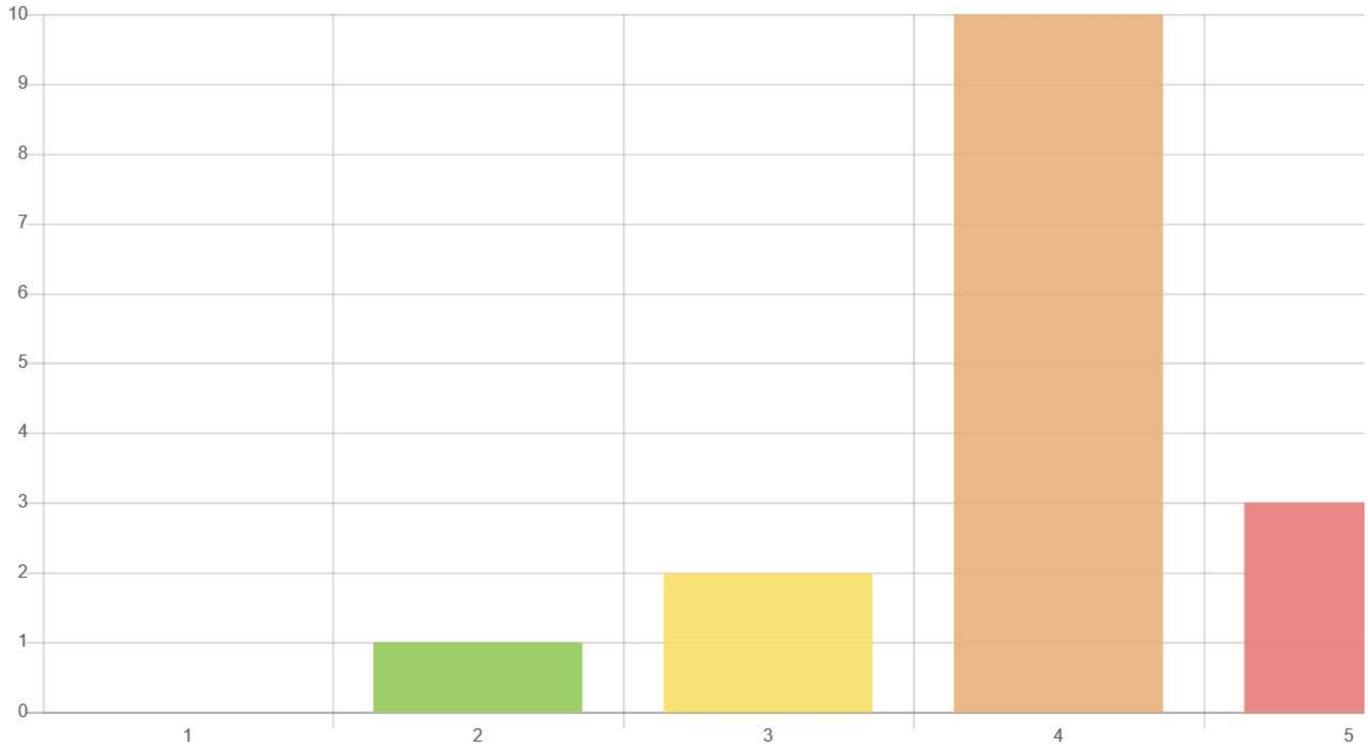
In you experience would you agree that these factors contribute significantly to maintenance human errors considering some situational examples that are given.

9 High workload:• Too many commitments that I am in charge of.• The feeling that tasks are too much for me.• Postponement of urgently needed recreation.• Too many duties that I have to do.• Not enough time to fulfil my daily assignments.• Overload through different duties that I need to take care of.• Situations with so many difficulties that I cannot deal with all of them.• The feeling that it is all too much for me.



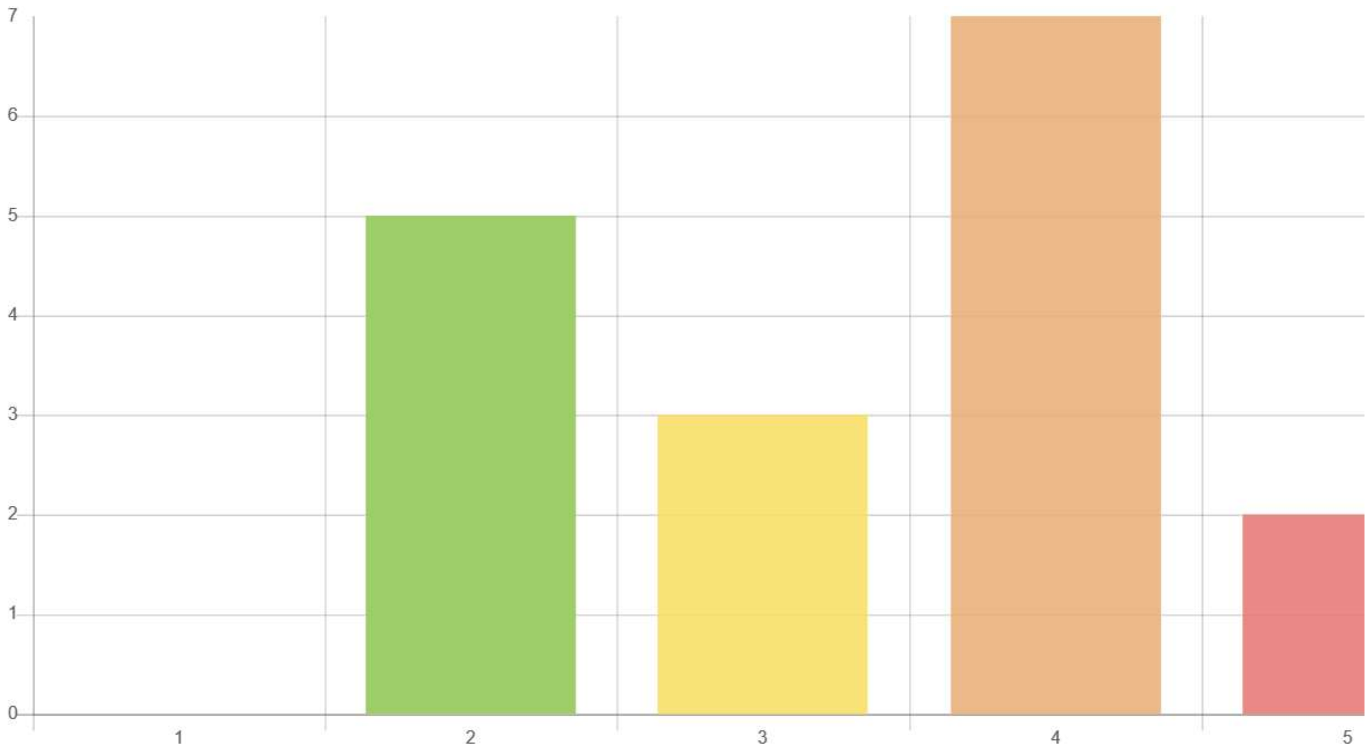
	1	2	3	4	5	Standard Deviation	Responses	Weighted Average
Strongly disagree - Stongly agree	0 (0%)	5 (29%)	2 (12%)	**7 (41%)**	3 (18%)	2.42	17	3.47 / 5
								3.47 / 5

10 Time pressure:• I feel high time pressure at work.• I feel very busy at work.• I find that the given time at work is very limited.• I always feel in a hurry during work hours.• I do not have sufficient time to finish what I should do at work.



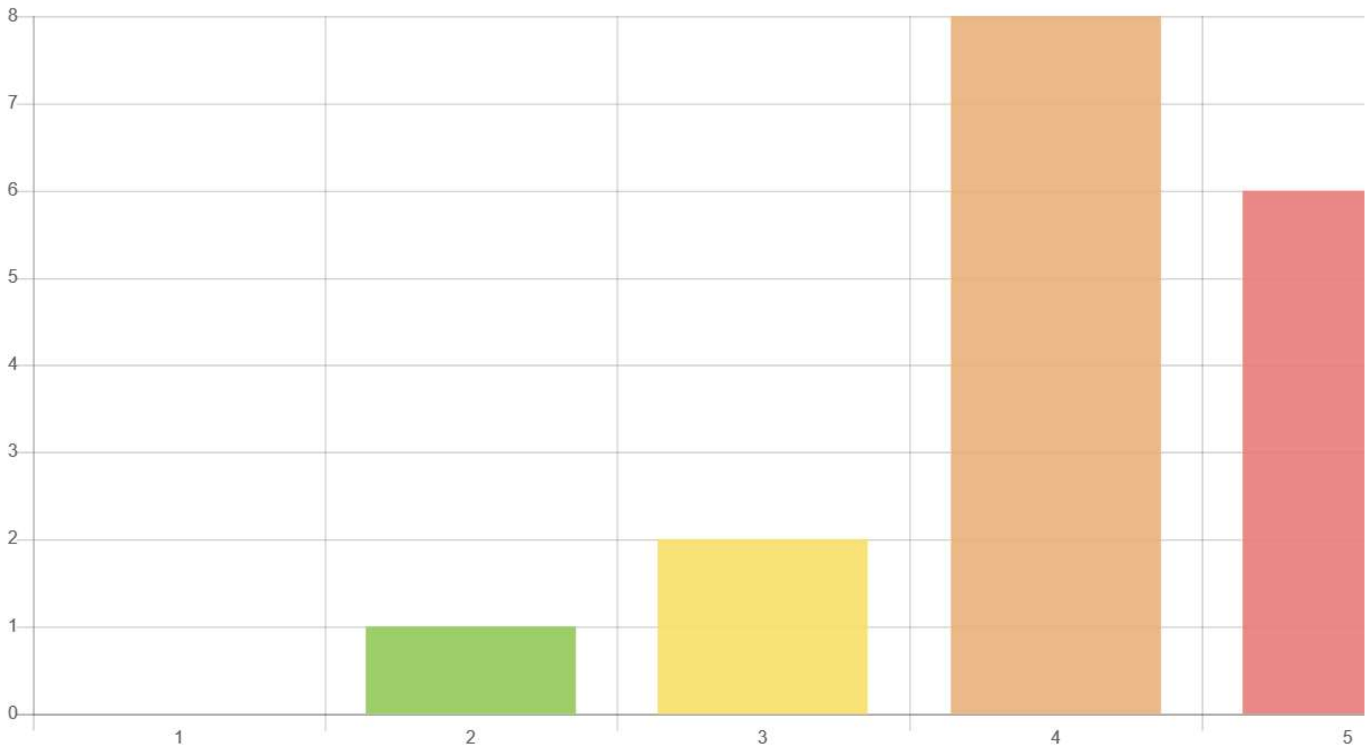
	1	2	3	4	5	Standard Deviation	Responses	Weighted Average
Strongly disagree - Stongly agree	0 (0%)	1 (6%)	2 (13%)	**10 (63%)**	3 (19%)	3.54	16	3.94 / 5
								3.94 / 5

11 Fatigue:• My motivation is lower when I am fatigued,• Exercise brings on my fatigue,• I am easily fatigued,• Fatigue interferes with my physical functioning,• Fatigue causes frequent problems for me,• My fatigue prevents sustained physical functioning,• Fatigue interferes with carrying out certain duties and responsibilities,• Fatigue is among my three most disabling symptoms, and• Fatigue interferes with my work, family, or social life.



	1	2	3	4	5	Standard Deviation	Responses	Weighted Average
Strongly disagree - Stongly agree	0 (0%)	5 (29%)	3 (18%)	**7 (41%)**	2 (12%)	2.42	17	3.35 / 5
								3.35 / 5

12 Communication• receiving the information needed to do your job on time?• conflicts being handled appropriately through proper communication channels?• your supervisor listening to you?• your supervisor offering guidance for solving job-related problems?• your supervisor trusting you?• your supervisor being open to ideas?• information on the requirements of your job?• your meetings being well organised?• information on how you are being evaluated?• recognition of your efforts?• your superior's understanding of the problems faced by subordinates?



	1	2	3	4	5	Standard Deviation	Responses	Weighted Average
Strongly disagree - Stongly agree	0 (0%)	1 (6%)	2 (12%)	**8 (47%)**	6 (35%)	3.07	17	4.12 / 5
								4.12 / 5

13 Comments, personal views and opinions (optional):

Time pressure is often self-induced (inadequate planning)

The focus is primarily technical and not so much on the people.

The factors missing is that the majority of field staff are not sufficiently trained, skilled, knowledgeable enough on task performance, sufficiently motivated and focused when performing maintenance task. the consequence of the aforementioned, is the factors indicated in the questions. Staff are lacking confidence while executing tasks.

High workload and time pressure normally gets blamed - the bottom line is more that of poor planning

Recognition of contribution is essential

Peaks of High work load contribute to time pressured and fatigue. An evenly spread workload through planning could remove peaks and level workload

These are some of the reasons gathered from the investigations, I do agree with them, however I think the organization should focus on training the employees to work under pressure and be able to manage workload, with the current situation in Eskom, numbers are being reduced and customer satisfaction is on of our values. Hence we need to adjust to work with speed and precision

there are underlying factor that induces psychological and physiological stress. Lack of resources and operational equipment having to be shared among employees leads to time pressure. Also stand still time waiting for the site to be prepared for work leads to an increase time preasure.

A high work load leads to fatigue which directly impacts negatively on the time required to do a certain task. An individual that is tired and stressed also does not communicate that effectively. This creates a vicious cycle that does lead to errors and result in less than desirable results.

Measuring the most influential maintenance human factors

The below illustrates the percentage of technicians that ranked each factor as the most influential:

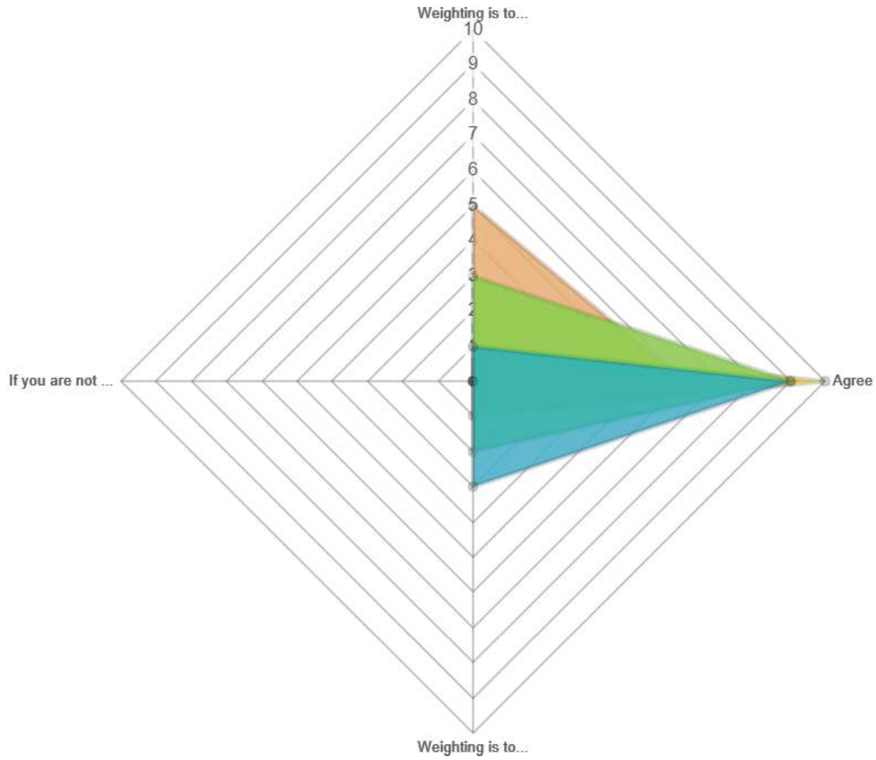
High Workload 24%

Time Pressure 19%

Fatigue 15%

Communication 14%

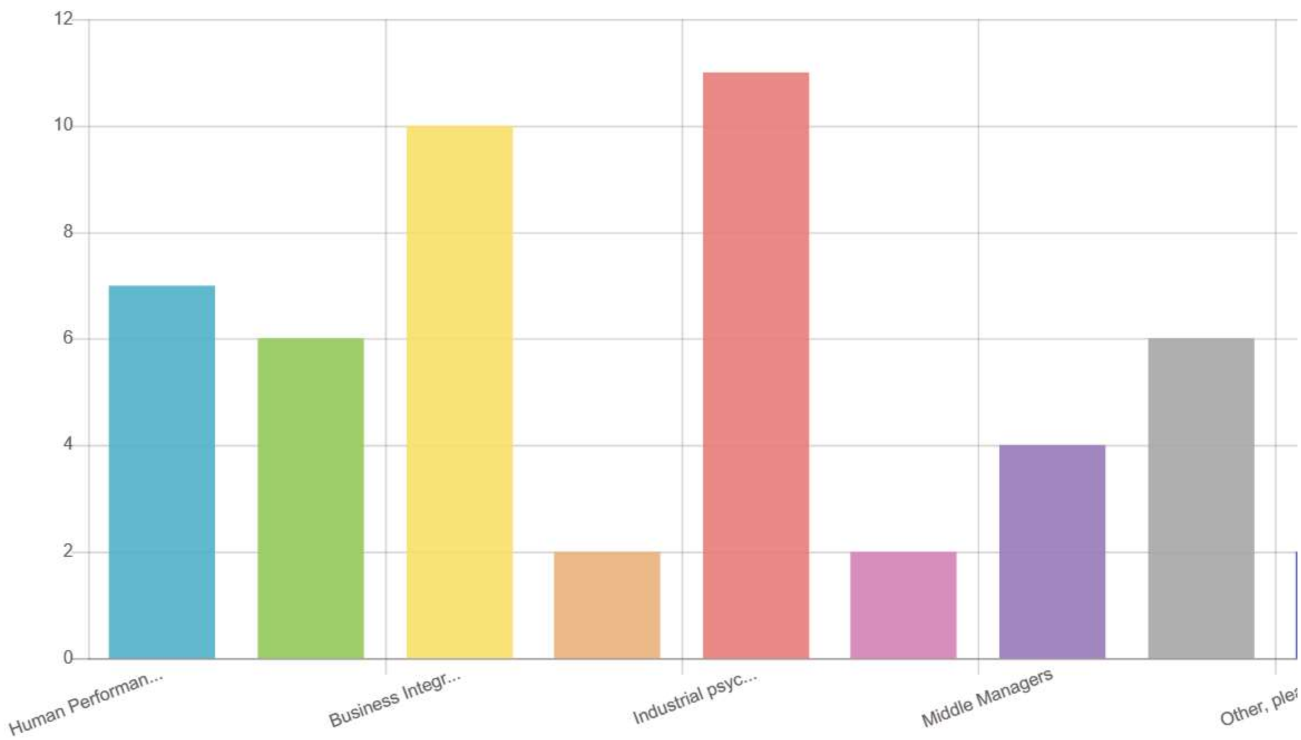
14 If weighting of these factors were to be normalized to 100% as illustrated below, what would your opinion be on the weight of each factor:



	Weighting is to low	Agree	Weighting is to high	If you are not in agreement, what would you suggest the weighting should be:	Standard Deviation	Responses	Weighted Average
High workload 33%	1 (8%)	**9 (69%)**	3 (23%)	0 (0%)	3.49	13	2.15 / 3
Time pressure 26%	3 (21%)	**9 (64%)**	2 (14%)	0 (0%)	3.35	14	1.93 / 3
Fatigue 22%	1 (8%)	**10 (83%)**	1 (8%)	0 (0%)	4.06	12	2 / 3
Communication 19%	5 (45%)	**6 (55%)**	0 (0%)	0 (0%)	2.77	11	1.55 / 3
							1.92 / 3

High workload 33%	30
Time pressure 26%	20
Fatigue 22%	20
Communication 19%	30
High workload 33%	19
Fatigue 22%	15
Communication 19%	40
High workload 33%	20
Communication 19%	35
High workload 33%	25%
Time pressure 26%	25%
Fatigue 22%	20%
Communication 19%	30%
Time pressure 26%	Better management is needed can come down to 20%
Communication 19%	15%
Fatigue 22%	Fatigue is often the result of stress generated in this context because of lack of confidence and sufficient knowledge
Communication 19%	If effective communications takes place, those who lack confidence and knowledge will be identified. This is currently lacking.

15 In your opinion, if these factors were to be measure, who would be best suited to calculate / determine these measurements. These measurements of these factors will be done though academic and industry validated surveys. More than one option can be chosen.



41% (7) Human Performance Operating Committee member	**35%** (6) Human Performance Operating Committee appointed person	**59%** (10) Business Integration and Performance Management (BIPM)	**12%** (2) Chief Engineers
65% (11) Industrial psychologist within HR	**12%** (2) HR as an item: maintenance human factors	**24%** (4) Middle Managers	**35%** (6) Supervisors
12% (2) Other, please specify in as much detail as possible.			

50
Responses

a combination of information sources are needed that flows into dashboards.

To correctly identifying the correct KPI's to measure human performance and human performance issues one needs to actively understand the specific environment the individual / team is working in. It is not a one suite fits all model. One would need a combination of skill sets to adequately compile a true and just KPI / KPA for the individual / team not only to measure but to actively promote improvement.

16 Comments, personal views and opinions (optional):

Most of the persons who are directly involved with maintenance activity execution and those without vested interest, should be involved in the determination of these measures.

Communication and planning details need to be driven and tracked by management. Psychological factors need to be analysed by HR and psychologist.

Tx has done very well in setting error prevention techniques but we could do so much more to implement and study the work of this reasearch

2 of the most important factors in human performance management is to actively drive good communication (3 way) and encourage workers to have a questioning attitude. These two tools / skills are right through the work cycle and is quickest to assist in identifying error traps in the work environment. If having a questioning attitude instilled in the work force, it will make them uncomfortable with unknowns in the work environment and together with good communication between all involved these issues can be mitigated. Other human performance tools will naturally start to follow.

Maintenance Human Factors Validation **(H.4. Round 2)**

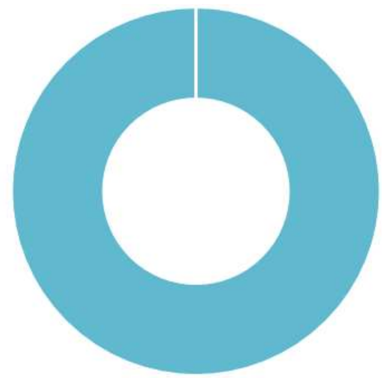
Informed consent

Your participation in this study is entirely voluntary. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes. Your comments and opinions will not be shared with any other participant.

A declaration is also made that your comments and opinions shall in no way influence your continued relationship with the research team. It is therefore asked that you respond to the questions as honestly as possible.

You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. Your withdrawal will in no way influence your continued relationship with the research team.

1 By clicking continue you agree that: I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach. I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.



100% (15)
Continue

0% (0)
Cancel

7.5
Standard Deviation

15
Responses

Personal Information

The aim of this questionnaire is to determine your expert opinion, on the measurement model proposed by the researcher. This model is based on the results from a questionnaire sent to maintenance staff / field workers within Transmission at the end of 2019.

Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

2 Email address

Censored for confidentiality

3 Name and surname

Censored for confidentiality

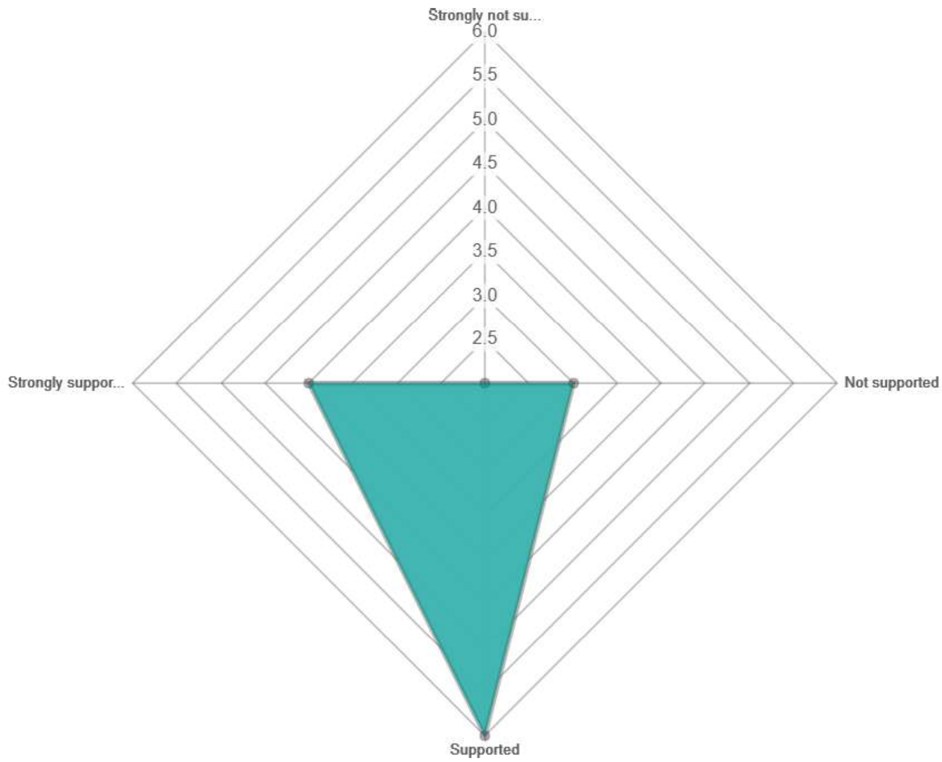
Research Question 1a

Maintenance human factors are the softer human root causes that lead up to a human error being made. Some examples are high workload, fatigue, working under extreme time pressure and a breakdown of communication. Not all maintenance human factors cause human error; however, the cause of human error share similar factors with maintenance human factors.

From the first round questionnaire, all participants agreed/strongly agreed to the below statements:

- Awareness of these most influential maintenance human factors could benefit maintenance performance within Transmission.
- Awareness of these most influential maintenance human factors could lead to reduced human errors.

4 From the first round questionnaire, 58% of participants disagreed/strongly disagreed with the below statements (26% of the participant remained neutral and only 16% agreed/strongly agreed): The most influential maintenance human factors are actively being managed by management.The most influential maintenance human factors are actively being managed by supervisors. Would you therefore support that these statements are valid:



	Strongly not supported	Not supported	Supported	Strongly supported	Standard Deviation	Responses	Weighted Average
The most influential maintenance human factors are NOT actively being managed by management.	2 (13%)	3 (20%)	**6 (40%)**	4 (27%)	1.48	15	2.8 / 4
The most influential maintenance human factors are NOT actively being managed by supervisors.	2 (13%)	3 (20%)	**6 (40%)**	4 (27%)	1.48	15	2.8 / 4
							2.8 / 4

5 Comments, personal views and opinions (optional):

Due to the wording "NOT actively" it is supported. If the word "actively" was left out I would not agree with this statement.

Managers and supervisors are aware of some of the human factors, however because of the known challenges in the organization. e.g. funding for production equipment, these factors are accepted. Some of the managers and supervisors are not focusing on those particular issues as they might not be viewed as serious

These factors have not been adequately identified - and is subsequently not effectively managed.

Pressure is on completion numbers, and often lack the quality check necessary to determine if staff need training or activities improved.

Compliance to Performance Targets receives priority

In my opinion, Supervisors and Managers do not encourage and facilitate a questioning attitude and good 3 way communication. This without proper planning is most probably one of the biggest error traps created in the work place.

Supervisors tend to be on the staff side of the fence. Need arises to ensure that supervisors realise they are part of management

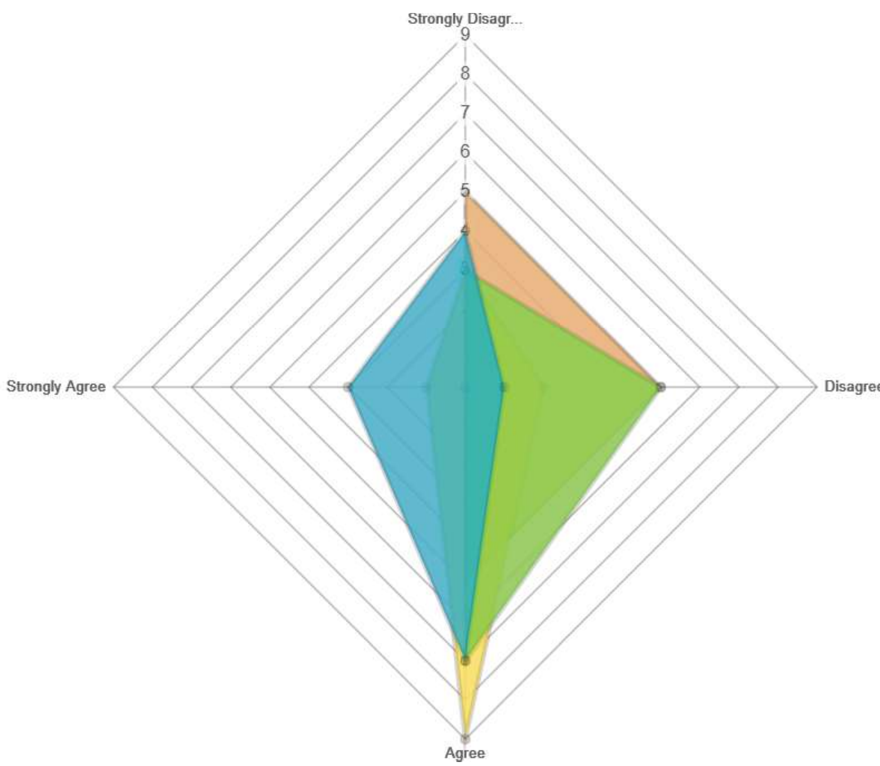
The practice of integrating human factors into day to day work and operating processes are not demonstrated through the use of the incident investigation processes. This process is triggered by a human and organisational event. We do not always listen to the human when they tell us that they are about to make an error and stop the work. There have been situations when people have been successful in exercising their right to refuse unsafe work.

Research Question 1b

Participants response to the statement “The most influential maintenance human factors within Transmission is well known and documented.” Were:

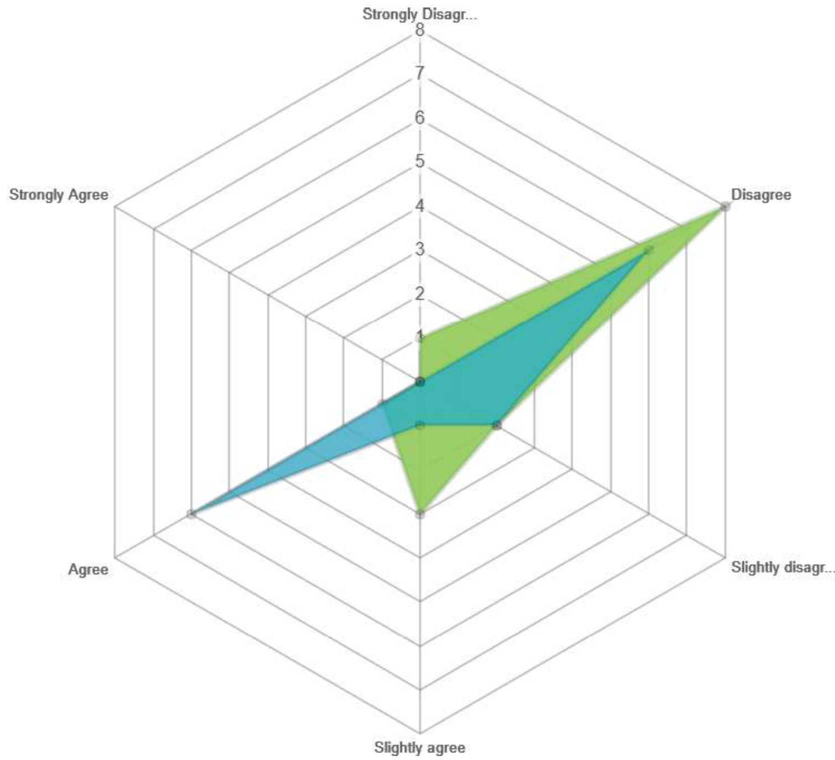
31% disagreed/strongly disagreed,
21% neutral, and
47% agreed/strongly agreed

6 To understand the different responses from the participants, please answer the following questions. In your experience:



	Strongly Disagree	Disagree	Agree	Strongly Agree	Standard Deviation	Responses	Weighted Average
Knowledge of human error causes are based on work experience.	4 (27%)	1 (7%)	**7 (47%)**	3 (20%)	2.17	15	2.6 / 4
Knowledge of human error causes are based on record keeping, historical data and mathematical calculations.	3 (20%)	5 (33%)	**7 (47%)**	0 (0%)	2.59	15	2.27 / 4
Knowledge of the underlying human factor that lead to the human errors are based on work experience.	3 (20%)	2 (13%)	**9 (60%)**	1 (7%)	3.11	15	2.53 / 4
Knowledge of the underlying human factor that lead to the human errors record keeping, historical data and mathematical calculations.	**5 (33%)**	5 (33%)	5 (33%)	0 (0%)	2.17	15	2 / 4
							2.35 / 4

7 Based on the above questions kindly re-answer the original question (now split into two parts), taking in to consideration that maintenance human factors are the softer human root causes that lead up to a human error being made.



	Strongly Disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly Agree	Standard Deviation	Responses	Weighted Average
"The most influential maintenance human factors within Transmission is well known"	0 (0%)	**6 (40%)**	2 (13%)	1 (7%)	6 (40%)	0 (0%)	2.57	15	3.47 / 6
"The most influential maintenance human factors within Transmission is well documented."	1 (7%)	**8 (53%)**	2 (13%)	3 (20%)	1 (7%)	0 (0%)	2.63	15	2.67 / 6
									3.07 / 6

8 Comments, personal views and opinions (optional):

I believe that the human factors are known and from my experience in the position, I know what things to look out for. My gird has done a study on human errors, there are investigation reports of the previous incidents in the organization that can be looked at in order to establish the trend. The information is there but there is no deep dive that has been done

Many human errors will be investigated - often this will happen in isolation in the region where the incident happened. It might be documented after the investigation, but the processes to share is not well defined / implemented.

My experience is that human errors are only documented if the error resulted is an incorrect operation/incident associated with the power network.

Investigations does not go into Human Factor analysis. There is perceptions of human factors floating around

Lack of Planning (Failure to identify risks / wrong risk perception) and poor communication in my opinion are the leading causes of human errors.

Human error is well understood in Tx but not integrated across Tx as in-depth data. WC grid and NEG does very well in integrating and documenting human factors. However this is not a standard practice across the transmission grid

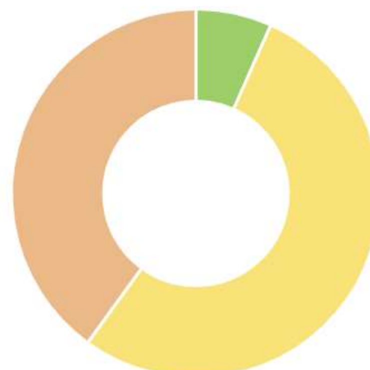
Research Question 2

From the first round questionnaire, more than 90% of all participants agreed/strongly agreed to the below statements:

Measuring these most influential maintenance human factors could benefit the maintenance performance within Transmission.
Measuring these most influential maintenance human factors could lead to reduced humans errors.
Measuring these most influential maintenance human factors could lead to better management of these human factors.

9 Participant's response to the statement "The most influential maintenance human factors within Transmission are being measured within an official performance framework." Were: 55% strongly disagree & disagree, 22% neutral, and 22% agreed & strongly agreed Would you therefore support that the below statement is valid:

"The most influential maintenance human factors within Transmission are NOT being measured within an official performance framework.



0% (0)
Strongly Disagree

7% (1)
Disagree

53% (8)
Agree

40% (6)
Strongly Agree

3.34
Standard Deviation

15
Responses

3.33 / 4
Weighted Average

Most influential maintenance human factors

From the first round questionnaire, more than 80% of all participants agreed/strongly agreed that **time pressure** and **communication** contribute significantly to maintenance human errors.

10 Participant's response that high workload contributes significantly to maintenance human errors were: 29% strongly disagree & disagree, 12% neutral, and 59% agreed & strongly agreed. Would you therefore support that the below statement is valid:

High workload contributes significantly to maintenance human errors.

7% (1)
Strongly Disagree

40% (6)
Disagree

33% (5)
Agree

20% (3)
Strongly Agree

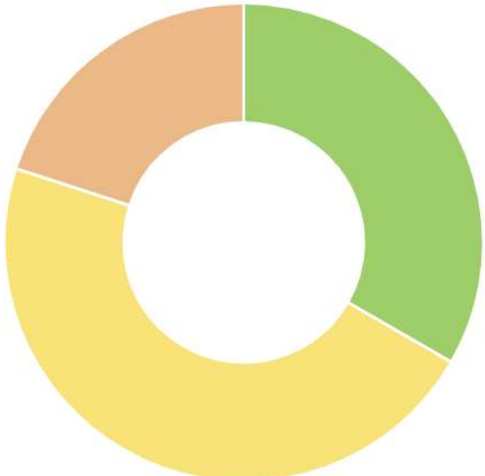
1.92
Standard Deviation

15
Responses

2.67 / 4
Weighted Average

11 Participant's response that fatigue contributes significantly to maintenance human errors were: 29% strongly disagree & disagree, 18% neutral, and 53% agreed & strongly agreed. Would you therefore support that the below statement is valid:

Fatigue contributes significantly to maintenance human errors.



0% (0)
Strongly Disagree

33% (5)
Disagree

47% (7)
Agree

20% (3)
Strongly Agree

2.59
Standard Deviation

15
Responses

2.87 / 4
Weighted Average

12 Comments, personal views and opinions (optional):

The above factors do contribute to human errors but I disagree with contributing significantly to it.

Operating and maintenance activities requires due diligence and mental alertness hence the agreement of the above statements

Fatigue plays a role - I slightly agree. It is also linked to planning- that is why I propose that planning should have a higher weight

The errors are often made because those involved are not skilled enough or they are not following a good work plan for the task in hand.

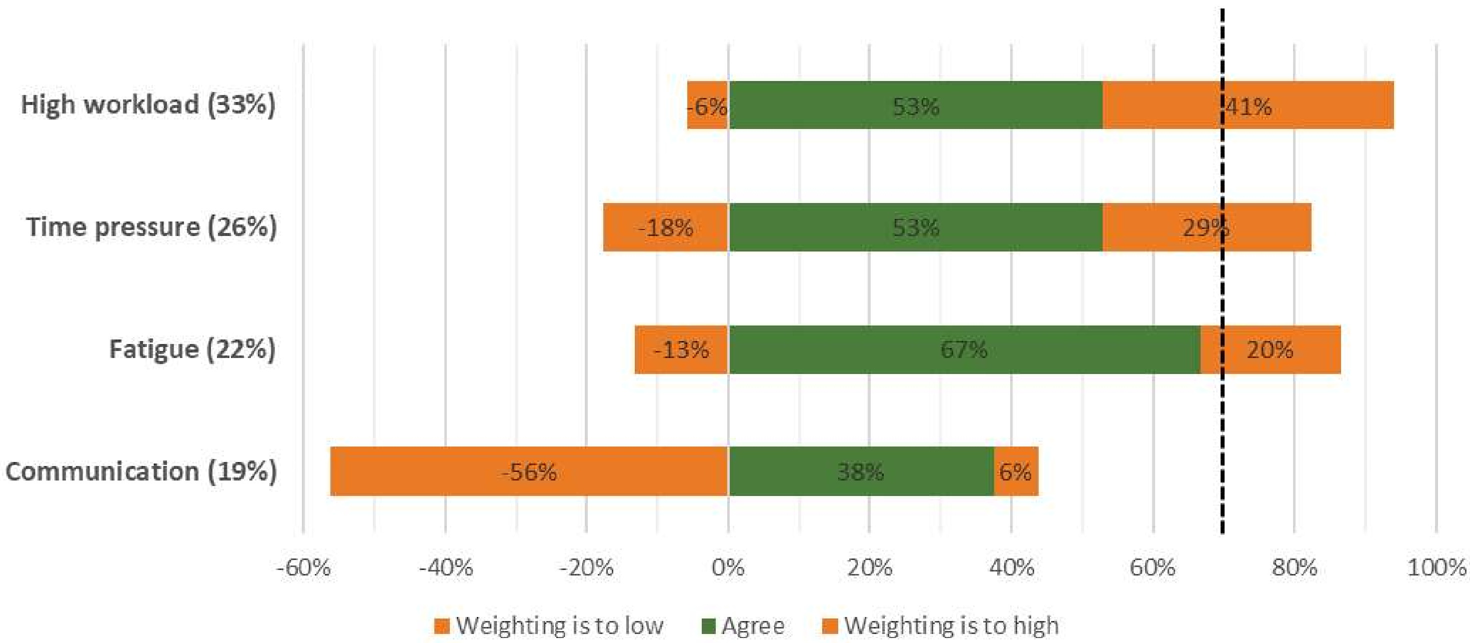
When a person is tired and under significant work pressure the person tends to focus only on the short term goal of each step in the process. Fatigue increases the chances of laps in concentration and decrees the ability to identify risks and error traps due to loss of concentration.

The people that is more productive, has less errors per activity than those that performs less activities.

The high workload is often as a result of inadaquate resources which people have to wait for.

Measuring the most influential maintenance human factors

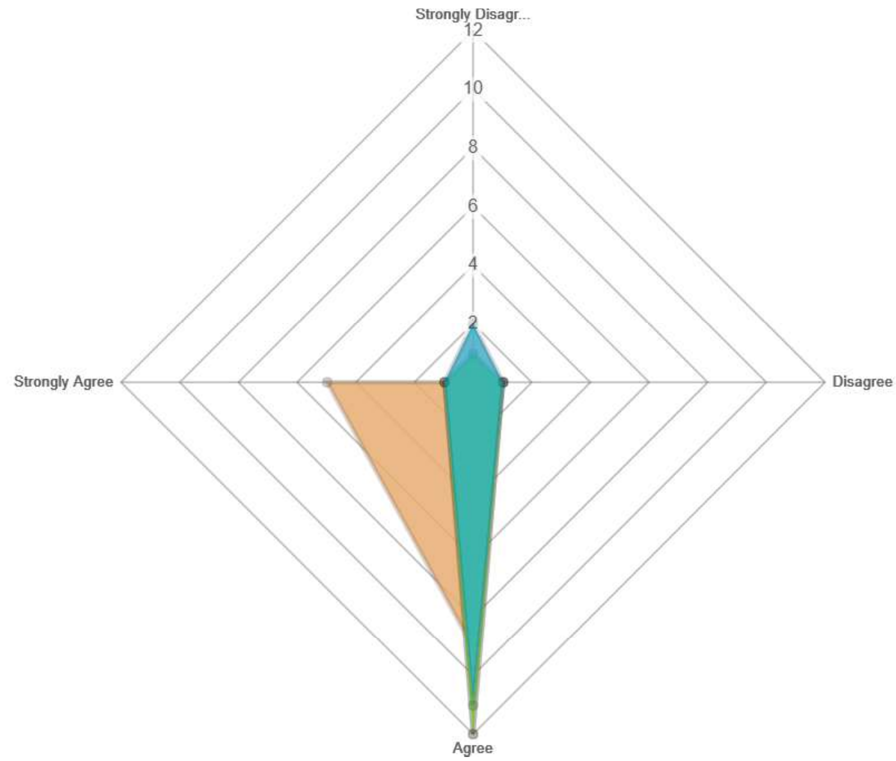
Feedback regarding weightings to measure each element are shown below.



Taking the results into consideration the weighting were changed as below

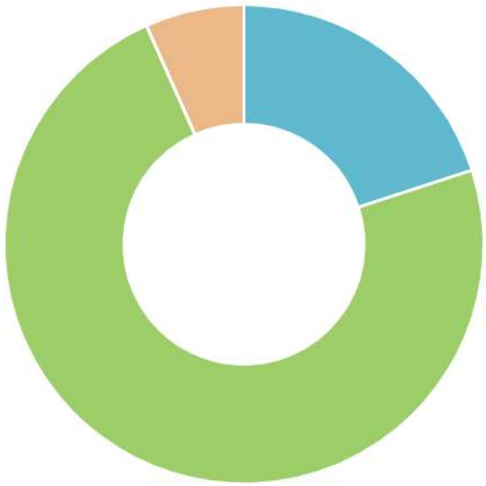
	Round 1 wuights	Round 2 suggested weights
High workload	33%	28%
time pressure	26%	24%
fatigue	22%	22%
communication	19%	26%

13 Would you therefore support the adjusted weightings?



	Strongly Disagree	Disagree	Agree	Strongly Agree	Standard Deviation	Responses	Weighted Average
High workload 28%	2 (13%)	1 (7%)	**11 (73%)**	1 (7%)	4.21	15	2.73 / 4
Time pressure 24%	1 (7%)	1 (7%)	**12 (80%)**	1 (7%)	4.76	15	2.87 / 4
Fatigue 22%	1 (7%)	1 (7%)	**12 (80%)**	1 (7%)	4.76	15	2.87 / 4
Communication 26%	0 (0%)	1 (7%)	**9 (60%)**	5 (33%)	3.56	15	3.27 / 4
							2.93 / 4

14 From the first round questionnaire the below 4 options received equally the highest rating when it was asked would be best suited to calculate / determine these measurements. Kindly indicate from these 4 options who you think would be best suited to calculate / determine these measurements.



20% (3)
Human Performance Operating Committee appointed person

73% (11)
Business Integration and Performance Management

0% (0)
HR as an item: maintenance human factors

7% (1)
Middle Managers

4.32
Standard Deviation

15
Responses

15 Comments, personal views and opinions (optional):

Weightings on "High workload" and "Time pressure" should be slightly lowered and added to the other two factors.

There are already processes and procedures in place from HR to assist managers to manage employees, however they do not support operations especially with the current state in the organization e.g. employees must have resting periods, this is not always possible, there aren't enough resources and there must be continuity of supply to avoid load shedding. As a manager you must always find the balance

It is my view that communication plays a key role and should have a higher weight (40%) - many of the other issues can be reduced through effective communication (planning)

They would need skills related to human performance appointed in BIPM to assist.

Combination of A and B really but the responsibility would be with B and with HPOC support

I am a Senior Supervisor in the High Voltage Transmission environment. I work in the Nuclear grid and am a Human Performance Trainer. I was involved in the creation and roll out of human performance training in Eskom from 2014 already. In my opinion the two most important human performance tools that creates the most impact on performance related issues are good communication and having a questioning attitude. Utilizing these two tools together with good planning reduces work pressure. Another focus area (error trap) that I have identified over the years are when plans change on short notice. This causes normally changes in the risk profile, without revisiting the plan and redoing a risk analysis normally increases risk and my result in a human error. When the situation changes the plan needs to change too! By failing to realize this, we actually fail to plan. Thus to sum it up. 1. Ensure that you plan in detail. 2. Be aware that the plan may change on short notice. 3.Revisit your plan often to evaluate your risk profile (Situational awareness). 4. Keep communicating about the job with the people involved.(Team leader to workers and visa versa during steps) (3 way Communication) 5. Constantly asking if you are still OK. (Questioning attitude) By encouraging these principals and instilling this in your work culture it will have positive results and continuous improvement in performance with a reduction in human errors.

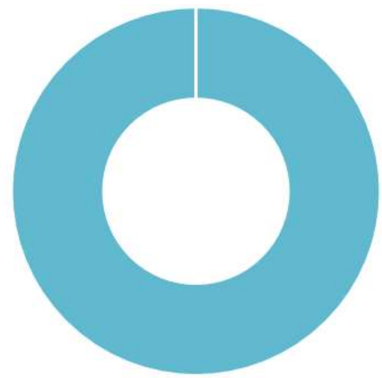
Maintenance Performance Framework Validation
(H.5. Round 1)

Your participation in this study is entirely voluntary. All information obtained from the questionnaire is strictly confidential and will only be used for research purposes. Your comments and opinions will not be shared with any other participant.

A declaration is also made that your comments and opinions shall in no way influence your continued relationship with the research team. It is therefore asked that you respond to the questions as honestly as possible.

You have the right to withdraw at any stage without any penalty or future disadvantage whatsoever. Your withdrawal will in no way influence your continued relationship with the research team.

1 By clicking continue you agree that: I, hereby voluntarily grant my permission for participation in the project as explained to me by Rina Peach. I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.



100% (18)
Continue

0% (0)
Cancel

9
Standard Deviation

18
Responses

Personal Information

The aim of this questionnaire is to determine your expert opinion, on the measurement model proposed by the researcher. This model is based on the results from a questionnaire sent to maintenance staff / field workers within Transmission at the end of 2019.

Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

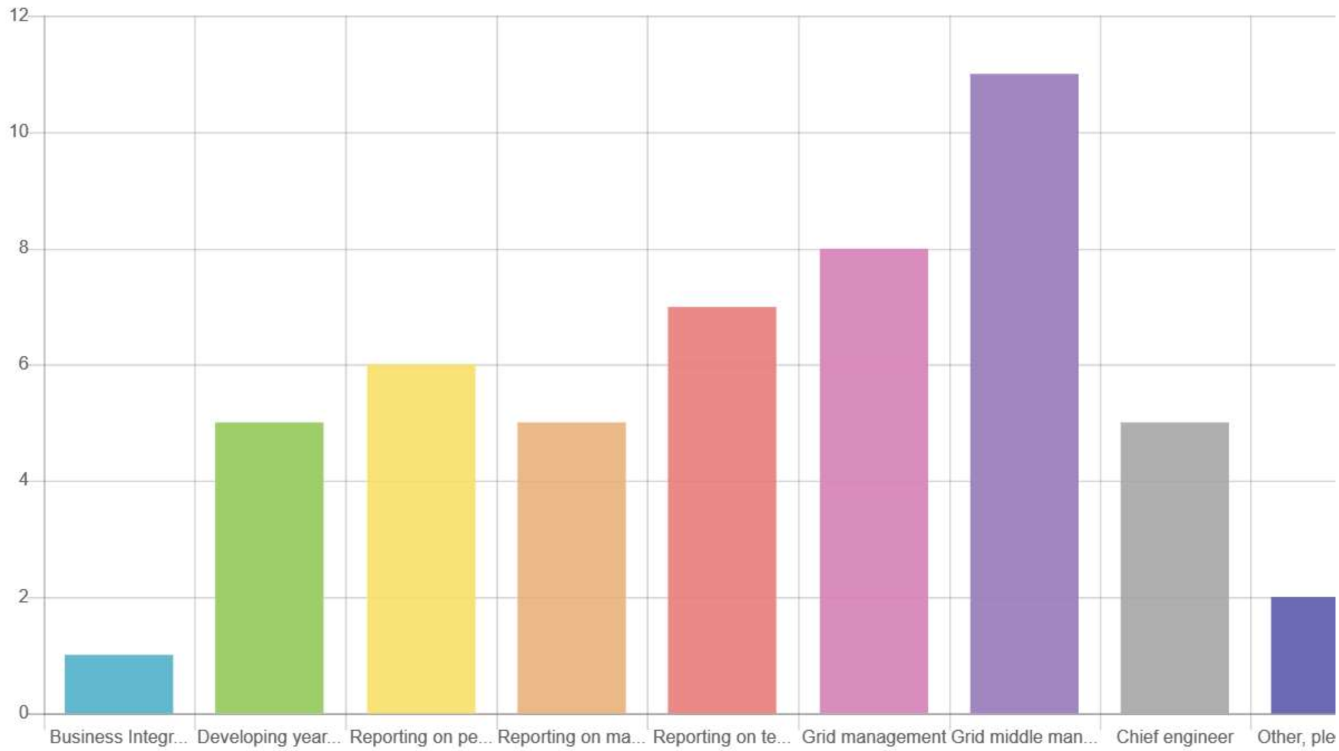
2 Email address

Censored for confidentiality

3 Name and surname

Censored for confidentiality

4 Applicable area of experience in maintenance human factors (more than one option can be selected)



6% (1)
Business Integration and Performance Management (BIPM)

29% (5)
Developing yearly performance measurements

35% (6)
Reporting on performance measurements

29% (5)
Reporting on maintenance performance

41% (7)
Reporting on technical performance

47% (8)
Grid management

65% (11)
Grid middle management

29% (5)
Chief engineer

12% (2)
Other, please specify in as much detail as possible. Example: Academic researcher (Switzerland), focusing on maintenance performance measurements/frameworks with in power transmission.

50
Responses

previous submission

[redacted] Asset Managment

Research Question

Definitions:

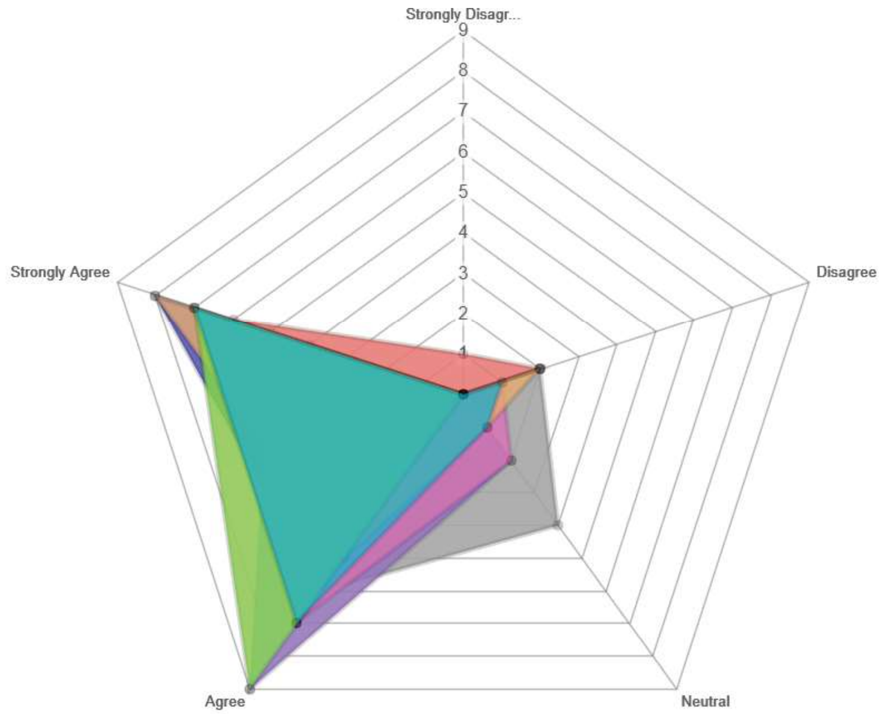
Maintenance human factors are “factors external and internal that either positively or negatively affect the maintenance technician’s ability to perform maintenance tasks”.

Maintenance performance frameworks can be used to quantitatively measure and track key performance factors to ensure management of these factors. From the questionnaire sent to maintenance staff / field workers within Transmission the following maintenance human factors were identified as the most influential maintenance human factors, that have contributed to a personal maintenance error made by the technician: high workload, time pressure, fatigue and communication.

By including the most significant maintenance human factors with corresponding measurements in a maintenance performance framework, proactive action can be taken to reduce maintenance human errors, identify performance gaps, achieve higher operational reliability and improve the overall performance of the maintenance department.

From this the researcher proposes a Total Maintenance Performance (TMP) measurement framework within Transmission inclusive of Maintenance Human Factor Performance.

5 In you experience, would you agree that the following elements should be included in a Total Maintenance Performance (TMP) measurement framework:



	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Standard Deviation	Responses	Weighted Average
System performance	0 (0%)	1 (6%)	1 (6%)	**7 (44%)**	7 (44%)	3.12	16	4.25 / 5
Equipment performance	0 (0%)	0 (0%)	0 (0%)	**9 (56%)**	7 (44%)	3.97	16	4.44 / 5
Maintenance planning	0 (0%)	2 (13%)	0 (0%)	**7 (44%)**	7 (44%)	3.19	16	4.19 / 5
Maintenance completion %	0 (0%)	2 (13%)	1 (6%)	5 (31%)	**8 (50%)**	2.93	16	4.19 / 5
Maintenance Human Factor Performance (MHFP)	1 (6%)	2 (13%)	0 (0%)	**7 (44%)**	6 (38%)	2.79	16	3.94 / 5
Maintenance cost ratio %	0 (0%)	1 (7%)	2 (14%)	**7 (50%)**	4 (29%)	2.48	14	4 / 5
Maintenance errors	0 (0%)	0 (0%)	2 (13%)	**9 (56%)**	5 (31%)	3.43	16	4.19 / 5
Personnel cost ratio %	0 (0%)	2 (13%)	4 (25%)	**6 (38%)**	4 (25%)	2.04	16	3.75 / 5
Safety	0 (0%)	2 (13%)	0 (0%)	6 (38%)	**8 (50%)**	3.25	16	4.25 / 5
								4.13 / 5

6 Comments, personal views and opinions (optional):

No comments

I suggest a skill level (Accreditation) factor should be included.

Focus on the quality of planning, vs the actual execution and cost of execution vs benefit (plant failures after maintenance)

Safety plays an important role for both personnel and equipment

All of the above are contributing factors to maintenance performance. It is however essential to ensure that the measure are realistic and consider local ditracting initiatives when compared internationally eg incidence of conductor theft in 3rd vs. 1st world countries

TMP should measure efficiency (resource utilization) and effectiveness (how did it effect performance outcome)

You need to include competence and reliability after maiantenance

Quality maintenance is informed by the standards and procedures, human (Compliance to procedures), budget, resources (employees and tools), outages. It will be difficult to measure the human factor with the current situation in Eskom, we do not have high reach truck in order to do quality maintenance, we also do not have a budget for production equipment to buy the necessary tools, employees are forced to take shortcuts. Getting outages is a struggle due to the fact that Eskom must keep the lights on

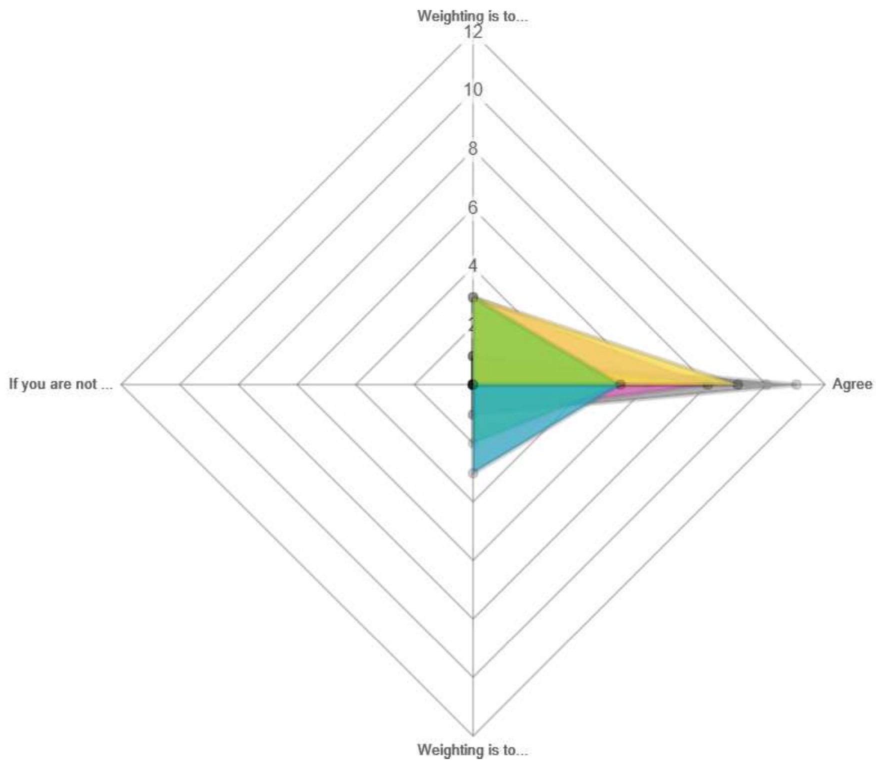
Not too sure what is the definition for System Performance related to your research. The above measures need to be measured related to maintenance. for Example: Equipment Performance related to non-maintenance and non-human related impacts should be excluded.
The maintenance cost ratio % and Personnel ratio % as a measure might be challenging in the Transmission environment due to the vast differences in site, equipment types, geographical areas and different skill sets/contractors used to do maintenance.

Default (Losses, equipment failure, safety incidences) due to human fault

Weighting of TMP elements

Enter some body text

7 If weighting of the Total Maintenance Performance (TMP) measurement framework element were to be normalized to 100% as illustrated below, what would your opinion be on the weight of each factor:he weight of each factor:



	Weighting is to low	Agree	Weighting is to high	If you are not in agreement, what would you suggest the weighting should be:	Standard Deviation	Responses	Weighted Average
System performance (25%)	0 (0%)	**5 (63%)**	3 (38%)	0 (0%)	2.12	8	2.38 / 3
Equipment performance (15%)	3 (30%)	**5 (50%)**	2 (20%)	0 (0%)	1.8	10	1.9 / 3
Maintenance planning (10%)	3 (25%)	**9 (75%)**	0 (0%)	0 (0%)	3.67	12	1.75 / 3
Maintenance completion % (10%)	1 (11%)	**8 (89%)**	0 (0%)	0 (0%)	3.34	9	1.89 / 3
Maintenance Human Factor Performance (MHFP) (10%)	0 (0%)	**9 (100%)**	0 (0%)	0 (0%)	3.9	9	2 / 3
Maintenance cost ratio % (10%)	3 (25%)	**8 (67%)**	1 (8%)	0 (0%)	3.08	12	1.83 / 3
Maintenance errors (5%)	1 (14%)	**6 (86%)**	0 (0%)	0 (0%)	2.49	7	1.86 / 3
Personnel cost ratio % (5%)	1 (8%)	**11 (85%)**	1 (8%)	0 (0%)	4.49	13	2 / 3
Safety (10%)	1 (9%)	**10 (91%)**	0 (0%)	0 (0%)	4.21	11	1.91 / 3
							1.93 / 3

System performance (25%)	5
Maintenance planning (10%)	15
Maintenance completion % (10%)	25
Maintenance Human Factor Performance (MHFP) (10%)	5
Maintenance errors (5%)	15
Safety (10%)	5
System performance (25%)	System performance is not only affected by maintenance activities, many other factors play a roll.
Maintenance errors (5%)	This factor plays a significant part of the maintenance quality level.
System performance (25%)	15%
Equipment performance (15%)	20%
Maintenance Human Factor Performance (MHFP) (10%)	15%
Maintenance errors (5%)	10%
System performance (25%)	20
Equipment performance (15%)	20
Maintenance completion % (10%)	10
Maintenance Human Factor Performance (MHFP) (10%)	5
Safety (10%)	5
Equipment performance (15%)	25%
Maintenance completion % (10%)	5%
Maintenance Human Factor Performance (MHFP) (10%)	5%
Maintenance errors (5%)	10 to 15%
Maintenance cost ratio % (10%)	5%
Maintenance errors (5%)	10%

8 Comments, personal views and opinions (optional):

Safety in general is very important but it is already measured through a number of other business KPIs. Should the Safety weighting for the TMP measure be too high, too much double counting will take place.

Where we need more focus, the weighting needs to increase. What we have under control can have a reduced rating.

Maintenance completion at 10% is a bit low for me, I feel 15% - 20% would be better

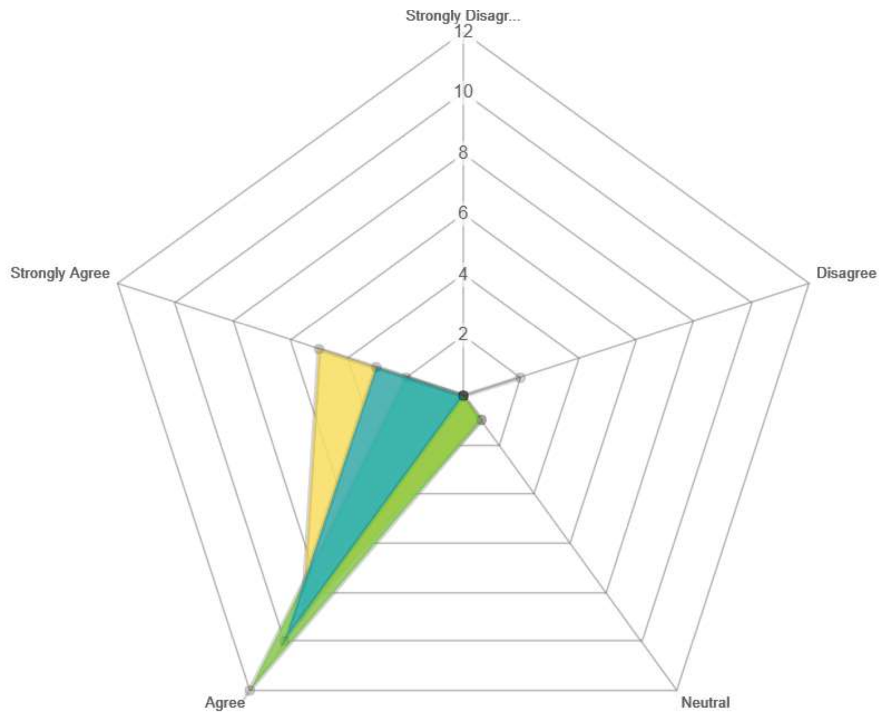
Effectiveness {SP(15%); EP(10%); MHPF(10%); ME(5%); Safety(10%)} = 50% vs Efficiency {MCR(20%); MP(10); MC(10); PCR(10)} = 50%

There are no weights to agree to??

Benefits of the proposed TMP

Enter some body text

9 In you experience would you agree to the following research statements:



	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Standard Deviation	Responses	Weighted Average
Inclusion of Maintenance Human Factor Performance within a TMP could benefit maintenance performance within Transmission.	0 (0%)	2 (13%)	0 (0%)	**10 (67%)**	3 (20%)	3.69	15	3.93 / 5
The proposed TMP could benefit maintenance performance within Transmission.	0 (0%)	0 (0%)	1 (7%)	**12 (80%)**	2 (13%)	4.56	15	4.07 / 5
The proposed TMP could benefit overall technical performance within Transmission.	0 (0%)	0 (0%)	1 (7%)	**9 (60%)**	5 (33%)	3.52	15	4.27 / 5
								4.09 / 5

10 Comments, personal views and opinions (optional):

The above was rated based on that the system that measure the performance does not take more time to capture and analyse then to gain the benefit of learning from mistakes/errors. If the measure will be punitive then people will not come forth with human related errors to improve the maintenance quality. I the case of Operating errors there are systems in place that we can use to determine what did the human say or indicate that the person is suppose to do and we can monitor it from Network records/indications. In the case of maintenance Quality the Transmission systems does not measure the quality of the maintenance but only the quality of the end product: electricity to the customer. Maintenance quality might only be seen later when some equipment fails which was maintained years ago or even latent design flaws or even bad workmanship from Contractors during the installation years ago. Maintenance quality might also be seen much later if a certain type of fault is occurring only after some time that the settings has been implemented wrong.

Maintenance Performance Framework Validation
(H.6. Round 2)

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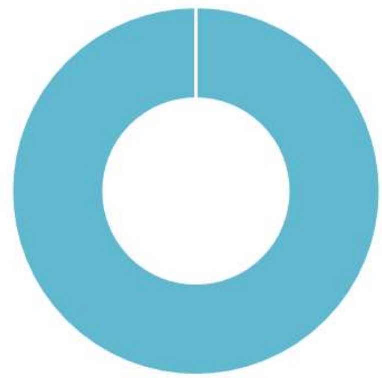


100% (14)
Continue

0% (0)
Cancel

7
Standard Deviation

14
Responses

Personal Information

The aim of this questionnaire is to determine your expert opinion, on the measurement model proposed by the researcher. This model is based on the results from a questionnaire sent to maintenance staff / field workers within Transmission at the end of 2019.

Please provide the followings details. However, please note that all information will be kept confidential and will not be shared. It is only for record-keeping purposes.

2 Email address

Censored for confidentiality

3 Name and surname

Censored for confidentiality

TMP Element

From the first round questionnaire, more than 80% of all participants agreed/strongly agreed to the below statements regarding the benefits of the proposed Total Maintenance Performance (TMP):

Inclusion of Maintenance Human Factor Performance within a TMP could benefit maintenance performance within Transmission.

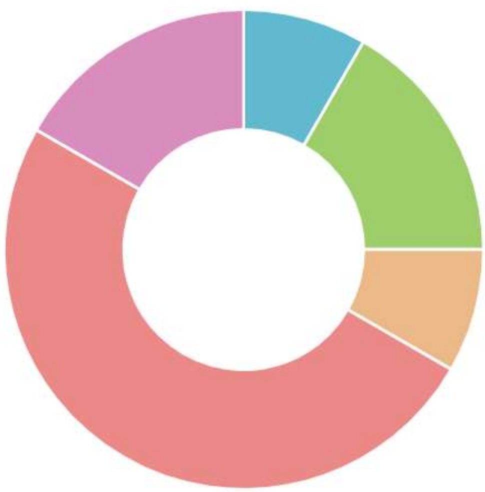
The proposed TMP could benefit maintenance performance within Transmission.

The proposed TMP could benefit overall technical performance within Transmission.

In the first questionnaire, 9 elements were proposed to be included in a TMP measurement framework.

4 More than 70% of all participants agreed/strongly agreed that 8 of the 9 elements should be included in the TMP as per the graph below. Participant's response to include "Personnel cost ratio%", were: 13% strongly disagree & disagree, 25% neutral, and 63% agreed & strongly agreed Would you therefore support that including "Personnel cost ration%" into the TMP is valid:

Personnel cost ratio %



8% (1) Strongly Disagree

17% (2) Disagree

0% (0) Slightly Disagree

8% (1) Slightly Agree

50% (6) Agree

17% (2) Strongly Agree

1.91 Standard Deviation

12 Responses

4.25 / 6 Weighted Average

5 Comments, personal views and opinions (optional):

Depending on what behaviour need to be driven by TMP or what want to be achieved by TMP, it could or could not be included. In my view TMP should be mainly driving planning and execution (completion, quality and maintenance cost) of maintenance, hence strongly disagreeing with this statement. It could be included in other metrics required for profitability reporting.

Its quite important for an organization that has challenges with resources, this will give an indication on how much is being spent on the individual. Other industries are looking at implementing human machines or robot to save costs

This will also determine the skills level used to do maintenance

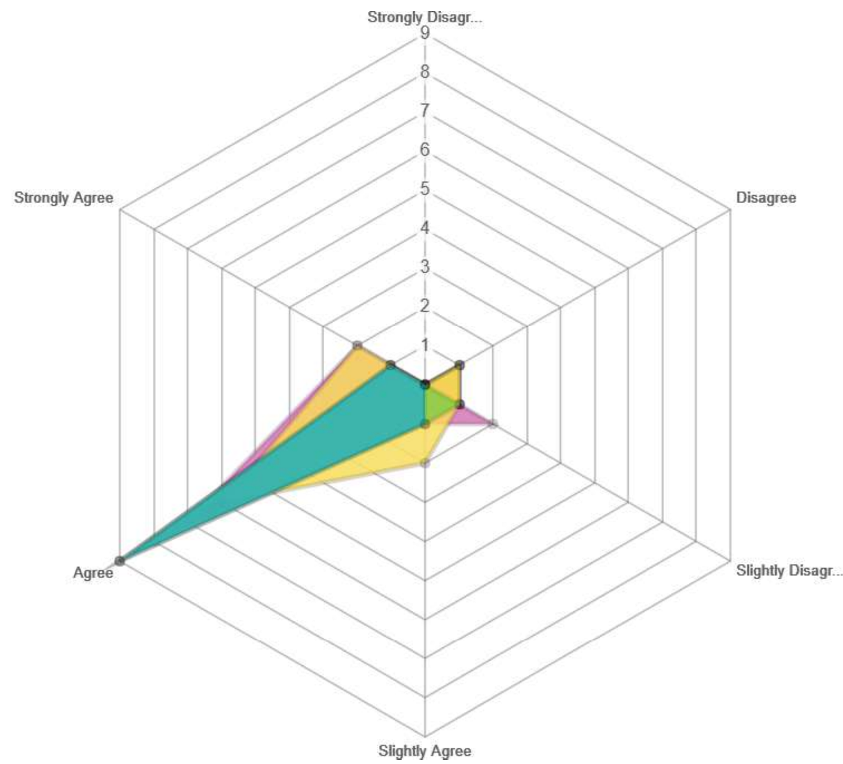
If we are driving business efficiencies then it makes sense to include

Efficiency drive

Weighting of TMP elements

Enter some body text

6 In the first round weightings to measure each element were proposed. The responses to the weightings are shown below. Taking the results into consideration the weighting were changed as below. Were more than 70% of the participant agreed to the weighting (round 1), support of the weighting was not asked for again. Maintenance Indicator Round 1 Weighing Round 2 suggested weights System performance 25% 15% Equipment performance 15% 20% Maintenance planning 10% 10% Maintenance completion % 10% 10% Maintenance Human Factor Performance (MHFP) 10% 10% Maintenance cost ratio % 10% 10% Maintenance errors 5% 10% Personnel cost ratio % 5% 5% Safety 10% 10%



	Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree	Standard Deviation	Responses	Weighted Average
System performance (15%)	0 (0%)	1 (8%)	0 (0%)	1 (8%)	**9 (75%)**	1 (8%)	3.16	12	4.75 / 6
Equipment performance (20%)	0 (0%)	0 (0%)	1 (8%)	1 (8%)	**9 (75%)**	1 (8%)	3.16	12	4.83 / 6
Maintenance planning (10%)	0 (0%)	1 (8%)	1 (8%)	2 (17%)	**6 (50%)**	2 (17%)	1.91	12	4.58 / 6
Maintenance Human Factor Performance (MHFP) (10%)	0 (0%)	1 (8%)	1 (8%)	0 (0%)	**9 (75%)**	1 (8%)	3.16	12	4.67 / 6
Maintenance cost ratio % (10%)	0 (0%)	1 (8%)	1 (8%)	1 (8%)	**8 (67%)**	1 (8%)	2.71	12	4.58 / 6
Maintenance errors (10%)	0 (0%)	0 (0%)	2 (17%)	1 (8%)	**7 (58%)**	2 (17%)	2.38	12	4.75 / 6
									4.69 / 6

7 Comments, personal views and opinions (optional):

Weighting for System Performance too high, maintenance completion too low. MHFP, Safety and Personnel cost Ratio to be measures in other metrics.

I think planning is very key, it is the core of everything

Increase the maintenance planning weight - about 15-20%. Consider reducing the maintenance cost ratio to compensate.

In my opinion, the Maintenance errors could be the result or the MHFP or vice versa, so somehow maybe reduce the one or the other %, and the shortfall of that % should be added to Maintenance Planning and Maintenance Completion maybe

There should be a better balance between effectiveness and efficiency