Development of a Model for the Implementation of Industry 4.0 Technologies in Rolling Stock Maintenance

by

Marius Tim Wippel

Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering (Engineering Management) in the Faculty of Engineering at Stellenbosch University
This thesis has also been presented at Reutlingen University, Germany, in terms of a double–degree agreement

Supervisor: Dr. J.L. Jooste
Co–supervisor: Prof. Dr. D. Lucke

March 2021

Stellenbosch University https://scholar.sun.ac.za

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: ....March 2021..................

Copyright © 2021 Stellenbosch University
All rights reserved

Stellenbosch University https://scholar.sun.ac.za

Abstract

Globalisation and the growth in world population are causing increased human mobility. As a result, new mobility solutions are entering the market, leading to increasing intermodal competitiveness. This implies that traditional means of transport such as rolling stock must be operated with more efficiency to withstand intermodal competition. Achieving greater efficiency is demanding for rail operators. They are being challenged by increasing complexity and safeguarding the availability of passenger rolling stock, bringing maintenance and emerging technologies into focus. To stay competitive and operate economically, rail operators need to optimise their maintenance strategies. Emerging technologies shape the Industry 4.0 environment and contribute towards improving processes.

This research work proposes a model for rail operators which supports them in their decision to implement Industry 4.0 technologies in rolling stock maintenance. The model consists of various phases and considers the various main mechanical systems of rolling stock as well as the related appropriate maintenance strategy. Relevant criteria are identified for selecting a suitable maintenance strategy for the model user's rolling stock system. In addition, a customised selection of emerging technologies is carried out based on the rail operator's technological maturity level. A systematic literature review revealed the suitable Industry 4.0 technologies which are applicable for maintenance processes. The maturity level is derived from the major prerequisites of the technologies and is determined via a questionnaire. An economic consideration of Maintenance Performance Indicators (MPIs) determines whether an investment is worthwhile based on the current technological maturity level. For future research the model proposes relevant activities which are influenced by the findings of the conducted online survey with subject matter experts. Therefore, this work contributes towards enabling rail operators for decision–making regarding Industry 4.0 technology integration and thereby increases maintenance process efficiency.

Keywords:
Rolling stock, maintenance, Industry 4.0 technologies, maturity level

Stellenbosch University https://scholar.sun.ac.za

Opsomming

Globalisering en die groei in wêreldpopulasie is verantwoordelik vir meer menslike mobiliteit. Dit lei daartoe dat nuwe mobiliteitsoplossings tot die mark toetree en gevolglik neem intermodale kompeterendheid toe. Dit impliseer dat tradisionele maniere van vervoer, soos spoor rollende bates, meer doeltreffend bestuur moet word om intermodale kompetisie te weerstaan. Om groter doeltreffendheid te behaal is veeleisend vir spooroperateurs. Hulle word uitgedaag deur die toenemende kompleksiteit en sekerheid van beskikbaarheid van passasier rollende bates, wat fokus plaas op instandhouding en opkomende tegnologieë. Om kompeterend en ekonomies lewensvatbaar te bly, moet spooroperateurs hul instandhoudingstrategieë optimiseer. Opkomende tegnologieë vorm die Industrie 4.0 omgewing and dra by tot prosesverbeteringe.

Hierdie navorsing stel ’n model voor vir spooroperateurs wat ondersteuning bied met hul besluite om Industrie 4.0 tegnologieë te implementer vir rollende bate instandhouding. Die model bestaan uit verskeie fases en neem die verskeie hoof megansiese stelsels van rollende bates, sowel as die geassosieerde toepaslike instandhoudingstrategie, in ag. Relevante kriteria word geïdentifiseer vir die seleksie van ’n geskikte instandhoudingstrategie vir die modelgebruiker se rollende bate sisteem. Bykomend word ’n aanpasbare seleksie van opkomende tegnologieë uitgevoer wat gebaseer is op die spooroperateur se tegnologiese volwassenheidsvlak. ’n Sistematiese literatuurstudie het aan die lig gebring wat die geskikte Industrie 4.0 tegnologieë is wat toepaslik is vir instandhoudingsprosesse. Die volwassenheidsvlak is afgelei van die vernaamste voorvereistes van die tegnologieë en is bepaal deur middel van ’n vraelys. ’n Ekonomiese oorweging van MPIs bepaal watter belegging lonend is, gebaseer op die huidige tegnologiese volwassenheidsvlak. Die model stel relevante aktiwiteite voor vir toekomstige navorsing wat beïnvloed word deur die bevindinge van ’n uitgevoerde aanlyn opname met vakdeskundiges. Hierdie werk dra gevolglik by tot die bevoegheid van spooroperateurs in besluitneming rakende Industrie 4.0 tegnologie integrasie en daarby versterk dit die doeltreffendheid van die instandhoudingsproses.

Sleutelwoorde:
Rollende bates, instandhouding, Industrie 4.0 tegnologie, volwassenheidsvlak

Stellenbosch University https://scholar.sun.ac.za

Acknowledgements

"Ever tried. Ever failed. No matter. Try again. Fail again. Fail better."
– Samuel Beckett (1906–1989)

First and foremost, I would like to thank everyone who assisted me to conduct and conclude this study during the last two years.

I would like to express my deep and sincere gratitude to my supervisors Dr. Wyhan Jooste and Prof. Dr. Dominik Lucke for providing invaluable guidance throughout the research. I extend my heartfelt thanks to Prof. Dr. Vera Humel and Prof. Dr. Daniel Palm who enabled the entire study programme.

I am extremely grateful to my family for their love, caring and sacrifices for educating and enabling this path for me. Without your exceptional support, I would never have been given this opportunity.

I also express my thanks to my fellow students for the countless discussions, inspirational conversations and wonderful times which we have shared.

The Author
November 2020

Stellenbosch University https://scholar.sun.ac.za

Contents

Declaration ii

Abstract iii

Opsomming iv

Acknowledgements v

List of Figures x

List of Tables xiii

List of Acronyms xv

1 Introduction 1

1.1 Theoretical Background 1
1.2 Problem Statement and Research Questions 5
1.3 Research Objectives 5
1.4 Research Design and Methodology 6
1.5 Delimitations and Limitations 7
1.6 Thesis Outline 8
1.7 Chapter Summary 9

2 Literature Review 10

2.1 Introduction of the Methodology 11
2.2 Rolling Stock 11
2.2.1 Railways in the Transport Sector 12
2.2.2 Classification of Rolling Stock 13
2.2.3 Rolling Stock Systems 16
2.2.4 Summary of Rolling Stock 27
2.3 Maintenance 27
2.3.1 Definition of Maintenance 28
2.3.2 Maintenance Measures 28
2.3.3 Maintenance Strategies 29
2.3.4 Performance Management 35

Stellenbosch University https://scholar.sun.ac.za

2.3.5 Maintenance in Rolling Stock 37
2.3.6 Summary of Maintenance 39
2.4 Industry 4.0 Technologies Application in Maintenance 40
2.4.1 Systematic Literature Review Approach 40
2.4.2 Bibliometric Results 42
2.4.3 Identified Industry 4.0 Technologies Application in Maintenance . . 44
2.4.4 Benefits Implementing Industry 4.0 Technologies in Maintenance . . 53
2.4.5 Summary of Industry 4.0 Technologies 54
2.5 Technological Maturity 54
2.5.1 Maturity Models 55
2.5.2 Comparison of Maturity Models 55
2.5.3 Summary of Technological Maturity 57
2.6 Chapter Summary 57

3 Industry 4.0 Technology Maturity Assessment **58**
3.1 Survey Design 58
3.2 Survey Objectives 59
3.3 Survey Planning 59
3.4 Questionnaire Design 60
3.4.1 Part 1: Welcome Screen 60
3.4.2 Part 2: Digitalisation in the Rail Industry 60
3.4.3 Part 3: Implementation of Industry 4.0 Technologies in Maintenance 61
3.4.4 Part 4: Technological Maturity Level 61
3.4.5 Part 5: Demographic Data 62
3.5 Conducting the Survey 63
3.6 Survey Data Analysis 63
3.7 Survey Results 65
3.7.1 Results of Direct Data Analysis 66
3.7.2 Results of Indirect Data Analysis 71
3.8 Survey Results Discussion 78
3.9 Chapter Summary 81

4 Industry 4.0 Technology Implementation Model **82**
4.1 Model Concepts 82
4.2 Model Requirements 84
4.3 Model Structure 85
4.4 Phase 1: Selection of Maintenance Strategy for Rolling Stock Systems . . . 86
4.4.1 Model Elements 86
4.4.2 Multicriterion Classification 87
4.5 Phase 2: Selection of Industry 4.0 Technologies based on the Maturity Level 97
4.5.1 Model Elements 97

Stellenbosch University https://scholar.sun.ac.za

4.5.2 Prerequisite Categorisation . . . 98
4.6 Phase 3: Decision regarding Implementation . . . 101
4.6.1 Model Elements . . . 102
4.6.2 Decision Tree . . . 102
4.7 Phase 4: Future Programme . . . 105
4.7.1 Model Elements . . . 106
4.7.2 Roadmap . . . 106
4.8 Requirements Assessment . . . 109
4.9 Chapter Summary . . . 110

5 Validation of the Model **111**
5.1 Face Validation . . . 111
5.2 Validation Feedback . . . 113
5.3 Chapter Summary . . . 115

6 Conclusions and Recommendations **116**
6.1 Research Overview . . . 116
6.2 Summary of Research Results . . . 118
6.3 Contributions of the Research . . . 121
6.4 Concluding Remarks . . . 121
6.5 Limitations . . . 122
6.6 Recommendations and Future Research . . . 123
6.7 Chapter Summary . . . 124

References **125**

Appendices **138**

A Survey Data **139**
A.1 Research Ethics Committee Approval . . . 140
A.2 Letter of Electronic Consent . . . 143
A.3 Survey Questionnaire . . . 146
A.4 Survey Results Direct Analysis . . . 159
A.5 Survey Results Indirect Analysis – Region . . . 199
A.6 Survey Results Indirect Analysis – Maturity Level . . . 210

B Details of I4.0TIM **221**
B.1 Direct Insertion Method . . . 221
B.2 Overview of Degrees of Criticality . . . 223
B.3 Maturity Level Questionnaire . . . 224
B.4 Maturity Level Calculation . . . 226
B.5 Industry 4.0 Prerequisites . . . 227
B.6 Calculations for the Performance Indicators . . . 228

Stellenbosch University https://scholar.sun.ac.za

C Validation Data **229**

C.1 Validation Questionnaire 230

C.2 Questions and Feedback 231

Stellenbosch University https://scholar.sun.ac.za

List of Figures

1.1 Increase in means of transport in South Africa from 2003 to 2013 2
1.2 Comparison of useful lifespans 3
1.3 Research framework 6
1.4 Thesis roadmap 8

2.1 Overview of the research fields 10
2.2 Railways in the transport sector 12
2.3 Classification of railway vehicles 14
2.4 Subdivision of passenger standard gauge trains 15
2.5 Overview of the bogie and its components 17
2.6 Functional principle of a DC motor with a dropping resistor or chopper . . 19
2.7 Functional principle of a single–phase AC motor 19
2.8 Functional principle of a pulsating current motor 19
2.9 Functional principle of a three–phase motor 20
2.10 Types of brake systems for rail vehicles 21
2.11 Main components of a pantograph 22
2.12 Structure of a screw coupling 23
2.13 Coupling principle of a Willison and Janney coupling 24
2.14 Coupling principle of a Scharfenberg coupling 25
2.15 Principle structure of the entry system 26
2.16 Subdivision of maintenance 28
2.17 Maintenance tasks 29

Stellenbosch University https://scholar.sun.ac.za

2.18 Reference model of maintenance strategies 30
2.19 Systematic literature review process 42
2.20 Documents published per year 42
2.21 Documents source types 43
2.22 Field of industry application 43
2.23 Industry 4.0 technologies applied in maintenance 44
2.24 Structure of CPSs 50
2.25 Classification of AI algorithms 51

3.1 Overview of the technological maturity level calculation 64
3.2 Overview of the sources of acquisition 65
3.3 Overview of the survey response 66
3.4 Current status regarding digitalisation in the rail industry 66
3.5 Industry 4.0 enabling technologies of greatest importance in rolling stock maintenance 67
3.6 Benefits from emerging technologies in rolling stock maintenance 67
3.7 Current status in the rail industry regarding the implementation of Industry 4.0 enabling technologies in rolling stock maintenance 68
3.8 Challenges the rail industry face regarding Industry 4.0 technologies in rolling stock maintenance 68
3.9 Rolling stock systems where Industry 4.0 technologies are applied 69
3.10 Average percentage of employees working in the maintenance department in the rail industry 70
3.11 Regions where the participants gained experience 71
3.12 Current status regarding digitalisation in the rail industry according to the different regions 72
3.13 Industry 4.0 enabling technologies of greatest importance in rolling stock maintenance according to the different regions 72
3.14 Maintenance area for Industry 4.0 technology application according to the different regions 73

Stellenbosch University https://scholar.sun.ac.za

3.15 Benefits from emerging technologies in rolling stock maintenance according to the different regions . . . 73
3.16 Challenges the rail industry faces regarding Industry 4.0 technologies in rolling stock maintenance according to the different regions . . . 74
3.17 Rolling stock systems where Industry 4.0 technologies are applied according to the different regions . . . 74
3.18 Current status regarding digitalisation in the rail industry according to the different maturity levels . . . 75
3.19 Industry 4.0 enabling technologies of greatest importance in rolling stock maintenance according to the different maturity levels . . . 76
3.20 Maintenance area for Industry 4.0 technology application according to the different maturity levels . . . 76
3.21 Benefits from emerging technologies in rolling stock maintenance according to the different maturity levels . . . 77
3.22 Challenges the rail industry faces regarding Industry 4.0 technologies in rolling stock maintenance according to the different maturity levels . . . 77
3.23 Rolling stock systems where Industry 4.0 technologies are applied according to the different maturity levels . . . 78

4.1 Model classification . . . 83
4.2 I4.0TIM . . . 85
4.3 First phase of I4.0TIM . . . 86
4.4 Second phase of I4.0TIM . . . 97
4.5 Third phase of I4.0TIM . . . 101
4.6 Decision tree logic diagram for appropriate implementation . . . 103
4.7 Fourth phase of I4.0TIM . . . 106
4.8 Roadmap . . . 107
4.9 Fulfilment assessment of the general and practical model requirements . . . 110

5.1 Participants feedback about the relevance, applicability and logical description of the model . . . 115

Stellenbosch University https://scholar.sun.ac.za

List of Tables

1.1 Development of the modal split for passenger transport in Germany in the years 2013 to 2018 . . . 3

1.2 Summary of secondary research objectives . . . 6

2.1 Methodology of the literature review . . . 11

2.2 Inclusion and exclusion criteria . . . 41

2.3 Implementation benefits of Industry 4.0 technologies in maintenance . . . 53

2.4 Comparison of maturity models in the context of Industry 4.0 . . . 56

3.1 Enabling technologies and their main prerequisites . . . 62

3.2 Maturity level scale . . . 65

3.3 Sample size of the regions . . . 71

3.4 Sample size of the technological maturity levels . . . 71

3.5 Average technological maturity level per technology . . . 75

4.1 Overview of rolling stock systems . . . 87

4.2 Maintenance strategies organised according to their degree of development 87

4.3 Overview of the criticality criteria . . . 88

4.4 Weight assignment to the criteria . . . 91

4.5 Criterion c_1: Impact on health & safety . . . 92

4.6 Criterion c_2: Influence for rolling stock reliability . . . 92

4.7 Criterion c_3: Influence for rolling stock availability . . . 93

4.8 Criterion c_4: Impact on environment . . . 93

4.9 Criterion c_5: Maintenance costs . . . 93

Stellenbosch University https://scholar.sun.ac.za

4.10 Criterion c_6: Existence of alternative systems . . . 94
4.11 Criterion c_7: Impact for customers . . . 94
4.12 Criterion c_8: Failure frequency . . . 94
4.13 Criterion c_9: Impact for rail operation . . . 95
4.14 Maintenance strategy selection according to criticality index I_c . . . 96
4.15 Variety of Industry 4.0 technologies . . . 98
4.16 Overview of the characteristics . . . 98
4.17 Ordinal scale of categories and related weighting for each characteristic . . . 99
4.18 Overview of the calculation of the total weighting factor WF_t . . . 100
4.19 Total weighting factor WF_t assignment according to technological maturity level . . . 101
4.20 Expected challenges . . . 108
4.21 Maintenance areas for implementation . . . 108
4.22 Expected benefits . . . 109
4.23 Most promising emerging technologies . . . 109

B.1 Degrees of criticality of criterion c_i . . . 223
B.2 Maturity level scale . . . 226
B.3 Industry 4.0 technologies and their main prerequisites . . . 227

Stellenbosch University https://scholar.sun.ac.za

List of Acronyms

AC Alternating Current

AI Artificial Intelligence

ANN Artificial Neural Network

AR Augmented Reality

CBM Condition–based Maintenance

CMS Condition Monitoring System

CPS Cyber–physical System

DC Direct Current

DCU Door Control Unit

DIN German Institute for Standardisation

EBM Electron Beam Melting

EBO Railway Construction and Operating Regulations

ESBO Railway Construction and Operating Regulations for Narrow–gauge Railways

EU European Union

FDM Fused Deposition Modelling

GPS Global Positioning System

HVAC Heating, Ventilation and Air Conditioning

IoT Internet of Things

I4.0TIM Industry 4.0 Technology Implementation Model

LED Light–emitting Diode

LOM Laminated Object Modelling

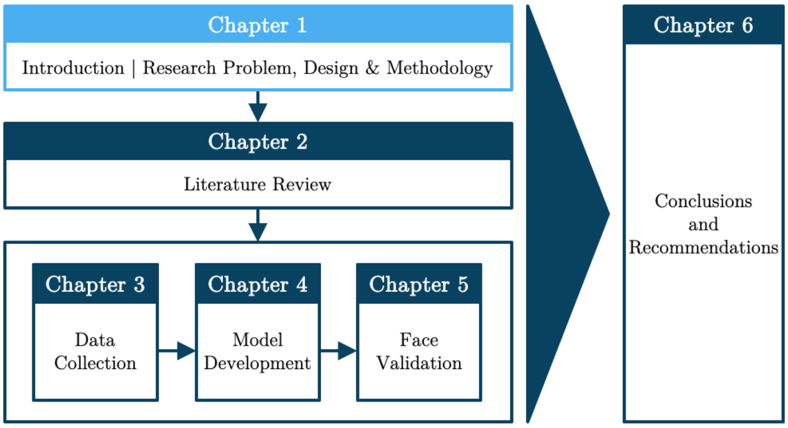
Stellenbosch University https://scholar.sun.ac.za

MPI	Maintenance Performance Indicator
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
OEM	Original Equipment Manufacturer
QC	Quality Criterion
RFID	Radio Frequency Identification
SLA	Stereolithography
SLS	Selective Laser Sintering
TBM	Time–based Maintenance
VR	Virtual Reality

Stellenbosch University https://scholar.sun.ac.za

Chapter 1

Introduction



The objective of this chapter is to delineate the background of this study. Information about international competition in the transport sector is provided and current maintenance strategies in the railway sector are discussed. Furthermore, the current challenges in the rail industry are underlined. These lead into the problem statement and consequently, the resulting research questions are stated. Next, the research objectives are defined and the research design and methodology of this thesis are explained. Finally, the delimitations and limitations are discussed and a brief overview of the thesis chapters is provided.

1.1 Theoretical Background

Today, numerous transport possibilities are available. Intermodal competition, in particular, makes it possible for almost all social classes to make use of this newfound mobility. Many innovative transport services have entered the market in recent years. Consequently, traditional transport modes are experiencing pressure from them. Examples include car–sharing, bike–sharing or E–scooters (Neumann and Krippendorf 2016, p. 77). The result is that the traditional transport sector needs to focus on improving the maintenance approaches of their fleet and network infrastructure (Roy et al. 2016, p. 669). This will

Stellenbosch University https://scholar.sun.ac.za

benefit not only passenger traffic, but freight traffic as well. Enhanced mobility promotes global trade and thus enables the global exchange of goods.

In the case of South Africa, public transport is experiencing an overall increase in usage. Statistics South Africa (2013, p. 96) states that there was an increase in usage in the metropolitan, urban and rural sector from 2003 to 2013 (Figure 1.1). Taxis, especially, experienced an enormous increase in the rural sector. Buses also showed an average increase in all areas. They are the nation's second most popular means of transport after taxis. In contrast to taxis and buses, the train sector did not record such strong growth. The urban and rural sector have each grown by only one percent from 2003 till 2013. This can be attributed to the poor infrastructure of the public rail industry as well as to the related service attributes (Statistics South Africa 2013, p. 96).

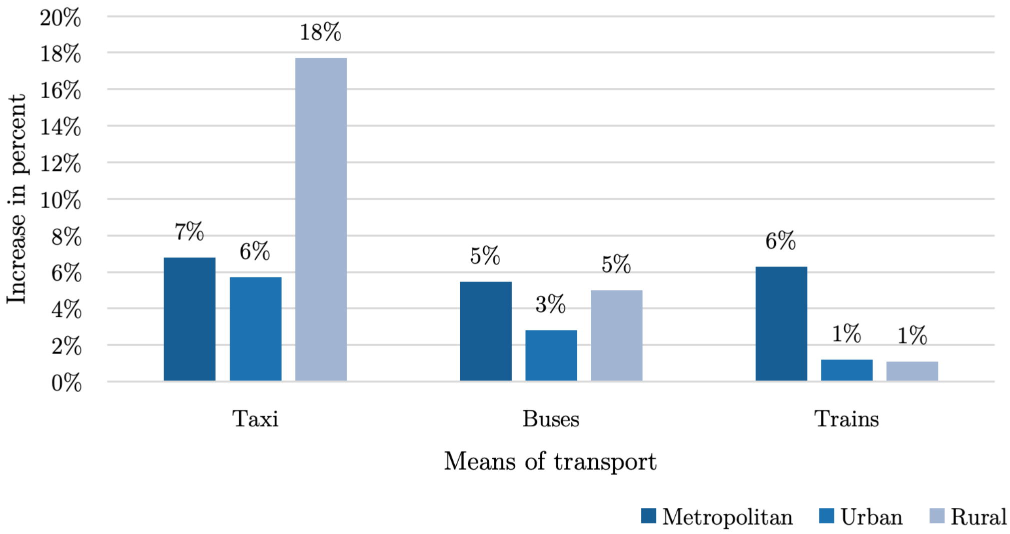


Figure 1.1: Increase in means of transport in South Africa from 2003 to 2013 (Statistics South Africa 2013, p. 96)

Relating to Germany, the development of the modal split in passenger transport demonstrates divergent trends as can be seen in Table 1.1. There, motorised private transport provides the majority of passenger transport at 79.1 percent in 2018. However, in this area figures declined compared with 2013. Contrary to this, an opposite trend is identified for rail passenger transport. There has been an increase of half a percentage point since 2013. The figures for public road passenger transport have remained almost the same. The different tendencies can, on the one hand, be attributed to growing awareness of environmental protection. On the other hand, the respondents indicated the comfort and speed factor as a plus for public transport (Statista 2019, p. 13).

Stellenbosch University https://scholar.sun.ac.za

Table 1.1: Development of the modal split for passenger transport in Germany in the years 2013 to 2018 (Statista 2019, p. 8)

Year	Motorised individual transport	Rail passenger transport	Public road passenger transport
2013	80.5 %	7.8 %	6.7 %
2014	80.4 %	7.8 %	6.8 %
2015	80.1 %	7.7 %	6.9 %
2016	80.1 %	7.8 %	6.7 %
2017	80.0 %	7.8 %	6.7 %
2018	79.1 %	8.3 %	6.7 %

The figures for South Africa and Germany indicate that motorised transport is the most popular means of transport. In comparing the means of transport there is asymmetry between the useful lifespan of road and rail. In contrast to automobiles, rolling stock has a useful life of from 25 up to 40 years. During this time span, for example, the VW Golf underwent six innovation cycles and the German high–speed train only one. As a result, trains must be functional, reliable and economical over a long period, compared to the other means of locomotion. This can only be achieved by efficient maintenance to ensure the functionality of the rolling stock (Lang et al. 2016, p. 5). A complete overhaul of the rail fleet is rarely done. The hardware components of a fleet only experience a complete overhaul approximately every 15 to 20 years (Verband der Bahnindustrie in Deutschland 2013, p. 2).

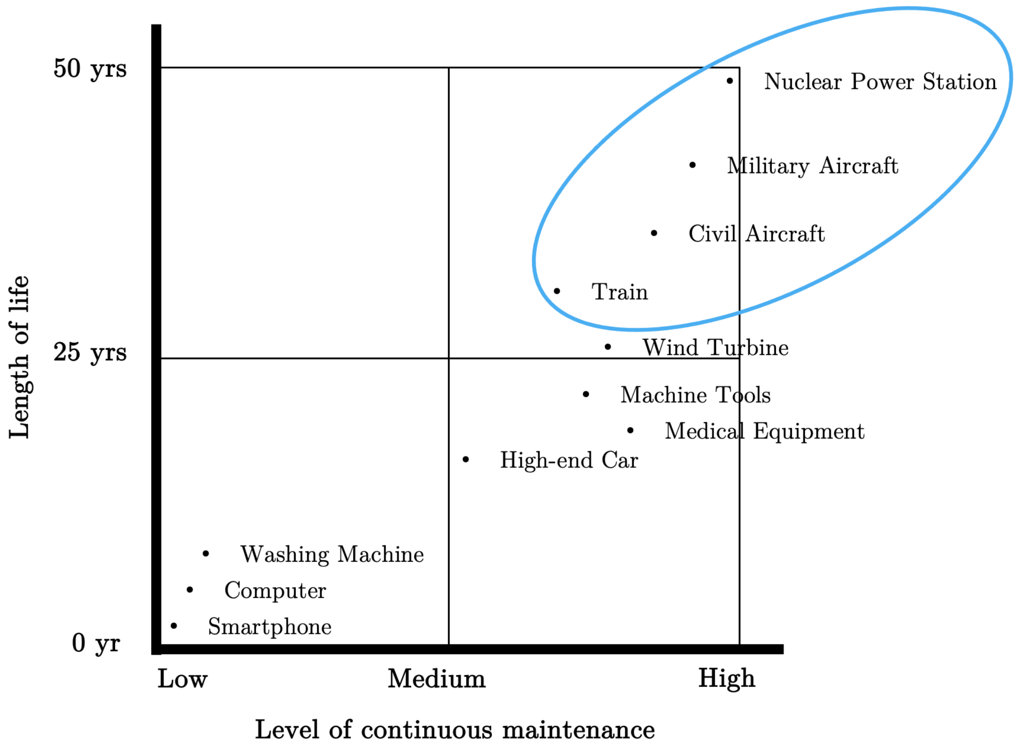


Figure 1.2: Comparison of useful lifespans according to Roy et al. (2016, p. 667)

Stellenbosch University https://scholar.sun.ac.za

Figure 1.2 shows the emphasis on maintenance for the rail industry. Trains are directly categorised under aircraft and nuclear power plants in relation to continuous maintenance. This fact underlines the relevance of maintenance due to the long useful life of trains.

Currently rail operators use predominately preventive maintenance strategies related to time or usage for strongly regulated components and components which can lead to malfunction of the train. Examples would be the pantograph, the axles or the doors. This approach is also used for highly visible quality components related, for instance, to the ventilation system. For all the other components reactive maintenance strategies are applied, which is a concern, since parts are only repaired after failure (Stern et al. 2017, p. 6). Accordingly, the question arises, why are these two strategies so dominantly applied? Stern et al. (2017, p. 6) state that a fleet's legacy equipment limits the current maintenance tactics. Illustrating it practically, this means that nowadays railway companies have to retain 13 percent of their fleet for substitution, in case of malfunction of active trains. It indicates that if there is an existing fleet of 46 trains, six of them are permanently retained as a backup (Pieriegud 2018, p. 32). Furthermore, rail operators have to deal with challenges such as operational and maintenance costs, operational efficiency, capacity and congestion, train availability, punctuality and reducing delays, and competition due to the current maintenance tactics which are applied (Nomad Digital 2015, p. 3).

The industry is well aware of these challenges and is actively trying to counteract. The importance of maintenance is well documented. Accordingly, growing employment figures are experienced in the rail industry to address the challenges. This is evident from an increase of 14 percent related to maintenance activities in Germany from 2009 to 2014 (Neumann and Krippendorf 2016, p. 17). To fully overcome these challenges, efficient and sustainable asset maintenance is required.

Industry 4.0 technologies can support the improvement of maintenance process efficiency. In the midst of fundamental changes brought about by Industry 4.0 technologies in maintenance, predominantly the aerospace, defence and nuclear industries are focusing on how to leverage these technologies. In the aerospace industry, Rolls–Royce is one of the organisations which is constantly trying to cut their service costs (Roy et al. 2016, p. 669). In contrast, the survey results by Nomad Digital (2015, pp. 3–4) reveal that one of the biggest challenges of the rail industry is to introduce new technologies. The rail industry indicates the necessity to identify suitable technologies for their processes as well as to reduce the dependency on obsolete systems as measures to overcome the challenge. These actions are required for the rail industry to improve their maintenance practices to a standard comparable with other industries.

Stellenbosch University https://scholar.sun.ac.za

1.2 Problem Statement and Research Questions

The key challenges and problems are identified in Section 1.1. In view of the fact that these challenges have to be overcome and that the levels of technological maturity determine the current maintenance strategies of rolling stock, the problem is that the rail industry is unaware of how to integrate Industry 4.0 technologies in the maintenance processes of rolling stock. Therefore, the rail operators have to deal with train availability issues along with inefficiency in operating their rolling stock.

To address the problem statement, the primary research question of this thesis is:

How can a model be developed for the implementation of Industry 4.0 technologies for rolling stock maintenance, taking into account the rail operator's technological maturity?

Five secondary research questions support the primary research question and need to be investigated:

1. Which maintenance strategies are applied for rolling stock?
2. Which Industry 4.0 technologies are generally possible to apply and suited for maintenance processes?
3. How can the potential benefits from implementing Industry 4.0 technologies be quantified?
4. How does a rail operator's technological maturity affect the implementation of Industry 4.0 technologies in maintenance?
5. How can the developed model be consolidated?

1.3 Research Objectives

The research objectives delineate why the research is carried out. In this thesis the primary research objective is stated as follows:

Development of a model which will support rail operators in their decision for implementing Industry 4.0 technologies in rolling stock maintenance

The primary research objective is addressed in Chapter 4. To achieve this research objective, secondary objectives are defined. Table 1.2 provides a summary of the secondary research objectives with an indication in which chapters they are realised.

Stellenbosch University https://scholar.sun.ac.za

Table 1.2: Summary of secondary research objectives

Seq	Research Objective	Chapter
1	Determine typical functional systems of rolling stock	2
2	Determine maintenance strategies for rolling stock	2
3	Gain an understanding of the technological maturity as well as an awareness of its measurement and indicators	2
4	Identify suitable Industry 4.0 technologies for maintenance processes	2
5	Determine the potential benefits of implementing Industry 4.0 technologies	2
6	Analyse the effects of the maturity level on the implementation of Industry 4.0 technologies in maintenance	3
7	Quantify the determined benefits from implementing Industry 4.0 technologies	3
8	Validate the developed model with subject matter experts	5
9	Draw conclusions and make recommendations regarding the developed model	6

1.4 Research Design and Methodology

In daily life, we are constantly trying to find solutions to problems. Creswell (2012, p. 3) points out that a close connection to research exists here. In principle, research always starts with posing a question, followed by collecting data to answer the question and then forming the answer to the question. For the research context, Creswell and Creswell (2018, p. 43) introduce a research framework which consists of three elements (Figure 1.3) that a researcher needs to consider.

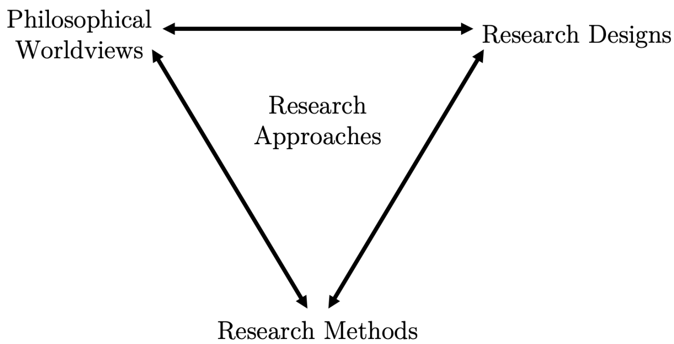


Figure 1.3: Research framework according to Creswell and Creswell (2018, p. 43)

Philosophical worldviews reflect the convictions of the researcher, which influence the way research is conducted. This study follows a pragmatic worldview. Pragmatism concentrates on applications and problem solutions. According to Creswell and Creswell (2018, p. 48) pragmatism results from actions, situations and consequences. The pragmatic worldview does not follow a particular monochrome approach but uses all possible methods to find a solution, which explains why it pursues a mixed method approach. The

Stellenbosch University https://scholar.sun.ac.za

purpose of selecting a research design is to identify the particular type of study and determine or select an appropriate strategy of inquiry that will provide specific guidance for procedures in the study. In principle there are three different types, which can be distinguished into qualitative, quantitative and mixed methods approaches (Creswell and Creswell 2018, p. 49). As already mentioned, a mixed method approach is applied in this study. The third element of the framework is about the specific research method which includes the form of data collection, analysis and interpretation (Creswell and Creswell 2018, p. 53). In this respect, four main parts of this study need to be distinguished. In the first part, a qualitative literature review is carried out to collect and analyse data to establish a foundation in rolling stock, maintenance and maturity categorisations. The literature review addresses the first three research objectives, covering the typical rolling stock systems, applied maintenance strategies and maturity models. In addition, a special form of literature research is applied in terms of systematic literature research, which addresses objectives four and five. Complementary to the literature review, a survey is conducted with rolling stock maintenance experts to quantify the benefits of implementing Industry 4.0 technologies and analyse the effects of maturity in the rail industry. In the second part of the study, the development of the model is addressed and related to the primary research objective of the study. Through the content analysis of the literature review and the results of the survey, the model is developed by synthesising the findings of both processes into the model. The third part of the study represents the validation of the model. The validation is performed to check whether the model is a practical solution for the rail industry to implement Industry 4.0 technologies in the maintenance processes. To achieve this, a face validation is carried out with subject matter experts. The final part of the study closes up by drawing conclusions and making recommendations for future research.

1.5 Delimitations and Limitations

Boundaries need to be established to limit the scope of the research. In this research study the following delimitations are defined:

- This thesis focuses on electrified rolling stock for passenger transport.
- This thesis focuses on mechanical components and systems for rolling stock.
- This thesis is bound to Industry 4.0 technologies for maintenance processes and not any other processes.

This study is limited in time for both conducting the survey as well as for interviewing subject matter experts for the face validation. Therefore, the delimitations and limitations of this research are set.

Stellenbosch University https://scholar.sun.ac.za

1.6 Thesis Outline

The thesis outline provides a brief overview of the chapters in this thesis. Each chapter provides a structural construct. Figure 1.4 illustrates the roadmap and chapter sequence of the thesis. The following paragraphs serve as a synopsis of each chapter.

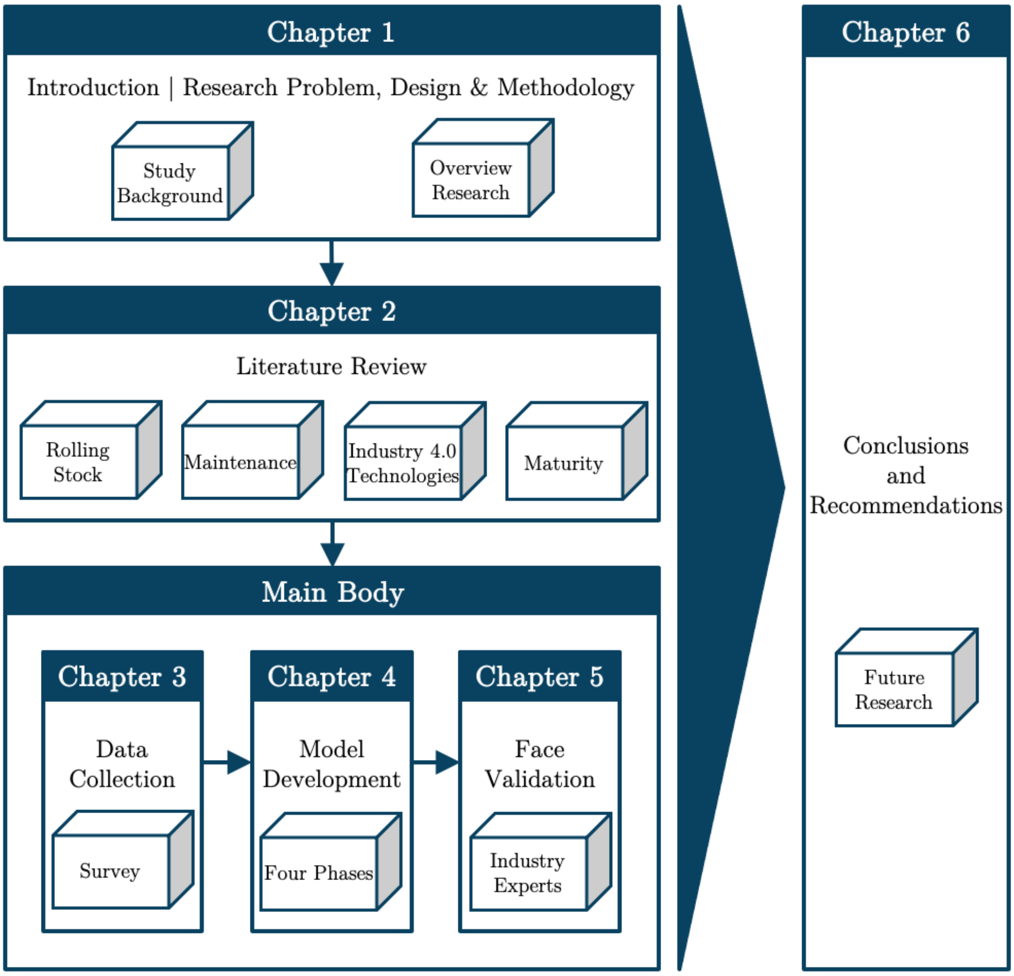


Figure 1.4: Thesis roadmap

Chapter 1: Introduction

Chapter 1 gives a general introduction to the topic. First, the background is discussed, which leads to the problem definition. Continuing with the resulting research questions and research objectives, the research design and methodology are set. Next, the relevant delimitations and limitations of this thesis are discussed and the chapter concludes with a thesis outline.

Chapter 2: Literature Review

The basis of this thesis is established in Chapter 2 by a literature review. The literature review covers the main mechanical systems of rolling stock, the maintenance strategies

Stellenbosch University https://scholar.sun.ac.za

and an analysis of maturity models. The analysis of Industry 4.0 technologies in the maintenance sector is aided by a systematic literature review.

Chapter 3: Data Collection
Chapter 3 presents the approach for the data collection by using a survey. First, an introduction to the survey is provided. The approach entails the structure of the survey and the design of the questions. The survey results are evaluated and conclusions are drawn from the results.

Chapter 4: Model Development
Chapter 4 proposes a solution in the form of a model of the stated problem. The model is divided into four different phases, which are all explained in detail.

Chapter 5: Face Validation
Chapter 5 concentrates on the validation of the proposed model. Subject matter experts participated in the face validation of the model. The results of the validations are presented.

Chapter 6: Conclusions and Recommendations
The last chapter reflects on the research which has been done and the contributions are highlighted. In addition, the designed model is considered critically. Chapter 6 concludes with the recommendations for future research.

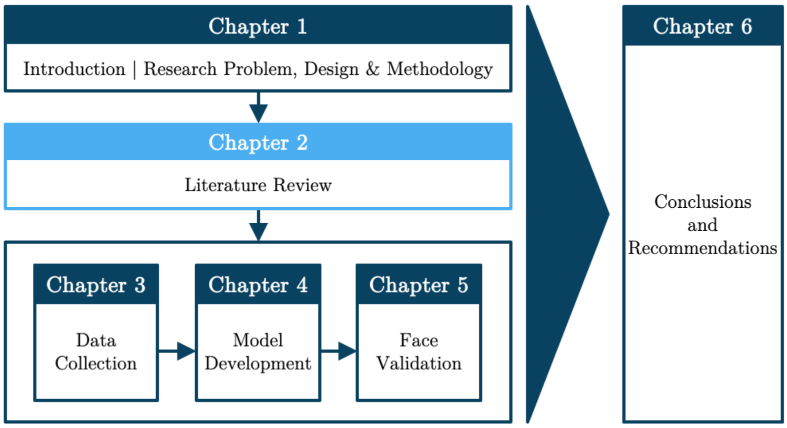
1.7 Chapter Summary

In this chapter the theoretical background of this study is introduced and the research problem is stated. In accordance with the research problem, the research questions are derived as well as the corresponding research objectives. The research design and methodology for this study is based on the pragmatic worldview and a mixed method approach. In conclusion, the thesis outline is covered, where the thesis roadmap is delineated.

Stellenbosch University https://scholar.sun.ac.za

Chapter 2

Literature Review



Literature reviews are ubiquitous in academic papers (Booth et al. 2016, p. 12). According to Snyder (2019, p. 333) a literature review is the key element for all scientific investigations. The central rationale for conducting a literature review is to indicate the awareness of current studies in the research field (Fink 2014, p. 5). They are used to summarise current research findings for a specific subject area. Furthermore, the literature review should fulfil premises regarding objectivity as well as a broad perspective including discrepant data (Winchester and Salji 2016, p. 308). Snyder (2019, p. 333) agrees and adds that it is a valuable method to show evidence on a higher level and to expose research gaps.

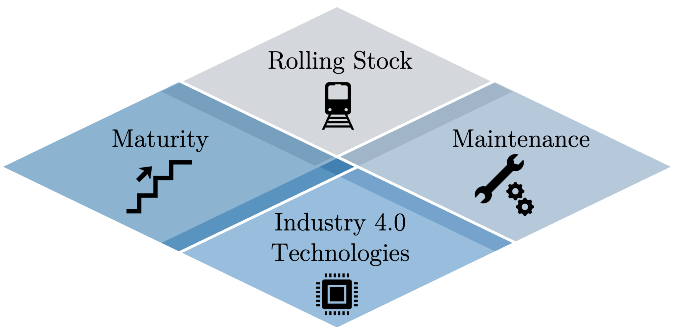


Figure 2.1: Overview of the research fields

Stellenbosch University https://scholar.sun.ac.za

In Figure 2.1 the four main research fields for this study are illustrated. The objective of the literature review is to get an understanding as well as an awareness of the current research in these fields. In particular, the connection between rolling stock maintenance and the application of Industry 4.0 technologies in maintenance is investigated, taking the degree of maturity into account.

2.1 Introduction of the Methodology

The following literature review is based on the methodology of Winchester and Salji (2016). This method divides the review into six different stages (Table 2.1). During the first stage, the research topic is defined. With regard to this study, the four main topics; namely, rolling stock, maintenance, Industry 4.0 technologies and maturity are applicable. The keywords and synonyms are then determined for the individual topics. Next, these terms are used to analyse the databases to identify the areas of interest. Subsequently, the data is assessed and extracted during the systematisation and evaluation step. Finally, the analysed literature is summarised and recorded in the following sections.

Table 2.1: Methodology of the literature review according to Winchester and Salji (2016, p. 310)

Stages	**Explanation**
Research topic	Implementation of Industry 4.0 technologies in rolling stock maintenance taking the maturity level of rail operators into account.
Keywords and search terms	Rolling stock, train, rail vehicle, railway Maintenance, asset management Industry 4.0, Industry 4.0 technologies, emerging technologies Maturity, readiness
Source of information	Scopus, Web of Science, Springer, Google Scholar
Collection of documents	The information is collected from 19 books, 62 papers and five norms.
Systematisation and evaluation	Extracted information is assessed and compared concerning keywords and topics .
Documentation of literature review	The analysed literature is summarised and written down.

2.2 Rolling Stock

Different expressions exist and are in general usage for rolling stock such as train, rail, or railway. As stated by the German Institute for Standardisation (DIN) 25003 the term rolling stock or rail vehicle refers to “track bound vehicles which are guided and borne

Stellenbosch University https://scholar.sun.ac.za

by means of flanged wheels on tracks formed of rails with a specific constant gauge" (Deutsches Institut für Normung e. V. 2011a, p. 4). Janicki et al. (2020, p. 17) simplify the definition and state that rolling stock refers to railway vehicles running on two parallel tracks with flanged wheels which carry both: goods and passengers. Besides railways, rail–guided railways also include similar vehicles such as tramways or underground railways (Deutsches Institut für Normung e. V. 2011a, p. 4). Key characteristics of rail vehicles are track adhesion as well as low friction between wheel and rail (Janicki et al. 2020, p. 17). Rail vehicles operate in the sophisticated system of rail transport and consist of highly complex systems and the subsystems themselves (Hecht 2014, p. 11). They constitute an integral part of the transport infrastructure for land transport systems.

2.2.1 Railways in the Transport Sector

Nowadays, there are many different modes of transport. Hence, it is essential to understand where rolling stock is classified. Intermodal competition is about the competition between the different air, land and water transport methods, carrying either people or goods (Figure 2.2). The land–based methods are subdivided into road and rail.

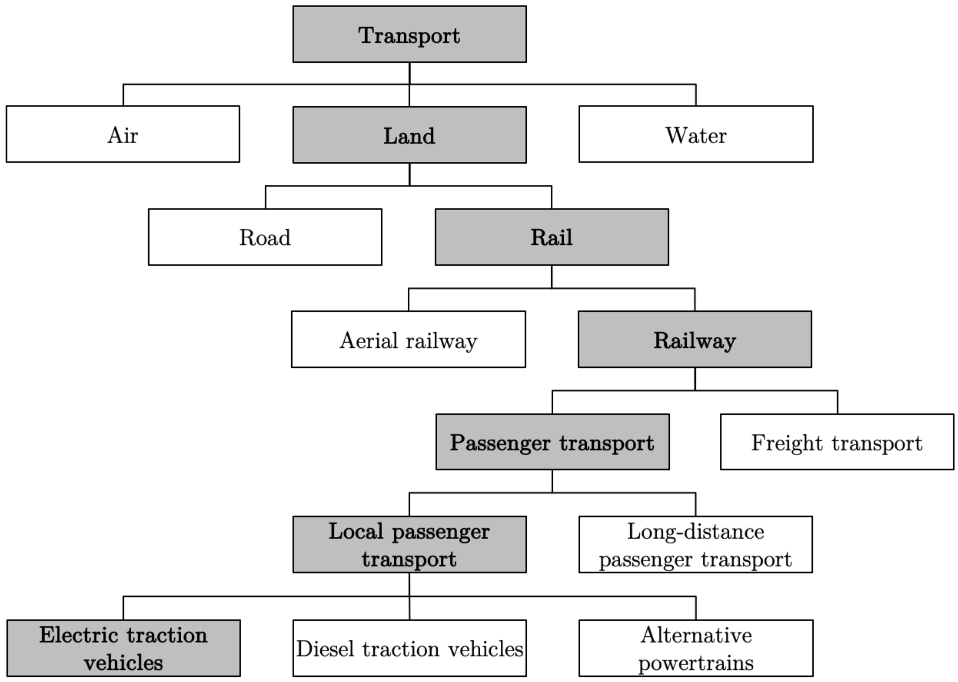


Figure 2.2: Railways in the transport sector according to Dellmann (2014, p. 15), Filipović (2015, p. 5), Allianz pro Schiene e. V. (2018) and Janicki et al. (2020, p. 18)

Rolling stock is further categorised under rail, which can be split into passenger and freight transport. On the passenger transport side both local and long–distance passenger transport exist. Regarding the mode of transportation for local passenger transport, there are different types of drive technologies, where the traditional ones are electrical or with

Stellenbosch University https://scholar.sun.ac.za

fuel. The emphasis in this study is on electric traction rail vehicles. Today, three–quarters of passenger rolling stock is electrified. Therefore, electrified rail vehicles contribute to improving the environmental impact of transport, as rail transport accounts for only two percent of the world's transport energy demand (International Energy Agency 2019). The environmental friendliness is justified because modern electrified vehicles are able to recoup a large part of the energy used by feeding it back into the rail network. In other words, the energy recovered from braking energy is fed back into the rail network and can be reused (Bundesnetzagentur 2017, p. 36).

2.2.2 Classification of Rolling Stock

The German regulations Railway Construction and Operating Regulations (EBO) and Railway Construction and Operating Regulations for Narrow–gauge Railways (ESBO) regulate the construction of rail vehicles and the operational management of the railway system. They divide rail vehicles according their purpose into either standard or special vehicles (Figure 2.3). In other countries, special vehicles are also classified as operational, service or auxiliary vehicles. Standard vehicles are vehicles necessary for the regular operation of a railway. Under certain restrictions such as speed or payload, they can operate freely in rail operations. In contrast, special vehicles are deployed for special tasks related to railways. They are frequently used for maintenance and repair of rail systems and operate with or without traction drive (Janicki et al. 2020, p. 25).

A further subdivision of standard vehicles is specified in DIN 25003, which also refers to the regulations EBO and ESBO. They can be categorised into traction units and wagons (Deutsches Institut für Normung e. V. 2011a, p. 2). Traction units are primarily used for hauling trains or run individually as a train. Thus, they are equipped with their own traction drive (Janicki et al. 2020, p. 29). The form of propulsion can vary. Traditional drive technologies are electrical or with fuel. Electrically powered vehicles are supplied with energy via catenary systems (Janicki et al. 2020, p. 26). In contrast, internal combustion vehicles are usually equipped with a diesel engine. Meanwhile, according to Allianz pro Schiene e. V. (2018) innovative drive systems such as hydrogen fuel cells or hybrid solutions are also in existence.

In the definition of DIN 25003, traction units can ultimately be divided into locomotives, power cars and motor coaches (Deutsches Institut für Normung e. V. 2011a, p. 2). In comparison to a powered car, a locomotive can be uncoupled from a train and operated independently of it. A powered car forms the head or the end of a multiple unit. Multiple units and motor coaches are powered vehicles for the transport of payload. The difference between the two lies in the ability of the motor coach which can be used as a single vehicle that runs independently as a train. The composition of a multiple unit can only be changed in the workshop. On the wagon side, it is noticeable that they do not have

Stellenbosch University https://scholar.sun.ac.za

their own traction drive and are thereby non–powered vehicles. On the one hand, there are passenger coaches in passenger transport which are used to transport people and their goods. In freight traffic, the transport of cargo is executed by freight wagons. They can have different shapes depending on the type of cargo. For instance they may be open or closed, high or low, single or multilevel. Special types of wagons also exist which assist in internal railway work (Janicki et al. 2020, pp. 27–31).

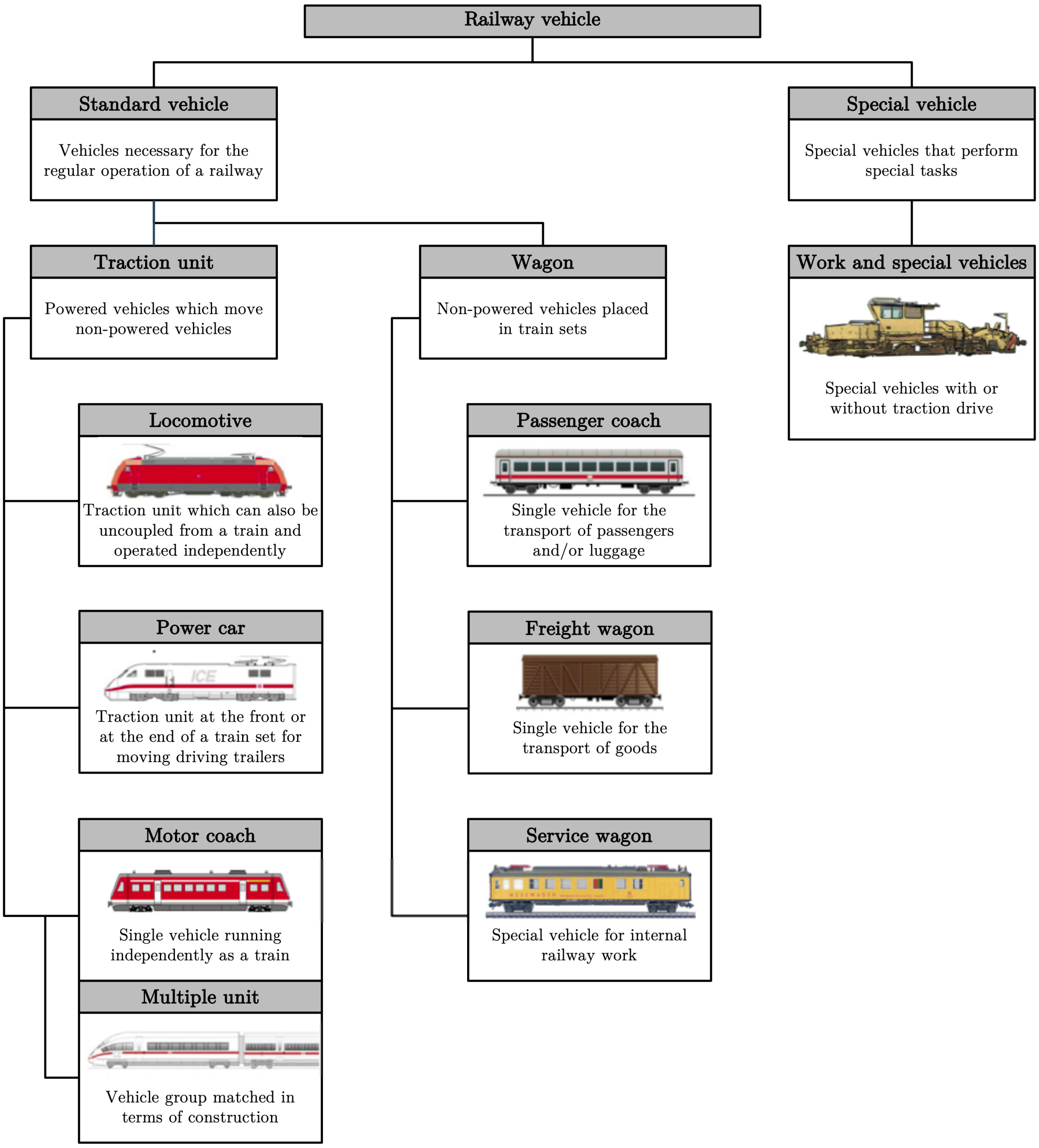


Figure 2.3: Classification of railway vehicles according to Deutsches Institut für Normung e. V. (2011a, p. 2) and Janicki et al. (2020, p. 28)

DIN 25003 gives an overview of how rail vehicles can be classified. However, it does not provide further specific information on the operational use of rail vehicles. More detailed insight is provided about the passenger transport rolling stock and its operation area.

Stellenbosch University https://scholar.sun.ac.za

A distinction can be drawn between standard gauge trains and local public transport vehicles. Local transport vehicles are mainly used in cities. These include, for example, tramways, light rails or undergrounds. Standard gauge trains can be divided into four different groups based on a variety of indicators (Figure 2.4).

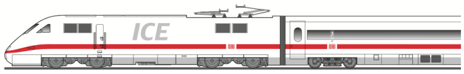
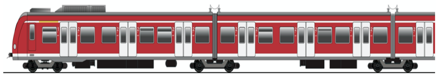
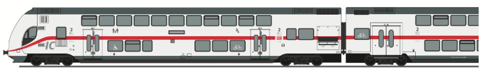
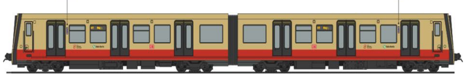
Long–distance	Short distance
High-speed train Average travel speed: 120 – 220 km/h Distance between stops: 50 – 100 km Standard gauge: 1435 mm 	**Commuter train** Average travel speed: 40 – 80 km/h Distance between stops: 2 – 10 km Standard gauge: 1435 mm 
Long-distance train Average travel speed: 100 – 150 km/h Distance between stops: 20 – 50 km Standard gauge: 1435 mm 	**Suburban train** Average travel speed: 40 – 60 km/h Distance between stops: 750 m – 3 km Standard gauge: 1435 mm 

Figure 2.4: Subdivision of passenger standard gauge trains according to Schindler (2014, p. 190)

Today's most advanced development in the long–distance transport of rolling stock is high–speed trains. Not only does the special technology play a role in high–speed trains, but it is also an interplay of infrastructure, rolling stock, operating conditions and cross–sectoral issues (Leboeuf 2018, p. 5). They frequently run on specially designed high–speed lines or on upgraded lines on which speeds of up to 360 km/h are possible in regular operation (Janicki et al. 2020, p. 50). Usually, high–speed trains are also compatible with the classical rail network, although speeds of only up to 220 km/h are reached here (Leboeuf 2018, p. 4). This is primarily because these networks are also used by other rolling stock. In long–distance passenger transport, long–distance trains also operate, whereby these run significantly slower and have a shorter stopping distance. Long–distance trains are usually characterised by being locomotive–hauled (Schindler 2014, pp. 190–191).

Commuter trains can also be locomotive–hauled. However, motor coaches are deployed for modern vehicles. The field of application for commuter trains is passenger transport between suburbs and the city centre as well as for reverse commuting (Zullig Jr and Phraner 2000, p. 5). They transport a large number of people every day, especially commuters, and therefore have more seats than rolling stock in long–distance transport (Gray 1989, p. 12). Another difference lies in their speed and stopping distance. They are significantly slower and their distance between stops is much shorter being from two to ten kilometres. The last category belonging to standard gauge trains is suburban trains which differ only slightly from the regional trains. This rolling stock category primarily connects the close–surrounding area with the cities.

Stellenbosch University https://scholar.sun.ac.za

2.2.3 Rolling Stock Systems

As explained in Section 2.2.2, rail vehicles are classified into different categories due to their wide variety. Nevertheless, rail vehicles have basic technical similarities despite the high variety. This study focuses on the main mechanical components and systems of passenger rolling stock. Especially the mechanical components and systems are in operation for the longest period of time and only receive a complete overhaul every 15 to 20 years (Verband der Bahnindustrie in Deutschland 2013, p. 2). Principally the components and systems can be divided into two categories: operational–relevant systems and systems for passenger rolling stock. The first–mentioned category is essential for the technical operation of rolling stock and thus forms the basic elements for rail operations. For the technical operation of rolling stock running gear, drive technology, brake unit, pantograph and traction and buffer gear are responsible. The interaction of all components enables the rail operation we know today. Without these components the operation of rolling stock would not be possible. For passenger comfort, the second category assumes a central role and entails an increasing complexity of systems. Over the years, not only the components necessary for operation have evolved, but also the equipment for passenger vehicles. Here, customer requirements have become increasingly crucial. For the commuter, not only is the safety of vehicles important, but also their comfort during the trip. In the past trains used to be equipped without sanitary facilities or Heating, Ventilation and Air Conditioning (HVAC), but today this is standard equipment for a passenger rail vehicle. The other systems in this group are the door system and indoor lighting system. In the following sections, all systems from both categories are examined in more detail for their technical characteristics.

2.2.3.1 Running Gear

For rail vehicles, the choice of the route is not made by the driver as it is with cars but is instead controlled from the signal box (Ihme 2016, p. 13). The guidance of the vehicles on the rail is undertaken by the running gear (Janicki et al. 2020, p. 34). Running gear serves as a generic term for all components which form the interface with the track (Janicki et al. 2020, p. 118). According to Kwasnicki (2014, p. 350) running gear must fulfil three primary functions. For the absorption of various forces during operation it must fulfil a supporting function. Furthermore, it is responsible for the track guidance, meaning that the vehicle is guided laterally in the rail. For driving and braking, the running gear must transmit forces to fulfil these two functions. The basic structure of the running gear forms the chassis frame, where all the different assemblies are connected and placed (Kwasnicki 2014, p. 359). Essentially, a distinction can be made between single–axle running gear and bogies running gear. A special feature is the Jacobs bogie, where the ends of two bodies rest on one bogie (Kwasnicki 2014, pp. 357–358; Janicki et al. 2020, p. 122). Bogie vehicles are very common because they achieve good running behaviour on curves even with long

Stellenbosch University https://scholar.sun.ac.za

vehicles due to the short wheelset distances in the bogie frame (Ihme 2016, p. 179). It is called a bogie (Figure 2.5) once a running gear is equipped with two or more wheelsets mounted in a frame which can rotate about a pivot point concerning the vehicle body (Janicki et al. 2020, p. 130). As stated by Kwasnicki (2014, p. 353) and Janicki et al. (2020, p. 130), there is a difference between motor bogies, where all axles are powered and carrying bogies, which are non–powered. The bogie frame of non–powered vehicles is connected to the pivot point in the body via the centre plate. The body is supported laterally by sliding surfaces mounted under the body, which rest on sprung or unsprung slides of the bogie. Some types are equipped with a cradle to absorb vibrations between the bogie and car body. This ensures smooth running behaviour (Janicki et al. 2020, p. 131). The bogie suspension also contributes to smooth running. Rails, like roads, also have unevenness, so rail vehicles must be sprung for a pleasant drive comfort (Ihme 2016, p. 141). If the suspension is between the wheelset and the bogie, it is referred to as primary suspension. It is called a secondary suspension if it acts between the bogie frame and the vehicle body. Thus, it is especially responsible for driving comfort. Air suspension systems offer a particularly high level of ride comfort. This is why they are applied as a secondary suspension in more recent passenger coaches as well as motor coaches. Alternatively, coil springs are installed. These are also used for the primary suspension as well as other springs such as leaf springs, parabolic springs or rubber springs (Janicki et al. 2020, pp. 134–135). Moreover, hydraulic vibration dampers are mounted parallel to the springs to reduce vibrations, as the spring elements have only minimal inherent damping (Janicki et al. 2020, p. 139).

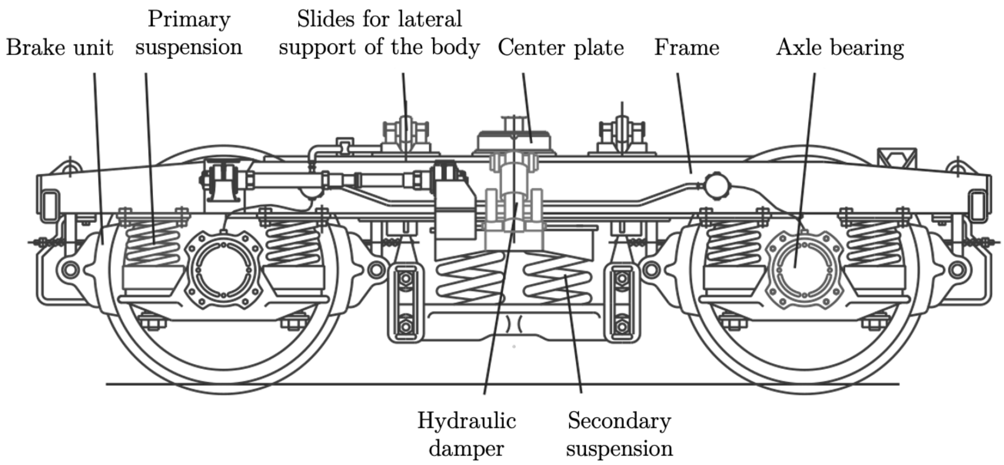


Figure 2.5: Overview of the bogie and its components (figure extracted from Wikipedia (2015))

The wheelset guidance is responsible for functionally reliable guidance of the wheelsets. In the case of bogies, the wheelset guidance connects the wheelset to the bogie frame via the bearing housing (Janicki et al. 2020, p. 138). The connection between vehicle and rail is provided by the wheelset. Components of the wheelset are the wheelset axle, the two wheels and their bearings. Depending on the wheelset type, the brake discs or

Stellenbosch University https://scholar.sun.ac.za

drive elements can also be attached to the wheelset axle (Janicki et al. 2020, p. 123). The wheelset axles transfer the load of the rolling stock via the wheels to the rails. The wheelset is mounted on the bogie with wheelset bearings. Hence, they form the transition between the stationary and rotating components. Today, rolling bearings are commonly preferred for this purpose (Janicki et al. 2020, p. 129). For the wheels, there are two different types of construction. For wheels with wheel tyres, the wheel tyre is connected to the wheel rim by a frictional connection. In contrast, the wheel disc and tread of a monobloc wheel are made of one piece (Janicki et al. 2020, p. 127). Monobloc wheels are predominantly utilised in modern vehicles (Kwasnicki 2014, p. 363).

2.2.3.2 Drive Technology

As already mentioned in Section 2.2.2 different drive technologies exist. In modern rolling stock, the electric drive prevails. In electrified lines, the required traction power is supplied from the outside by the contact wire, as is common practice today, or by the conductor rail (Karch 2014, p. 378). Historically, Direct Current (DC) systems with 1.5 kV and 3 kV as well as single–phase Alternating Current (AC) systems with 15 kV (16 2/3 Hz) and 25 kV (50 Hz) were established in Europe (Filipović 2015, p. 193; Ihme 2016, p. 60; Janicki et al. 2020, p. 199). In contrast, rail vehicles in South Africa are operated at 3 kV, 25 kV or 50 kV grids (Frey 2012, p. 9). To transform the supplied electrical energy into kinetic energy, the pantograph (Section 2.2.3.4) supplies the traction unit with the required electrical energy. Transformers ensure that the voltage is transformed down to the lower voltage which is required for the traction motors (Janicki et al. 2020, p. 200). According to Filipović (2015, p. 59) and Janicki et al. (2020, pp. 213–214) the following traction motors are used for electric traction units:

- *DC motor*: Supply with pure DC
- *Single–phase AC motor*: Supply with single–phase AC
- *Pulsating current motor*: Supply with DC with harmonics
- *Three–phase motor*: Supply with AC

DC motors (Figure 2.6) are mainly installed in older rolling stock. This is due to the high susceptibility and wear, since the energy transfer from the stator to the rotor is realised by carbon brushes (Janicki et al. 2020, p. 213). DC motors are controlled by dropping resistors or a chopper (Ihme 2016, p. 63). Thus, a high resistance value implies a low voltage at the drive and low revolutions, which are needed for starting. A contrary effect is obtained by a low resistance value, whereby the cruising speed is reached. The benefit of a chopper compared to dropping resistors is the higher efficiency. The chopper “chops” the input voltage to achieve a lower clamping voltage on the motor (Janicki et al. 2020, pp. 208–209).

Stellenbosch University https://scholar.sun.ac.za

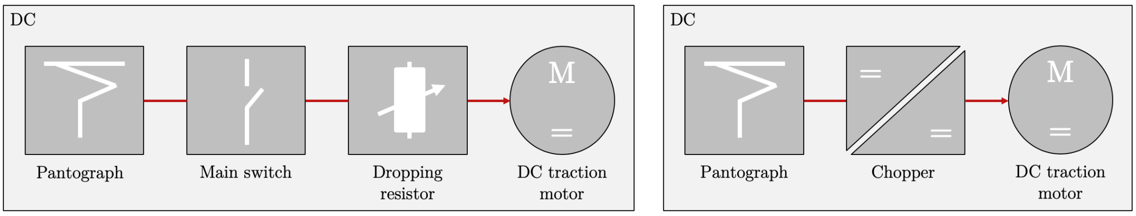


Figure 2.6: Functional principle of a DC motor with a dropping resistor or chopper (Janicki et al. 2020, pp. 209–210)

Likewise, the single–phase AC motor is predominantly utilised in older rail vehicles. Janicki et al. (2020, p. 213) justify this because of the high maintenance effort as well as the high space requirements and weight. The single–phase AC motor is equipped with transformers upstream of the motor (Figure 2.7). The catenary current flows via the pantograph and main switch to the transformer. There, various voltages can be transmitted to the traction motor using the low voltage windings. Thus, the speed is controlled by changing the applied voltage (Janicki et al. 2020, p. 208).

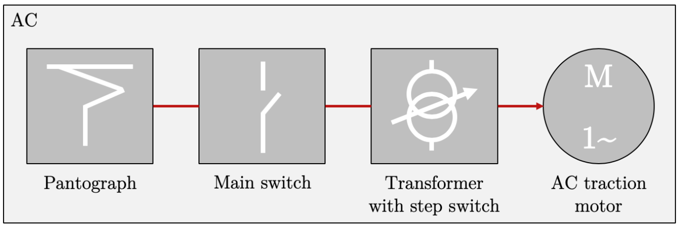


Figure 2.7: Functional principle of a single–phase AC motor (Janicki et al. 2020, p. 209)

Simple power electronics are used for a pulsating current motor. Here, AC from the catenary is converted into DC either by a transformer or a converter. Consequently, the total voltage consists of the superposition of DC and AC. The functional principle of the motor is illustrated in Figure 2.8.

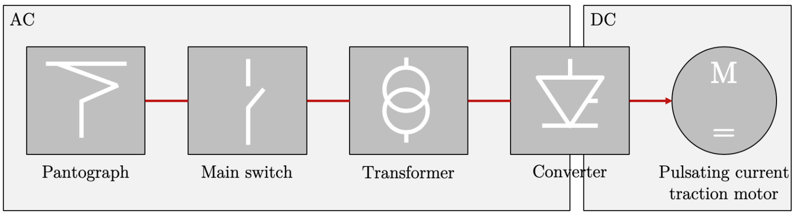


Figure 2.8: Functional principle of a pulsating current motor (Janicki et al. 2020, p. 209)

All new traction units are equipped today with a three–phase motor as a standard traction motor. This motor offers particular advantages due to its robustness, higher power density and low maintenance, as the carbon brushes are omitted (Gratzfeld 2014, p. 389; Janicki et al. 2020, p. 210). Power electronics are used to convert the catenary voltage into the required traction motor voltage. A combination of an H–bridge and pulse inverter is used for this purpose. The H–bridge converts the single–phase AC voltage of the catenary received from the transformer into a DC voltage and passes it on to the pulse inverter

Stellenbosch University https://scholar.sun.ac.za

(Figure 2.9). Capacitors are used as intermediate energy storage devices to balance the power supply and demand. Afterwards, the pulse inverter generates a three–phase output voltage with variable frequency and voltage for the traction motor (Janicki et al. 2020, pp. 210–214) .

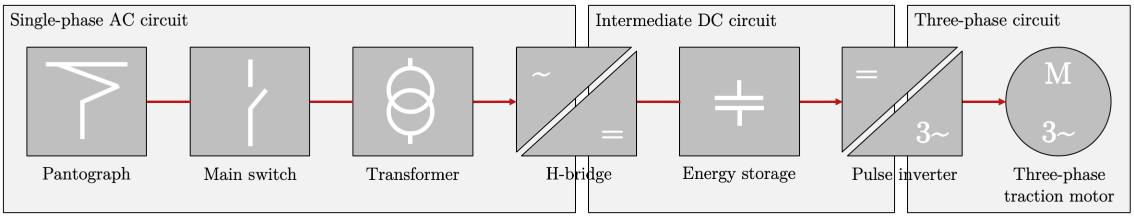


Figure 2.9: Functional principle of a three–phase motor (Janicki et al. 2020, p. 212)

2.2.3.3 Brake Unit

As well as acceleration, braking is also a major challenge for railway technology. The braking unit has to fulfil some main tasks in this context. It must be possible to reduce the speed of rolling stock so that they can come to a standstill if necessary. They must also be able to provide drag braking, for example, to keep the speed constant on a slope. A restraining function must be available if rolling stock is to be secured against unintentional movement for a limited or unlimited period of time (Gfatter et al. 2007, p. 16). Furthermore, Deutsches Institut für Normung e. V. (2019a, pp. 14–15) mentions consistency, self–activity and inexhaustibility as functions which braking systems must always fulfil. Consistency indicates that all vehicles in a train set are connected to the braking system so that each local braking unit generates a braking force. It is also essential that the brake can be operated from a central location on the rail vehicle or, in the case of passenger rolling stock, that it can be triggered via the emergency braking system. Self–activity ensures that rolling stock stops if the brake line is inadvertently interrupted. The inexhaustibility guarantees that sufficient braking power is available for repeated brake and release processes.

There are different types of brake systems, which are illustrated in Figure 2.10. Brake systems can be divided into adhesion dependent and adhesion independent brake systems. In the case of adhesion dependent brakes, the brake forces are transmitted to the contact points between the wheels and rails. The opposite principle applies to adhesion independent brake systems, as the brake force acts directly on the rail against the direction of travel (Janicki et al. 2020, p. 355). Friction brakes, as well as dynamic brakes, belong to the adhesion dependent brakes. They offer the highest level of safety for braking systems in rail vehicles (Berger 2014, p. 421). Three different types of friction brakes can be distinguished. Block brakes transmit the braking force directly to the treads of the wheels by using brake pads, whereas disc brakes transmit the braking force through brake shoes onto cast iron brake discs. For drum brakes, the brake force is transferred to the wheel

Stellenbosch University https://scholar.sun.ac.za

by brake drums which are mounted on the wheelset axle (Janicki et al. 2020, p. 355). As specified by Berger (2014, p. 421) and Janicki et al. (2020, p. 357) the control of friction brakes can be accomplished by dissimilar media. Above all, compressed air brakes have been established, where braking force is generated by compressed air in a brake cylinder. Electro–hydraulic brakes are predominantly installed in vehicles with limited space. As a working medium, hydraulic fluid is responsible for generating a much higher working pressure. The major advantage of dynamic brakes is that they are wear–free compared with the friction brakes. Therefore, dynamic brakes are often used in addition to mechanical friction brakes, since they achieve a high braking effect, especially at higher speeds. The electro–dynamic brake is installed in electrically powered vehicles. Here, the traction motors are switched over to generators during the braking process. On the other hand, a hydro–dynamic brake is utilised in traction units with internal combustion engines (Janicki et al. 2020, pp. 355–357).

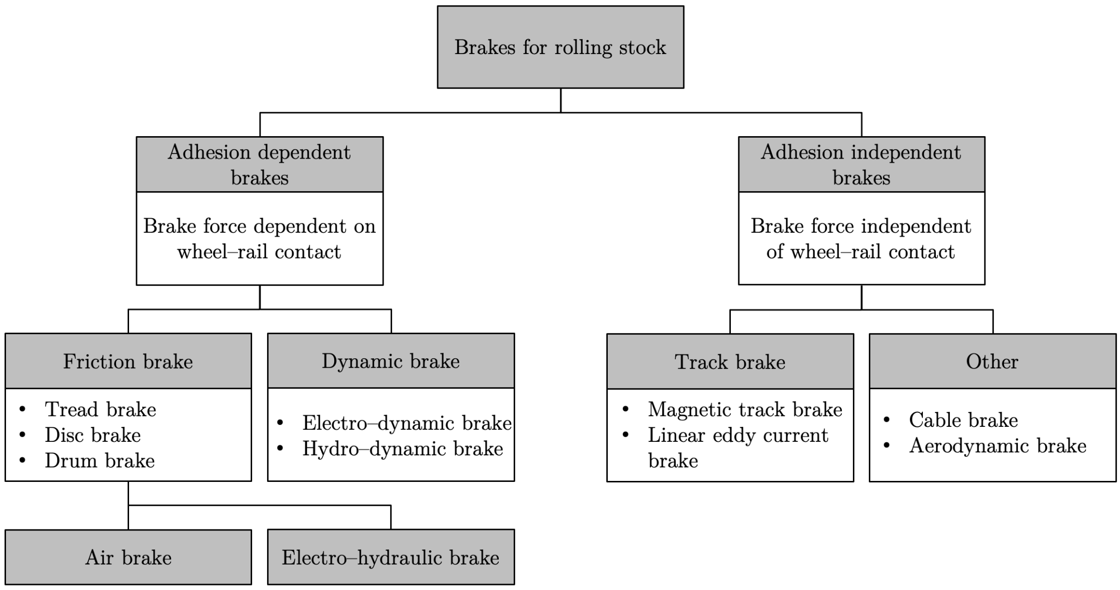


Figure 2.10: Types of brake systems for rail vehicles according to Berger (2014, p. 421) and Janicki et al. (2020, p. 356)

The most widely used type of adhesion independent brakes is the track brake. It is commonly applied in addition to wheel brakes. In the case of the magnetic track brake, it is lowered onto the rail and magnetically attracted to generate a frictional force. Thus, it acts directly on the rail, whereas the linear eddy current brake allows contact–less and wear–free power transmission and is hence independent of weather conditions. The magnetic field generated by the linear eddy current brake generates eddy currents which counteract the exciter field of the train. However, it must be taken into account that this operating principle leads to extreme heating of the rail (Janicki et al. 2020, p. 358).

Stellenbosch University https://scholar.sun.ac.za

2.2.3.4 Pantograph

In electric rolling stock, power is supplied from the catenary. The pantograph provides the connection between the contact wire and the traction unit (Filipović 2015, p. 173). When the vehicle starts moving, the pantograph is lifted pneumatically and applied to the catenary. It is challenging to maintain constant contact with the contact wire, as there are differences in height during the drive. In case of an interruption between the contact wire and the pantograph, electric arcs are caused and this leads to possible defects. To ensure redundancy, the traction units are normally equipped with two pantographs (Filipović 2015, p. 174; Janicki et al. 2020, p. 216).

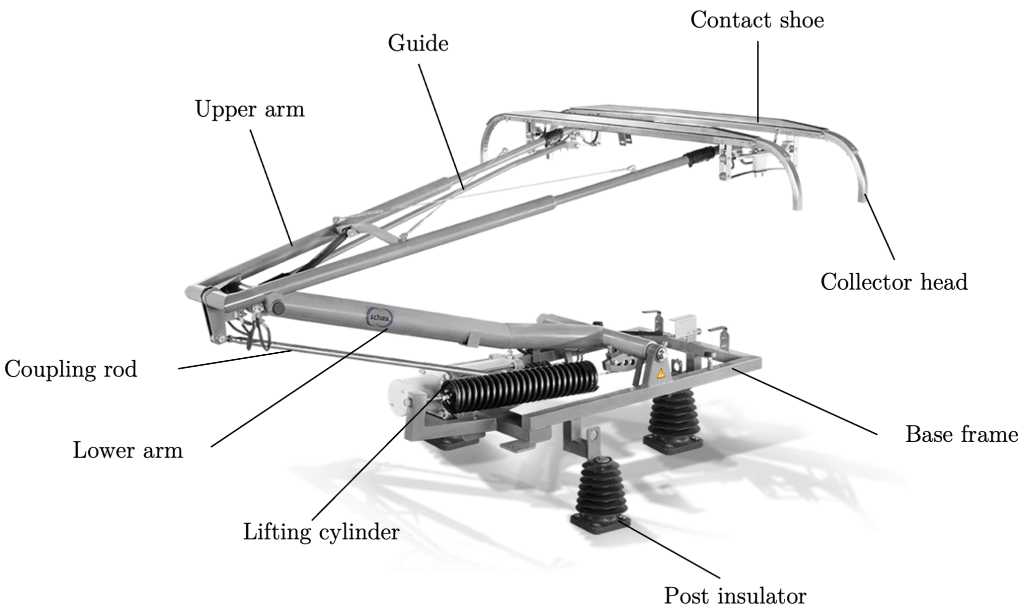


Figure 2.11: Main components of a pantograph (figure extracted from Schunk Carbon Technology (2020))

A pantograph consists of various components which are illustrated in Figure 2.11. The pantograph is connected to the traction unit via a base frame and supporting insulators. The lower part of the pantograph is attached to the base frame via a swinging support which can be lifted pneumatically. The upper arm is connected to the lower arm via a control link. At the end of the upper arm is the collector head, on which the contact shoes are mounted. The contact shoes form the contact to the contact wire and are individually sprung (Dinmohammadi 2019, p. 284). They are mostly made of carbon. In contrast to copper or aluminium, carbon protects the contact wire and has an additional lubricating effect (Filipović 2015, p. 174).

Stellenbosch University https://scholar.sun.ac.za

2.2.3.5 Traction and Buffer Gear

Since their introduction, rolling stock operates mostly as a train set. In other words, they are composed of several individual vehicles or wagons. Consequently, it is necessary to create an optimal connection between the individual units. The connection must be able to withstand mechanical loads which occur when travelling curves, uphill or downhill. At the same time, shocks must be absorbed and, in modern vehicles, data must be transmitted (Kobert and Busch 2014, p. 436). Principally, a distinction is made between mechanical, semi–automatic and fully automatic coupling systems. The mechanical coupling system includes the screw clutch. Nowadays it is predominantly used only on the African continent. The Willison and Janney couplings are semi–automatic coupling systems, which are applied mainly in America, Australia and the southern part of Africa (Janicki et al. 2020, p. 156). Primarily used in passenger transport is the Scharfenberg coupling (Kobert and Busch 2014, p. 440).

The manually operated screw coupling consists of the coupling spindle with the coupling nuts, the coupling hook, the foldable toggle and the coupling lugs (Figure 2.12). For the coupling process, the coupling hook is manually hung into the tow hook of the other rail vehicle. Thus, the transmission of traction is achieved by this screwed connection (Janicki et al. 2020, p. 166). In contrast, the compressive forces which occur during braking are passed on over side buffers. The transmission of compressed air and electricity in this coupling system is effected over separate cables, which are also connected manually during the coupling operation (Kobert and Busch 2014, pp. 436–437).

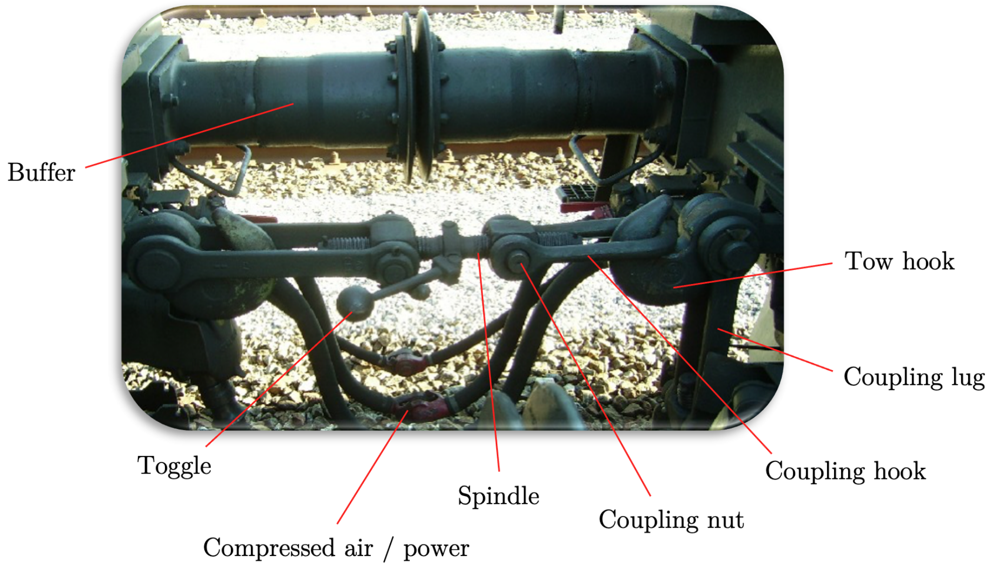


Figure 2.12: Structure of a screw coupling (figure extracted from Lämmli (2020))

Stellenbosch University https://scholar.sun.ac.za

The Willison, as well as the Janney coupling, are both claw couplings, which are semi–automatic centre buffer couplings that create a mechanical connection between the vehicles. With the use of these models, the side buffers are not absolutely necessary (Kobert and Busch 2014, pp. 437–439). As emphasised by Stuhr (2013, p. 29) the characteristic feature of the Janney coupling is the movable knuckle, through which the tractive force is transmitted. The rear lever of the knuckle is automatically locked in the coupling head during the coupling process. In the Willison coupler, the transmission of traction is not only affected by the moving elements of the coupling lock, as can be seen in Figure 2.13. In both couplings, the uncoupling is done manually by a pulling mechanism (Stuhr 2013, pp. 29–31).

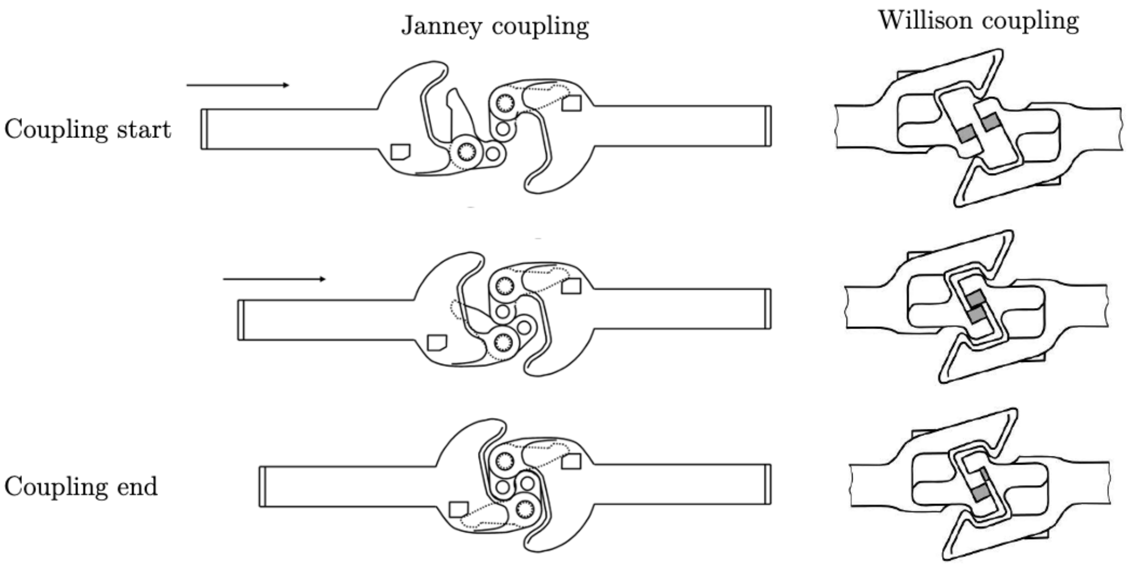


Figure 2.13: Coupling principle of a Willison and Janney coupling according to Stuhr (2013, pp. 29–31)

Today's coupling systems work according to the Scharfenberg principle. The Scharfenberg coupler consists of the head section with lock and electric contact coupling and the linkage with shock protection (Janicki et al. 2020, pp. 162–163). Figure 2.14 shows the coupling principle of the Scharfenberg coupling. The two coupling heads are pre–centred by a cone and a hooper. The coupling eye of one head slides into the recess of the core of the other head. This ensures that the couplings have a rigid and backlash–free connection when coupled (Kobert and Busch 2014, p. 441). During the automatic coupling process, the electrical and pneumatic lines are also connected together (Janicki et al. 2020, p. 163). A front hatch protects the coupling against external influences when it is not in use. Decoupling of this type is possible manually as well as automatically (Janicki et al. 2020, p. 165).

Stellenbosch University https://scholar.sun.ac.za

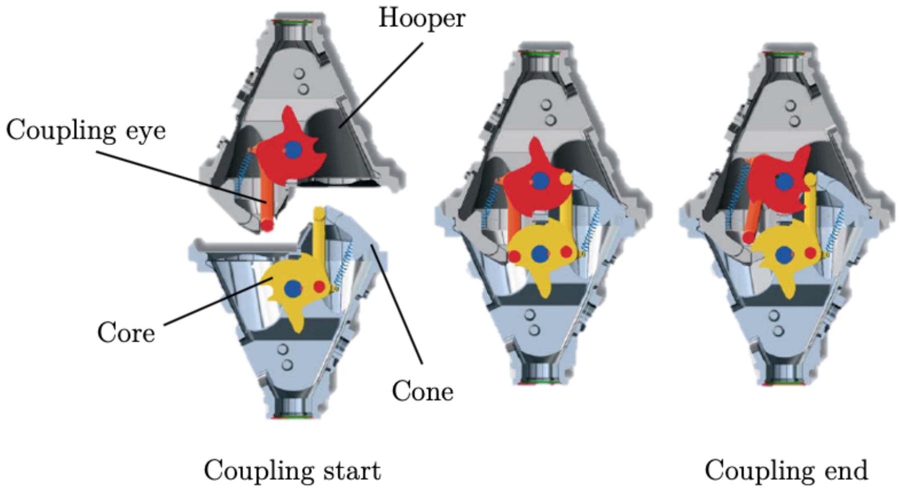


Figure 2.14: Coupling principle of a Scharfenberg coupling according to Stuhr (2013, p. 37) and Kobert and Busch (2014, p. 441)

2.2.3.6 Door System

A central element of passenger transport in rolling stock is the door systems. They must ensure safe, comfortable and smooth boarding and reliable opening and closing of the doors. The punctuality, reliability and economic efficiency of rail transport also depends to a large extent on the door systems. The passenger door is used for passenger change and is therefore decisive for passenger exchange (Janicki et al. 2020, p. 530). Due to the high demands for passenger safety and the complexity of door systems, they have a relatively high susceptibility for failure. This hinders the passenger flow, resulting in delays, particularly in local transport (Bramauer 2014, p. 457). With regard to passenger safety, pinch protection at the door systems must detect trapped objects or persons to interrupt the closing process. The door systems have also to be protected against unintentional opening during the trip. In an emergency, an emergency opening function is needed to ensure that the doors can be opened by hand (Janicki et al. 2020, p. 531). Basically, an entrance system of rolling stock consists of the entry door, the Door Control Unit (DCU) and the steps. However, according to Bramauer (2014, p. 464) and Janicki et al. (2020, p. 524) rigid steps are not, strictly speaking, part of the door system. Rigid as well as movable steps serve as an entry aid and adapt to different platform heights (Janicki et al. 2020, p. 529).

In Figure 2.15 the essential elements of the entry system are illustrated, which consist of the drive, the door panels, the steps, the control and detection elements as well as visual and acoustic display elements for the passengers. Door systems with pneumatic drives are used in older passenger rolling stock. Today, only electric drives are mounted because they are easier to control. The door panels must meet high comfort standards, such as water and draught tightness as well as sound and heat insulation. The door panels are

Stellenbosch University https://scholar.sun.ac.za

opened by a button which can be operated by the passengers themselves (Bramauer 2014, pp. 459–460). Other door systems can be found inside rolling stock, which mainly define individual areas in the wagons (Janicki et al. 2020, p. 521).

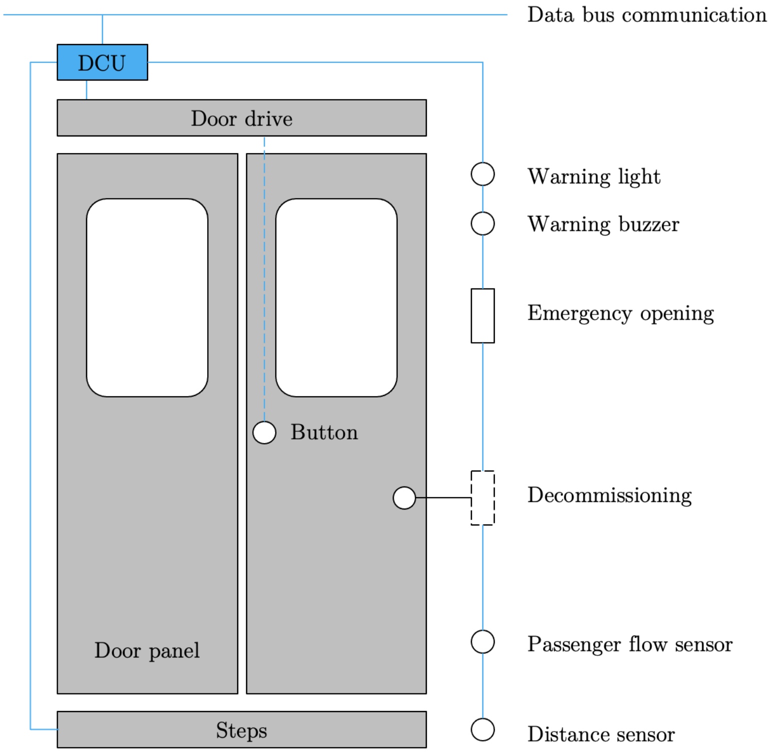


Figure 2.15: Principle structure of the entry system according to Bramauer (2014, p. 460)

2.2.3.7 Heating, Ventilation and Air Conditioning (HVAC)

Most of the electrical energy is not only needed to power the rail vehicles, but also for the HVAC in modern vehicles. As explained by Janicki et al. (2020, p. 548), they are mainly installed for comfort reasons in the passenger coaches and driver's cabs of the vehicles. In principle they have three basic air–conditioning functions: heating/cooling, dehumidifying and ventilating (Hofer 2014, p. 477). To fulfil these basic functions, either cold vapour air conditioners or airborne air conditioners are employed. Cold vapour air conditioners have a cooling circuit in which the circulating gaseous refrigerant is compressed. This leads to condensation and the resulting heat can be transferred. If the process is reversed, the resulting cooling by evaporation is passed on. Airborne air conditioners do not use any environmentally harmful coolants. Here, the air is compressed and cooled down via a heat exchanger. Electric heating registers in the air conditioner are used for heating (Janicki et al. 2020, pp. 549–551). The air conditioning units are either installed on the roof area or under the vehicle. They draw in the outside air and then transfer the air to the HVAC systems (Janicki et al. 2020, p. 553). Hofer (2014, p. 476) primarily defines three tasks which HVAC systems fulfil. There must be a balance of heat exchange so that the

Stellenbosch University https://scholar.sun.ac.za

passengers feel neither too cold nor too warm. Moreover, HVAC systems must guarantee hygienic requirements. This applies, for example, to air pollution, the elimination of fragrances or the standardisation of carbon dioxide limits. Finally, the air pressure must also be kept constant despite external influences such as wind or tunnels.

2.2.3.8 Indoor Light System

The interior lighting of rail vehicles is divided into general and emergency lighting. In general lighting, the passenger compartment, boarding area, sanitary area, stairs and service rooms are illuminated. Passenger compartment lighting is generally a combination of direct and indirect lighting. In emergency mode, only escape route lighting is provided. In the case of staircase lighting, supplementary step lighting is installed alongside ceiling lighting. The entrance area is illuminated much brighter than the other areas. This is necessary because the tread edge must be clearly visible, ensuring passenger safety. Service areas such as the driver's cab are also adequately illuminated to permit unrestricted operation (Miluchev 2014, pp. 472–473). For energy–efficient reasons, nowadays only Light–emitting Diodes (LEDs) are used for interior lighting (Janicki et al. 2020, p. 518).

2.2.3.9 Sanitary Facilities

Today's rail vehicles not only have sophisticated interior lighting but also enclosed sanitary facilities. These are installed especially in long–distance and regional trains. To ensure their proper operation, water tanks for processed water are installed in the roof space of the vehicles as well as wastewater tanks. Today's toilet systems work by vacuum to transfer the wastewater to the wastewater tank. Electronic systems can indicate operating conditions as well as faults in sanitary facilities (Janicki et al. 2020, pp. 513–515).

2.2.4 Summary of Rolling Stock

The first research field essential for this study is rolling stock. Therefore, this section first defines rolling stock and classifies railways in general and provides an overview of railway vehicles. Finally, rolling stock systems are discussed, whereby operational systems and systems for passenger coaches are distinguished.

2.3 Maintenance

Since the beginning of the first industrial revolution at the end of the eighteenth century, machines and assets have undergone continuous technological progress. Due to the increased complexity of machines and assets, maintenance has become increasingly more

Stellenbosch University https://scholar.sun.ac.za

important. In the following section, the different maintenance measures and strategies, performance management of maintenance as well as maintenance in rolling stock is discussed in more detail.

2.3.1 Definition of Maintenance

According to the DIN EN 13306, maintenance is defined as a "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (Deutsches Institut für Normung e. V. 2017, p. 8). Consequently, maintenance is always performed where it is necessary to ensure and maintain the functionality and thus the value of technical assets. During the lifetime of an asset, various factors such as wear, ageing and corrosion cause changes of state. The lifetime depends significantly on the reliability of the design and adherence to the maintenance and operating instructions. Besides, the conditions under which the assets are used must be taken into account as well as natural processes that cause changes without usage (Strunz 2012, pp. 1–2).

2.3.2 Maintenance Measures

In general, maintenance comprises of four main measures, which are illustrated in Figure 2.16. These are defined according to DIN 31051 and are briefly described in the following paragraph.

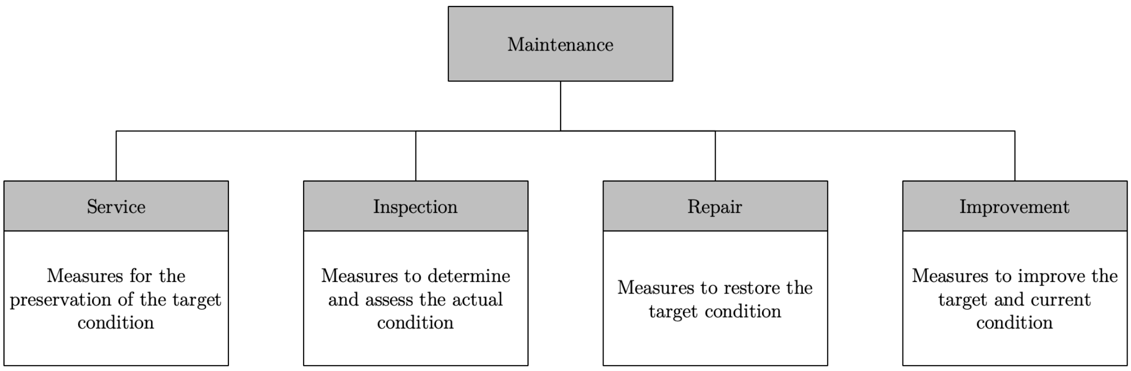


Figure 2.16: Subdivision of maintenance according to Deutsches Institut für Normung e. V. (2019b, p. 12)

The purpose of the *service* is to preserve the initial condition of the asset and thus postpone the reduction of the wear margin. The wear margin describes the range for the functional fulfilment of an asset under defined conditions (Deutsches Institut für Normung e. V. 2019b, p. 5). The delay can be achieved by conservation, for example, to increase protection against external influences. The *inspection* is primarily concerned with determining, analysing, and assessing the actual condition of an asset. Consequently, measures are

Stellenbosch University https://scholar.sun.ac.za

derived based on these results (Deutsches Institut für Normung e. V. 2019b, p. 5). If the wear margin is used up, *repair* is usually carried out. This includes all measures that restore the asset to a functional state (Deutsches Institut für Normung e. V. 2019b, p. 6). The repair can be carried out either by repairing the faulty part or by replacing it (Matyas 2016, p. 39). The last basic measure considers the *improvement* of maintenance. This comprises the combination of all technical and administrative measures, as well as measures that are taken by management to increase the functional reliability of an asset without changing its original function (Deutsches Institut für Normung e. V. 2019b, p. 6). According to Matyas (2016, p. 41), the functional reliability can be increased by eliminating a weak spot. In Figure 2.17, the individual maintenance tasks and the influence of the individual measures on the wear curve are summarised and visualised graphically.

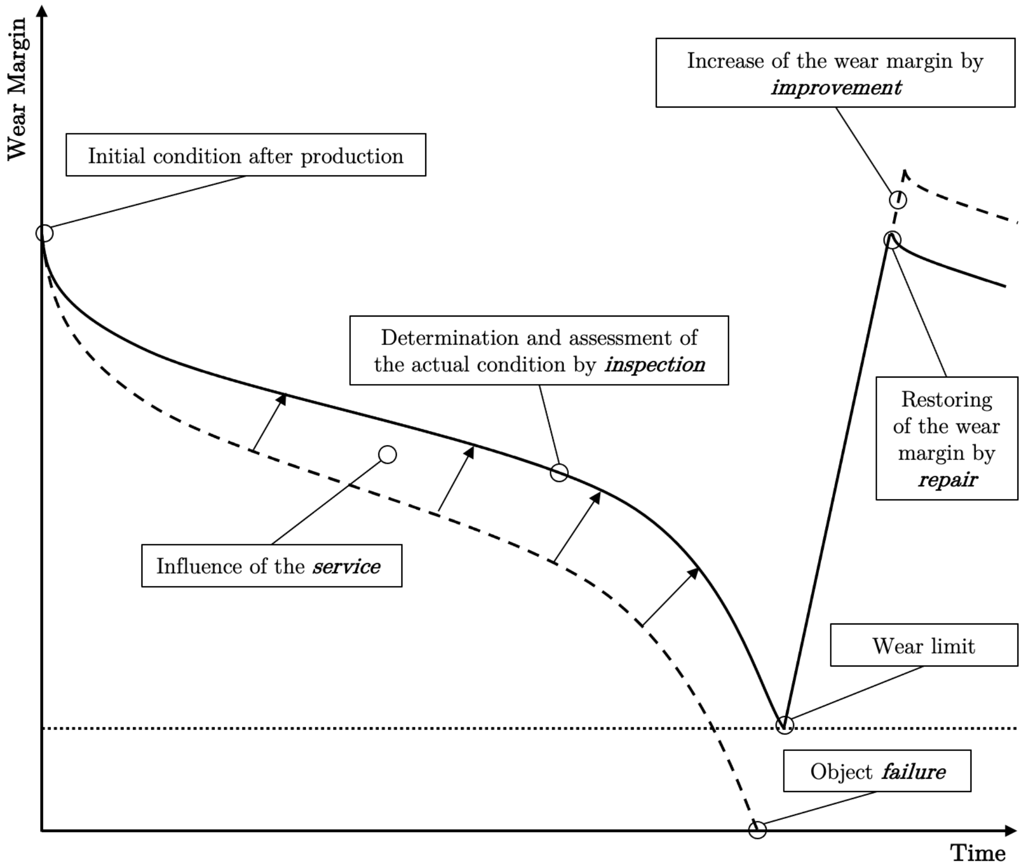


Figure 2.17: Maintenance tasks according to Deutsches Institut für Normung e. V. (2019b, p. 8)

2.3.3 Maintenance Strategies

The maintenance strategy is the approach taken to achieve the maintenance objectives (Deutsches Institut für Normung e. V. 2017, p. 9). It regulates the time, the type of measures and the frequency of their execution for the maintenance assets. When selecting the maintenance strategy, legal, safety, technical, production–relevant and economic

Stellenbosch University https://scholar.sun.ac.za

aspects must be considered (Ryll and Freund 2010, p. 26).

At the beginning of the first industrial revolution, the first event–driven maintenance measures began. At that time, however, these were still very unstructured and followed more of a fire brigade principle. Maintenance first came into focus during the First World War. Military leaders recognised the significance of maintenance. Over the decades, maintenance and the respective strategies developed constantly (Gohres and Reichel 2018, p. 4). The reference model of maintenance strategies gives a good overview of the development of maintenance strategies (Figure 2.18). At first glance, it is apparent that, in contrast to the other maintenance strategies, only reactive maintenance is performed after the failure has occurred. In the following sections, the respective maintenance strategies are discussed in more detail.

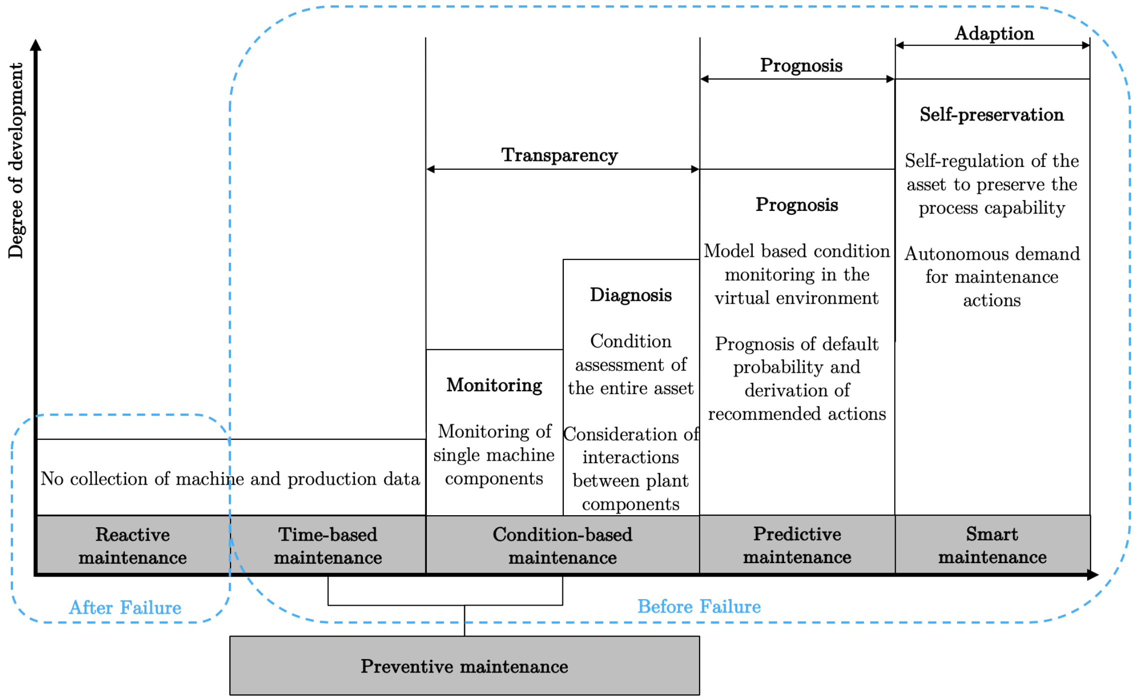


Figure 2.18: Reference model of maintenance strategies according to Kurz (2016, p. 15) and Jimenez et al. (2020, p. 540))

2.3.3.1 Reactive Maintenance

Reactive maintenance, which is also called breakdown maintenance, is the simplest strategy. According to Ryll and Freund (2010, p. 27), this is strictly speaking not a strategy, because a strategy strives for a long–term oriented goal. In the case of reactive maintenance, the maintenance activities are only performed after a malfunction has occurred or after the asset has failed (Pawellek 2016, p. 174; Mühlnickel et al. 2018, p. 352). Thus, this procedure primarily requires a prompt and spontaneous reaction in case of failures. There

Stellenbosch University https://scholar.sun.ac.za

is no maintenance planning and therefore no preventive measures are taken in advance (Mühlnickel et al. 2018, p. 352).

Ryll and Freund (2010, p. 28) and Mühlnickel et al. (2018, p. 352) point out that this procedure seems at first to be a very cost–effective strategy and they justify this with the low planning effort as well as with the replacement of the component only when it actually fails. However, companies can hardly allow these uncontrolled breakdowns, since they have to have the necessary maintenance resources such as personnel, spare parts, tools or auxiliaries available in case of failure (Ryll and Freund 2010, p. 28). Furthermore, the lack of anticipation of the failure often results in a delay, which leads to a high time pressure in maintenance (Mühlnickel et al. 2018, p. 352). Normally, reactive maintenance is therefore only used in exceptional cases if there is redundancy or the asset is of minor importance (Matyas 2002, p. 14).

2.3.3.2 Preventive Maintenance

Preventive maintenance can be subdivided into Time–based Maintenance (TBM) and Condition–based Maintenance (CBM). With TBM, the replacement of components is executed in defined intervals, independently of the actual condition of the component. The intervals are determined either time–related or event–related, for example, according to calendar time, operating hours, driven kilometres or others (Ryll and Freund 2010, p. 28; Pawellek 2016, p. 174). Therefore, the replacement of the component is carried out without taking into account its actual current condition and is based only on experience (Pawellek 2016, pp. 174–175; Mühlnickel et al. 2018, p. 354). Matyas (2002, p. 14) states that the difficulty is the determination of the time interval for the optimal operating time. This depends on the different mean time between two damages, on the different varieties of the duration of use, on bad damage records and insufficient statical damage experience. As a consequence, components are mostly replaced too early, which leads to increased consumption of resources, since the wear margin is not used optimally (Ryll and Freund 2010, p. 29). Now, the dilemma between the reactive and preventive maintenance strategy becomes clear. In the context of TBM, a reduction of downtime costs is achieved, but at the same time, the preventive costs increase. Despite the full utilisation of the wear margin in reactive maintenance, the disadvantages due to the unplannability of measures and possible consequential damage to other components prevail (Ryll and Freund 2010, p. 29). In principle, the difficulty with TBM is that all components of a technical asset exhibit different failure behaviours. Thus, different maintenance intervals must be performed due to the different expected lifetimes. Consequently, this strategy is used primarily for technical assets with a high–risk level for humans and the environment. It is also applied for components where periodic replacement is required by law, such as the four–year maintenance of substations, or where the maintenance costs are very cheap concerning the breakdown costs (Ryll and Freund 2010, pp. 29–30).

Stellenbosch University https://scholar.sun.ac.za

The pace of development for CBM has increased rapidly in the past decades. This was primarily achieved by the standardisation of interfaces. In contrast to the other maintenance strategies mentioned before, the control parameter for activating maintenance tasks is changed. Now the control parameter is no longer the time as for TBM, but the condition, which can be described by the wear margin (Ryll and Freund 2010, p. 30). The intention of CBM is to significantly reduce the downtime costs by supporting asset monitoring (Mühlnickel et al. 2018, p. 352). Condition monitoring is realised by using the procedures and tools of technical diagnostics. On the one hand, this can be carried out in the simplest form, for example by regular inspections by humans. Alternatively, a so–called Condition Monitoring System (CMS) can be installed, which reduces the effort needed for manual inspections (Ryll and Freund 2010, p. 31). According to Jardine et al. (2006, p. 1484), a CMS consists of three key elements:

1. *Data acquisition*: Obtaining the relevant data
2. *Data processing*: Analysis and interpretation of the data
3. *Maintenance decision–making*: Recommendation of efficient maintenance strategies

The automated monitoring of a CMS is done using sensors, which are attached to the corresponding components and thus constantly supply the CMS with data. In the monitoring stage (Figure 2.18) the emphasis lies on the monitoring of selected individual components, whereas in the diagnosis stage the asset itself is considered (Mühlnickel et al. 2018, pp. 354–355). Due to the high investment costs of a CMS it must be taken into account that as many components as possible should be monitored with as few sensors as necessary (Ryll and Freund 2010, p. 31; Mühlnickel et al. 2018, p. 354). This strategy is mainly implemented for components where the wear reserve is technically measurable and economically reasonable. If both prerequisites are fulfilled, CBM is characterised above all by its resource efficiency as well as by the proactive maintenance measures that can be optimally planned in terms of time (Ryll and Freund 2010, p. 31; Mühlnickel et al. 2018, p. 354).

2.3.3.3 Predictive Maintenance

The traditional subdivision of maintenance strategies includes also predictive maintenance, besides reactive and preventive maintenance (Zhang et al. 2019, p. 2215; Jimenez et al. 2020, p. 540). The aim of the strategy is to monitor the health of the asset, detect incipient faults and forecast the exact moment of failure (Montero-Jiménez and Vingerhoeds 2018, p. 237). Consequently, predictive maintenance belongs to the prognosis stage. This strategy became particularly attractive in the last decade, as more and more data became available by condition monitoring (Gashi and Thalmann 2019, p. 15). Statistical analysis methods or simulation methods are applied to evaluate and interpret the recorded

Stellenbosch University https://scholar.sun.ac.za

sensor data (Mühlnickel et al. 2018, p. 355). Thereby it is possible to identify failure patterns and predict failures (Fedele 2011, p. 45; Mühlnickel et al. 2018, p. 355). It becomes apparent that predictive maintenance prevents malfunctions before they occur (Matyas 2002, p. 15).

In particular, potential or hidden malfunctions are to be identified to prevent their development (Matyas 2002, p. 15; Ryll and Freund 2010, p. 31). According to Matyas (2002, p. 15) and Ryll and Freund (2010, p. 33), malfunctions can be grouped into four different categories:

- *Hidden malfunctions*: Special attention should be paid here, as they can have serious consequences; however, there is usually no immediately noticeable influence on the functional process.
- *Safety and environmental malfunctions*: This involves guaranteeing asset safety, preventing personal injury and taking environmental protection regulations into account.
- *Operational relevant malfunctions*: This malfunction causes a downtime of the asset, which consequently leads to a reduction of the asset's availability.
- *Non–operation relevant malfunctions*: Only repair costs are accrued in the case of malfunction.

First and foremost, it is not only about the prevention of malfunctions, but by predictive maintenance it is also possible to optimise the trade–off between maintenance, performance cost and increase in availability and reliability (Selcuk 2017, p. 1671; Sakib and Wuest 2018, p. 268; Zhang et al. 2019, p. 2215). The drivers on the hardware level are downsizing and price decline of sensor, electronic and communication technology. On the software level, the use of digital tools is facilitated by various technologies such as the virtualisation of servers, cloud technologies or web services (Lucke et al. 2017, p. 76). Currently, the greatest difficulty of predictive maintenance is the evaluation of sensor data and the preparation of the forecast. The reason lies primarily in the fact that wear curves are difficult to generalise and therefore often only isolated solutions for assets exist (Mühlnickel et al. 2018, p. 355).

2.3.3.4 Smart Maintenance

The currently most advanced form of maintenance can be found in the so–called "smart maintenance", also known as maintenance 4.0. So far, no clear scientific definition is available in the literature. According to Henke et al. (2019, p. 11) smart maintenance can be described as "learning–oriented, self–regulated and intelligent with the objective of maximising the technical and economic effectiveness of maintenance measures by using

Stellenbosch University https://scholar.sun.ac.za

digital applications, taking into consideration the respective existing production system". Bokrantz et al. (2020b, pp. 11–12) specify it and subdivide smart maintenance into the following four different dimensions:

- *Data–driven decision–making*: It is about the extent to which decisions are based on data. It can include both the augmentation and automation of human decision–making.
- *Human capital resource*: Individual knowledge, skills, abilities and other characteristics of the maintenance employees are considered. Smart maintenance requires highly qualified employees who are mainly characterised by creativity and improvisation in order to execute this new maintenance strategy (Akkermans et al. 2016, p. 8; Henke et al. 2019, p. 15).
- *Internal integration*: The maintenance function is incorporated as part of the intra–organisational whole. This implies that cross–functional collaboration takes place within the company between the different divisions. More precisely, it involves an exchange of data, information, knowledge and close synchronisation.
- *External integration*: The maintenance function is incorporated as part of the inter–organisational whole which refers especially to networks and strategic partners. This includes the flow of data, information, knowledge, products and services between the various parties.

This demonstrates that these four dimensions are crucial for the implementation of smart maintenance in a company. But what exactly does intelligent maintenance imply, besides considering these four dimensions? Smart maintenance is about creating self–preservation of the asset by preserving process capability via self–regulation. This is accomplished by current and expected strains, whereby regular adjustments of maintenance strategies are carried out. The foundation is provided by intelligent systems that can optimise themselves independently and preserve their own functionality. Not only is sensor data of an asset recorded, as in previous strategies, but by means of smart objects, a continuous exchange of information between the individual software modules is achieved. By equipping them with information technology, they combine various functions such as identification, communication and sensor technology. Moreover, smart objects can independently request maintenance measures and share them with others (Mühlnickel et al. 2018, pp. 355–356). According to Wegener (2020, p. 39) the exchange of information can be shared between different disciplines such as the manufacturer, operator and industrial service. This reveals the enormous potential of smart maintenance to increase both performance and economic profitability and hence plays a key role in Industry 4.0 (Wegener 2020, p. 8).

As stated by Bokrantz et al. (2020a, pp. 4–8) several factors can influence the adoption of smart maintenance or even facilitate or inhibit its implementation. These can be grouped

Stellenbosch University https://scholar.sun.ac.za

into the three main categories: change, investment and interface. In order to implement smart maintenance, it requires changes in technology, skills and organisation. These types of change can be affected by cultural aspects, algorithm interpretability (e.g. data–driven decision–making) or leadership abilities for maintenance. The investment context considers investment in tangible and intangible assets. Tangible assets refer to information and communication technology, which could be sensors, IT infrastructure or software. For the effective use of tangible assets, intangible assets are required. Complementary investments in new skills or company infrastructure are essential to obtain these intangible assets. Eventually, interfaces are included which affect the establishment of external inclusion. These embrace digital platforms, openness and IT security.

2.3.4 Performance Management

Looking at the different maintenance strategies, it is apparent that each strategy has its strengths but also its weaknesses. The biggest challenge for companies today is to choose the most effective and efficient strategy. This is necessary to improve operational capabilities, reduce maintenance costs and remain competitive. Kumar et al. (2013, p. 235) also point out that maintenance performance measurement enables companies to understand the value created by maintenance. Furthermore, Kumar et al. (2013, p. 235) argue that this enables companies to review current maintenance strategies and justify investment in new technologies. An essential part of the maintenance performance measurement is to determine the Maintenance Performance Indicators (MPIs). This entails that the maintenance strategies are linked to the overall organisational strategy (Tsang 2002, p. 30). Generally speaking, performance indicators according to the European Environment Agency (1999, p. 11) serve to compare the current condition with a specific set of reference conditions. The distance between the current situation and the desired situation is measured. This is known as "distance to target assessment". In terms of MPIs the situation of the current maintenance strategy is compared and measured against the desired strategy. The main difficulty is to select suitable MPIs which reflect the organisational strategy and at the same time provide maintenance management with quantitative information regarding the maintenance strategy (Kumar et al. 2013, p. 238). The most frequently used MPIs can be classified into three different categories based on their focus (Campbell and Reyes-Picknell 2016, pp. 194–201):

- *Equipment performance*: The fundamental concern here is whether the system works or not. However, looking closely, a much more sophisticated analysis occurs. On the one hand, it is a matter of determining what the availability and reliability of the system is. Furthermore, it is essential to ascertain how long the average maintenance of the system takes. Thus, the maintainability is measured. It is also examined how quickly the system can be operated and whether it provides the required quality. For a successful equipment performance test, it is usually necessary to look at the

Stellenbosch University https://scholar.sun.ac.za

performance trend over time. Equations (2.1) to (2.6) provide an outline of the calculation.

$$Availability = \frac{Scheduled\ uptime - all\ downtime}{Scheduled\ uptime} \tag{2.1}$$

$$Reliability = \frac{Total\ operating\ time}{Number\ of\ failures} \tag{2.2}$$

$$Maintainability = \frac{Total\ downtime\ from\ failures}{Number\ of\ failures} \tag{2.3}$$

$$Process\ rate = \frac{Ideal\ cycle\ time}{Actual\ cycle\ time} \tag{2.4}$$

$$Quality\ rate = \frac{Quality\ product\ produced}{Total\ product\ produced} \tag{2.5}$$

$$Overall\ equipment\ effectiveness = Availability \cdot Process\ rate \cdot Quality\ rate \tag{2.6}$$

- *Cost performance*: Maintenance costs are crucial to make important equipment specific decisions. Typically, maintenance costs are separated into labour (wages), materials (parts, components used by maintenance) services (all shops, facilities and warehouses) and other (special services, training, planning and support functions). Campbell and Reyes-Picknell (2016, p. 197) also propose a different approach to separation. The costs can be divided into specific areas such as labour, materials, services and technical support, which are all influenced by management and staff. On the other hand, it is useful to record the costs of a specific piece of equipment directly, so that for a job or work order the corresponding costs for labour, materials and services are recorded. Finally, the type of expenditure for labour, materials and all services is recorded, which is used to monitor trends in key components. The relevant MPIs in relation to the costs specified by Stefanovic et al. (2015, p. 19) are summarised in Equations (2.7) to (2.9).

$$Direct\ maintenance\ costs = Corrective\ maintenance\ costs + Preventive\ maintenance\ costs \tag{2.7}$$

$$Breakdown\ severity = \frac{Breakdown\ costs}{Direct\ maintenance\ costs} \tag{2.8}$$

$$Percentage\ cost\ of\ personnel = \frac{Staff\ costs}{Maintenance\ costs} \tag{2.9}$$

- *Process performance*: In this context it is ensured that the equipment works at top performance. In general, it is difficult to make clear specifications. However, there are general criteria which can be applied for guidance. On the one hand, unplanned work must be kept as low as possible. This means that if at least 95 percent of the total working hours are planned for maintenance, the performance is considered to be

Stellenbosch University https://scholar.sun.ac.za

in the top quarter. Furthermore, the schedule compliance rate is a valuable indicator of whether the company is in constant firefighting mode or avoiding it. If this figure is over 70 percent, the company is in the top quarter. Another performance indicator is indicated by the work orders. For this purpose the ratio between the completed and total tasks is examined. When it comes to process performance, the inventory should not be neglected. Thereby it is identified whether too many spare parts are kept in stock. Equations (2.10) to (2.13) present the calculations for the outlined process performance.

$$Planning\ rate = \frac{Planned\ work}{Total\ work\ done} \tag{2.10}$$

$$Schedule\ compliance\ rate = \frac{Total\ labour\ hours\ completed}{Total\ labourhours\ scheduled} \tag{2.11}$$

$$Work\ order\ rate = \frac{Number\ of\ completed\ tasks}{Number\ of\ received\ tasks} \tag{2.12}$$

$$Stores\ inventory\ turnover = \frac{Total\ value\ of\ stores\ issued\ to\ maintenance}{End\ of\ year\ stores\ value} \tag{2.13}$$

2.3.5 Maintenance in Rolling Stock

Rolling stock maintenance serves to maintain or restore the nominal condition of rail vehicles over the entire operating time (Rösch 2014, p. 529). According to Deutsches Institut für Normung e. V. (2011b, p. 15) the nominal condition is the state that represents the totality of possible conditions between the new condition and the limit condition. In case of a continued operation of rail vehicles beyond the limit condition, the operational safety as well as the reliability would be exceeded so that the rail vehicle is not allowed to continue operating. A change in condition is due to wear of the components. The wear of rail vehicles is caused by various influences and loads such as friction, impact and vibration stress, the ageing process and thermal stress (Rösch 2014, p. 529). Nevertheless, to ensure trouble–free operation, regular maintenance is essential. After all, it is not the infrastructure but the rail vehicles that are the most maintenance–intensive part of the railway system. Therefore, rail vehicles are most susceptible for failure when their maintenance is neglected (Asekun and Fourie 2015, p. 136). Mergenthaler and Käser (2014, p. 2520) justify the susceptibility for failure particularly with the permanent advancement of rail vehicles and the associated system diversity and increase in complexity. Umiliacchi et al. (2011, p. 1) expand on that as due to the complex structure, the failure of a subsystem can have serious effects on the operational process. For example, even a simple but not negligible malfunction such as not closing the doors correctly can have a negative effect on rail operations (Umiliacchi et al. 2011, p. 1). Rösch (2014, pp. 530–534) defines five essential objectives which the maintenance of rolling stock pursues:

Stellenbosch University https://scholar.sun.ac.za

- *Safety objective*: It must be ensured that rail vehicles in operation do not pose any hazards or risks from their current condition that exceed the socially accepted level. Besides, identified weak points must be eliminated, especially if they are of safety relevance.
- *Reliability objective*: Rolling stock operates in a networked environment and therefore a fast fault propagation occurs as soon as a subsystem is faulty. Hence, the aim is to keep the rolling stock in a fault–free condition by maintenance, so that no malfunction of the overall system or other subsystems is caused by them. In other words, it implies minimising the failure rate and maximising the Mean Time Between Failures (MTBF).
- *Availability objective*: The availability objective is a constant dilemma. On the one hand, rolling stock maintenance contributes significantly to the safe and reliable operation of the vehicles. From the other perspective, operation should not be impaired by the withdrawal of vehicles for maintenance. Consequently, the Mean Time to Repair (MTTR) ought to be kept as short as possible.
- *Ecological objective*: In rolling stock maintenance it is also necessary to identify harmful effects on the environment. For example, the soil or groundwater can be contaminated by lubricants, which can be avoided by alternative maintenance methods or technologies.
- *Economic objective*: Up to 20 percent of the life cycle costs of rail vehicles is generated by maintenance. Thus, maintenance is an essential control variable in intermodal competition. It is also of decisive importance in intramodal competition among rail companies, since the main cost types for access, such as track usage costs or energy costs, are regulated by law. This ensures fair conditions for all providers. It implies that maintenance is a crucial cause variable for the economic efficiency of a rail company.

Currently, reactive and preventive maintenance strategies are mainly applied in rolling stock maintenance (Rezvanizaniani et al. 2008, p. 516; Cheng and Tsao 2015, p. 404; Mergenthaler and Käser 2014, p. 2520; Franzen and Kuhlenkötter 2018, p. 64). Rezvanizaniani et al. (2008, p. 516) justify this with the conventional and conservative approach of rail companies. In general, corrective maintenance cannot be avoided due to component failure (Cheng and Tsao 2015, p. 404). If possible, this strategy should be avoided as it is associated with high costs. In the case of a breakdown, a maintenance team must be expected to be sent out and transport to the nearest depot must be organised. This may entail delays for other trains, which will result in fees for the incurred delays. To avoid this situation, more appropriate measures such as preventive maintenance are recommended to be applied (Umiliacchi et al. 2011, p. 1).

Stellenbosch University https://scholar.sun.ac.za

In recent years, preventive maintenance has established itself as the preferred strategy in rolling stock maintenance (Rezvanizaniani et al. 2008, p. 516; Umiliacchi et al. 2011, p. 2). With this strategy the rail companies manage to reduce the risks of failure, but at the same time the maintenance costs increase with regular preventive maintenance (Cheng and Tsao 2015, p. 404). The frequency of preventive maintenance is primarily determined by laws and regulations (Rezvanizaniani et al. 2008, p. 516). Moreover, the choice of the rail vehicle maintenance strategy has an impact on passenger comfort, in contrast to the processing strategy. Railway companies want to achieve an optimum balance between the factors of safety, comfort and costs. The choice of a suitable maintenance strategy for achieving an optimum balance is complicated because, in addition to non–metric selection factors such as safety or quality, metric evaluation factors like maintenance, storage or shortage costs must also be taken into account (Cheng and Tsao 2015, p. 404).

Current main trends in rolling stock maintenance are CBM and predictive maintenance. Although these strategies have been known for about 20 years, the rail vehicle industry is struggling to implement them (Schwilling et al. 2016, p. 5). The intention of CBM is to predict an early anomaly of conditions and to derive respective maintenance measures. Diagnostic systems in rail vehicles enable the system to record wear inventories and to compare them with the qualitative and technical requirements necessary for operation. It is essential to have a correspondingly long advance warning time so that preventive maintenance can be undertaken before component failure occurs. Thus CBM offers significant advantages compared to the traditional maintenance mix of corrective and preventive maintenance of rail vehicles. On the one hand, wear margins can be exploited in much more detail. Likewise, the risk of failure can be significantly reduced owing to condition monitoring and the feeding of the acquired data into the CMS (Linke et al. 2018, p. 56). Umiliacchi et al. (2011, p. 2) add that despite the additional installation of sensors for monitoring the components, maintenance costs are significantly reduced. A further reduction in rail vehicle maintenance costs is achieved at the next level, for instance in predictive maintenance. This is the case because only limited additional implementation costs are required for the upgrade. It can be much more effective, since the time of occurrence of the fault is already estimated here. Although modern maintenance strategies are now available, rail vehicle companies struggle to implement them and digitalisation challenges the rail industry (Schwilling et al. 2016, p. 10).

2.3.6 Summary of Maintenance

The second research field essential for this study is maintenance. This section starts with an definition of maintenance. The individual maintenance measures and strategies are discussed before finally covering the main MPIs and concluding with rolling stock maintenance.

Stellenbosch University https://scholar.sun.ac.za

2.4 Industry 4.0 Technologies Application in Maintenance

Warren Bennis stated that "the factory of the future will have only two employees, a man and a dog. The man will be there to feed the dog. The dog will be there to keep the man from touching the equipment" (Fisher 1991, p. 15). In the current fourth industrial revolution, also known as Industry 4.0, we are still far away from this long–term version. Nevertheless, there are now some interesting technical solutions that are proving to be practical and efficient. Consequently, the focus is on selected technological solutions that pave the way to the next generation of technical applications. Thus, the long–term version is still pursued and in the long–run the objective will be to keep humans as far as possible away from assets. To determine which emerging technologies are particularly promising in maintenance, a systematic literature review is conducted in the following section. The purpose of the systematic literature review is to answer the second secondary research question (Section 1.2) and to provide results for the two corresponding objectives (Table 1.2, objective four and five). In other words, the purpose is to determine appropriate Industry 4.0 technologies for maintenance processes and the associated positive synergies.

2.4.1 Systematic Literature Review Approach

In the subsequent part, a systematic literature review is carried out in the field of maintenance linked to Industry 4.0 technologies. According to Mulrow (1994, p. 597) this method is a "fundamental scientific activity" which is necessary to deal with and process the quantity of literature. This makes it possible to test the findings for induction. Bem (1995, p. 173) states that otherwise there is the chance of huge and naive collections of different sources for literature reviews but with less content. Therefore, a systematic approach supports being specific and accurate to avoid bias. Besides, the method is a replicable investigation (Booth et al. 2016, p. 2). In Figure 2.19 an overview of the process of the systematic approach is provided.

The following systematic literature review is based on the suggested approach by Booth et al. (2016) and has been modified for this research. The approach is subdivided into five different phases. In the first phase the scope of this study, including the definition of the research questions, is determined (Section 1.2). The databases Scopus and Web of Science are subsequently selected for this study because of their extensive search field. The software Citavi is used to organise, structure and analyse the data. Microsoft Excel is applied as a supporting software for the transfer and first selection of the literature. The second phase is about searching. First, the search string is determined:

*maintenance or "asset management" AND "industry 4.0" AND technolog**

Stellenbosch University https://scholar.sun.ac.za

The search string focuses on the areas of maintenance and Industry 4.0 technologies to cover all the available research in this combined field. The string *maintenance or "asset management"* is limited to the article title, so the focus of the filtered documents is related to this research field. Regarding the second string *"industry 4.0" AND technolog**, the scope is broader and limited to the article title, abstract and keywords. The result of the systematic database search is 106 documents on Scopus and 63 documents on Web of Science. After the duplicates are removed, a total of 132 documents remained. As Greenhalgh and Peacock (2005, p. 1065) show, it is improbable that all relevant documents can be identified by a systematic search. To counteract this dilemma, a manual search is also included. This resulted in 18 documents. The purpose of the subsequent assessing phase is to limit the results to the field of interest. Therefore, the following inclusion and exclusion criteria are set (Table 2.2).

Table 2.2: Inclusion and exclusion criteria according to Palmarini et al. (2018, p. 216)

Inclusion criteria	**Exclusion criteria**
Study elaborates the use of Industry 4.0 technologies in maintenance.	Study that is not in English or German.
Study that presents the state of the art of Industry 4.0 technologies.	Study that is published before 2010.
	Study that is not related or applicable to industrial maintenance.

Next, the title and abstract of the documents have to be screened to get a more specific selection. At the end of the screening, 46 documents remained. Finally, the papers are analysed in terms of the Quality Criteria (QC) which are based on those established by Kitchenham et al. (2009, p. 9):

- *QC1*: The documents are described clearly.
- *QC2*: The used methodology is well elaborated and described.
- *QC3*: The technologies and case studies are up to date.
- *QC4*: The study results are applicable for rolling stock.
- *QC5*: Detailed study results are provided.

The outcome of the analysis by the QC resulted in 17 documents. The considerable reduction of documents is primarily due to QC4 and QC5. Many of the documents only contained excerpts of the results, meaning no detailed results are available. Furthermore, a significant number of the documents are designed for specific industrial solutions. Consequently, an application in other industries is not foreseen. In the fourth phase, the evaluation of these 17 documents takes place. First, the information from the literature is extracted and then analysed. In the last phase, a summary of the analysed data is written.

Stellenbosch University https://scholar.sun.ac.za

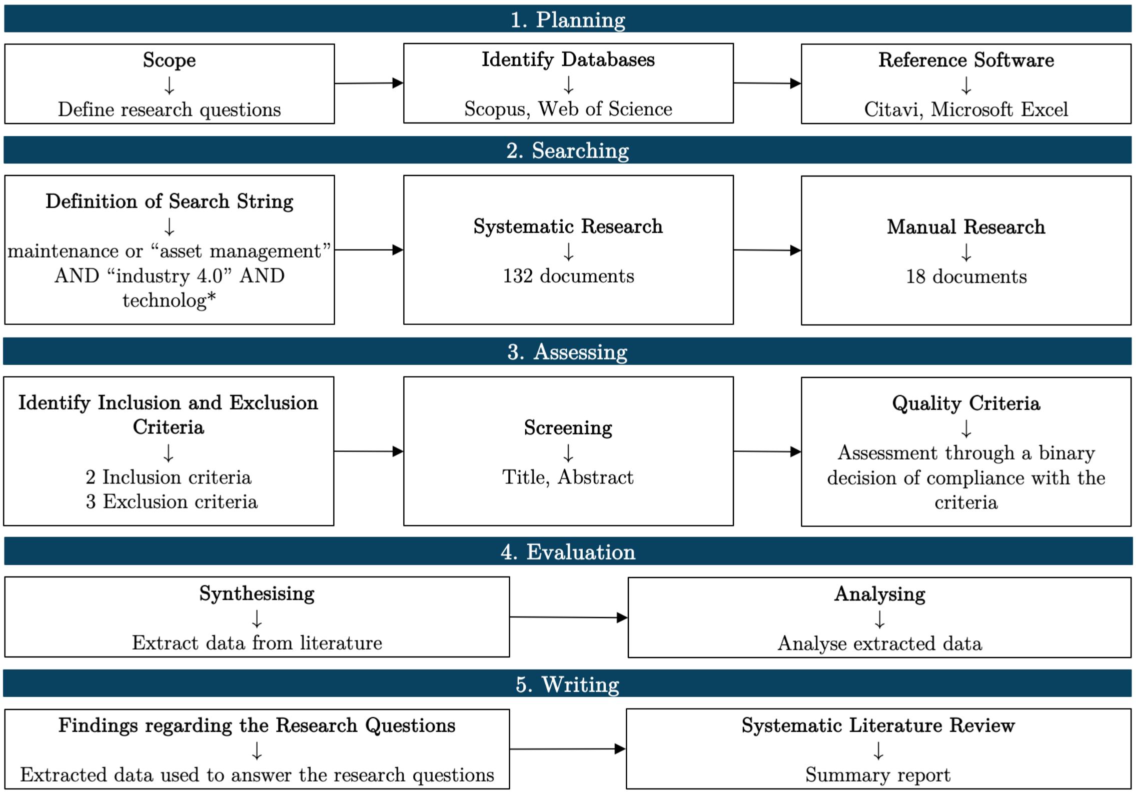


Figure 2.19: Systematic literature review process

2.4.2 Bibliometric Results

This section presents the bibliometric results of the 17 documents obtained from the systematic literature review. As can be seen in Figure 2.20, all the relevant documents have been published from 2014 onwards, with the largest number having been published in 2019.

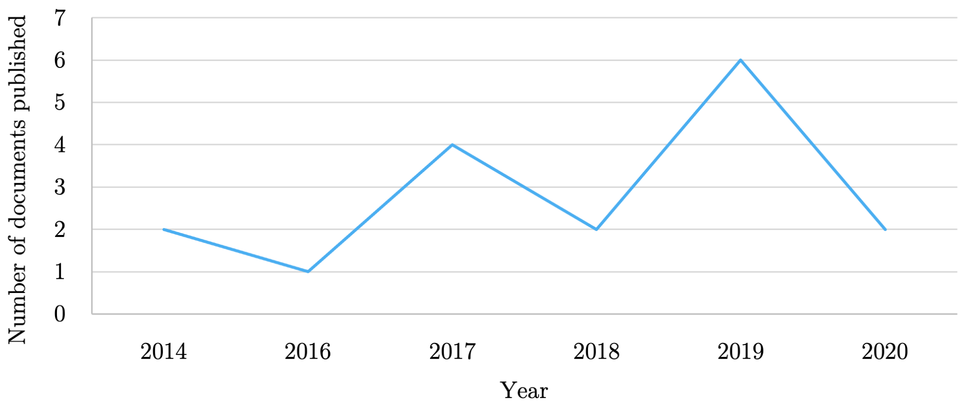


Figure 2.20: Documents published per year

In the current year 2020, only two documents appear. Reasons for this could be because the current year is still ongoing, papers presented have not yet been published and conferences had to be postponed due to the current Covid–19 pandemic. Nevertheless, 14 of the 17

Stellenbosch University https://scholar.sun.ac.za

documents were published between 2017 and 2020, indicating that there is current interest in this research area.

Figure 2.21 illustrates the different source types used in this research, where the absolute and percentage values are provided. Conference proceedings constitute the largest share with over 50 percent, followed by journals. This result supports the conclusion from the publication years that research in this area is new and important.

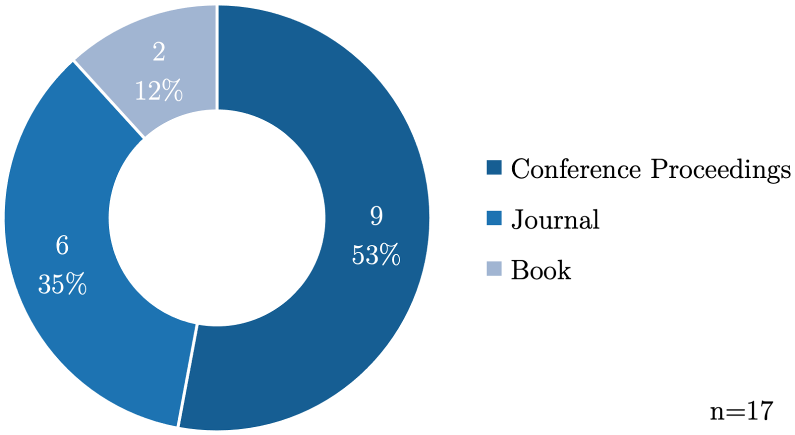


Figure 2.21: Documents source types

Figure 2.22 reports the main fields of application identified. By fields of application of Industry 4.0 technologies in maintenance is meant the industry environment which has been mentioned and considered in the 17 selected studies by the systematic literature review.

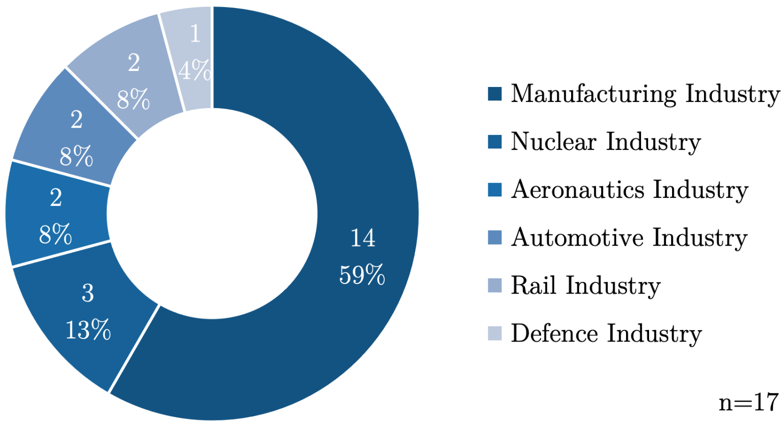


Figure 2.22: Field of industry application

It must be emphasised that some of the 17 selected studies mention several industries, which is reflected in the absolute results in brackets. The biggest slice of the chart is taken by the manufacturing industry. This is not surprising, since this is where the origin of Industry 4.0 lies. The studies also reveal that Industry 4.0 technologies in the maintenance sector are applied in other industries, including the rail industry. However, the research share in this field represents only a very small proportion related to the rail industry.

Stellenbosch University https://scholar.sun.ac.za

2.4.3 Identified Industry 4.0 Technologies Application in Maintenance

The systematic literature review has revealed that nine emerging technologies are essentially used in maintenance. The four technologies big data & analytics, Internet of Things (IoT), cloud computing and Virtual Reality (VR) are cited most frequently. Figure 2.23 shows that these are outlined in seven of the 17 documents. Following closely are Augmented Reality (AR) and cyber security with six appearances each. Furthermore, Cyber–physical Systems (CPSs), Artificial Intelligence (AI) and additive manufacturing are mentioned as promising technologies in maintenance. For the study the technologies AR and VR are reviewed collectively and classified as one technology. In the following sections, all eight technologies that have been identified are discussed in more detail.

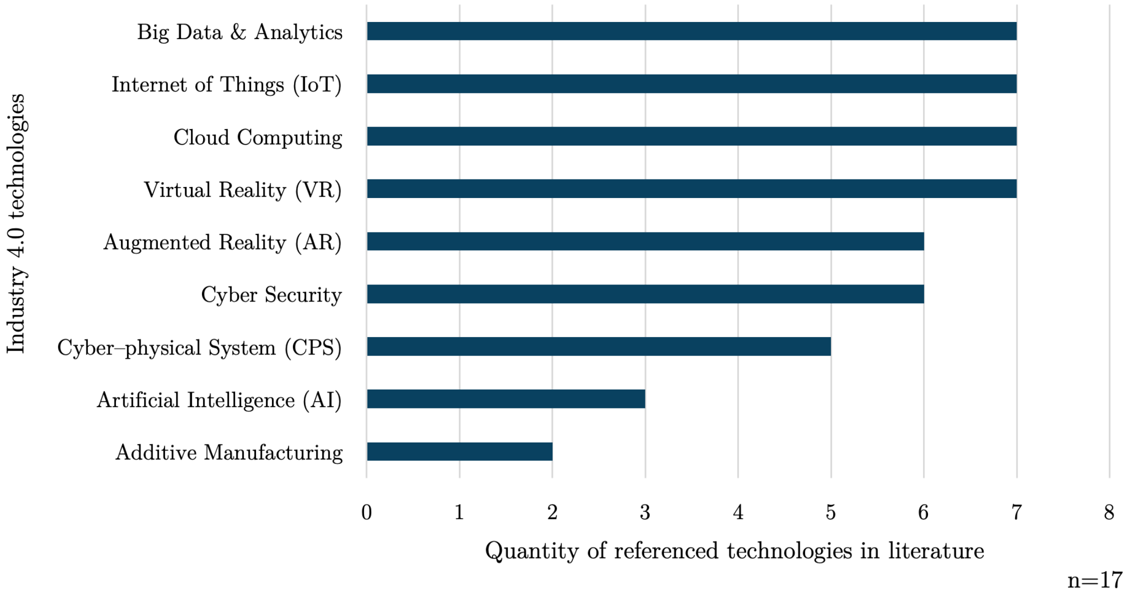


Figure 2.23: Industry 4.0 technologies applied in maintenance

2.4.3.1 Big Data and Analytics

In simple terms, big data is data that cannot be stored in a single storage unit. “Big” here depends on the size of the organisation and is therefore relative. In principle, it is a matter of finding new values within and outside of conventional data sources. Big data can be structured, unstructured or viewed as a stream. Through data analysis, it is possible to gain new insights of the data and discover new possibilities (Sharda et al. 2014, p. 28). Big data is characterised by the following different V’s (Sharda et al. 2014, pp. 547–549; Roy et al. 2016, p. 680; Jantunen et al. 2017, p. 345):

- *Volume* defines the enormous amount of data that is collected in companies today. This is due to the increased use of sensors or data collected using technologies such as Radio Frequency Identification (RFID) or Global Positioning System (GPS). Due

Stellenbosch University https://scholar.sun.ac.za

to the large volume of data and its complexity, storage and analysis would not be possible with conventional methods of data processing.

- *Variety* refers to the variety of data types and data sources. There are several different types of data such as text documents, videos, audio files and many more. It is estimated that about 80 percent of the data of organisations are in an unstructured or semi–structured format. However, big data makes it possible to sort and order this data and to identify connections.
- *Velocity* refers to the speed at which data is acquired, stored and analysed. Technologies such as RFID, automatic sensors, GPS devices or smart meters process data in almost real time. To react quickly is crucial for companies.
- *Veracity* denotes the accuracy, quality and truthfulness of data. The primary focus is on data quality.
- *Variability* refers to data whose meaning is constantly changing. This can be due to daily, seasonal or event–triggered peak data loads.
- *Value* indicates the added value of the data for the company. By analysing the large and rich amounts of data, organisations have better insight and can take more appropriate decisions. This allows them to achieve higher value proposition.

Data produced in asset management of rolling stock can be described in terms of the six V's. Due to the high complexity of rail vehicles and the resulting possibility of monitoring multiple components, a large amount of data can be produced in a short time. Besides, rail operators not only have access to data from the component monitoring of rail vehicles but also from the infrastructure such as tracks or catenaries. The technological ability to collect and evaluate data in real time makes it useful to monitor rail vehicles. This ensures rapid intervention in the event of malfunctions. Nevertheless, the large amount of data generated by rail vehicles means that the veracity of the data must be ensured. The validity of rail vehicle data suffers if, despite a large volume of data, these data cannot be sufficiently verified. Ultimately, the rail operator can increase the value proposition significantly by using big data, as it provides a better insight into the vehicle fleet and enables them to take appropriate measures.

According to Yang and Lin (2019, pp. 332–333) and Sahal et al. (2020, pp. 138–139), a big data platform has to consider different aspects to enable predictive maintenance. Data must be collected, analysed, stored and queried. Big data analysis allows the generation of new knowledge and the improvement of the accuracy of predictions. This is achieved by evaluating correlations between service events, component degradation and component design. However, it should be noted that the implementation of big data in maintenance systems results in high system complexity (Roy et al. 2016, p. 680).

Stellenbosch University https://scholar.sun.ac.za

2.4.3.2 Internet of Things (IoT)

Kostoláni et al. (2019, p. 131) define the IoT as an information network that is composed of various physical objects such as sensors, machines or cars and enables their interaction and cooperation. Hence, the difference between a CPS becomes visible. IoT provides the connection between assets with the help of the internet, whereas a CPS is more about the integration of technological devices with physical objects. CPSs form the basis for the IoT, since without the physical objects no information reception would be guaranteed. The IoT now creates the conditions for the remote availability of data from CPSs (Kostoláni et al. 2019, p. 131). Jasiulewicz-Kaczmarek and Gola (2019, p. 94) also highlight the role of IoT in terms of infrastructure. In maintenance 4.0, a IoT infrastructure is required, which creates a wireless connection of objects for the transmission of data to the data centre. By creating such an infrastructure with the IoT, asset management can be improved. Jasiulewicz-Kaczmarek and Gola (2019, p. 94) list the following five points in this context:

- *Greater adoption of predictive maintenance*: Application of IoT for the use of predictive maintenance to improve maintenance strategies.
- *Real–time data analysis*: Data availability in a virtual network for improved data analysis.
- *Precise performance indicators*: Automatic calculation of key performance indicators like MTTR or MTBF by the system itself.
- *Remote assets*: Remote generation of individual work orders by the assets in the maintenance system.
- *Recommended repair actions*: Failure data can be used in real time for automatic repair actions.

Jantunen et al. (2017, p. 345) emphasise that the IoT is not only useful for equipping new assets but also for upgrading and improving old assets. Such an upgrade also provides the possibility to monitor components of older assets by the use of sensors and to apply more modern maintenance strategies. Thus, with new as well as with old assets, IoT technologies can be used to collect and evaluate large amounts of data in real time to identify problems and derive appropriate measures (Jantunen et al. 2017, p. 345; Jasiulewicz-Kaczmarek and Gola 2019, p. 95).

2.4.3.3 Cloud Computing

Cloud computing provides the usage of distributed processing resources which can be accessed upon request. It is divided into software, which is provided via the internet or

Stellenbosch University https://scholar.sun.ac.za

can only be used as an interface, and hardware, which supplies these services in data centres. The current trend of IT services is to move away from local data storage towards large data centres (Ashjaei and Bengtsson 2017, p. 1562). This has become worthwhile because improved methods are now available for analysing large and varied data. Jantunen et al. (2017, p. 346) justify this with improved mathematical tools for the analysis as well as with the provision of platforms that enable the handling of the complex data. Since it is not economical for all companies to provide these computing resources, there is the possibility of hiring these resources. Consequently, it is also possible for companies without their own cloud infrastructure to generate higher computing power. In this case, billing is based on the pay–per–use method, for example related to the used computing power, carried out transactions, used bandwidth, transferred data or consumed storage space (Jantunen et al. 2017, p. 346). Ashjaei and Bengtsson (2017, p. 1562) and Kostoláni et al. (2019, p. 133) emphasise the current trend of fog computing. The core idea of fog computing is to bring the intelligent and processing units close to the generation of data. This is intended to avoid data transfer for analysis in the cloud. This brings all the advantages of cloud computing closer to the service user. As a result, more efficient data access and faster calculation and networking take place. Basically, Ashjaei and Bengtsson (2017, p. 1563) and Kostoláni et al. (2019, p. 133) name three essential layers which a platform for cloud computing should consist of:

- *Node layer* includes all the physical devices, which communicate and exchange data with the services provided by the fog layer.
- *Fog layer* composes of special computers functioning as gateways and offering fog services.
- *Cloud layer* exemplifies the location for storage, analysis and evaluation of data.

The integration of such a platform enables smart maintenance management. On the node layer, asset data is collected via sensors to monitor the condition of the assets. Operators receive the data on smart devices and can access the current information. Maintenance management tasks for low latency and high reliability requirements are performed on the fog layer, otherwise on the cloud layer (Jantunen et al. 2017, pp. 1563–1564).

2.4.3.4 Augmented Reality (AR) and Virtual Reality (VR)

AR and VR are technologies which support smart maintenance practices. VR is about creating a digital world in which the user can be immersed and interact (Jasiulewicz-Kaczmarek and Gola 2019, p. 93). In contrast hereto, in AR a superposition of digital objects occurs into the real world. This allows the user to see digital objects projected into the real world (Cachada et al. 2018, p. 145; Jasiulewicz-Kaczmarek and Gola 2019, p. 93). Cachada et al. (2018, p. 145) conclude that AR complements rather than replaces

Stellenbosch University https://scholar.sun.ac.za

reality. According to Cachada et al. (2019, p. 3796) the other main characteristics of AR are the real–time interaction as well as the visualisation and interaction in 3D context. For the application of AR different types of displays are used such as head–mounted displays, hand–held displays, see–through displays or projectors (Cachada et al. 2019, p. 3796). There are various application scenarios in maintenance. Maintenance tasks can be given directly to the worker through AR technologies. They can also perform a supporting task during the execution of the task by integrating required information into the working environment. Besides, AR technologies can be used for training purposes in maintenance (Jasiulewicz-Kaczmarek and Gola 2019, p. 94). In the field of training, the use of VR has also been applied and has proven its potential. In contrast to classical PC–based systems, VR is characterised by its high degree of immersion and subjective presence (Linn et al. 2017, p. 2). This reveals the more advanced maintenance training compared to traditional maintenance training, which is characterised by 2D materials such as pictures or manuals (Guo et al. 2020, p. 529). A further field of application of VR as well as of AR is remote maintenance. Linn et al. (2017, p. 2) present a concept for remote maintenance realised using VR. A live stream from the actual location is generated by a 360–degree camera and transmitted directly to the technician via VR glasses. This enables the technician to perform a visual inspection to identify potential problems without being on site. Furthermore, Guo et al. (2020, p. 529) note that the use of VR is valuable in the early design phase of components. With VR it is possible to visualise and simulate components to detect possible design errors at an early stage and to reveal assembly or maintenance weaknesses. However, what still needs to be improved when using VR in maintenance is the user–friendliness as well as the issues of portability and robustness for use in an industrial environment (Guo et al. 2020, p. 534).

2.4.3.5 Cyber Security

A desired consequence of Industry 4.0 is the increased connectivity and use of standard communication protocols (Kostoláni et al. 2019, p. 132). In Industry 4.0 the IoT forms the bridge between the digital world, including data analysis, and the physical world (Tuptuk and Hailes 2018, p. 93). Therefore, the IoT is a major challenge in the field of security. Particularly due to the sensitivity of data, for example during transmission and analysis, as well as the access to the control systems of assets, it is imperative to protect against external intrusion (Ashjaei and Bengtsson 2017, p. 1563). The basic principle of IT systems is usually defined by the three terms confidentiality, integrity and availability (Roy et al. 2016, p. 683; Tuptuk and Hailes 2018, p. 97). Confidentiality guarantees that assets can only be accessed by authorised persons, whereas integrity is about protecting assets against unauthorised changes. Eventually, availability ensures that assets are available to authorised persons at all approved times (Tuptuk and Hailes 2018, p. 97). Not only are IoT systems currently a topic in the field of cyber security but in accordance with

Stellenbosch University https://scholar.sun.ac.za

Roy et al. (2016, pp. 683–684) so also are CPSs. Three main cyber security threats are identified here. On the aware execution layer it would be possible, for instance, to carry out physical attacks on sensors and actuators. In the data transport layer, the threat is in the area of network architecture and the application control layer focuses on the storage of user data. This illustrates that threats exist not only on the software level but also on the hardware level (Roy et al. 2016, pp. 683–684). The danger of cyberattacks is visible in AI–based prognostic maintenance systems. Here it is important to differentiate whether these are natural failures or failures which are due to cyberattacks (Ochella and Shafiee 2019, p. 3430). To protect against attacks, there are static and active defence solutions. The static defence methods include regulations derived from industry standards and guidelines. For active defence there are cryptographic countermeasures for the detection and prevention of intruders. Here, encryption, identity and context–based access controls are integrated for protection (Tuptuk and Hailes 2018, p. 101). With the increasing autonomy of systems, the substantial challenge is to find suitable safety experts. Therefore companies are mostly dependent on third–party suppliers (Tuptuk and Hailes 2018, p. 104).

2.4.3.6 Cyber–physical System (CPS)

In accordance with Roy et al. (2016, p. 682) and Yang and Lin (2019, p. 331) a CPS is an essential core technology for Industry 4.0 and forms the basis for Industry 4.0. CPSs are systems which connect physical objects through networks. They form the technological driver for cooperation in organisations (Roy et al. 2016, p. 331). CPSs are equipped with sensors, actuators, a user interface and functions. The functions perform all tasks related to data collection, processing and output. Special about a CPS is that the sensors and actuators are smart embedded systems in the CPS. The novelty of a CPS lies in the use of the internet, software services and the application of open and global standards. This results in the opportunity for the availability of different applications in different areas of the organisation. Furthermore, Figure 2.24 illustrates the horizontal and vertical networking of a CPS. On the horizontal level communication with CPSs happens on the same level. Vertically, communication occurs with superordinate or subordinate systems (Lucke et al. 2014, p. 13). The autonomous communication of objects enables the common goal attainment within a CPS. Information is obtained via the CPSs, which can record the current status of an object in real time and subsequently form the basis for big data analytics (Roy et al. 2016, p. 331). Besides enabling big data analysis, it integrates IoT and cloud computing (Yang and Lin 2019, p. 331). Referring to maintenance, a CPS influences the prediction and trigger of service activities, enables remote diagnosis and can replace or optimise field service activities (Roy et al. 2016, p. 331).

Stellenbosch University https://scholar.sun.ac.za

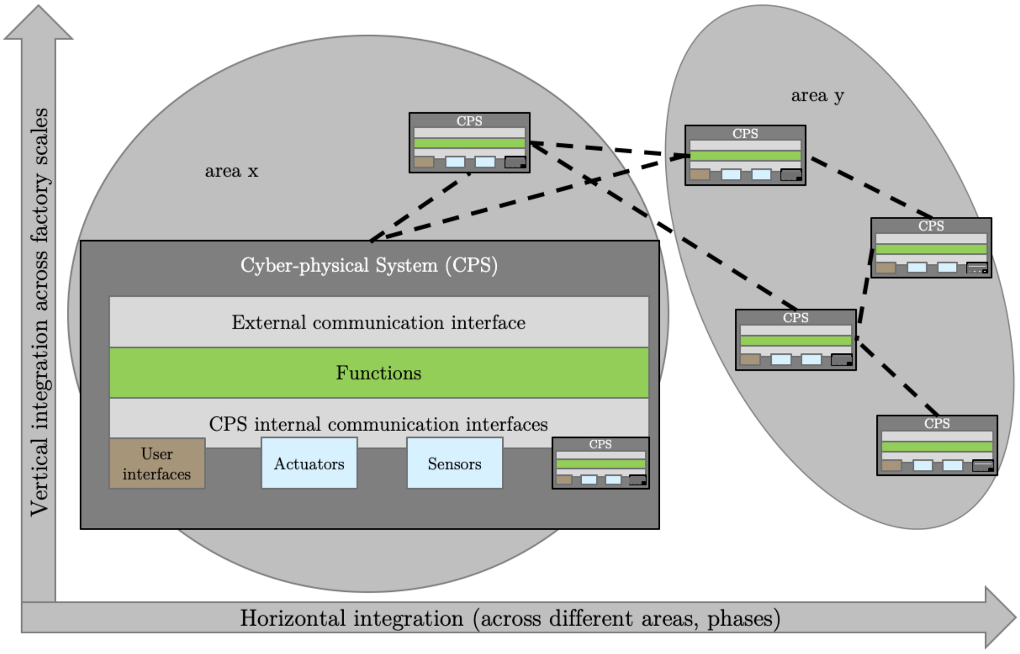


Figure 2.24: Structure of CPSs (Lucke et al. 2014, p. 13)

2.4.3.7 Artificial Intelligence (AI)

Ochella and Shafiee (2019, p. 3424) define AI as "the ability of a machine to display human–like intelligence, especially in response to its environment". In other words, the idea is to enable assets to carry out tasks that are contemplated by humans as smart or intelligent (Wang and Wang 2017, p. 3). According to Sharda et al. (2014, pp. 475–476), the following abilities, are considered to be signs of intelligence:

- Learning or understanding from experience
- Making sense out of ambiguous or contradictory messages
- Responding quickly and successfully to a new situation
- Using reasoning in solving problems and directing conduct effectively
- Dealing with perplexing situations
- Understanding and inferring in a rational way
- Applying knowledge to manipulate the environment
- Thinking and reasoning
- Recognising and judging the relative importance of different elements in a situation

Stellenbosch University https://scholar.sun.ac.za

AI is often used where large volumes of data are produced at high velocity. Traditional statistical methods are usually too slow for a permanent application. In such environments, AI techniques can show their strengths by recognising patterns in large data volumes (Ochella and Shafiee 2019, p. 3424). In principle, AI algorithms can be divided into three classes of learning: unsupervised, supervised and reinforcement (Figure 2.25). In reinforcement learning, the learning agent is trained to be based on a reward system, depending on whether a prediction is correct or false. Therefore, this type of algorithm is useful in maintenance decision support systems, where the results of maintenance activities are returned to the learning agent in the form of rewards. This helps to improve decision–making in the future. In supervised learning, the algorithm is given sample datasets and can be divided into classification and regression. If the output variable is continuous, it is a regression problem. In the case of discrete values, it is called a classification problem, where the target variable can only contain a predefined number of values. In contrast to supervised learning, unsupervised learning does not provide any data that has been previously classified. Therefore, this type of algorithm is particularly suitable for clustering to recognise patterns in data or for Artificial Neural Networks (ANNs) (Ochella and Shafiee 2019, p. 3429).

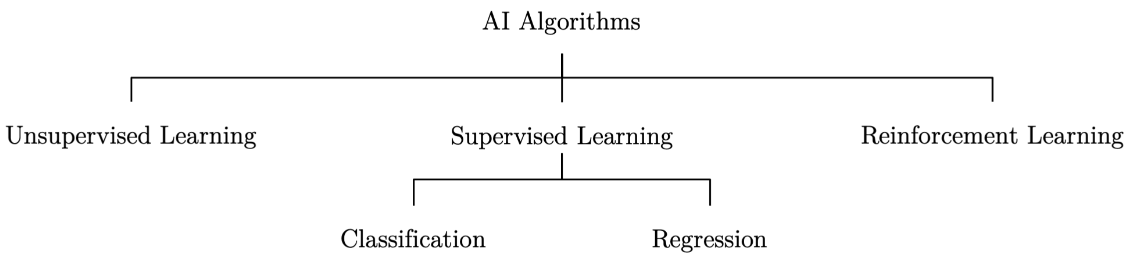


Figure 2.25: Classification of AI algorithms according to Ochella and Shafiee (2019, p. 3427)

In particular, ANNs are used in maintenance (Ochella and Shafiee 2019, p. 3426). These are based on the mechanisms of the human biological brain. Because of the biological network structure, the human brain can process data and information quickly and accurately. ANNs simulate these processes of the human brain and are particularly suitable for non–linear applications. Even in changing environments ANNs have the possibility to adapt. Therefore, they can solve difficult problems and make the right decisions at the same time. For the application of ANNs artificial, software–based computer technologies are used, which simulate the functions of neurons in the brain. The generated neural network receives the data, analyses it and then decides whether the determination is correct. If the output is incorrect, the connections between the neurons are modified by the algorithm. The more the ANN is fed with data, the better the connections between the neurons become so that correct decisions are made (Wang and Wang 2017, pp. 3–4). From a structural point of view, deep learning is a kind of ANN. The major difference between ANNs and deep learning algorithms is that the features are not designed by developers, but are rather self–learned from the data through a generalised learning approach. Hence,

Stellenbosch University https://scholar.sun.ac.za

deep learning has also found application in maintenance. Due to the high data generation by monitoring assets, deep learning can be used to identify patterns for error prediction. Deep learning allows to information to be found in the data which would otherwise have been ignored and would have led to failures (Wang and Wang 2017, p. 6). In the field of fault diagnosis, ANNs have become established (Wang and Wang 2017, p. 6; Ochella and Shafiee 2019, p. 3426). They are particularly useful in fault detection and classification. However, the biggest barrier currently lies in the compatibility of older systems with newer ones, and the way data is generated in companies varies. This leads to the fact that only customised AI–based prognostic maintenance systems can be established (Ochella and Shafiee 2019, p. 3429).

2.4.3.8 Additive Manufacturing

Additive manufacturing can be seen as complementary to the traditional cutting machines like turning or milling. Meanwhile, there are different additive manufacturing processes available. Ceruti et al. (2019, p. 517) classify them according to the raw material used in the respective additive process. Fused Deposition Modelling (FDM) or Stereolithography (SLA) use liquid material. With FDM, the material is supplied through a nozzle, melted there and finally applied in layers on a building platform. A laser is used to harden the photosensitive liquid resin in layers for SLA. In contrast, Selective Laser Sintering (SLS) and Electron Beam Melting (EBM) use discrete particles. Here, a powdery raw material is melted locally by a laser. With these two processes it is possible to produce high–strength materials. Ultimately, solid sheets are used for Laminated Object Modelling (LOM). A 3D object is created by bonding adhesive–coated thin sheets of paper, plastic or laminates. It is obvious that each of these processes has its own specific field of application. The special attraction of additive manufacturing is the maximum design freedom of complex shapes. So they are not limited like the conventional production technologies and can even produce organic freeform geometries (Roy et al. 2016, p. 676). In maintenance there are many possible applications for additive manufacturing. As soon as digital models are available, parts can be manufactured. If a topology is optimised in advance and lattice–based structures are used, even complex component geometries can be produced, which cannot be realised with chip removal processes. Furthermore, additive manufacturing can contribute to the production of spare parts. Consequently, the storage of spare parts is reduced in warehouses. A further possibility is to exchange digital models between the producers. This saves transport routes and allows the required parts to be produced directly on site. Optimised spare parts can also be employed for maintenance. In this case, already optimised digital models are utilised for component production with additive manufacturing. Ceruti et al. (2019, pp. 520–521) mention all these possibilities, but they also point out that legal regulations currently still limit this development and additional certifications are necessary.

Stellenbosch University https://scholar.sun.ac.za

2.4.4 Benefits Implementing Industry 4.0 Technologies in Maintenance

The systematic literature review revealed seven main benefits associated with the implementation of Industry 4.0 technologies in maintenance. An overview of the benefits with the corresponding sources is presented in Table 2.3.

Table 2.3: Implementation benefits of Industry 4.0 technologies in maintenance

Benefits	**Sources**
Increase in the system reliability	Roy et al. 2016, p. 685; Ashjaei and Bengtsson 2017, p. 1568; Jantunen et al. 2017, p. 346; Linn et al. 2017, p. 2; Wang and Wang 2017, p. 7; Cachada et al. 2018, p. 145; Tuptuk and Hailes 2018, p. 97; Jasiulewicz-Kaczmarek and Gola 2019, p. 94; Kostoláni et al. 2019, p. 134; Guo et al. 2020, p. 530
Cost reduction	Sharda et al. 2014, p. 554; Roy et al. 2016, p. 682; Jantunen et al. 2017, p. 346; Linn et al. 2017, p. 1; Wang and Wang 2017, p. 7; Ceruti et al. 2019, p. 518; Jasiulewicz-Kaczmarek and Gola 2019, p. 94; Guo et al. 2020, p. 529; Sahal et al. 2020, p. 147
Time savings	Roy et al. 2016, p. 680; Jantunen et al. 2017, p. 345; Linn et al. 2017, p. 1; Cachada et al. 2019, p. 3798; Ceruti et al. 2019, p. 525; Jasiulewicz-Kaczmarek and Gola 2019, p. 94; Guo et al. 2020, p. 528; Sahal et al. 2020, p. 141
Gain a competitive advantage	Lucke et al. 2014, p. 36; Jantunen et al. 2017, p. 346; Linn et al. 2017, p. 2; Wang and Wang 2017, p. 9; Cachada et al. 2018, p. 146; Cachada et al. 2019, p. 3795; Jasiulewicz-Kaczmarek and Gola 2019, p. 94
Increase in the quality assurance	Roy et al. 2016, p. 682; Linn et al. 2017, p. 1; Cachada et al. 2018, p. 145; Ceruti et al. 2019, p. 518; Kostoláni et al. 2019, p. 134; Sahal et al. 2020, p. 146
Increase in the transparency of assets	Roy et al. 2016, p. 683; Jantunen et al. 2017, p. 345; Cachada et al. 2018, p. 140; Jasiulewicz-Kaczmarek and Gola 2019, p. 93; Kostoláni et al. 2019, p. 134
Increase the safety of employees	Roy et al. 2016, p. 685; Jantunen et al. 2017, p. 346; Wang and Wang 2017, p. 6; Guo et al. 2020, p. 533

The most common argument is that the use of emerging technologies increases the system reliability of an asset. This is because the use of these technologies reduces downtime, which helps to increase reliability. Besides, by using them, the health status of the as-

Stellenbosch University https://scholar.sun.ac.za

sets is monitored, which also has a positive effect on reliability. Emerging technologies also have a major impact on companies' costs. Often the acquisition costs are somewhat higher, although the sensors, actuators and other components become more affordable. Nevertheless, companies can save costs in the long term. In addition to cost savings, there are also advantages in time. Time savings are achieved, for example, through more efficient processes, faster extraction of information, faster identification of problems or shorter transport routes. As a result, companies have the opportunity to improve their performance and gain a competitive advantage over their competitors. Advantages of quality assurance are primarily related to the improvement of maintenance processes. These can be optimised especially through the use of CPSs, AR or VR. With the aid of CPSs, big data, the IoT and the cloud, it is possible to detect unknown errors, to create a history of the assets and thus to increase the transparency of the assets. Lastly, technologies such as AR or VR improve the safety of personnel while carrying out maintenance.

2.4.5 Summary of Industry 4.0 Technologies

The third research field essential for this study is Industry 4.0 technologies. A systematic literature search reveals the nine most important Industry 4.0 technologies for application in maintenance. These emerging technologies are discussed in detail and the resulting benefits are outlined.

2.5 Technological Maturity

According to the Oxford Dictionary (Hornby 2005, p. 948) the term maturity is defined as a "state of being fully grown or developed". The Merriam–Webster Dictionary (Mish 2004, p. 443) specifies the term similarly as "the quality or state of being mature". This means that the term maturity describes the degree of perfection in a specific area or field. In the context of companies, the term readiness is frequently used as a synonym for the term maturity. According to the Oxford Dictionary (Hornby 2005, p. 1255) readiness describes "the state of being ready or prepared for something". Hence, the terms maturity and readiness can be distinguished. Schumacher et al. (2016, p. 162) specify the distinction by pointing out that the readiness valuation happens prior to the maturity valuation. It is thereby determined whether a company is ready to execute a certain action. On the contrary, the degree of maturity describes the state of development in relation to a task (Pacchini et al. 2019, p. 1). For instance, the maturity level can be used to analyse a particular process in a company. The evaluation can subsequently reveal the current status and improvement measures can be taken. Additionally, a way for the future can be demonstrated.

Stellenbosch University https://scholar.sun.ac.za

2.5.1 Maturity Models

Numerous maturity models can be identified in the literature. Several maturity models exist in different disciplines like economics, the natural sciences or humanities (Kohlegger et al. 2009, p. 51). These models are usually a supporting instrument to evaluate and ascertain the present state. Taking a closer look at the area of maturity models in the field of Industry 4.0, there are models from leading consulting companies, industrial federations and the scientific field. These models usually differ in their complexity, their dimensions as well as in their industry focus. Not considered for this study were the models from leading consulting companies due to their commercialised and generic nature. Since the scientific literature often does not clearly distinguish between the terms "maturity" and "readiness", readiness models are also included in the analyses. Finally, the following three models are selected for closer examination due to their appropriate scope and structure:

- *Model 1*: Industry 4.0 maturity index (Schuh et al. 2020)
- *Model 2*: A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises (Schumacher et al. 2016)
- *Model 3*: The degree of readiness for the implementation of Industry 4.0 (Pacchini et al. 2019)

2.5.2 Comparison of Maturity Models

In this section, the maturity models are discussed in more detail. Since the introduction and implementation of Industry 4.0 in companies is a complex and time–consuming task, all three models are divided into several stages. This enables a step–by–step transformation, which usually has to be planned over years. An overview of the comparison is provided in Table 2.4.

The model of Schuh et al. (2020) is divided into six development stages. The first stage starts with "computerisation" and ends with stage six "adaptability". The first two stages refer to digitalisation. However, in the following four stages the step–by–step conversion to Industry 4.0 begins. All the models consider the degree of maturity in various so–called dimensions. Each dimension is further subdivided. The model of Schuh et al. (2020) is categorised into the four structural areas; resources, information systems, culture and organisational structure. Finally, each of these four areas is clustered into two principles. This is required to determine the necessary competencies for the respective maturity level. For example, the category "information systems" is divided into information processing and integration. This subsequently results in the maturity level for the category "information systems". This procedure is then applied individually for the various functional areas

Stellenbosch University https://scholar.sun.ac.za

Table 2.4: Comparison of maturity models in the context of Industry 4.0

Description	Model 1	Model 2	Model 3
Research Context	Industry 4.0 maturity	Industry 4.0 maturity and readiness	Industry 4.0 readiness
Dimensions	Resources Information systems Culture Organisational structure	Strategy Leadership Customers Products Operations Culture People Governance Technology	Technology
Items	Eight items grouped into the four dimensions	62 items grouped into the 8 dimensions (only examples are provided)	Eight enabling technologies
Maturity levels	1. Computerisation 2. Connectivity 3. Visibility 4. Transparency 5. Predictive capacity 6. Adaptability	1. Complete lack Levels 2 – 4 are not described in detail 5. State of the art	1. Embryonic 2. Initial 3. Primary 4. Intermediate 5. Advanced 6. Ready

such as development, production, logistics, service and marketing/sales to determine the maturity level.

Compared to Schuh et al. (2020) the model of Schumacher et al. (2016) consists of five maturity levels. Level one represents a complete lack of characteristics supporting the concept of Industry 4.0 where level five indicates the prerequisite characteristics. Furthermore, the model is broken down more finely and considers eight different dimensions (Table 2.4). From the dimensions it can be seen that an attempt is made to draw a holistic picture of the company's situation. The dimensions are split into 62 assessment items, which are not further discussed in detail. For each item, a question with a Likert–scale from one (not distinct) to five (very distinct) is applied. Based on the item's questions the maturity level of each dimension is calculated and can be summarised for the company itself in the final step.

Pacchini et al. (2019) refer in the model to six degrees of readiness. These degrees are split up into different percentages. The lowest degree of readiness is between zero and ten percent and is called "embryonic". The following degree of readiness is between ten and 25 percent. Analogously, this scheme is continued to the highest degree of readiness, which is called "ready". Compared with the other models, that of Pacchini et al. (2019) refers

Stellenbosch University https://scholar.sun.ac.za

to only one dimension: technology. This dimension is further differentiated into eight enabling technologies of Industry 4.0. Six requirements are defined for each technology. Out of the 48 prerequisites, only examples are provided in the paper. The prerequisites from the foundation for evaluating the degree of readiness are based on a questionnaire with a scale of 0 to 3 for each enabling technology. In the final instance, the degree of readiness is determined for each technology.

In summary, it is evident that all three models are practice–oriented. All three are intended to assist companies in identifying a possible path for Industry 4.0. All three also target manufacturing companies. Schuh et al. (2020) and Schumacher et al. (2016) include various parameters when looking at the company, which can be identified by numerous dimensions. On the other hand, Pacchini et al. (2019) focus their approach exclusively on the technological requirements concerning Industry 4.0. This results in a different approach, which is more detailed in the dimension of technology than the other two models. Finally, it must be critically added that particularly for the approaches of Schumacher et al. (2016) and Pacchini et al. (2019) detailed information on the approaches is not fully available.

2.5.3 Summary of Technological Maturity

The fourth research field essential for this study is technological maturity. It starts with a terminology definition and then investigates ways of describing the maturity level of companies. For this reason, different maturity models are examined concerning Industry 4.0 and the differences between the models are highlighted.

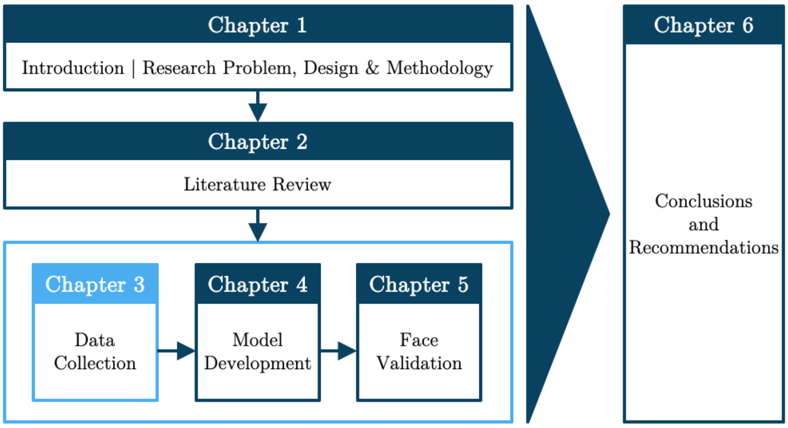
2.6 Chapter Summary

This chapter serves to elaborate a basic understanding of the important fields which are necessary for this study. It starts by classifying the rail system in a more detailed way. The main mechanical components of electric passenger rail vehicles are identified, which can be grouped into operational relevant systems and equipment for passenger rolling stock and the current maintenance strategies in the rail system are explained. Besides, a systematic literature review identifies the currently nine most promising emerging technologies in maintenance and their associated benefits. In conclusion, different Industry 4.0 maturity models are analysed, which enables companies to determine their current maturity level.

Stellenbosch University https://scholar.sun.ac.za

Chapter 3

Industry 4.0 Technology Maturity Assessment



The objective of this chapter is to conduct an online survey with subject matter experts. The chapter begins with the design of the survey. This is followed by an explanation of the process which is pursued. The process consists of defining the objective, the preparation for the survey and conducting the survey. Thereafter, the findings are analysed and discussed.

3.1 Survey Design

Sue and Ritter (2012, p. 3) define surveys as "a system for collecting information". To ensure that all aspects of the survey process are considered the researcher has to take a holistic approach. Therefore, the process starts with the definition of the objectives and concludes with the data analysis and the survey findings. An online survey is considered to be a suitable method for this study. With an online survey, it is possible to contact many people within a short period of time and get answers just as quickly. Not only is the speed important, but also the economic aspects. Finally, it should be mentioned that online surveys have a wide geographical reach. This implies that with a survey it is relatively

Stellenbosch University https://scholar.sun.ac.za

easy to address people worldwide. This is of particular interest to this study, as the effects of the degree of maturity are analysed and it is important to obtain a cross–regional assessment.

The survey design is based on the process proposed by Sue and Ritter (2012). First, the research objectives are defined. This is followed by the planning phase of the survey. Here the survey software is chosen, ethical and legal problems of a survey are considered and the sampling method is selected. Next, the survey questions are determined and their sequence is defined. Once these sub–processes are completed, the survey can be carried out. After finishing the survey, the results are evaluated and the survey results are reported.

3.2 Survey Objectives

First of all, it is important to define the survey objectives. The primary objective of this survey is to empirically evaluate the effects of the maturity level for the implementation of Industry 4.0 technologies in maintenance as well as to quantify the benefits of implementing Industry 4.0 technologies as determined by the literature review. Therefore, the survey addresses the third and fourth secondary research questions as well as the corresponding research objectives six and seven (Table 1.2).

3.3 Survey Planning

The survey planning phase is concerned with choosing the appropriate survey software and considering the ethical and legal issues. LimeSurvey is used as the survey software because of its ease of survey creation and administration, the clear evaluation and the possibility of data export. According to Sue and Ritter (2012, p. 3), the ethical and legal problems are in essence for briefing the participants about the survey and assuring them of confidentiality and anonymity. The survey within the scope of this study is carried out anonymously and the data is only used for this purpose and not passed on to third parties. This is also communicated to the participants at the beginning of the survey. The documents regarding the research ethics committee approval and the letter of electronic consent are provided in Appendix A.1 and Appendix A.2. Convenience sampling is the method applied in this study. In this method, a random sample is taken from the population. The population for this study includes all persons who are subject matter experts in the maintenance of electric rolling stock in passenger transport.

Stellenbosch University https://scholar.sun.ac.za

3.4 Questionnaire Design

When designing a questionnaire it is significant to first define the survey questions. There are different possibilities for the question formats. For this study open–ended questions and closed–ended questions are employed. The closed–ended questions make up the majority of the questions. The reasons for this are for better evaluation of the questions as well as a higher probability of convincing participants to participate in the survey. The sequence of questions is then determined. According to Sue and Ritter (2012, p. 2), it is advisable that the survey starts with simple questions and then follows with the topics in a logical order. The questionnaire for this survey is divided into four parts, which are explained in more detail in the following sections. A detailed overview of the survey can be found in Appendix A.3.

3.4.1 Part 1: Welcome Screen

The welcome screen is kept very simple and clear. The participant has the option to answer the survey either in English or in German. First, there is a short introduction, as well as the explanation that the survey is carried out within the scope of the thesis. Afterwards, the participant is briefed about the topic of the survey and the purpose of the survey is explained. The participant also receives information about the approximate duration of the survey and confirmation that all data is collected, stored and evaluated anonymously. A status bar allows the participant to see his current progress in completing the survey, which primarily serves as a motivational tool.

3.4.2 Part 2: Digitalisation in the Rail Industry

The subsequent section is about introducing the participant to the topic. For this reason, the first three questions deal with digitalisation in the rail industry in general. First, the participants are asked to what extent the topic of digitalisation is already being discussed in the rail industry and whether digitalisation has already found its first applications. Besides, it is interesting to know what the maintenance experts' assessment of digitalisation is regarding different business areas. In other words, what is the level of performance of maintenance in the area of digitalisation compared to the other business areas. Through these questions, the participant is slowly introduced to the topic of digitalisation and gets the first insight into the survey.

Stellenbosch University https://scholar.sun.ac.za

3.4.3 Part 3: Implementation of Industry 4.0 Technologies in Maintenance

This section of the survey aims to obtain more detailed information on the use of Industry 4.0 technologies in rolling stock maintenance. The first question to be considered is which of the Industry 4.0 technologies identified in Section 2.4.3 are of greatest importance in rolling stock maintenance. The purpose is to investigate whether these technologies are also applied in the rail industry, since the literature review revealed that these technologies are primarily implemented in the manufacturing industry. It wants to ascertain whether the technologies are already an integral part of the rail industry or not. If the technologies are already in operation, it is of interest where the rail industry applies them and for which rail systems. For example, whether they are utilised in the planning and organisation of maintenance or rather for monitoring the systems. For the rolling stock components, all main components identified in Section 2.2.3 are listed for selection. Ultimately, it is important to determine what consequences have resulted from the implementation. On the one hand, it is necessary to quantify the positive effects identified by the literature search in Section 2.4.4. On the other hand, it is essential to verify which challenges the rail industry has to struggle with during the implementation and the impacts or effects which have resulted from the implementation.

3.4.4 Part 4: Technological Maturity Level

After the section about the implementation of Industry 4.0 technologies in maintenance; the focus for this part lies on the technological maturity level. Here it is crucial to determine the level of maturity experienced by subject matter experts in the rail industry, especially concerning rail vehicles. For each technology identified in Section 2.4.3 three questions are asked. Because of time limits and limitations in the scope of this work, these questions concentrate only on the three main prerequisites. These are derived from the systematic literature review findings. Each question can be assigned a value from one to five. The value of one indicates that no realisation has occurred in the rail industry, whereas five implies that a complete realisation has occurred in the rail industry. Table 3.1 provides an overview of the respective technologies and their main prerequisites.

Stellenbosch University https://scholar.sun.ac.za

Table 3.1: Enabling technologies and their main prerequisites

Technologies	Main prerequisites
Big data & analytics	Infrastructure to collect and store data
	Digital secure systems for data organisation
	Know–how for data handling
Internet of Things	Network to share and use data
	Creation of virtual image of the equipment
	Embedded systems for information processing
Cloud computing	Broadband internet access
	Cloud capable IT infrastructure
	Software and data compatible for the cloud
Augmented Reality & Virtual Reality	Display virtual objects
	Supporting hardware
	Performance of remote tasks
Cyber security	Security of internal data storage
	Data protection in cloud services
	Secure internal and external data exchange
Cyber–physical System	Systems communication
	Independent situation assessment and decision–making by the equipment
	Sensors and actuators to collect information
Artificial Intelligence	Self–learning systems
	Virtual assistants
	Training of equipment with data
Additive manufacturing	High process standardisation
	3D models of components
	Expertise of 3D printing

3.4.5 Part 5: Demographic Data

In the last part of the survey, demographic data is collected. The purpose of the demographic data is to get background information from the respondents. It is significant to ascertain in which region the participants have mainly gained experience in the rail industry. Furthermore, it is of interest to investigate in which area they have gathered experience. This implies whether the respondent reports from the perspective of a rail operator or a rolling stock manufacturer. Another important aspect is whether the participants have experience in passenger or freight transport. Finally, the estimated percentage of employees in the maintenance department is surveyed, to establish whether or not many people are employed in the maintenance department compared to the other departments.

Stellenbosch University https://scholar.sun.ac.za

3.5 Conducting the Survey

The survey is carried out cross–sectionally. In other words, it is conducted only once and not performed several times in a row. The survey is active for a period of one month. Potential participants are identified in advance via various channels. The first source is the list of exhibitors which is available on the InnoTrans website. InnoTrans is the most important trade fair worldwide for rail transport technology. This enables a selection to be made of the majority of companies active in the industry. Besides, the internet, in general, serves as an aid for the identification of worldwide rail operators. Small and regional companies have been identified, such as the Agilis Eisenbahngesellschaft in Regensburg, as well as large corporations such as the National Railroad Passenger Corporation in the United States. Based on these results, the participants are contacted via social networks. For the German–speaking countries, the online network Xing is primarily used, namely for Germany, Austria and Switzerland. The online network LinkedIn is used for international markets. Both online networks serve to maintain the professional network, which means that most people have a link to their employer and share their professional experiences in their profile. To identify suitable respondents, the companies are researched using the search function of the networks. Subsequently, it is possible to identify suitable participants from among those networked with their companies. The identified possible participants are contacted, informed about the reasons for the research and are asked about their interest in participating in the online survey. In case of a positive feedback, a link for participation is provided. Besides the acquisition of participants via online networks, subject matter experts are also contacted by email. These are detected predominantly through the researcher's private contacts.

3.6 Survey Data Analysis

The data received in LimeSurvey is transferred to Microsoft Excel to ensure better evaluation possibilities and clearer presentation of the data. The data is evaluated directly, meaning that the frequency distribution of descriptive statistics allows the evaluation of each question or topic area. Regarding the open–ended questions, the answers are summarised to the key findings. For the indirect data analysis the regions in which the participants are active in rolling stock maintenance are reviewed. It is evaluated whether there are different perceptions of Industry 4.0 technologies in rolling stock maintenance. The allocation to the different regions is based on the classification of the The World Bank (2020). Simply, this signifies that the respondents' answers are categorised into the regions Africa, America, Asia and Europe. The questions are subsequently filtered by region and the answers are checked for characteristics.

Stellenbosch University https://scholar.sun.ac.za

Furthermore, the indirect data analyses include the determined maturity level to evaluate if effects exist for the maturity level. The calculation of the technological maturity level is aligned with the model of Pacchini et al. (2019), which is presented in Section 2.5.2. Figure 3.1 gives an overview of the calculation of the technological maturity level.

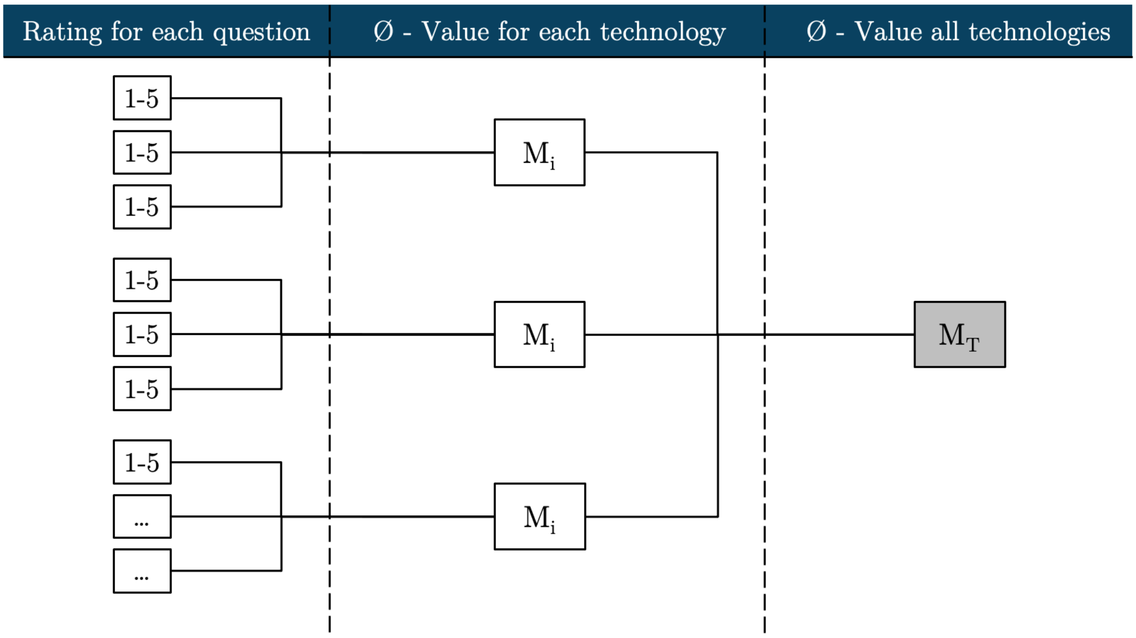


Figure 3.1: Overview of the technological maturity level calculation

To calculate the degree of maturity, the answers to the questions regarding the technologies are utilised (Section 3.4.4). For each technology, three questions are asked, for which a value of one to five can be assigned. Afterwards, the maturity level M_i for each technology is determined. Equation (3.1) presents the calculation for each technology.

$$M_i = \frac{\sum rating}{max\ points\ possible} \cdot 100 \tag{3.1}$$

Once the maturity level has been determined for all technologies, the total technological maturity level M_T can be derived. The calculation for this purpose is given by Equation (3.2).

$$M_T = \frac{\sum M_i}{\sum number\ of\ technologies} \tag{3.2}$$

After the calculation, the results are classified according to the maturity level scale, which is presented in Table 3.2. A value of one implies that there is a very low level of maturity, whereas a maturity level of five indicates that a very mature level exists.

Stellenbosch University https://scholar.sun.ac.za

Table 3.2: Maturity level scale

Technological maturity level	Classification in [%]
Maturity level 1	$0 \leq M_T \leq 20$
Maturity level 2	$20 < M_T \leq 40$
Maturity level 3	$40 < M_T \leq 70$
Maturity level 4	$70 < M_T \leq 90$
Maturity level 5	$90 < M_T \leq 100$

Once the levels of maturity have been determined, the survey question results are filtered according to the levels of maturity. The filtering process is the same as for the regions, except this time it is based on the maturity levels. To be able to derive a trend, the precisely determined maturity levels of one to five are grouped into low (< 47%), medium (< 67%) and high (≤ 100%) maturity level. These thresholds are derived from the results of the evaluation and are hence determined on this basis. The questions are then filtered accordingly and the answers evaluated.

3.7 Survey Results

The survey link is sent in total to 220 people. A detailed overview is summarised in Figure 3.2. The response rate is 56 percent, meaning that finally, 124 respondents participated in the survey.

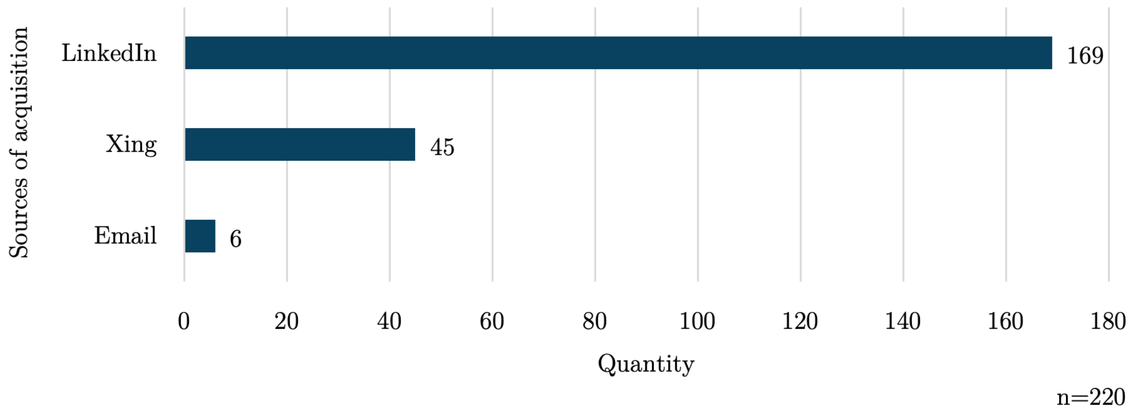


Figure 3.2: Overview of the sources of acquisition

However, 42 of the participants abandoned the survey relatively early. Therefore only the 82 fully answered surveys are included in the evaluation (Figure 3.3). The sample size of the survey results is 82. Considering the response rate, it is still very high at 37 percent.

Stellenbosch University https://scholar.sun.ac.za

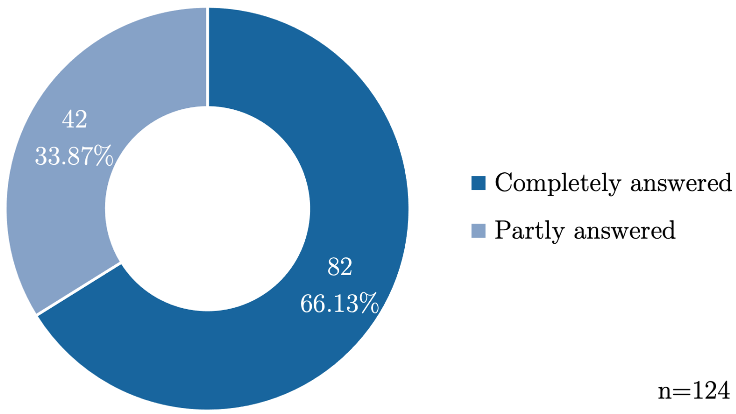


Figure 3.3: Overview of the survey response

3.7.1 Results of Direct Data Analysis

In this section, the major results of the direct data analysis are discussed. An evaluation of all questions including also the absolute numbers is provided in Appendix A.4. In the beginning, it is determined how the participants see the topic of digitalisation in general in the rail industry. Concerning digitalisation, the majority of participants (57.32 percent) state that the rail industry is currently working on the implementation of individual projects. Only a very small proportion of just over two percent believe that digitalisation is not important for the rail industry. Detailed results are presented in Figure 3.4.

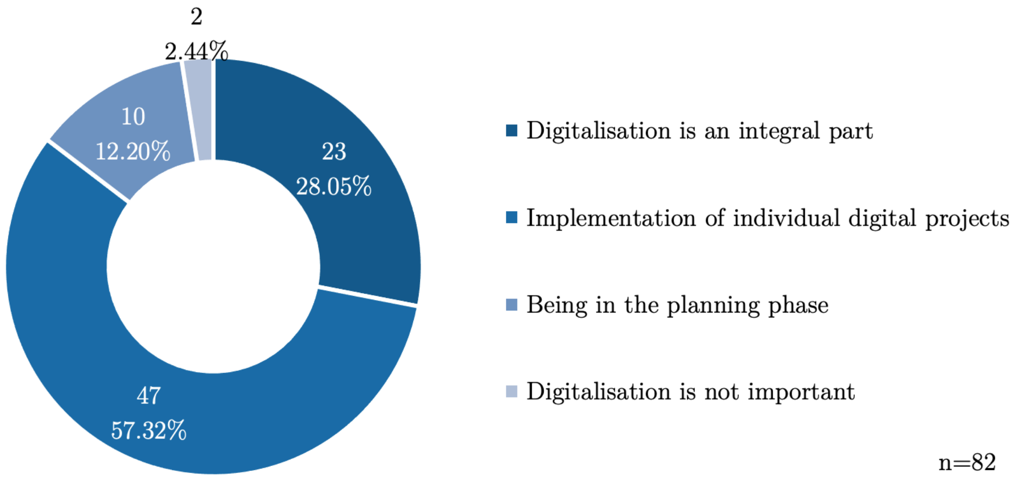


Figure 3.4: Current status regarding digitalisation in the rail industry

In the field of emerging technologies in maintenance, it is clear that big data & analytics is seen as particularly promising with over 80 percent. Big data & analytics is followed by IoT with almost 60 percent (Figure 3.5). Furthermore, it should be emphasised that all participants consider at least one of the technologies to be promising, as none of the participants rejected all technologies.

Stellenbosch University https://scholar.sun.ac.za

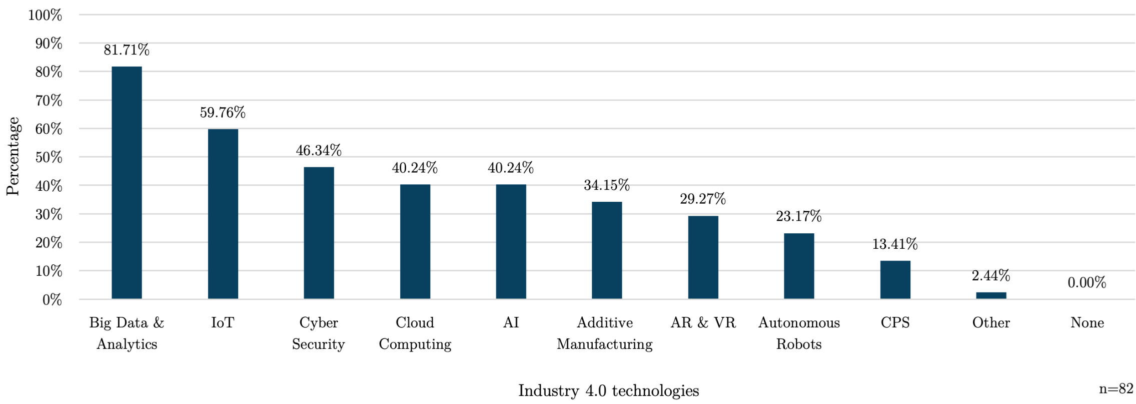


Figure 3.5: Industry 4.0 enabling technologies of greatest importance in rolling stock maintenance

The benefits derived from Industry 4.0 technologies, as identified by the literature review in Section 2.4.4, are all confirmed overall by the participants, as Figure 3.6 reveals. More than 90 percent of the participants see a particular improvement in system reliability. According to the results, the technologies also make a significant contribution to increasing quality assurance and reduction in costs.

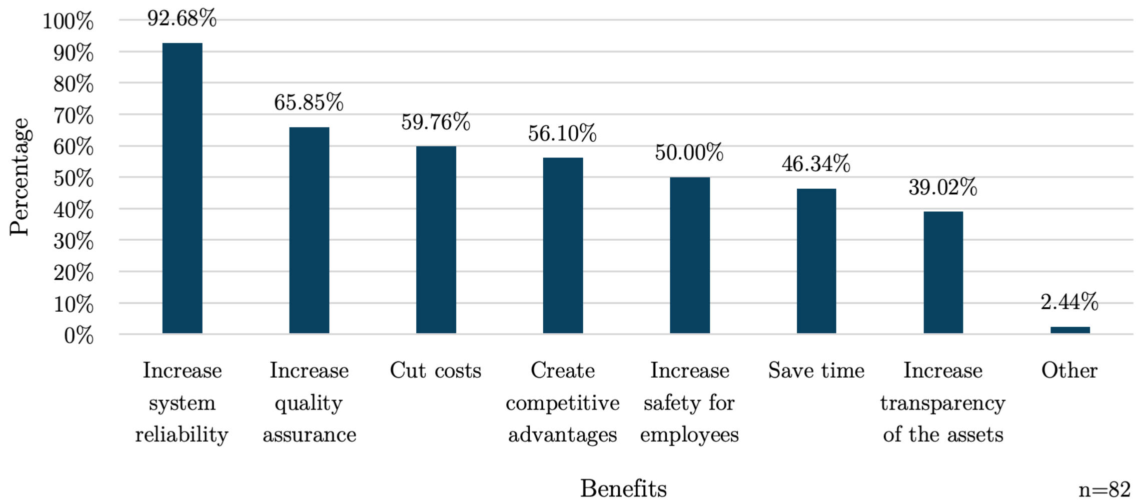


Figure 3.6: Benefits from emerging technologies in rolling stock maintenance

As far as the current status of implementation of emerging technologies is concerned, exactly half of the respondents are still in the planning phase. Only 7.32 percent have no plans at all at the moment. In contrast, more than 18 percent are already using these technologies and regularly update them. Figure 3.7 presents the results for the current implementation status.

Stellenbosch University https://scholar.sun.ac.za

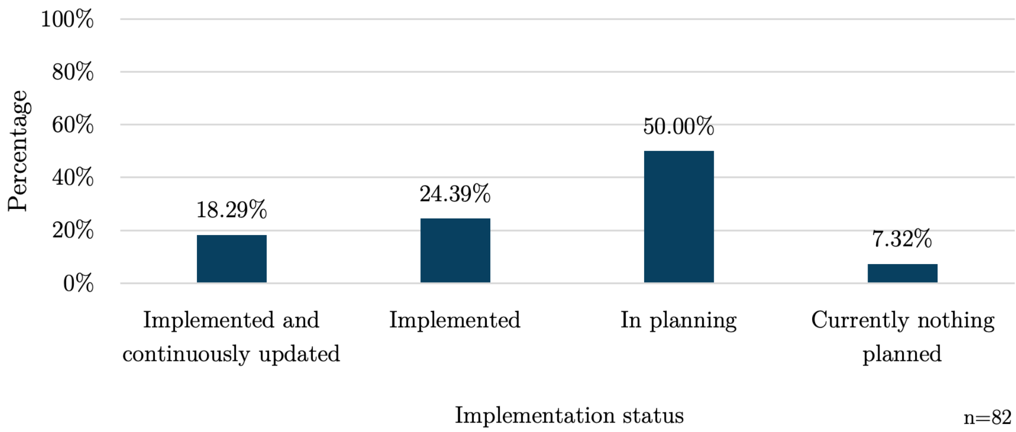


Figure 3.7: Current status in the rail industry regarding the implementation of Industry 4.0 enabling technologies in rolling stock maintenance

The fact that half of the respondents are still in the planning phase is also reflected in the results of the challenges regarding Industry 4.0 technologies in maintenance (Figure 3.8). More than 80 percent of the respondents have to deal with challenges. When specifying the challenges, almost 55 percent of the respondents state that there is a lack of qualified maintenance personnel with competences for emerging technologies. The respondents also frequently experience difficulties in corporate strategy and in providing information on implementation.

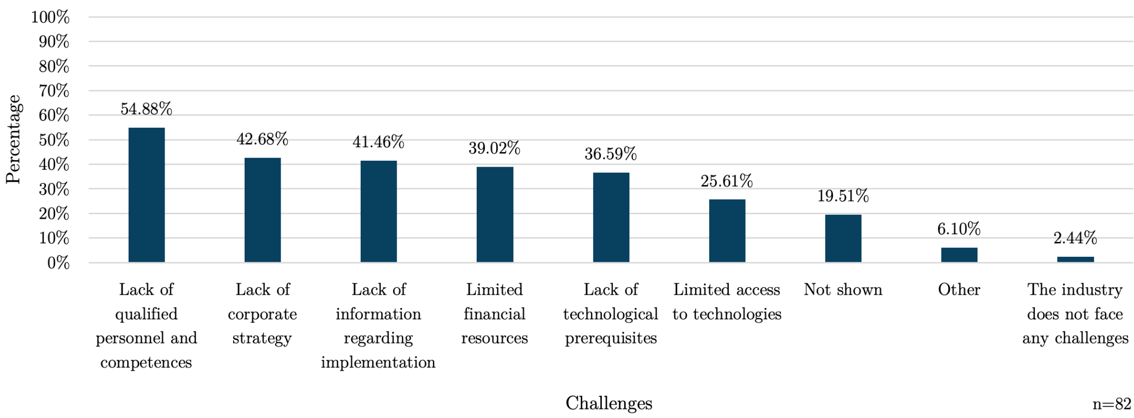


Figure 3.8: Challenges the rail industry face regarding Industry 4.0 technologies in rolling stock maintenance

Regarding the rolling stock systems in which emerging technologies are applied, more than 60 percent state that they are utilised in the traction motor, wheels and HVAC. Figure 3.9 also indicates that 7.32 percent do not use these technologies anywhere. So it is the same percentage as mentioned above (Figure 3.7), where no implementation is currently planned.

Stellenbosch University https://scholar.sun.ac.za

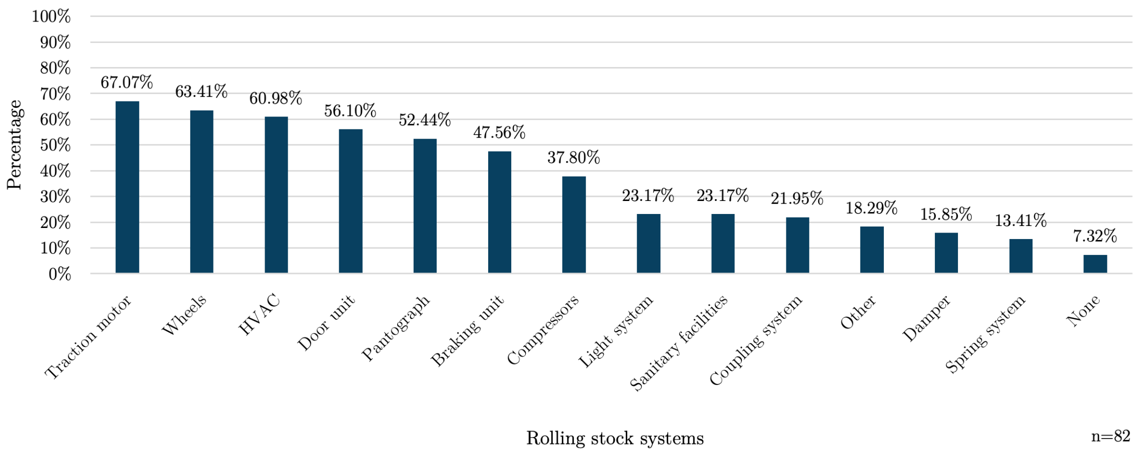


Figure 3.9: Rolling stock systems where Industry 4.0 technologies are applied

The open–ended question regarding the impact or effects of the implementation of Industry 4.0 technologies has been answered by 56 participants. The summary of the responses is as follows:

- Maintenance optimisation in general
- Higher reliability of rolling stock systems and of maintenance planning
- Improvement in troubleshooting
- Higher efficiency through data basis gained by the emerging technologies
- Reduction in maintenance costs
- Reduction of downtime
- Difficulties in implementation of emerging technologies

The most common answers state that there is a general improvement in maintenance. For example, one participant responds that it is "easier to maintain all components". On the other hand, it is pointed out that the general improvements in maintenance resulted in fewer maintenance activities. This is demonstrated by the fact that according to the answers it is possible to switch from a preventive to a predictive maintenance strategy. Besides the general maintenance improvements, increased reliability is mentioned. In principal this refers to the reliability of components such as brake systems as well as to improved reliability in maintenance planning. Positive effects are also achieved during troubleshooting. A respondent states that the "disturbance can be overcome immediately and passengers are not harmed because the condition of the monitored component is clear". The positive effects during troubleshooting refer primarily to time reduction and the improved diagnostic capability for troubleshooting. Furthermore, the responses reveal an increased efficiency. The justification for an increase in efficiency is primarily the availability of a more solid data basis, which is gained through the usage of Industry 4.0

Stellenbosch University https://scholar.sun.ac.za

technologies. The technologies enable the collection of more asset data, which provides additional information and increases the efficiency of the maintenance processes. A significant influence is also noted regarding the costs. According to the subject matter experts, a cost reduction for the maintenance costs themselves as well as for the subsequent costs of downtime is achieved. It is also mentioned that there are overall cost reductions for life cycle costs. The positive impacts and effects predominate in the responses. However, some negative experiences are also described. It is reported that there are difficulties in implementation. Due to the lack of knowledge regarding implementation, there are problems and there is confusion.

Concerning the personnel situation in maintenance, it is noted that more than 60 percent of the respondents suppose that on average more than 20 percent of the entire company is involved in maintenance (Figure 3.10). In contrast, only 10.98 percent state that the figure is less than five percent.

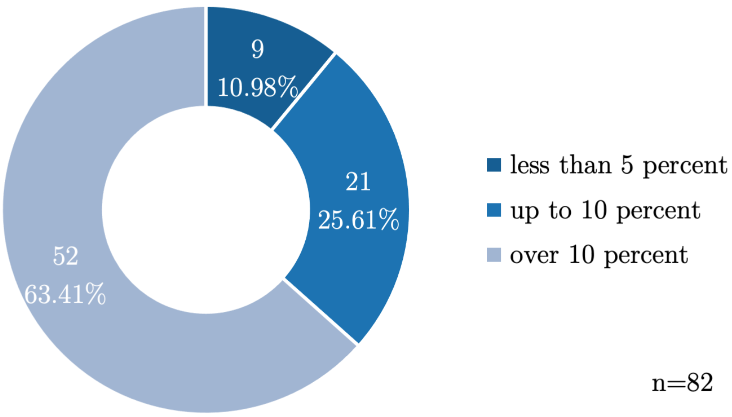


Figure 3.10: Average percentage of employees working in the maintenance department in the rail industry

Demographic data indicates the region where the respondents are employed in the rail industry. More than half of the respondents are employed in the European rail industry (Figure 3.11). A particularly large number of subject matter experts from Germany participated in the survey. The proportion of subject matter experts from Africa, America and Asia is approximately equally distributed.

Stellenbosch University https://scholar.sun.ac.za

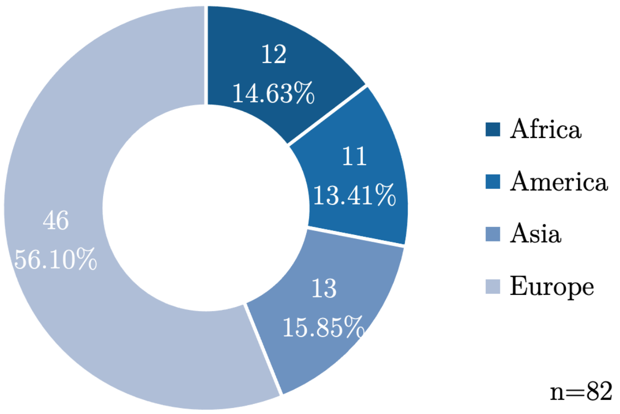


Figure 3.11: Regions where the participants gained experience

3.7.2 Results of Indirect Data Analysis

The indirect data analysis for the categorisation by regions resulted in the following sample size, which is provided in Table 3.3. Table 3.4 contains the sample size of the maturity levels. The overall results from the indirect analysis as well as the absolute numbers are provided in Appendix A.5 and Appendix A.6. The findings of both analyses are summarised in the following paragraphs.

Table 3.3: Sample size of the regions

Region	**Sample size**
Africa	12
America	11
Asia	13
Europe	46

Table 3.4: Sample size of the technological maturity levels

Maturity level	**Sample size**
Low	18
Medium	52
High	12

3.7.2.1 Region Results

In general, digitalisation is most advanced in America (Figure 3.12). All of the respondents indicate here that the rail industry is either an integral part of it or is currently working on individual digital projects. In Europe, it is evident that almost 70 percent of the respondents state that individual projects are being implemented. Africa is the most markedly lagging behind, as the majority is still in the planning phase.

Stellenbosch University https://scholar.sun.ac.za

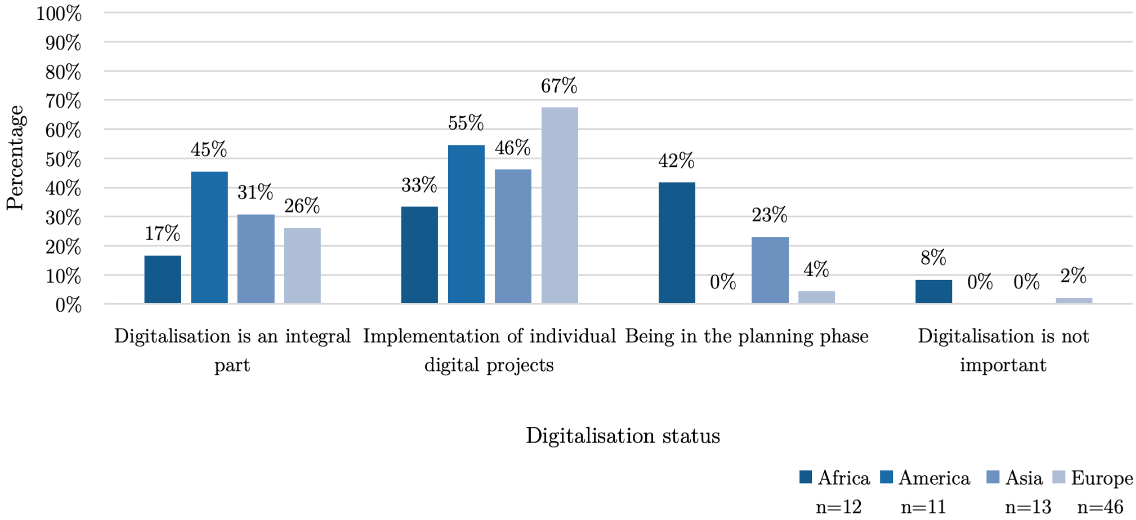


Figure 3.12: Current status regarding digitalisation in the rail industry according to the different regions

All four regions see big data & analytics as the most promising technology (Figure 3.13). IoT also scores very well with values of at least 50 percent. It is noticeable that in America cloud computing and AI are particularly considered useful for maintenance. For cyber security there are different opinions. America and Europe assume that cyber security is powerful. On the other hand, subject matter experts from Asia regard this area as less interesting.

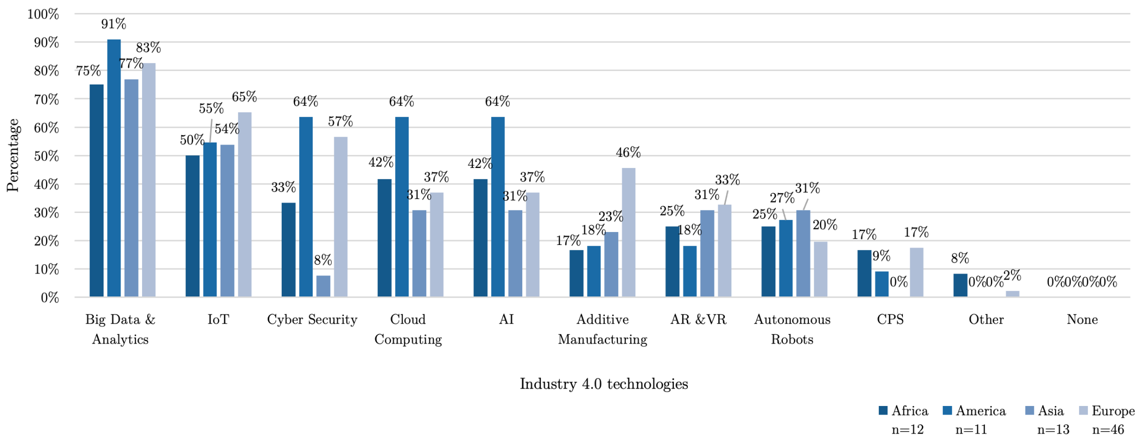


Figure 3.13: Industry 4.0 enabling technologies of greatest importance in rolling stock maintenance according to the different regions

In Asia and Europe, the use of emerging technologies is particularly applied for monitoring systems. The European subject matter experts identified as having potential for data collection. In contrast, in Africa and America, the use of emerging technologies is considered appropriate for planning and organisation purposes, as illustrated by Figure 3.14.

Stellenbosch University https://scholar.sun.ac.za

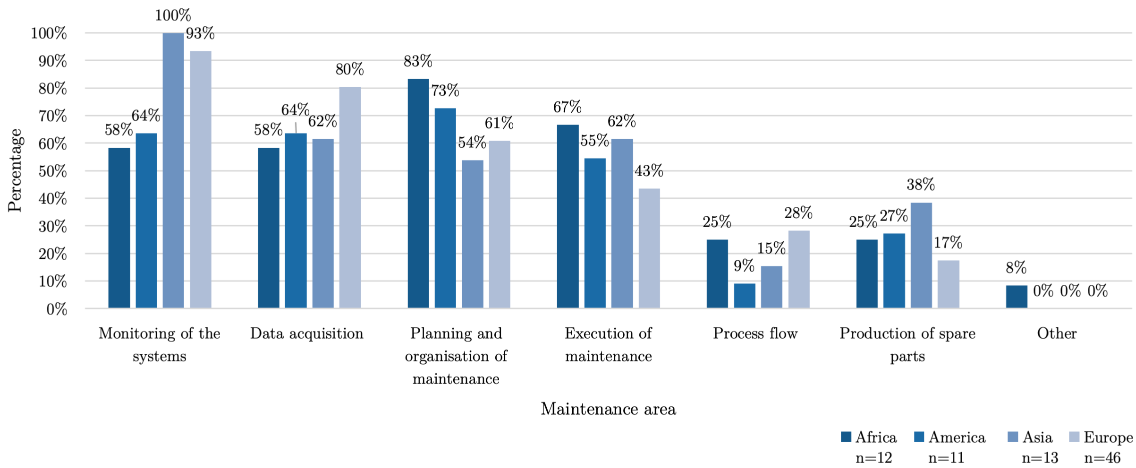


Figure 3.14: Maintenance area for Industry 4.0 technology application according to the different regions

All four regions agree that there is increased system reliability with Industry 4.0 technologies. In America, the use of emerging technologies is also associated with improvements in quality and cost savings. The time advantages are clearly lagging behind in all regions, which Figure 3.15 demonstrates.

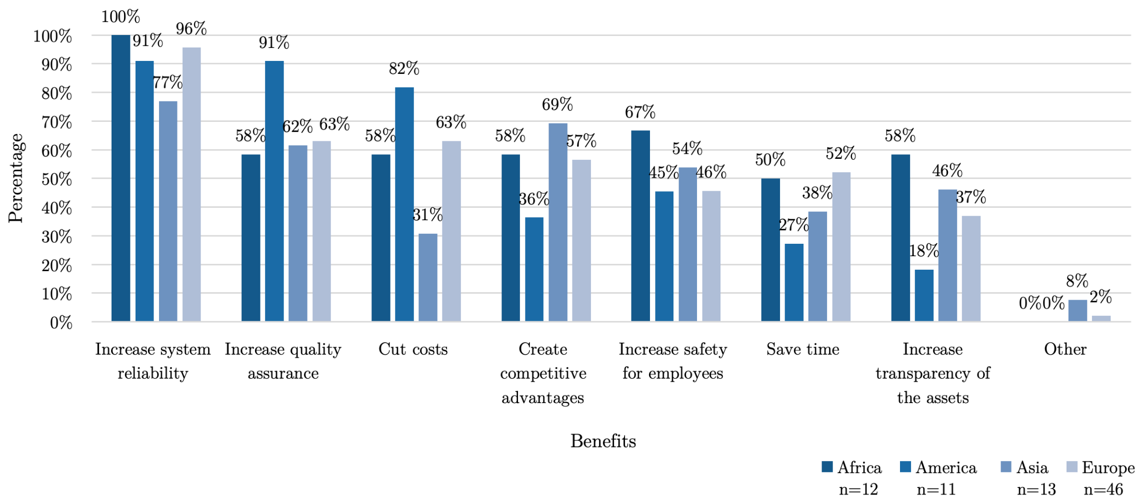


Figure 3.15: Benefits from emerging technologies in rolling stock maintenance according to the different regions

As far as challenges are concerned, it can be noted that almost 60 percent of the respondents from Africa do not see any challenges for emerging technologies in maintenance (Figure 3.16). The same applies to the Asian region at almost 40 percent. In America, challenges are seen above all in the area of corporate strategy and information on implementation. All four regions confirm the challenges regarding the lack of qualified personnel.

Stellenbosch University https://scholar.sun.ac.za

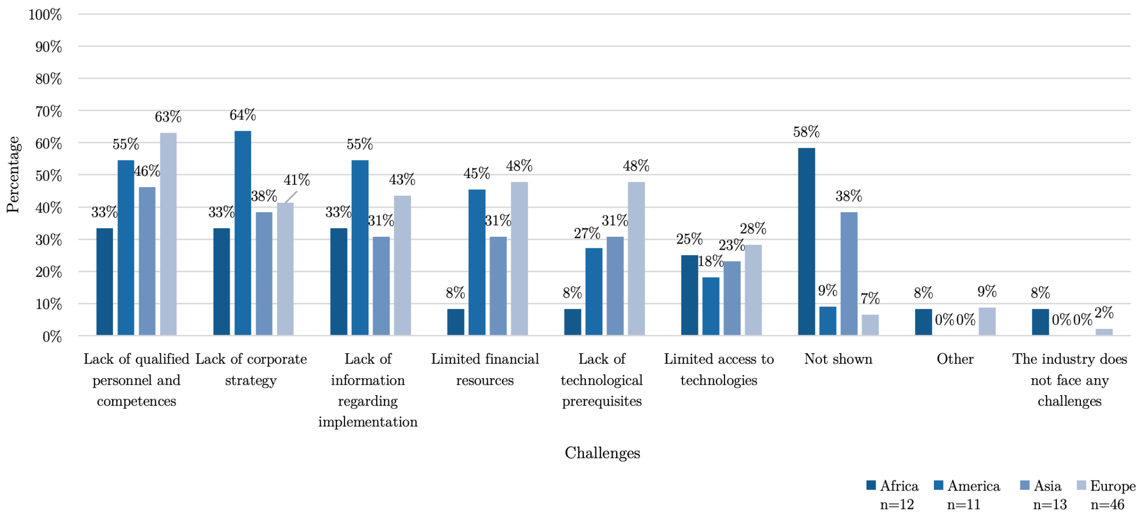


Figure 3.16: Challenges the rail industry faces regarding Industry 4.0 technologies in rolling stock maintenance according to the different regions

The most potential for implementation of the technologies is expected to be in the field of traction motor, pantograph, wheels, door unit and HVAC. However, the least potential is anticipated in the spring system, damper, light system and sanitary facilities. The results are illustrated in Figure 3.17.

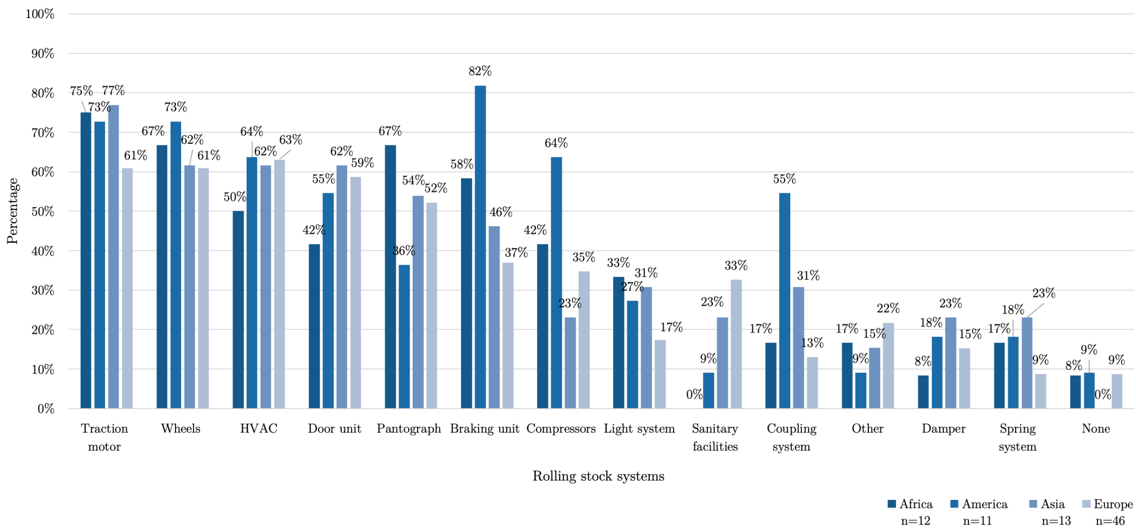


Figure 3.17: Rolling stock systems where Industry 4.0 technologies are applied according to the different regions

3.7.2.2 Maturity Level Results

Among the emerging technologies, it is clear that the highest average maturity level of over 60 percent tends to be in cloud computing, big data & analytics and cyber security. In contrast, the calculations signify that AI currently has the lowest average degree of

Stellenbosch University https://scholar.sun.ac.za

maturity in the rail industry. Table 3.5 displays the results of the calculations of the average maturity level of the individual technologies.

Table 3.5: Average technological maturity level per technology

Technologies	Technological maturity level
AI	41.87%
AR & VR	52.85%
CPS	54.23%
IoT	56.67%
Additive manufacturing	57.48%
Cyber security	62.44%
Big data & analytics	64.88%
Cloud computing	66.02%

For digitalisation in general, it can be observed in Figure 3.18 that digitalisation is an integral part of the industry with a very high degree of maturity at 75 percent. If the level of maturity is medium, individual projects are currently being implemented. The same is valid for a low degree of maturity, although 27.78 percent are still in the planning phase.

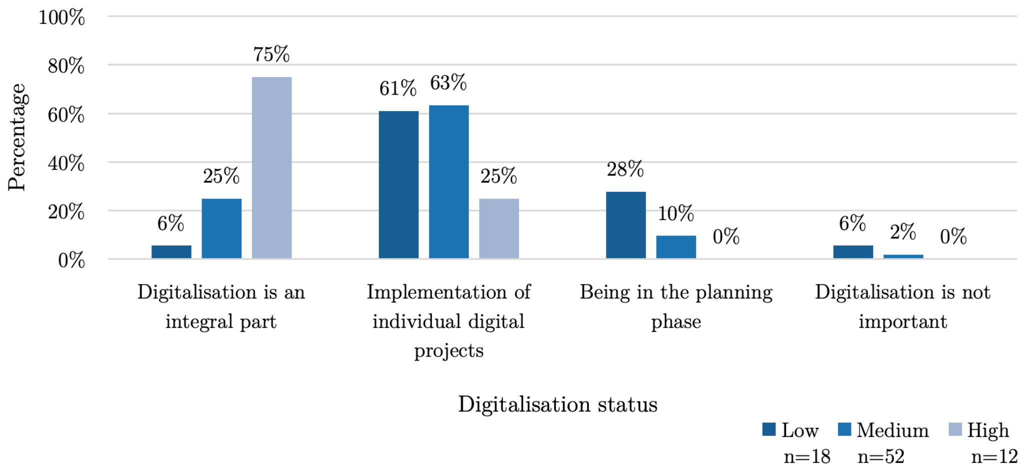


Figure 3.18: Current status regarding digitalisation in the rail industry according to the different maturity levels

When comparing Industry 4.0 technologies, it is evident that with a low, medium and high level of industrial maturity, especially big data & analytics and IoT are considered important technologies in maintenance (Figure 3.19). CPSs tend to be the least influential ones.

Stellenbosch University https://scholar.sun.ac.za

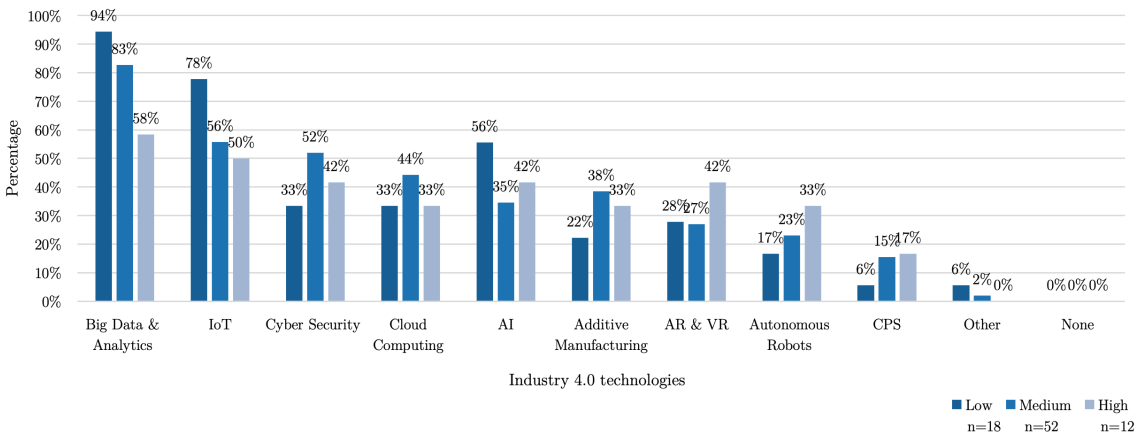


Figure 3.19: Industry 4.0 enabling technologies of greatest importance in rolling stock maintenance according to the different maturity levels

Emerging technologies in general are employed at all levels of maturity for monitoring the systems (Figure 3.20). Less importance is attributed to the process flow or the production of spare parts.

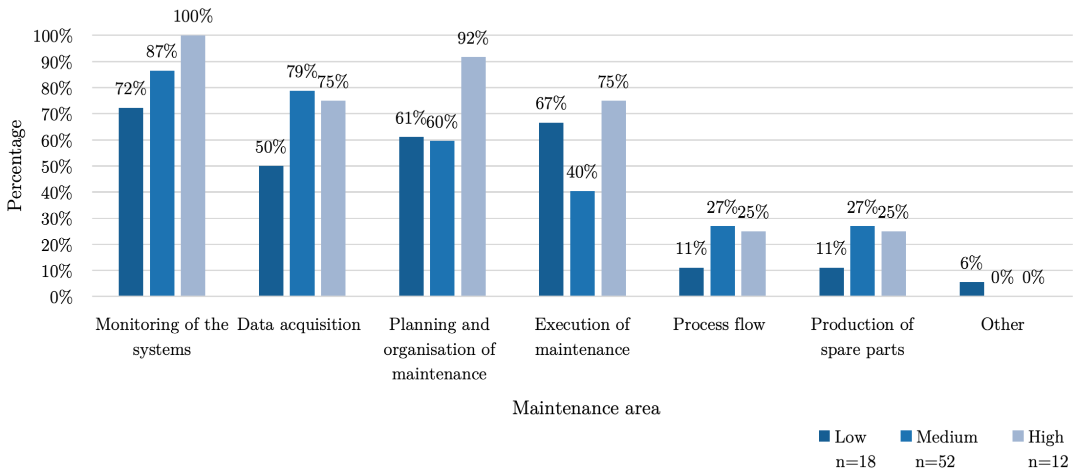


Figure 3.20: Maintenance area for Industry 4.0 technology application according to the different maturity levels

All three levels of maturity see a particular advantage in system reliability. Figure 3.21 reveals that a high degree of maturity results in quality improvements, time savings, increased safety for employees and a competitive advantage. Competitive advantages are also experienced by the industry with medium maturity level as well as possibilities for cost savings, which is also confirmed by the industry with low maturity level.

Stellenbosch University https://scholar.sun.ac.za

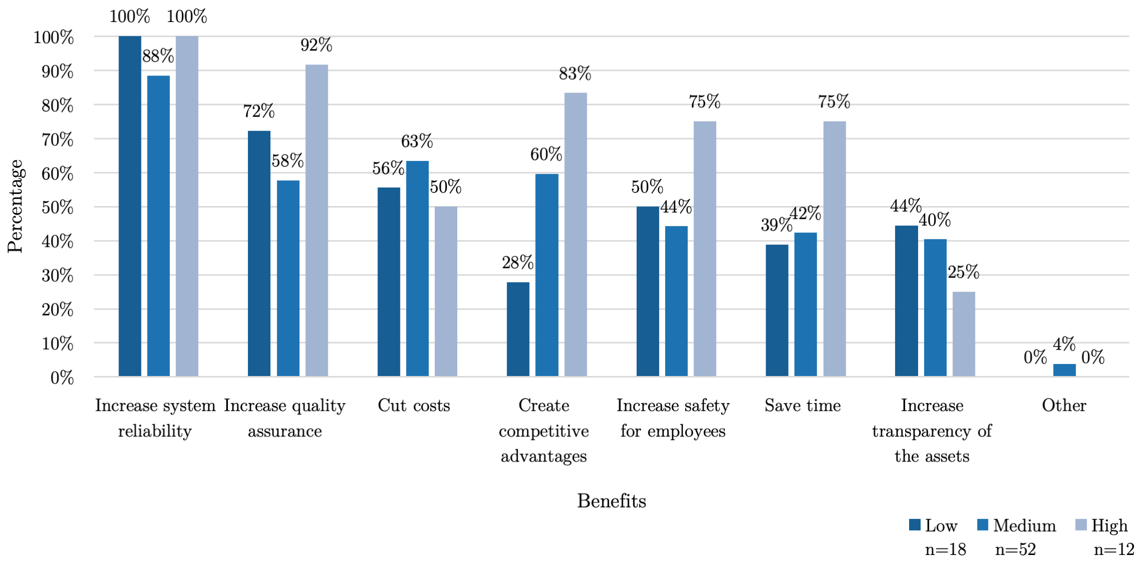


Figure 3.21: Benefits from emerging technologies in rolling stock maintenance according to the different maturity levels

Figure 3.22 demonstrates that at all three levels of maturity perceive a lack of qualified personnel for the application of emerging technologies. The industry with a low level of maturity also recognises a need to catch up in terms of corporate strategy as well as in obtaining information for implementation. The industry with a high degree of maturity also faces challenges in implementation. In addition, the limited financial possibilities play a role, which is also emphasised by the industry with a medium degree of maturity.

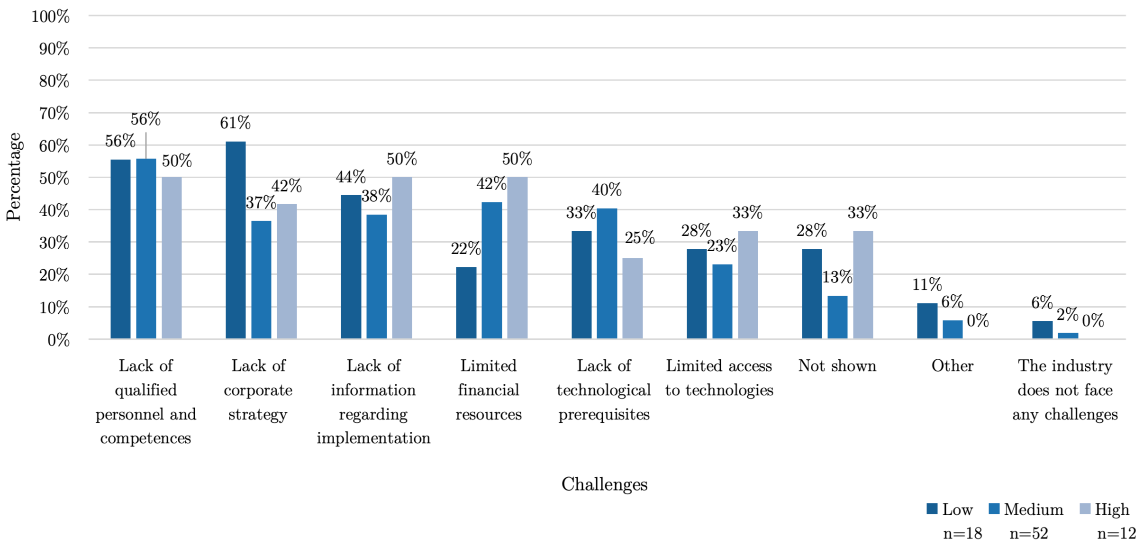


Figure 3.22: Challenges the rail industry faces regarding Industry 4.0 technologies in rolling stock maintenance according to the different maturity levels

Similar to the advantages and challenges of the technologies, there is one specific field where all three levels of maturity consider the implementation of Industry 4.0 technologies as useful: the wheels. It is remarkable that the area with a high degree of maturity is 100

Stellenbosch University https://scholar.sun.ac.za

percent in accordance (Figure 3.23). The same applies to the traction motor. Industries with a low or medium maturity level see further potential for implementation in the HVAC.

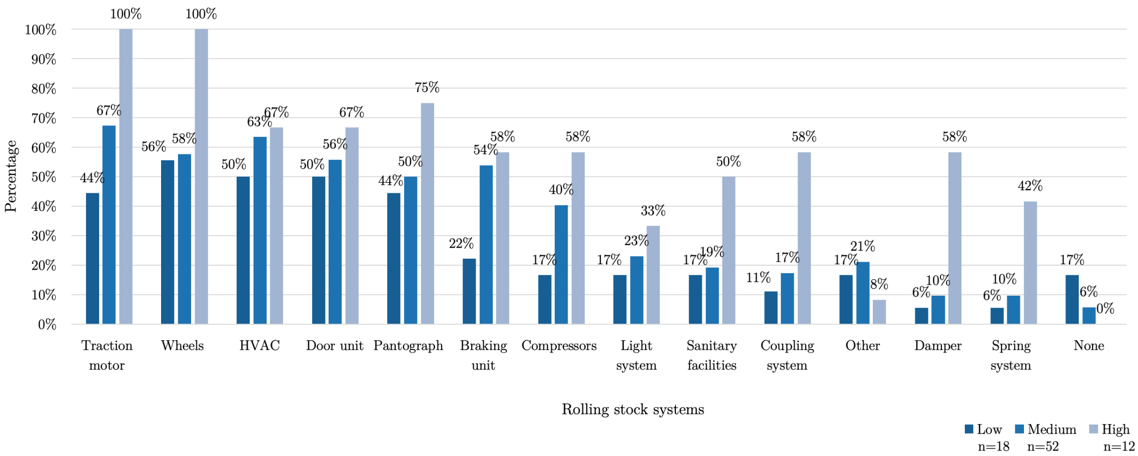


Figure 3.23: Rolling stock systems where Industry 4.0 technologies are applied according to the different maturity levels

3.8 Survey Results Discussion

The high response rate of 37 percent of fully completed questionnaires denotes how important the topic is at the moment. Many of the respondents expressed their interest in the survey results and gave positive feedback regarding the survey. The high response rate can be explained by the current interest in the topic as well as the strong networking of the industry. In the online networks Xing and LinkedIn it is clearly discernible that many participants are networked with each other. This is not only apparent at a regional level, but also internationally. It is noticeable that the industry collaborates on this topic and that there is a mutual exchange with each other.

According to the results of the survey, the topic of digitalisation is very present in the rail industry. However, only 28 percent of respondents declare that digitalisation is already an integral part of the industry. Therefore, the industry is still in the initial phase of digitalisation. Compared to other company departments, maintenance performs very well in the area of digitalisation. Thus, there is great interest and much potential is expected in this area. The results of the direct evaluation reveal that all listed technologies are considered substantial for rolling stock maintenance. Why CPSs are perceived to be the least important appears unclear at first glance. The results of the literature review indicate that CPSs are especially fundamental for data acquisition. According to the responses, the majority of the industry is currently in the planning phase of implementing the technologies, so it can be assumed that there is still a knowledge deficit for CPSs and the importance is underestimated.

Stellenbosch University https://scholar.sun.ac.za

The quantification of the results for the benefits of Industry 4.0 technologies confirms all the benefits revealed by the literature review. Thus, the benefits are also valid for rolling stock maintenance. The improvement in system reliability is particularly noticeable. This refers to the contribution of technologies to increase the availability of rolling stock by improving its reliability. As a result, the rail operators' problem of rolling stock availability issues identified in Section 1.2 can be counteracted. As explained in Section 1.1, there has been a significant increase in the numbers of maintenance personnel. According to the survey results, more than 60 percent confirm that more than ten percent of the company's workforce is involved in maintenance. However, the challenges point to the fact that there is no shortage of personnel, but of qualified personnel with the necessary skills. Thus, the rail industry faces difficulties in acquiring skilled personnel capable of handling emerging technologies. The rail industry is a very traditional industry, which often acts conservatively and sticks to existing methods. This explains why the participants perceive a clear lack of corporate strategy. Access to technologies is seen as the least important. As a result, the majority of companies in the rail industry already have access to emerging technologies. It is verified that the application of the technologies makes sense for all of the mentioned components of the rail vehicles. Accordingly, the application is not only advantageous for the operationally relevant components but also for components which are responsible for passenger comfort. In summary, the technologies are to be used wherever it is possible. The predominantly positive effects and impact of the implementation of the technologies leads to the conclusion that the rail industry has a positive attitude towards them. The rail industry wants to benefit from the application of the technologies to achieve positive utilities in various maintenance areas. However, the occasional comments on negative effects indicate that the rail industry is currently struggling with implementation problems. The knowledge concerning practical implementation is still missing to eliminate the confusion during the implementation.

The indirect analysis for the regions revealed interesting anomalies in the evaluation of the technologies. Cyber security is classified as hardly relevant in the Asian region. This may be since cyber security is already fully integrated or is given less priority. In America, cyber security is rated as very important. One reason for this is that the connection between cloud computing and AI is recognised. Both technologies also stand out for this region with significantly higher values. All regions agree with the monitoring of the systems in which emerging technologies can be applied. The reason for this is that solutions already exist in the industry and experience has been gained. Furthermore, the maintenance areas process flow and production of spare parts are rated significantly lower. This is explainable because the potential here has not yet been recognised and the regions are still investigating. The benefits of the technologies are prioritised similarly in all regions. In contrast, when it comes to challenges, it is striking that participants with experience in Africa do not currently see any challenges. This is explainable because 25 percent of the participants from Africa do not currently plan to implement the technologies and therefore

Stellenbosch University https://scholar.sun.ac.za

do not anticipate any challenges.

The degree of maturity reveals that there is a direct correlation regarding digitalisation. This implies that at higher levels of maturity, digitalisation is more advanced. Indirect analysis by maturity level suggests that the rail industry wants to move away from local data transmission and storage. This is apparent by the fact that cloud computing has reached the highest level of maturity of all technologies. The lowest level of maturity currently exists for AI. This result reflects the findings of the literature review. Up to now, the least amount of literature has been published for AI in maintenance, which is why the rail industry has only limited knowledge from the field of research. It is noticeable that there are irregularities regarding the current maturity levels of the technologies and the importance of the technologies. As already explained, cloud computing currently has the highest level of average maturity, but it is considered to be of less importance for rolling stock maintenance. A contrary result can be seen with IoT. This is explainable by the complexity of the implementation of IoT, whereby the industry is currently trying to find solutions for integration. The rail industry with a low level of maturity expects a lot of potential for IoT and big data & analytics. This is intended to collect and analyse more information about the assets to increase the transparency of the assets. This is apparent, as the benefit of asset transparency is rated at 44 percent quite high for the industry with a low level of maturity. All three industry maturity levels declare that the most significant benefit is in system reliability. In the case of low and high maturity levels, this is even confirmed by all respondents. However, the overall results are more obvious in the case of benefits in the industry with a high degree of maturity. This is particularly evident in the competitive advantages, security improvements and time savings. Due to the high degree of maturity, the benefits can already be better quantified, which makes the answers more explicit. The same is observed for the evaluation for the use of the technologies. The industry with a high degree of maturity endorses the application for the traction motor and wheels at 100 percent. Overall, the industry with a high degree of maturity considers the use of emerging technologies for all components to be possible, which can be concluded from the high ratings. As far as challenges are concerned, it can be observed that especially the industry with a low level of maturity experiences a lack of corporate strategy. Thus, the low level of maturity is caused by a lack of prioritisation regarding the importance of Industry 4.0 technologies for corporate strategy. Moreover, the situation of financial resources is perceived as challenging, especially in medium and high maturity industries. Here, financial resources seem limited to allow further progress. Industry 4.0 technologies provide the industry with a high degree of maturity with the capabilities for monitoring systems as well as for planning and organising maintenance. Particularly in planning and organisation, the industry perceives a higher potential. This is explained by the fact that emerging technologies are already being applied and have thus demonstrated efficient advantages.

Stellenbosch University https://scholar.sun.ac.za

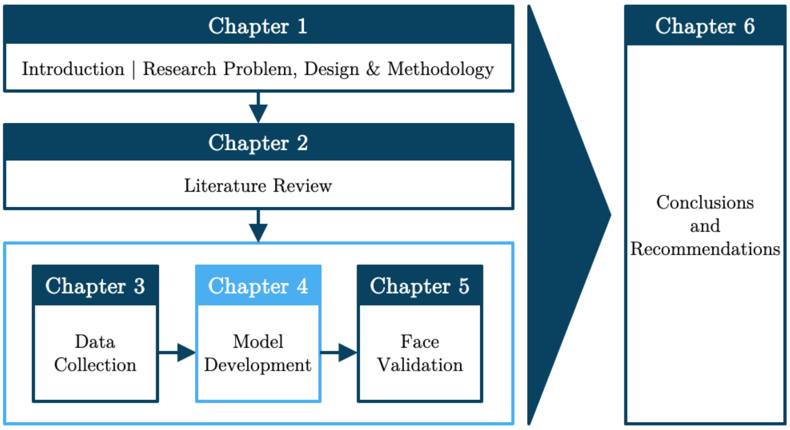
3.9 Chapter Summary

This chapter serves to assess the Industry 4.0 technology maturity in rolling stock maintenance. For this purpose, the conducted online survey is presented in this chapter. On the one hand, the planning process is explained and the objectives of the survey are outlined. On the other hand, the direct and indirect results of the survey are presented. Finally, all results are discussed and assessed.

Stellenbosch University https://scholar.sun.ac.za

Chapter 4

Industry 4.0 Technology Implementation Model



The objective of this chapter is to develop a model for the implementation of Industry 4.0 technologies in rolling stock maintenance. Therefore, the Industry 4.0 Technology Implementation Model (I4.0TIM) introduces a solution for the identified problem in Section 1.2. The findings from the literature review as well as those from the online survey are applied to develop the I4.0TIM. Before developing the I4.0TIM, the model is first classified and the general and practical requirements for the I4.0TIM are defined. Next, the general structure of the I4.0TIM is explained before the individual phases are delineated in detail.

4.1 Model Concepts

The model concept according to Stachowiak (1973, p. 132) states that a model cannot completely represent the investigated system. In fact, a simplified image is always created, which is considered relevant for the respective model user. Page (1991, p. 4) confirms this view and explains that in the transition from the original system to the model abstraction and idealisation occur. By the simplified representation, it is possible to analyse complex

Stellenbosch University https://scholar.sun.ac.za

facts and make them tangible. However, it is important to depict the central characteristics with sufficient accuracy.

Models can be classified according to Figure 4.1. The classification of models can be divided into physical and intangible models. Verbal and graphical–descriptive models are used to develop informal models. These might also represent intermediate stages in the development of formal models. Findings are obtained either by analytical calculation or by simulation. In the case of an analytical model, the results are determined by a closed solution cycle. In contrast to this, simulation models concentrate on the illustration of system behaviour (Page 1991, pp. 4–5).

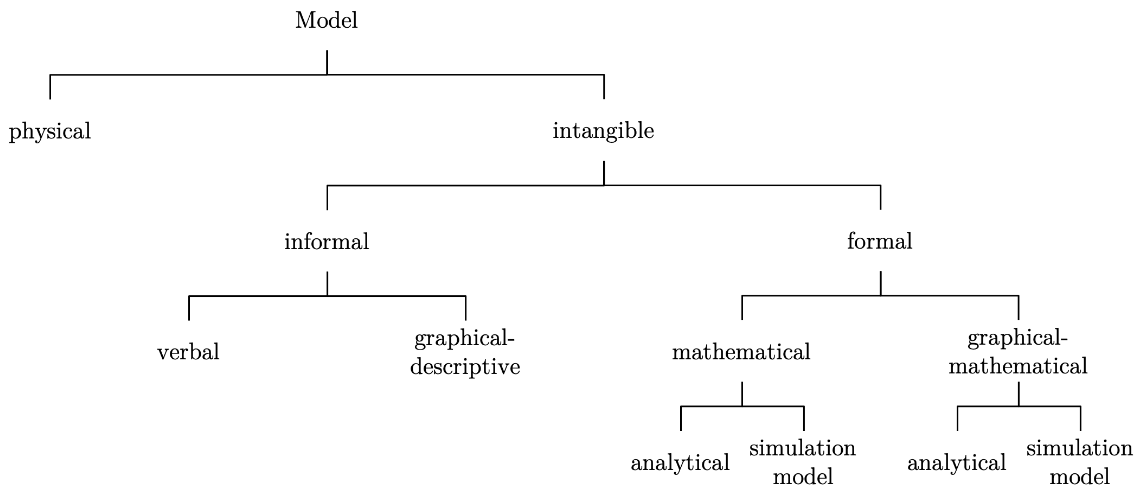


Figure 4.1: Model classification (Page 1991, p. 5)

The purpose of a model is determined by the research question and the objectives. Models can be categorised according to their intended purpose into descriptive, causal, prognostic, decision–making and normative models. Descriptive models describe reality and provide answers as to how things happen. In contrast, causal models try to explain reality and find answers to why something happens. Prognostic models predict reactions and evaluate different alternatives. In the case of decision models, the objective is to find the best solution to a problem from among various alternatives. Thereby the question of which decision would be the best is clarified. Finally, normative models describe ethical criteria and give answers to what should be (Holzbaur 2007, pp. 258–259).

With this study, the model to be developed is classified as a decision model. More precisely, it is an intangible, formal mathematical analytical decision support model. The purpose of this model is to combine all model elements to generate a final decision for the user. To be specific, this indicates that the I4.0TIM addresses the primary research question and the primary objective defined in Section 1.2 and Section 1.3. The I4.0TIM is based on the following four elements:

- *Rolling stock systems*

Stellenbosch University https://scholar.sun.ac.za

- *Maintenance strategies*
- *Industry 4.0 technologies*
- *Maturity assessment*

The individual model elements are aligned with the support of various approaches. For this purpose, the approaches are specially adjusted and developed.

4.2 Model Requirements

The I4.0TIM must fulfil general requirements as well as practical requirements. The general requirements resulting from the primary research objective of this study (Section 1.3) are listed and explained below:

- *Consideration of individual preferences*: The I4.0TIM has to consider several individual preferences regarding system selection and emerging technology selection. The I4.0TIM user has to be enabled to examine the rolling stock systems for the suitability which is most interesting for individual purposes. The same applies to Industry 4.0 technologies. An individual selection has to be available for this case.
- *Integration of the technological degree of maturity*: Rail operators of different dimensions and regionality have varying degrees of maturity. Consequently, the model must consider this aspect and apply to both the technological leaders of the industry as well as to the more immature companies.

In addition to the general requirements, the I4.0TIM must meet practical requirements concerning its application in an industrial environment. These are listed and described below:

- *Generality of the I4.0TIM*: The I4.0TIM should support rail operators with different degrees of technological maturity in selecting emerging technologies for maintenance processes and in identifying suitable systems for this purpose.
- *Modularity of the I4.0TIM*: Companies usually have limited time, personnel and financial resources available. To ensure efficiency, the underlying I4.0TIM must be modular and consist of several phases. Depending on the resources of the rail operator it should be possible to carry out those phases required for the company. However, the use of all phases is to be preferred.
- *Constant consistency of the I4.0TIM*: The phases of I4.0TIM must support a continuous flow of information. The interfaces, more specifically the inputs and outputs of the respective phases, must be clearly defined and harmonised.

Stellenbosch University https://scholar.sun.ac.za

4.3 Model Structure

The developed I4.0TIM supports rail operators with different degrees of technological maturity to implement Industry 4.0 technologies in rolling stock maintenance. The I4.0TIM is modularly structured and influenced by the results of the literature review of rolling stock systems, maintenance strategies and maturity assessment. Moreover, the results of the conducted survey are integrated into the I4.0TIM.

The I4.0TIM, illustrated in Figure 4.2, has four main phases in which the model elements and approaches are presented. The following four phases are integral to the I4.0TIM:

- *Phase 1: Selection of maintenance strategy for rolling stock systems*
- *Phase 2: Selection of Industry 4.0 technologies based on the maturity level*
- *Phase 3: Decisions regarding implementation*
- *Phase 4: Future programme*

Each phase of I4.0TIM consists of model elements of the preceding phases and a respective approach. As is apparent from Figure 4.2, phases 1 and 2 are independent of each other. Phase 3 comprises the first two phases and thus processes their results. This is also valid for phase 4, whereby in this case the results of all previous phases are taken into account. The boxes with the grey tones represent the respective phases, the light blue dashed boxes the model elements and the dark blue boxes the approach applied.

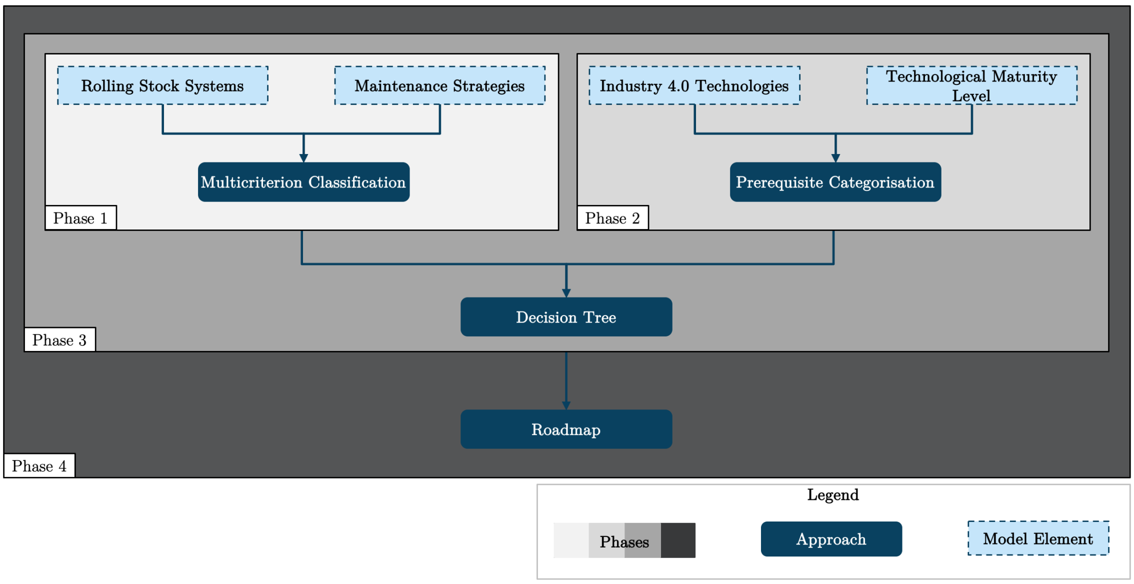


Figure 4.2: I4.0TIM

Stellenbosch University https://scholar.sun.ac.za

4.4 Phase 1: Selection of Maintenance Strategy for Rolling Stock Systems

The first phase of the I4.0TIM consists of the model elements *rolling stock systems* and *maintenance strategies*. The objective of the first phase is to define suitable maintenance strategies for the rolling stock systems. More precisely, in this phase, the rolling stock systems are determined by the user of the I4.0TIM for which predictive maintenance or smart maintenance is prioritised. Thus, it is decided which rolling stock systems require a change of maintenance strategy to predictive or smart maintenance and which do not. A multicriterion classification is applied as an approach to determine the possible systems (Figure 4.3). In this study, this approach is based on the approach introduced by De León Hijes and Cartagena (2006).

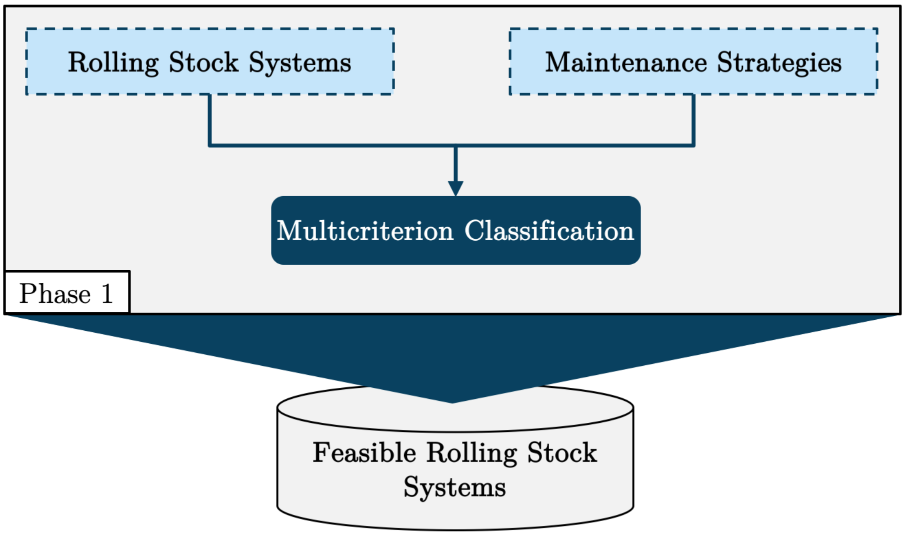


Figure 4.3: First phase of I4.0TIM

4.4.1 Model Elements

First, the model elements must be defined. In the case of rolling stock systems, the results of the survey revealed that all rolling stock systems identified by the literature review can be upgraded by Industry 4.0 technologies. Therefore, all components are considered for the I4.0TIM. An overview of the components is provided in Table 4.1.

Stellenbosch University https://scholar.sun.ac.za

Table 4.1: Overview of rolling stock systems

Index s_i	Rolling stock systems
s_1	Bogie
s_2	Traction motor
s_3	Brake unit
s_4	Pantograph
s_5	Traction & buffer gear
s_6	Door system
s_7	HVAC
s_8	Light system
s_9	Sanitary facilities

The results of the literature review indicate that there are different strategies for maintenance. In Section 2.3.3 it becomes apparent that five maintenance strategies are differentiated. Each of these strategies has its advantages in certain areas, but the corresponding disadvantages must also be considered. In Table 4.2 the five maintenance strategies are listed concerning the degree of development.

Table 4.2: Maintenance strategies organised according to their degree of development

Degree of development	Maintenance strategies
Very low	Reactive maintenance
Low	TBM
Middle	CBM
High	Predictive maintenance
Very high	Smart maintenance

To assist the I4.0TIM user to decide which rolling stock systems are suitable for predictive or smart maintenance, the multicriterion classification is explained in more detail in the next section.

4.4.2 Multicriterion Classification

The following multicriterion classification is built on nine different steps. First, the rolling stock systems are defined, which needs to be examined for this purpose. The process is followed by the definition of the criticality criteria and the direct insertion method. Afterwards, the weight assignment is performed and the criterion and weighting vector can be determined. To get uniform scales, the degrees of criticality are defined. The following criticality vectors are determined by the I4.0TIM user. Finally, the criticality index determines which maintenance strategy is best for the rolling stock systems.

Stellenbosch University https://scholar.sun.ac.za

4.4.2.1 Systems Determination

The first step of the multicriterion classification is to determine the rolling stock systems. For this purpose the systems defined by the model element *rolling stock systems* are available. All nine systems are already mentioned in Table 4.1.

4.4.2.2 Definition of the Criticality Criteria

The next step is to define the criticality criteria. The aim is to compile a detailed classification of the systems, which is to be used as a reference for the maintenance strategy to be applied. For rolling stock maintenance the following criteria are considered as relevant, which are enumerated in Table 4.3 to determine the criticality of the previously defined systems.

Table 4.3: Overview of the criticality criteria

Index c_i	**Criticality criteria**
c_1	Impact on health & safety
c_2	Influence for rolling stock reliability
c_3	Influence for rolling stock availability
c_4	Impact on environment
c_5	Maintenance costs
c_6	Existence of alternative systems
c_7	Impact for customers
c_8	Failure frequency
c_9	Impact for rail operation

In Section 2.3.5 five essential objectives of rolling stock maintenance are explained: safety, reliability, availability, ecology and economy. As these objectives are essential, all of them are considered by the criticality criteria. In the case of health & safety, it is necessary to evaluate to what extent the system influences the safety performance of the passengers. For example, the braking system is probably more critical in terms of safety than the HVAC. Since rolling stock operates in a networked environment, the reliability of the individual systems must be included as a criterion. The environmental impact is taken into account, as the systems use, among other things, lubricants, which can cause an impact on the environment. Maintenance costs vary significantly from system to system, thus they are taken into account as a criterion.

Furthermore, four additional criteria are added. Firstly, the existence of alternative systems is considered. That implies whether a particular system is redundant. For example, most rolling stock is equipped with two pantographs, so in the case of failure, another can be deployed. The same is valid for wagons. Here several door systems are common. In this context it becomes apparent why the impact on customers is included as a criterion.

Stellenbosch University https://scholar.sun.ac.za

Thus the systems that are made available for the comfort of the customers, such as the door systems or HVAC, are considered in the criteria. After all, customer satisfaction is a key factor in passenger rolling stock. Moreover, it is relevant to include failure frequency as a criterion. This is justified by the fact that train systems indicate various failure frequencies. For example, a system can only fail once a year or daily during train operation. The key issue here is the impact of the failure on rail operations. Therefore, the failure of the system leads to penalties as it has an impact on the entire rail operation.

4.4.2.3 Direct Insertion Method

Once the criteria have been determined, the direct insertion method is followed to determine the relative importance of the individual criteria. In this procedure according to De León Hijes and Cartagena (2006, p. 446), the importance of each criterion is compared with that of the others. If the criterion is more important compared to the others, its weight is greater. However, its value is not yet known. Assuming that $c_a,\ c_b,\ \ldots,\ c_n$ is the set of criteria with a random order, the objective of the procedure is to obtain a list that is ordered from least to most. This is done starting with the first element of the unordered list, c_a, and assigning it as the first element of the ordered list. Then the next criterion is taken from the unordered list and its relative importance is compared to the criteria of the ordered list. It is important to start at the top of the ordered list, where the least important criterion is located. The procedure continues until a suitable place in the ordered list is found for the criterion. A suitable place is then found when the level of importance is higher than the one compared to the previous one but lower than or equal to the following one. If two criteria are of equal importance, they are placed at the same level in the list and separated by a comma. The order of the criteria at the same level does not matter as this step gives the relative weight of each criterion according to its importance and not according to its numerical value. In Expression (4.1) the ordered list is generally presented, which is obtained after ordering the individual criteria. Thereby n criteria are taken into account and ordered in a list with m levels $(l_1,\ l_2,\ \ldots\ l_m)$, where: $m \leqq n$.

$$\begin{aligned} &l_1)\ c_a,\ c_b,\ \ldots,\ c_i \\ &l_2)\ c_j,\ c_k,\ \ldots \\ &l_m)\ \ldots,\ c_n \end{aligned} \tag{4.1}$$

For the previously defined nine criteria, this implies that first c_1 is taken and added to the ordered list. Then the procedure is continued with c_2. For the comparison of both criteria, it becomes noticeable that the reliability is higher weighed and is therefore placed below c_1. An explanation is revealed by the survey results, which verify that reliability is the most important factor. Hence, this is a decisive factor in rail operations. c_3 is weighted the

Stellenbosch University https://scholar.sun.ac.za

same as c_2. For maintenance, a balanced degree of reliability and availability is required. The impact on the environment c_4 is added to the same level as c_1. Since the influence on health & safety as well as the environmental influence is currently still governed by very strict legal regulations and will require changes in the coming years regarding Industry 4.0 technologies, both criteria are placed at the same level and lower than c_2 and c_3. The allocation for c_5 is made between the two existing levels because although maintenance costs have the highest priority in management, the importance of reliability and availability predominates for rolling stock operation. For c_6 the relative importance is higher compared to c_1 and c_4, because it is crucial if system redundancy exists. On the same level c_7 is allocated afterwards. Reasons, therefore, are the rising influence on customers which have to be considered in any case, but the relative importance outweighs the maintenance costs. The criterion of the failure frequency is to be seen on the same level as the maintenance costs and is thus assigned to the same level. Finally, c_9 is inserted above the influence of reliability and availability. The result of the direct insertion method is provided in Expression (4.2). An overview of the outcomes of the individual partial steps is available in Appendix B.1.

$$\begin{aligned} &l_1)\ c_1,\ c_4 \\ &l_2)\ c_6,\ c_7 \\ &l_3)\ c_5,\ c_8,\ c_9 \\ &l_4)\ c_2,\ c_3 \end{aligned} \tag{4.2}$$

4.4.2.4 Weight Assignment

After determining the relative importance of each criterion, the weighting is ascertained for each level. To simplify the evaluation of the criteria De León Hijes and Cartagena (2006, p. 447) suggest a value of one for the first level l_1 which represents the lowest weighting. This means that $w(l_1) = 1$. Afterwards, the weighting of the second level criteria l_2 is set. Here the importance of the second level criteria is assessed as being twice as high compared to level 1, which results in a weighting of $w(l_2) = 2$. As a logical consequence of the evaluation of l_3 a linear combination of the criteria of the two previous levels is sought which is equivalent to a level 3 criterion. Thus it is ascertained that $w(l_3) = 3$, which means that the sum of a level 2 criterion and a level 1 criterion is equivalent. Criteria of the fifth level l_5 are by far the most weighted with 5. These should be distinguishable from the others and are therefore equivalent, for instance, to the sum of one level 3 criterion and one level 2 criterion or two level 2 criteria and one level 1 criterion. An overview of the weight assignment for all criteria is contained in Table 4.4.

Stellenbosch University https://scholar.sun.ac.za

Table 4.4: Weight assignment to the criteria

Description	Assignment			
Level l_i	l_1	l_2	l_3	l_4
Criterion c_i	c_1, c_4	c_6, c_7	c_5, c_8, c_9	c_2, c_3
Weight w	1	2	3	5

4.4.2.5 Determination of the Criterion and Weighting Vector

So far, each level and thus automatically each criterion has been assigned a weight. Consequently, the list structure can be simplified and a criterion vector can be formed, as shown in Expression (4.3).

$$Criterion\ vector : \Big(c_a,\ c_b,\ c_c,\ \ldots,\ c_n\Big) \tag{4.3}$$

To get the criterion vector for the previously defined list (Table 4.4), the list is inverted. Because nine criteria are defined the criterion vector is as specified in Expression (4.4).

$$Criterion\ vector\ for\ I4.0TIM : \Big(c_2,\ c_3,\ c_5,\ c_8,\ c_9,\ c_6,\ c_7,\ c_1,\ c_4\Big) \tag{4.4}$$

The criterion vector is accompanied by an identical vector of identical length, which is defined as the weighting vector. In this vector each element w_i represents the weight of the criterion c_i of the criterion vector. Hence, Expression (4.5) is generally valid.

$$Weighting\ vector : \Big(w_a,\ w_b,\ w_c,\ \ldots,\ w_n\Big) \tag{4.5}$$

Thus the weighting of the criteria in Table 4.4 and the criterion vector defined in Expression (4.4) results in the following weighting vector, which is represented in Expression (4.6).

$$Weighting\ vector\ for\ I4.0TIM : \Big(5,\ 5,\ 3,\ 3,\ 3,\ 2,\ 2,\ 1,\ 1\Big) \tag{4.6}$$

4.4.2.6 Degree of Criticality

The following paragraph seeks to establish a uniform scale for the criteria. For this purpose, each criterion is divided into the same number d of categories. These represent the different degrees of possible criticality for a system to the criterion being assessed. Five degrees of criticality are defined for the application. The different degrees of criticality are graded as very high, high, normal, low and very low, which are assigned to the corresponding values 4, 3, 2, 1 and 0. It should be noted that the respective categories of

Stellenbosch University https://scholar.sun.ac.za

a criterion are formulated differently due to high diversity. The degrees of criticality for each criterion are presented in Tables 4.5 to 4.13.

Table 4.5 presents the individual degrees of criticality of criterion c_1. The influence of system failure on health & safety is measured. It is evaluated from irreversible to negligible. The indications are expressed in a general way, since for example the European Union (EU) railway legislation uses the term "safety critical component" but does not specify it more precisely (European Commission 2016). In a sense, there is no list of which components are included and how they are to be defined.

Table 4.5: Criterion c_1: Impact on health & safety

Value	**Degrees of criticality**
4	Irreversible impact on health & safety
3	Enormous impact on health & safety
2	Reversible impact on health & safety
1	Low impact on health & safety
0	Negligible impact on health & safety

Criterion c_2 distinguishes between the degrees of criticality how the reliability behaves in case of failure. Puntis and Walley (1986, p. 296) refer to a range of five minutes as low technical causality up to a total failure of the railway vehicle as an extreme case. This implies that there are no restrictions in case of a malfunction and the rail vehicle can continue to operate or a total failure occurs (Table 4.6).

Table 4.6: Criterion c_2: Influence for rolling stock reliability

Value	**Degrees of criticality**
4	Total failure for rolling stock, recovery required
3	Able to proceed to termination station
2	Failed in service and a delay of more than five minutes
1	Failed in service and a delay of less than five minutes
0	No restrictions for operational use of rolling stock

The individual degrees of criticality for the influence on rolling stock availability are listed in Table 4.7. The availability of rolling stock depends strongly on the maintenance duration of a system. Using the MTTR as a reference value the average maintenance time of the system is known and thus the availability can be concluded. Szkoda (2014, p. 8) reveals in his study that the MTTR is strongly dependent on which maintenance measures are performed. This may last from a few hours up to several weeks. Therefore, the MTTR is indicated from negligible to more than one week for the degrees of criticality.

Stellenbosch University https://scholar.sun.ac.za

Table 4.7: Criterion c_3: Influence for rolling stock availability

Value	Degrees of criticality
4	MTTR more than a week
3	MTTR from four to seven days
2	MTTR from one to three days
1	MTTR less than one day
0	MTTR is negligible

As shown in Table 4.8, the degrees of criticality to the environment can be very extreme or negligible. Criterion c_4 must definitely be taken seriously, as public awareness is increasingly being sharpened on the topic of the environment. Although rail vehicles are a very environmentally friendly means of transport, it is imperative to avoid potential negative environmental impacts through maintenance. For instance, lubricants can contaminate the soil or groundwater. Efficient energy consumption and compliance with noise regulations must be ensured.

Table 4.8: Criterion c_4: Impact on environment

Value	Degrees of criticality
4	Extreme environmental harm
3	Major environmental harm
2	Serious environmental harm
1	Minimal environmental harm
0	Negligible impact on environment

The individual degrees of criticality relating to maintenance costs are formulated relatively generally in Table 4.9 so that they can be interpreted specifically for rail operators of different sizes, regions and resources. Therefore, the maintenance costs are defined from very low to very high.

Table 4.9: Criterion c_5: Maintenance costs

Value	Degrees of criticality
4	Very high maintenance costs
3	High maintenance costs
2	Normal maintenance costs
1	Low maintenance costs
0	Very low maintenance costs

Regarding criterion c_6 the redundancy of the system is assessed in Table 4.10. In other words, whether another system can replace the operated system in case of failure or no system can be provided.

Stellenbosch University https://scholar.sun.ac.za

Table 4.10: Criterion c_6: Existence of alternative systems

Value	Degrees of criticality
4	No redundant component
3	Possible to provide alternative component shortly after failure
2	Inferior component in reserve
1	Similar component in reserve
0	Redundant component available

The influence of comfort systems, but also of operationally relevant systems, can have a different degree of criticality regarding customer satisfaction as Table 4.11 illustrates. This can vary from negligible to an extreme in case of system failure.

Table 4.11: Criterion c_7: Impact for customers

Value	Degrees of criticality
4	Extreme negative impact for customer satisfaction
3	Major negative impact for customer satisfaction
2	Serious negative impact for customer satisfaction
1	Minimal impact for customers satisfaction
0	Negligible impact for customer satisfaction

Table 4.12 considers the degree of criticality of the failure frequency. Before assigning the values, it should be checked how regularly the system is in operation. Of course, this influences the error frequency considerably, because it makes a difference whether a system is operated daily or only sporadically. Concerning the different degrees of criticality, it should be noted that these relate to the monthly failure frequency. Manirajan et al. (2018, p. 790) evaluated field data of several rail vehicles. The results reveal a maximum of 25 failures per month and a minimum of less than one failure per month. Hence, these results serve as limits for the degrees of criticality for the failure frequency.

Table 4.12: Criterion c_8: Failure frequency

Value	Degrees of criticality
4	System fails very frequently ($>$ 25 failures per month)
3	System fails frequently ($10-25$ failures per month)
2	System fails with some frequently ($5-10$ failures per month)
1	System fails occasionally ($1-5$ failures per month)
0	System fails rarely ($<$ 1 failures per month)

Finally, Table 4.13 lists the degree of criticality of criterion c_9. Since rail vehicles operate in a complex environment and a malfunction of a rail vehicle system can severely disrupt the entire operation, the restrictions range from negligible to extreme.

Stellenbosch University https://scholar.sun.ac.za

Table 4.13: Criterion c_9: Impact for rail operation

Value	Degrees of criticality
4	Extreme restriction for rail operation
3	Major restriction for rail operation
2	Serious restriction for rail operation
1	Minimal restriction for rail operation
0	Negligible restriction for rail operation

A summary of the degrees of criticality of all criteria is presented in Appendix B.2 for transparency.

4.4.2.7 Determination of the Criticality Vector

In this step, the I4.0TIM is applied individually. In other words, after the rolling stock systems are defined, the criticality criteria are determined and weighted, the criterion and weighting vectors are known and the degree of criticality for each criterion is explained, the I4.0TIM user can now determine the criticality vectors. For each rolling stock system s_i the Tables 4.5 to 4.13 are iterated. During this process, the order of the criterion vector (Expression (4.4)) is adhered to. For each criterion c_i the degree of criticality d_i is determined and therefore d_i can receive the values 4, 3, 2, 1 or 0. The result is a list of n values, which is called the criticality vector. In general, the following Expression (4.7) is obtained.

$$Criticality\ vector: \Big(d_a,\ d_b,\ d_c,\ \dots,\ d_n\Big) \tag{4.7}$$

Because the I4.0TIM is based on nine criteria, the I4.0TIM user receives a criticality vector with nine values (Expression (4.8)). Since a separate criticality vector is determined for each rolling stock system s_i, the user finally obtains an overall result with nine criticality vectors.

$$Criticality\ vector\ for\ I4.0TIM: \Big(d_2,\ d_3,\ d_5,\ d_8,\ d_9,\ d_6,\ d_7,\ d_1,\ d_4\Big) \tag{4.8}$$

4.4.2.8 Determination of the Criticality Index

To get the numerical values of the evaluation the criticality index I_c is determined (Equation (4.9)). The numerator results from the scalar product of the criticality vector of the system s_i and the respective weighting vector. The denominator represents the highest score a rolling stock system can achieve, which is obtained by multiplying the number of criticality degrees and the sum of all weighting vector elements. The output value is

Stellenbosch University https://scholar.sun.ac.za

given in percent, where I_c has the following thresholds: $I_{c,min} = 0$ % and $I_{c,max} = 100$ %. The formula enables the user to consider the joined effect of the criticality degree and the weight of each criterion.

$$I_c = 100 \cdot \frac{\sum_{i=1}^{n} (d_i \cdot w_i)}{d \cdot \sum_{i=1}^{n} w_i} \tag{4.9}$$

where:

I_c = criticality index
n = number of criterion
d = number of criticality degrees of the criterion
d_i = criticality degree of a certain system according to the criterion c_i
w_i = weight of the criterion c_i

4.4.2.9 Assignment of the Criticality Index to Maintenance Strategies

The last part is to classify the nine previously determined criticality indices I_c. As explained at the beginning of phase 1, for the model element *maintenance strategies* five strategies are applicable (Table 4.2). The simplest strategy is represented by reactive maintenance, whereas smart maintenance is the most complex one and involves the most effort for implementation. The purpose of Table 4.14 is to assign the criticality index I_c to the maintenance strategies. In other words, the higher the criticality index I_c, the more reasonable it is to use a more sophisticated maintenance strategy. In conclusion to the I4.0TIM this implies that for rolling stock system s_i with a value of ≤ 35 percent predictive or smart maintenance is recommended. Thus, for the following phases of the I4.0TIM, only these rolling stock systems are further considered if they are above this limit.

Table 4.14: Maintenance strategy selection according to criticality index I_c

Maintenance strategy	**Criticality index I_c in [%]**	**Further consideration**
Smart maintenance	$I_c \geq 50$	Yes
Predictive maintenance	$35 \leq I_c < 50$	Yes
CBM	$20 \leq I_c < 35$	No
TBM	$10 \leq I_c < 20$	No
Reactive maintenance	$I_c < 10$	No

Stellenbosch University https://scholar.sun.ac.za

4.5 Phase 2: Selection of Industry 4.0 Technologies based on the Maturity Level

In the second phase of the model, a prerequisite categorisation serves as the central approach. The two model elements in this phase are the *Industry 4.0 technologies* and the *technological maturity level*. The objective of this phase is to extract the Industry 4.0 technologies that are appropriate to the current technological maturity level of the I4.0TIM user. The application of the prerequisite categorisation enables an individual categorisation of emerging technologies concerning their applicability according to the current technological maturity level. At the end of this phase, the I4.0TIM user receives, as a result, the possible Industry 4.0 technologies which are applicable for the present situation. A detailed overview of phase 2 is provided in Figure 4.4

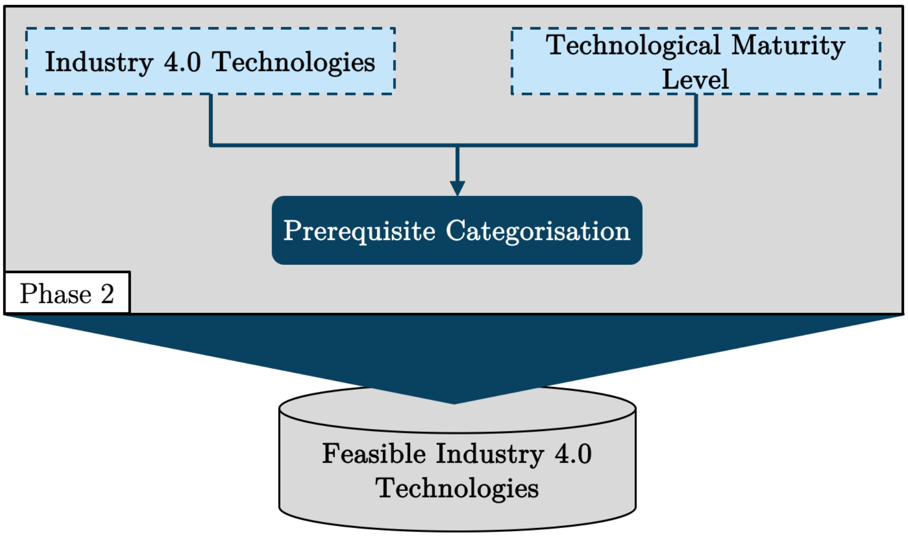


Figure 4.4: Second phase of I4.0TIM

4.5.1 Model Elements

Like phase 1, phase 2 comprises two model elements. The literature review revealed that nine emerging technologies (Section 2.4.3) are suitable for application in maintenance, whereas AR and VR are considered together. The survey confirmed the suitability of the technologies for applicability in rolling stock maintenance. Therefore, the technologies listed in Table 4.15 are available for the I4.0TIM user.

The determination of the technological maturity level is necessary for the subsequent approach. Therefore, each user of the I4.0TIM individually determines its technological degree of maturity. It is ascertained analogously as described in Section 3.6 and is thus the same procedure as described in the survey concerning the technological maturity level. The

Stellenbosch University https://scholar.sun.ac.za

Table 4.15: Variety of Industry 4.0 technologies

Index t_i	Industry 4.0 technologies
t_1	Big data & analytics
t_2	IoT
t_3	Cloud computing
t_4	AR & VR
t_5	Cyber security
t_6	CPS
t_7	AI
t_8	Additive manufacturing

questionnaire defined for this purpose is attached in Appendix B.3 and the corresponding technological maturity calculation in Appendix B.4.

4.5.2 Prerequisite Categorisation

The approach of the prerequisite categorisation consists of three parts. At the beginning, the prerequisite weighting factor is determined for each of the three prerequisites of a technology t_i. This is followed by the calculation of the total weighting factor for the respective technology t_i. Finally, it is examined whether the technology t_i can be implemented at the current maturity level or not.

4.5.2.1 Determination of the Weighting Factor

The first part serves to determine the prerequisite weighting factor wf. For each of the eight emerging technologies, three main prerequisites are determined. These are already listed in Table 3.1. For the I4.0TIM relevant information, an overview of the main prerequisites of the Industry 4.0 technologies is available in Appendix B.5. For each of the three main prerequisites of one technology, the weighting factor wf is calculated. The prerequisite weighting factor wf is derived from different characteristics (Table 4.16). These are intended to determine how difficult it is for the I4.0TIM user to fulfil the prerequisite.

Table 4.16: Overview of the characteristics

Index a_i	Characteristics
a_1	Costs to fulfil prerequisite
a_2	Complexity for the implementation of the prerequisite
a_3	Required know–how for the prerequisite
a_4	Dependencies of other systems for the prerequisite
a_5	Duration of the implementation for the prerequisite

Stellenbosch University https://scholar.sun.ac.za

The characteristics are concentrated on the five most important ones to make the approach as simple and user–friendly as possible. First, the costs are assessed. This entails the costs of fulfilling the prerequisite. If the prerequisite is already fulfilled, for example, the costs can be ignored. In contrast, the costs may be very high if the prerequisite is not yet fulfilled and the implementation is very cost–intensive. Another characteristic is the complexity for implementing the prerequisite. For this characteristic, it must be estimated how complex it is for the user of the I4.0TIM to implement the prerequisite in the company. Each prerequisite has different degrees of complexity for implementation; for instance, some are easier to implement than others. Therefore the required know–how is also included in the characteristics. For each prerequisite a specific know–how is necessary. This may already be available in the company or it has to be acquired externally. Likewise, prerequisites for the fulfilment of the system may depend on other systems. In a sense, certain systems have to be implemented beforehand to fulfil the prerequisite. The last characteristic to be covered is the time required for the implementation. Due to the previous characteristics, such as complexity or know–how, the time varies to fulfil the prerequisite. Therefore, the time duration until the prerequisite is fulfilled is also included for the characteristics.

Each of the five characteristics has four categories on an ordinal scale. A weight of 0, 1, 2, and 4 is assigned to each of these categories. The last category of the scale is weighted higher, emphasising difficulty of the highest category. This implies that the last category of the ordinal scale is particularly challenging to achieve the characteristic. Table 4.17 provides an overview of the categories for each characteristic and the weighting for each category.

Table 4.17: Ordinal scale of categories and related weighting for each characteristic

Characteristic a_i	Categories & Weighting			
	0	1	2	4
a_1	negligible	low	middle	high
a_2	negligible	low	middle	high
a_3	negligible	low	middle	high
a_4	negligible	low	middle	high
a_5	negligible	short	middle	long

To obtain the prerequisite weighting factor wf, Equation (4.10) is applied. Each category is determined individually by the I4.0TIM user on which category the prerequisite is classified. Once the respective prerequisite is determined for each characteristic, the corresponding weights are added and divided by the maximum number of points possible. The maximum number of points results from the number of characteristics and the maximum weighting. This always corresponds to a value of 20. For all three prerequisites of a technology t_i, this process is carried out separately, whereby three prerequisite weighting factors are ultimately obtained.

Stellenbosch University https://scholar.sun.ac.za

$$wf_{t,p} = \frac{\sum_{i=1}^{n} a_i}{max\ points\ possible} \tag{4.10}$$

where:

$wf_{t,p}$ = weighting factor of technology t and prerequisite p
n = number of characteristics
a_i = characteristic i

4.5.2.2 Calculation of the Total Weighting Factor

After determining the three prerequisite weighting factors $wf_{t,p}$ of an emerging technology t_i, the total weighting factor WF_t is calculated. As shown in Equation (4.11), the total weighting factor WF_t is the sum of the three corresponding prerequisite weighting factors $wf_{t,p}$.

$$WF_t = \sum_{p=1}^{n} wf_{t,p} \tag{4.11}$$

where:

WF_t = total weighting factor of technology t
n = number of prerequisites
$wf_{t,p}$ = weighting factor of technology t and prerequisite p

For a better understanding, the procedure is described in general terms in Table 4.18. If the total weighting factor WF_t of technology t is to be determined, the three corresponding prerequisite weighting factors $wf_{t,p}$ determined in Section 4.5.2.1 are utilised and are added together.

Table 4.18: Overview of the calculation of the total weighting factor WF_t

Technology t_i	**Prerequisite** p	**Weighting factors** $wf_{t,p}$	**Total weighting factor** WF_t
	1	$wf_{t,1}$	
t_i	2	$wf_{t,2}$	$\sum_{p=1}^{n} wf_{t,p}$
	3	$wf_{t,3}$	

Stellenbosch University https://scholar.sun.ac.za

4.5.2.3 Assignment of Total Weighting Factor to Maturity Level

Finally, it is necessary to verify whether the selected emerging technology t_i can be applied at the current technological maturity level. To determine whether this is the case, the total weighting factor WF_t is compared with the current technological maturity level. The lower the total weighting factor WF_t the lower the maturity level can be to implement the technology t_i. Inversely, a high total weighting factor WF_t requires a high level of maturity to enable the company to deploy the selected Industry 4.0 technology t_i. To be specific, the lowest total weighting factor indicates $WF_{t,min} = 0$ and the maximum value is $WF_{t,max} = 3$. The assignment is illustrated in Table 4.19. For the further phases of the I4.0TIM, only those technologies t_i which comply with the limits listed in Table 4.19 according to the corresponding technological maturity level are further considered.

Table 4.19: Total weighting factor WF_t assignment according to technological maturity level

Technological maturity level	Total weighting factor WF_t
Maturity level 5	$WF_t \geq 2.70$
Maturity level 4	$2.20 \leq WF_t < 2.70$
Maturity level 3	$1.60 \leq WF_t < 2.20$
Maturity level 2	$1.00 \leq WF_t < 1.60$
Maturity level 1	$WF_t < 1.00$

4.6 Phase 3: Decision regarding Implementation

The third phase of the I4.0TIM comprises the two model elements which result from phase 1 and phase 2. The objective of phase 3 is to determine whether the selected Industry 4.0 technology t_i is appropriate for the implementation of the selected rolling stock system s_i.

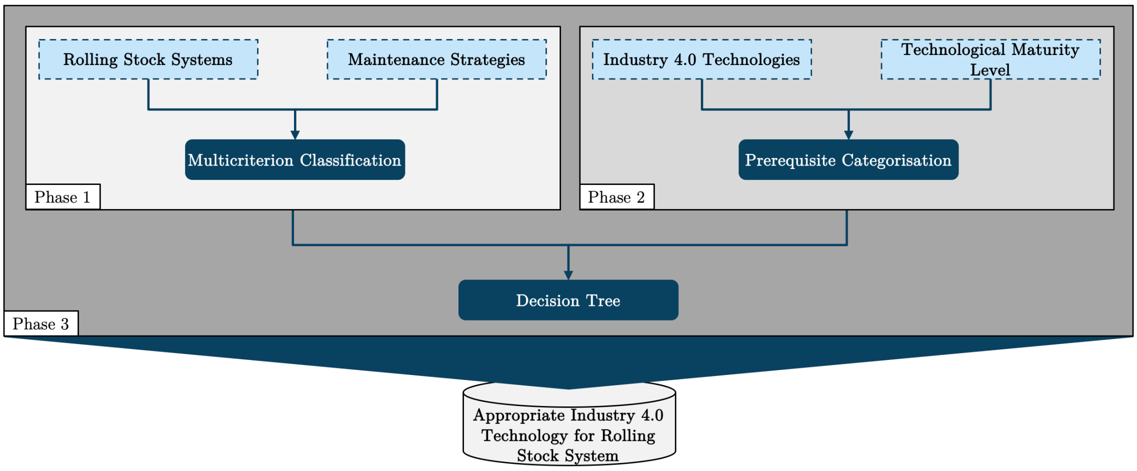


Figure 4.5: Third phase of I4.0TIM

Stellenbosch University https://scholar.sun.ac.za

A decision tree serves to evaluate the appropriateness of the selected emerging technology t_i. The decision tree has to be iterated to make a final "yes" or "no" decision regarding the implementation. How the individual model elements emerge and how the approach ensues is outlined in Figure 4.5.

4.6.1 Model Elements

In phase 1 the rolling stock systems for which a predictive or smart maintenance strategy is appropriate are identified. In the second phase, the Industry 4.0 technologies which are suitable for application at the current maturity level are determined. Thus, according to Expression 4.12, m rolling stock systems and n Industry 4.0 technologies are available for selection. Both numbers depend on how many rolling stock systems are selected in phase 1, whereby $m \leq 9$ is valid and similarly, $n \leq 8$ is valid for the specific Industry 4.0 technologies.

$$\begin{aligned} s_i &= m \\ t_i &= n \end{aligned} \tag{4.12}$$

where:

m = number of feasible rolling stock systems
n = number of feasible Industry 4.0 technologies

4.6.2 Decision Tree

According to Mitchell (1997, p. 52) a decision tree is "one of the most widely used and practical methods for inductive inference". In this case, a binary decision is made on the basis of the previous results as to whether implementation should proceed or not. The developed decision tree diagram consists of nodes, branches and leaves. The root node is the parent of all nodes and indicates the starting point. All other nodes with outgoing branches are test nodes, which can be recognised by their diamond shape. They always have two outgoing branches in the case of this decision tree. All leaves, which represent the result, are shown as an oval. The developed decision tree diagram is depicted in Figure 4.6. The first part is about general aspects, the second part about performance. In the following two sections both parts are discussed in detail.

Stellenbosch University https://scholar.sun.ac.za

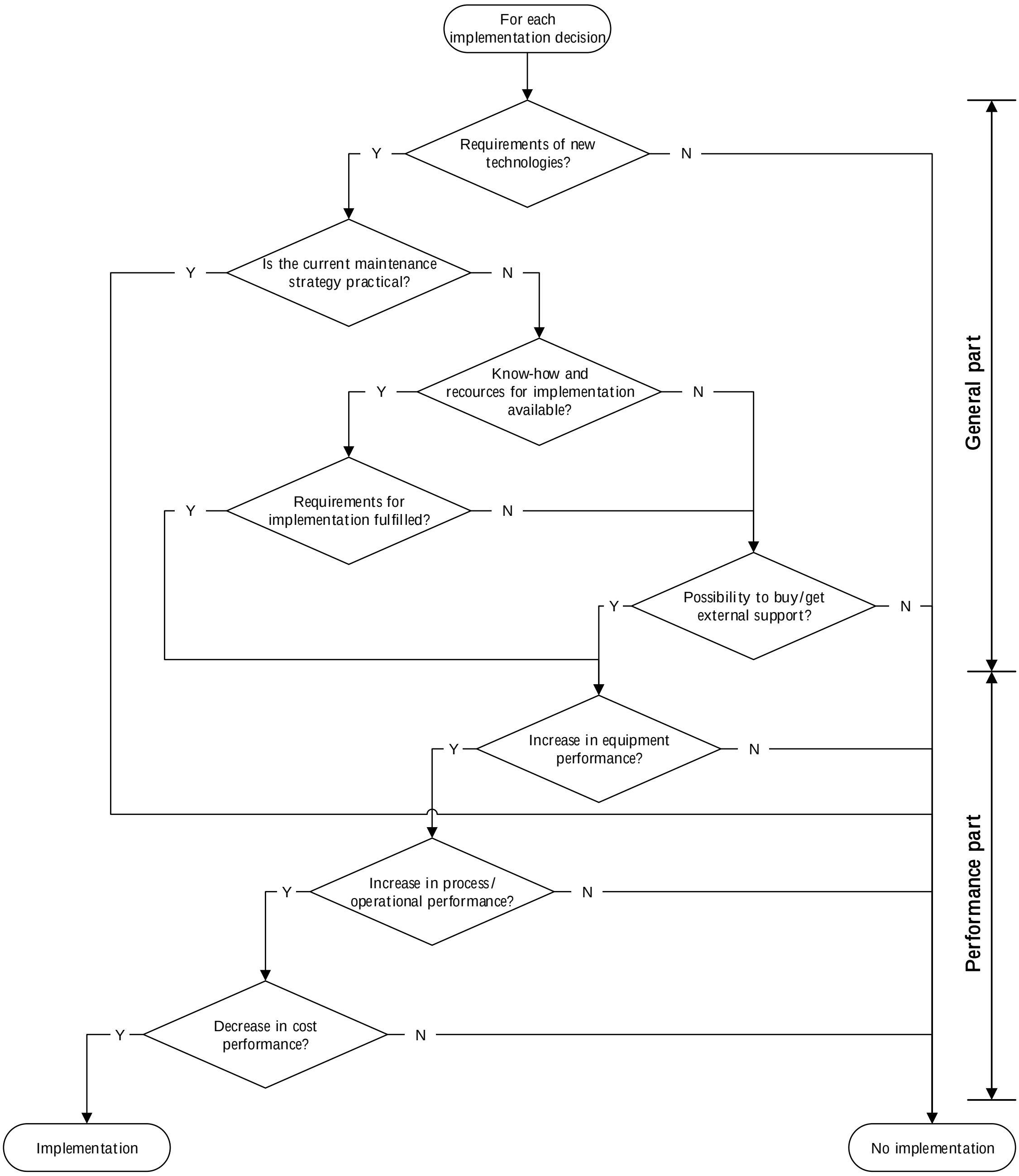


Figure 4.6: Decision tree logic diagram for appropriate implementation

4.6.2.1 General Part

The general part of the decision tree involves determining whether all the necessary preparations for implementation are available regarding the corresponding rolling stock system s_i and the corresponding technology t_i. It consists of five test nodes, which are explained below.

- *Requirement of emerging technology*: In the beginning, it is checked if there is a genuine demand for emerging technology t_i. It reconfirms whether the use of Industry

Stellenbosch University https://scholar.sun.ac.za

4.0 technology is required. So this test node makes it clear whether there is a real incentive for the selected technology t_i or not.

- *Practicability of current maintenance strategy*: Here it is checked whether the current maintenance strategy is practicable for the corresponding rolling stock system s_i or not. In other words, it is necessary to decide how the current maintenance strategy is assessed in terms of the rolling stock system s_i. If it is evaluated as practicable, although it is classified in phase 1 by the multicriterion classification for predictive or smart maintenance, no implementation of the emerging technology t_i should be performed and the decision tree ends. If this is not the case and the current maintenance strategy is not practicable, then the next test node is examined.

- *Availability of know–how and resources for implementation*: This test node determines whether the company already has its know–how and resources for implementing technology t_i in the company. The know–how refers to the employees, which means to validate if there are already employees who have experience in this area. In addition, there may already be know–how regarding the technology t_i in a different department of the company, which could support the implementation process. In terms of resources, the question is whether software or physical equipment can be provided and whether there is enough personnel for the implementation available in the company.

- *Fulfilment of requirements for implementation*: This test node appears in the decision tree because before the implementation process can start it must be ascertained whether all main prerequisites of the corresponding technology t_i from Table 3.1 are fulfilled. These are considered to be basic prerequisites for a successful implementation of the corresponding technology t_i.

- *Possibility to buy/get external support*: The last test node in the general section of the decision tree is concerned about whether there are possibilities of external support. If the company is not able to fulfil all the previous points on its own, it must be investigated whether these can be obtained from external sources. This could be, for instance, the necessary software or hardware components or the required personnel, which should be hired additionally. As the use of emerging technologies in the maintenance of rail vehicles is already slowly becoming established, the rail operator can, for example, already develop individual solutions with the rail vehicle manufacturer.

4.6.2.2 Performance Part

The second part of the decision tree examines performance in more detail. In this part, the decisive quantification is performed to achieve a final decision. In a sense, MPIs have

Stellenbosch University https://scholar.sun.ac.za

to be analysed thoroughly for arriving at the final decision regarding the implementation. The three categories of MPIs identified in Section 2.3.4 are consequently integrated within the decision tree. Below the test nodes with the three essential categories of the MPIs are introduced.

- *Equipment performance*: This test node evaluates whether the use of the corresponding technology t_i would lead to an improvement in equipment performance compared to the current maintenance strategy. Thus, it is relevant to assess how the current equipment performance is regarding the corresponding system s_i. Simultaneously it must be evaluated whether it could be improved by implementing the technology t_i.
- *Process performance*: As a second test node of the performance part, the process is analysed in depth. Positive effects must be evident in the planning of maintenance, schedule compliance, work orders or and stock–keeping. Though it is not for every technology t_i, it makes sense to analyse all mentioned subjects. Therefore, it is indispensable to evaluate in which area an improvement should be made.
- *Cost performance*: The last node that has to be inspected considers the costs. These are deliberately positioned at the end of the decision tree, as the influence of costs should be considered last. As costs are crucial for management, all the previously mentioned test nodes have to previously show an improvement to make the appropriate decision for the selected technology t_i. The significance of maintenance costs is demonstrated by examining the life cycle costs of rolling stock. Throughout the entire rolling stock life cycle, 31 percent of the costs are accounted by the initial capital investment, 25 percent for the operating costs and the majority of 44 percent is budgeted for maintenance (Office of Rail Regulation 2013, p. 7).

Appendix B.6 provides an overview of the formulas for calculating the respective performance category. These serve as orientation for the I4.0TIM user if no corresponding values are already available in the company when using the decision tree.

4.7 Phase 4: Future Programme

In the last and fourth phase of the model, after having gone through the previous three phases and in case of a positive result for the implementation of a technology t_i for a system s_i, a roadmap for future events is presented. The survey results (Section 3.7) provide information about possible situations and guidance. Hence the objective of this phase is to provide the I4.0TIM user with an outline of future prospects.

Stellenbosch University https://scholar.sun.ac.za

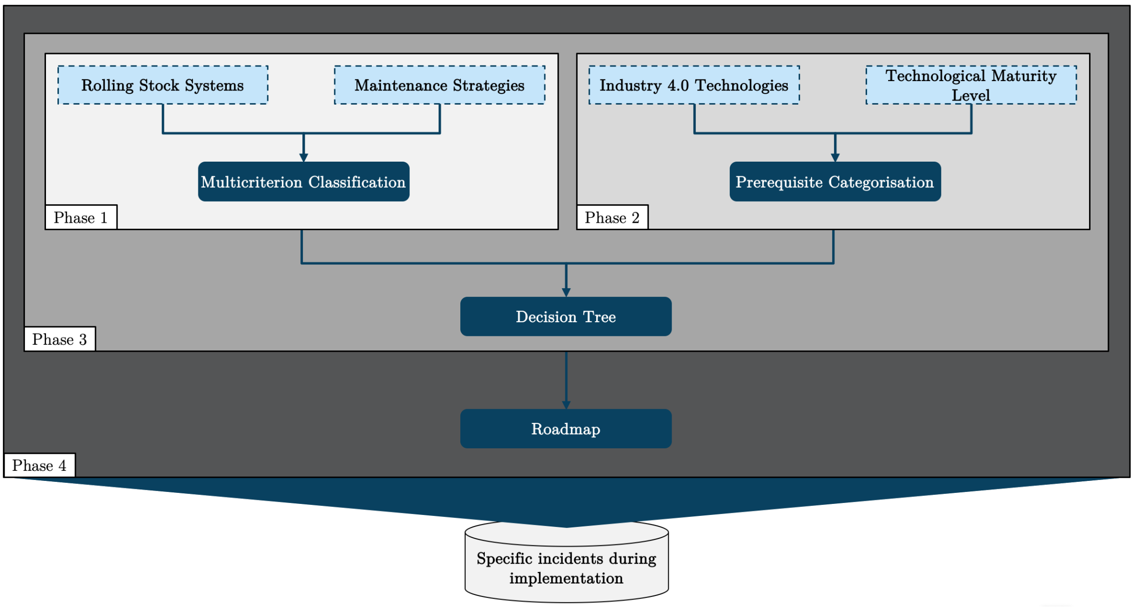


Figure 4.7: Fourth phase of I4.0TIM

4.7.1 Model Elements

The model elements in phase 4 consist of the suitable technology t_i and the appropriate system s_i. Both have been confirmed by phase 3 and are now ready for implementation. Depending on the number of technologies and systems that have successfully undertaken the phases, several technologies and systems may be appropriate for this phase.

4.7.2 Roadmap

The roadmap illustrated in Figure 4.8 concentrates on how the degree of maturity can increase over time. In other words, after the decision has been made regarding technology and system, three further milestones follow. The first is to make the necessary preparations so that the implementation runs smoothly. Furthermore, the challenges and maintenance areas of the implementation phase according to the maturity level and region are described. Finally, the follow–up covers the positive benefits and effects to be expected after implementation and possible technologies for further integration.

Stellenbosch University https://scholar.sun.ac.za

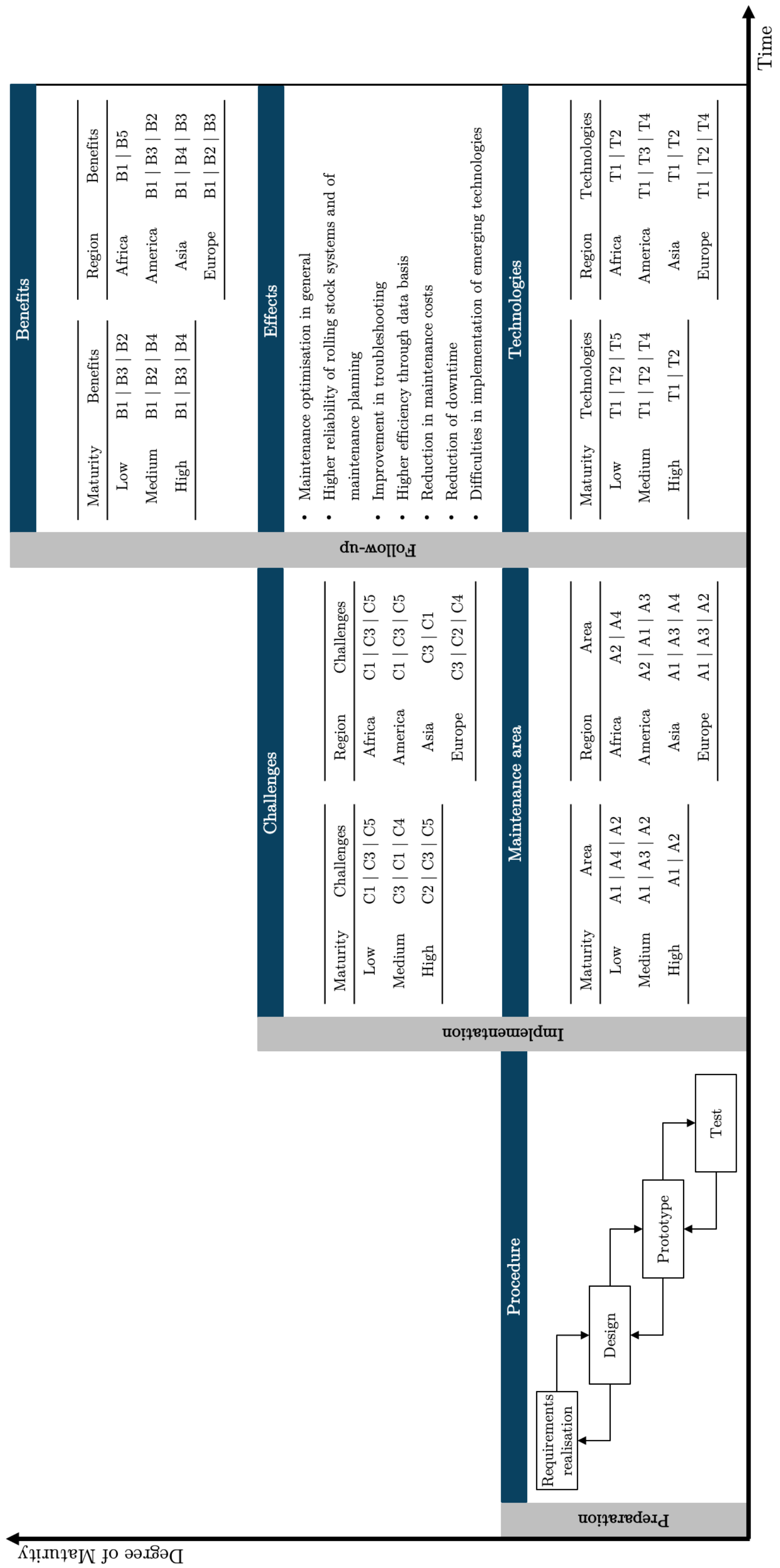


Figure 4.8: Roadmap

Stellenbosch University https://scholar.sun.ac.za

4.7.2.1 Preparation

The first milestone is about preparing for implementation. The central elements of the waterfall model provide support in these preparations. The preceding phases have already completed the feasibility analysis. Consequently, the technology requirements must first be implemented, if these are not yet available. Afterwards, a solution concept for the individual case has to be developed. A design is created where all requirements are taken into account and the existing interfaces, hardware and software are integrated. If a solution concept has been developed for this purpose, a prototype is built. This can either be a physical object, a virtual infrastructure, a programme or something similar. Insofar as a prototype is available, it is to be tested. It is recommended that the test is first performed on one rail vehicle. In the case of successful tests, it can be rolled out to the entire fleet before full integration across fleets occurs.

4.7.2.2 Implementation

The second milestone is the implementation in Figure 4.8. The results of the survey have revealed that there are different outcomes depending on maturity level or region. In terms of challenges, Figure 4.8 presents the two or three main challenges according to maturity level or region. The differentiation of the maturity levels into low ($< 47\%$), medium ($< 67\%$) and high ($\leq 100\%$) is analogous to Section 3.6. The meaning of the individual abbreviations is explained in Table 4.20.

Table 4.20: Expected challenges

Index	Challenges
C1	Lack of corporate strategy
C2	Limited financial resources
C3	Lack of qualified personnel and competences
C4	Lack of technological prerequisites
C5	Lack of information regarding implementation

The survey results also indicate various tendencies regarding the maintenance area where Industry 4.0 technologies are preferred to be implemented. The summary of the findings regarding the maintenance areas are presented in Table 4.21.

Table 4.21: Maintenance areas for implementation

Index	Maintenance areas
A1	Monitoring of systems
A2	Planning and organisation of maintenance
A3	Data acquisition
A4	Execution of maintenance

Stellenbosch University https://scholar.sun.ac.za

4.7.2.3 Follow–up

The final milestone considers what benefits will be experienced after technology integration. The results of the survey reveal that different benefits can be expected depending on the degree of maturity or the region. Table 4.22 gives an overview of the benefits.

Table 4.22: Expected benefits

Index	Benefits
B1	Increase system reliability
B2	Cut costs
B3	Increase quality assurance
B4	Create competitive advantages
B5	Increase safety for employees

Regarding implementation effects, there were no clear results in terms of technological maturity or region. The results of the survey have shown that similar effects can be expected regardless of maturity or region. The most significant are listed in Figure 4.8.

In addition to the benefits, the most promising technologies for further implementation are ranked by maturity level and region. This illustrates which technology is the most important in each category. An explanation is presented in Table 4.23.

Table 4.23: Most promising emerging technologies

Index	Technologies
T1	Big data & analytics
T2	IoT
T3	Cloud computing
T4	Cyber security
T5	AI

4.8 Requirements Assessment

The general and practical requirements are defined before designing the model. An overview of the resulting evaluation of the requirements is provided in Figure 4.9. The first two phases of the model consider the individual selection of components and Industry 4.0 technologies. The phases are adaptive and can be iterated for all or only selective rolling stock systems s_i and emerging technologies t_i. Furthermore, phases 3 and 4 are designed in a manner that they are independent of the previous decisions in phases 1 and 2 and are suitable for all scenarios. Consequently, the *consideration of individual preferences* is completely fulfilled for the I4.0TIM. The individuality is also included in the determination of the degree of maturity. The degree of maturity of the model user is determined by a de-

Stellenbosch University https://scholar.sun.ac.za

General Requirements	• Consideration of individual preferences	●
	• Integration of the technological degree of maturity	●
Practical Requirements	• Generality of the I4.0TIM	◕
	• Modularity of the I4.0TIM	●
	• Constant consistency of the I4.0TIM	●

Requirements fulfilment: ○ not at all ◔ hardly ◑ partly ◕ primarily ● fully

Figure 4.9: Fulfilment assessment of the general and practical model requirements

veloped questionnaire. Thus, the *integration of the technological degree of maturity* is fully assured. In addition, the *generality of the I4.0TIM* is ensured primarily by the calculated degree of maturity. All phases of the model enable the optimal possibilities for implementation regardless of whether a very high degree or quite low degree of maturity exists. However, the requirements for the emerging technologies are rather sophisticated, meaning that if the level of maturity is quite low, no technology may be considered. The I4.0TIM is divided into four independent phases. Each phase can be executed independently from the previous ones, whereby the *modularity of the I4.0TIM* is completely fulfilled. The clearly defined inputs and outputs of the respective phases ensure the *constant consistency of the I4.0TIM*. Before every phase, the model user is provided with the model elements, which represent the inputs and the outputs are presented in the cylinder.

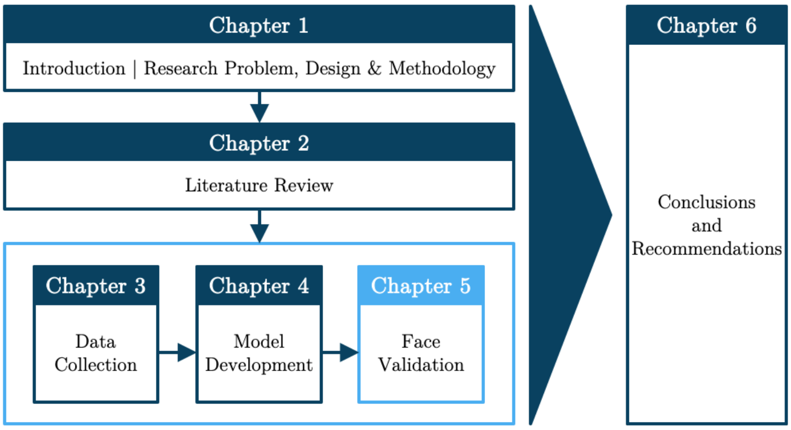
4.9 Chapter Summary

In conclusion, this chapter described the model developed for this study as well as the individual phases composed by the I4.0TIM. The I4.0TIM has the potential to support rail operators for their decision of implementing Industry 4.0 technologies in their rolling stock maintenance processes. The validation of this statement is carried out in Chapter 5.

Stellenbosch University https://scholar.sun.ac.za

Chapter 5

Validation of the Model



The objective of this chapter is to validate the developed I4.0TIM proposed in Chapter 4. Quality assurance can be accomplished by the validation of the model which will assess whether the I4.0TIM and its associated four phases could add value to rail operators' maintenance processes. The chapter starts with the background of the validation process and introduces the validation methodology applied for this study. The I4.0TIM is validated utilising face validation which is conducted by face–to–face interviews with subject matter experts from the maintenance departments of rail operators. The face validation approach and the findings are presented.

5.1 Face Validation

In general, validation is the process of delineating whether the model illustrates the real world system in a particular problem domain (O'Leary et al. 1990, p. 51). The key issue is to what extent the research results provide a correct answer (Gaber 2010, p. 471). Validation consists of two dimensions: verification and substantiation (O'Leary et al. 1990, p. 51). Verification is defined as the process of ensuring that the developed model corresponds to the conception and thus represents what the scientist intends to construct (Miser 1993, p. 212). The substantiation is about ensuring that the "model within its

Stellenbosch University https://scholar.sun.ac.za

domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Balci and Sargent 1981, p. 190).

As the name implies, face validity explores the question "on the face of things, do the investigators reach the correct conclusions?" (Gaber 2010, p. 471). Therefore, face validity can be contemplated as a test of internal validity, whereby this process involves the researcher examining the research processes from the view of an external user. According to Gaber (2010, p. 471) the researcher is required to step outside of the present research context and evaluate the observations from a common sense perspective. Effectively, this concerns whether or not the researcher draws the right conclusions from the data available.

Borenstein (1998, p. 229) states that "the main objective of a face validation is to achieve consistency between the designer's view and the potential user's view of the problem in a timely and cost–effective way". O'Leary et al. (1990, p. 53) specify it and point out that face validation assures that the formulated problem comprises the complete actual problem and is adequately structured so a respectable solution is obtained before the actual implementation occurs.

For this study, subject matter experts are asked to validate the model after attending a presentation given by the researcher. The presentation primarily covered a detailed explanation of the I4.0TIM in which all four phases were discussed. The model explanation is preceded by the primary research question and objective as well as the research methodology. The presentation is concluded by asking the participants to answer a questionnaire, which is used as a formal instrument to assess the validity of the model. The face validation questionnaire employed within this study is based on an extract from the case study conducted by Borenstein (1998, pp. 238–239). The relevant questionnaire is attached in Appendix C.1. The questionnaire encompasses five questions for the face validation process. The questionnaire aims to determine the overall opinion about the proposed solution in the form of the developed model. The strengths and weaknesses of the model are also examined. The logical description, applicability and relevance of the model are checked on a scale from very good to poor. In the end, possible improvements of the model are recorded.

The validation process is carried out with eight subject matter experts in rolling stock maintenance. The criteria for selection include that the participants have at least five years of professional experience in rolling stock maintenance. In addition, it is relevant that they represent different regions to guarantee diversity. All eight selected subject matter experts have at least five years of experience in rail vehicle maintenance. Some of them have even more than ten years of experience. This expertise is also reflected in the positions the participants hold in the industry. This ranges from maintenance operations manager, rolling stock engineer to head of rolling stock maintenance. The subject matter experts have gained experience in the following countries: three South Africa, two Saudi

Stellenbosch University https://scholar.sun.ac.za

Arabia, Syria, Pakistan and the United States of America. Since the participants are from different countries and it is complicated to schedule a uniform appointment because of the time difference, the presentation is held individually for each participant. This also provides the opportunity to address all individual questions after the presentation, before the validation process is conducted. The questionnaire is sent to the participants in advance to enable them to familiarise themselves with the questions and to have the questions available during the presentation. All of the participants were part of the online survey. Therefore, they are already familiar with the research topic.

5.2 Validation Feedback

The overall feedback of all participants about the developed model is positive so that the I4.0TIM is considered to be a suitable solution. A detailed examination of the feedback to all questions is presented in the following paragraphs. In Appendix C.2 the feedback from all participants to the questionnaire is available.

Overall, the participants see the model as very well constructed, practical and understandable. Three of the participants stated their overall view of the model that it is definitely designed to support the rail industry in implementing Industry 4.0 technologies. Furthermore, two participants pointed out that the model covers all essential elements of rolling stock maintenance as well as all maintenance strategies and is therefore very well designed. One participant specified that the consideration of smart maintenance is especially interesting because it can help to reduce the corrective downtime.

Concerning the strengths of the model, it is emphasised that the model is a very effective solution for the industry. It is further mentioned that so far only emerging technologies are under discussion, but there is no concrete proposal for implementation. In summary, the following strengths of the model can be outlined:

- The model selects the maintenance strategy based on the criticality of the components.
- The model supports the move from Industry 3.0 technologies to Industry 4.0 technologies.
- The theory part of the model is well explained.
- The model supports easy decision–making for maintenance strategies and Industry 4.0 technologies.
- The model is well organised by defining each phase and covers every aspect of maintenance.

Stellenbosch University https://scholar.sun.ac.za

- The model considers all the rolling stock components and ties them in a logical relation with maintenance strategies and Industry 4.0 technologies.
- The model is divided into several phases for assessing the applicability of emerging technologies and further advantages are the evaluation of the applicability as well as the adaptability and flexibility of the model.
- The model is developed timely, as the rail industry is only slightly away from the introduction of emerging technologies.

Addressing the weaknesses of I4.0TIM, five of the participants stated that they do not identify any weaknesses in the model. However, there is one participant who considered that the implementation of "the model in the rolling stock industry will normally take a long time to see the benefits of the model". It should be noted that the model is developed precisely for this reason, to be applied in the rail industry. Regarding the concern to see the benefits only in the long run, it is important to point out that the first benefits are already visible after the first three phases of the selection process. The model user then knows explicitly for which components Industry 4.0 technologies can be applied for the respective maturity level. The information is not available to the user beforehand, so the user benefits even before the implementation of phase 4 has been completed.

Other concerns are expressed that no practical implementation has been carried out yet and that the practical application of the model might lead to high costs. In this respect, it needs to be stressed that a practical application of the model, for example in the form of a case study, is not feasible in times of the COVID–19 pandemic. In other words, rail operators currently have different priorities than supporting an external case study in their company. It is for this reason that face validation is selected for the validation process of this study. Concerning the potentially high application costs of the model, the selection of technologies and maintenance strategies will initially only involve working time and thus personnel costs. Of course, the implementation of Industry 4.0 technologies can involve high acquisition costs for the company. However, it must be taken into account that in phase 3 of the model it is examined whether these technologies will be amortised and thus contribute positively to reducing maintenance costs in the long term.

Further points of criticism are expressed regarding the maturity level, that different scales for the regions should be introduced and the criticality criteria c_i should be re–evaluated. When determining the maturity level, the objective is to have a uniform scale for the degree of maturity. The objective is not to introduce a different scale for different regions when calculating the maturity level. The purpose of the unified scale is to enable companies to be comparable to others and to take further decisions based on the calculated degree of maturity. The considerations on the weighting of the criticality criteria c_i are questionable. In Section 4.4.2.3 it is explained why the order is established and in Section 4.4.2.4 the criteria are weighted accordingly. If the defined order and weighting of the weighting

Stellenbosch University https://scholar.sun.ac.za

vector is not suitable for the model user, the user may determine the weighting vector independently.

In question four of the questionnaire, the relevance and logical description of the model is considered very good by five participants and good by three. For the applicability of the model, it is assessed as very good by four and good by three participants and fair by one participant. The results of the fourth question consequently reflect the predominantly positive feedback of the participants and confirm the importance of the model for rail operators.

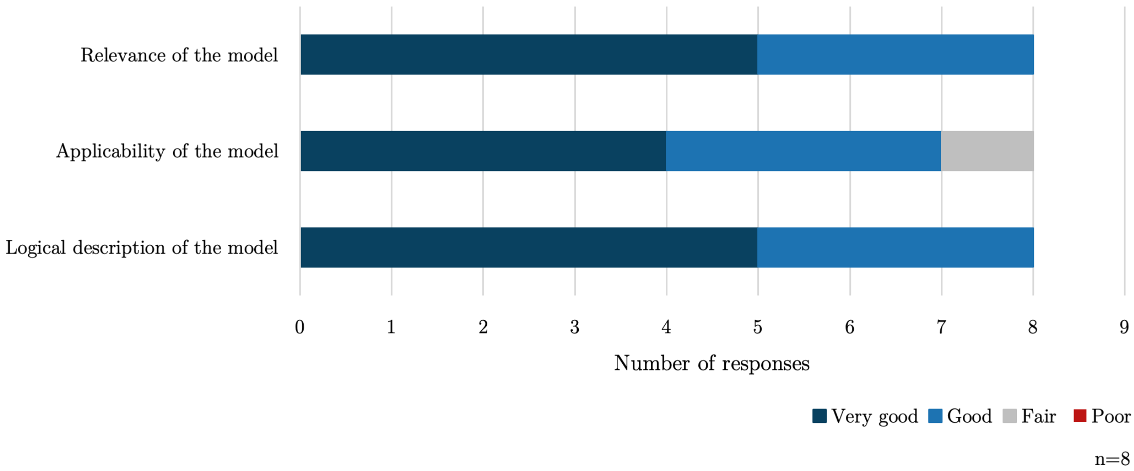


Figure 5.1: Participants feedback about the relevance, applicability and logical description of the model

Commenting on the improvements to the model, it is stated that the "next logical step would be to test it". It is pointed out that it is essential to present the model to the responsible people in maintenance as well as in management to obtain the benefits of the model. The improvements will be made after the implementation of the model. Furthermore, one participant emphasised that Original Equipment Manufacturers (OEMs) such as Siemens, Alstom or Bombardier already partly offer the integration of emerging technologies in maintenance. However, these are offered as a very expensive extra. Thus the model enables rail operators to make decisions for the implementation of emerging technologies on their own and not necessarily depend on the offers of OEMs.

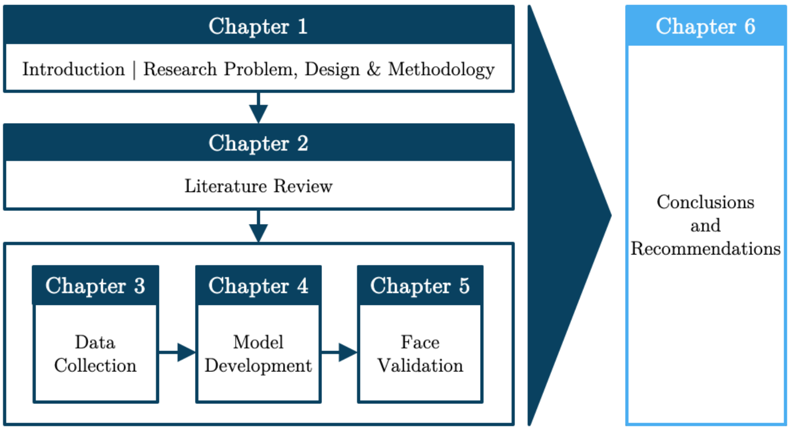
5.3 Chapter Summary

In this chapter the I4.0TIM is validated and a summary of the feedback of subject matter experts is presented. The face validation approach is explained and afterwards, the face validation is performed. The participants' feedback confirms the relevance, applicability and logical description of the model. In summary, the majority of the participants consider the application and implementation of the model for rail operators as important.

Stellenbosch University https://scholar.sun.ac.za

Chapter 6

Conclusions and Recommendations



The objective of this chapter is to provide a research overview and to summarise the research findings and draw conclusions. The contributions of this research are discussed and recommendations for future research are provided.

6.1 Research Overview

This study is presented in six chapters including the research background and research design, the literature review, the Industry 4.0 technology maturity assessment, the developed model, the validation and conclusions. The following paragraphs provide a brief summary of the chapter content.

Chapter 1 summarises the background of the study. The current developments in the means of transport in South Africa as well as in Germany are presented, with a special focus on the use of rail vehicles. It is stated that the maintenance of rail vehicles is particularly important due to their long useful life. However, it is emphasised that there are two main maintenance strategies in use today and the industry is struggling to develop towards the integration of emerging technologies. The problem statement is defined and the primary and the five secondary research questions as well as the nine research objectives

Stellenbosch University https://scholar.sun.ac.za

are derived from these findings. Consequently, the research design and methodology for the study are set, which are based on a pragmatic worldview and a mixed methods approach. The chapter concludes with the delimitations and limitations as well as the thesis outline, where the thesis roadmap provides an overview of the chapter sequence.

Chapter 2 contains a comprehensive literature review. First, rail vehicles are classified with railways and afterwards, the different types of rail vehicles are presented. Notably, rail vehicles are divided into long–distance transport and short distance transport based on their travel speed and number of stops. Despite the different types of use, rail vehicles have basic common components for passenger transport. These nine most important mechanical components are examined in detail and can be divided into operationally relevant systems and passenger comfort systems. Next, maintenance is analysed, describing the four maintenance measures as well as the five different maintenance strategies, which are differentiated according to their degree of development. Finally, the MPI as well as rolling stock maintenance is discussed more thoroughly. A systematic literature review identifies the nine major industry 4.0 technologies for maintenance and the benefits associated with each of them. Finally, different maturity models, which serve to determine the degree of maturity, are declared and compared.

Chapter 3 performs the Industry 4.0 technology maturity assessment. In this context, an online survey with subject matter experts is conducted. First, the survey design is explained, which objectives are pursued with the survey and which preparatory measures are taken in the planning phase. This is followed by an explanation of the questionnaire, which is divided into five main parts. After explaining the implementation, the results of the survey are evaluated. First, the results are directly and indirectly analysed and the main results are presented. Finally, the results are discussed. In summary, it can be said that the majority of the industry is still in the planning phase regarding the implementation of the technologies. Furthermore, it can be concluded that all technologies and advantages have been confirmed which were identified by the literature review. The challenges of using technologies are also confirmed.

Chapter 4 presents the I4.0TIM, which is considered to be a proposed solution for the problem identified in Section 1.2. In this context, the model concept is first explained and specified. Before the model is designed, the requirements of I4.0TIM are established, which are derived from the primary research question. These are divided into two general requirements and three practical ones. An overview of the I4.0TIM and all four phases of the model are presented before they are discussed in detail. In the first phase, the rolling stock system is prioritised in terms of maintenance strategies and suitable systems for predictive or smart maintenance are identified. In the second phase, the maturity of the model user is determined and suitable technologies for the respective maturity level are identified. The third phase examines whether or not an implementation of the selected technology t_i is suitable for the selected system s_i. The roadmap presented in the fourth

Stellenbosch University https://scholar.sun.ac.za

phase integrates the results of the survey and illustrates the path from preparation to implementation and follow–up.

Chapter 5 provides the validation of the I4.0TIM. For this purpose, the approach applied for face validation is explained first. Besides, the elaborated questionnaire is explained as well as the procedure for the validation itself. Regarding the validation feedback, it should be emphasised that the vast majority of respondents consider the model to be very relevant, applicable and logical. Thus the overwhelming majority of the participants is very positive and the model should be adopted by rail operators.

6.2 Summary of Research Results

The results of the primary and secondary research questions are summarised below. The purpose is to present the key findings and reflect the conducted research of this study.

Primary research question

How can a model be developed for the implementation of Industry 4.0 technologies for rolling stock maintenance, taking into account the rail operator's technological maturity?

This elaboration proposes a model which supports rail operators in their decision for implementing Industry 4.0 technologies in rolling stock maintenance. The findings of the secondary research questions are incorporated into the proposed solution of the primary research question. The developed I4.0TIM consists of four main phases. In the first phase, a multicriterion classification is used to prioritise the rail vehicle systems and determine the appropriate maintenance strategy for them. In the second phase, the Industry 4.0 technologies are categorised by a prerequisite categorisation according to the maturity level of the model user. The maturity level is determined by a specially developed questionnaire. For the third phase, a decision tree is used to decide whether an implementation of the emerging technology t_i is appropriate for the selected system s_i. The decision tree starts with a general part, examining whether all preparatory measures are in place. The next part, covering performance, examines whether improvement of the performance regarding the equipment, processes and costs can be expected. The last and fourth phase of the model focuses on presenting future prospects to the model user. Thus the roadmap integrates to a large extent the results of the survey and shows how the maturity level can be increased over time by integrating Industry 4.0 technologies.

Stellenbosch University https://scholar.sun.ac.za

First secondary research question

Which maintenance strategies are applied for rolling stock?

The comprehensive literature research has revealed that there are currently five different types of maintenance strategies, which can be distinguished according to the degree of development. The simplest and oldest is reactive maintenance, where a component is only replaced after failure. This is followed by preventive maintenance, which is differentiated between TBM and CBM. These strategies involve the preventive replacement of components or the replacement of components when a certain wear margin is reached. Predictive maintenance is found on the next level. This involves monitoring components and predicting component failure at an early stage. The most modern and also the latest strategy is smart maintenance. This strategy involves smart components exchanging information and trying to maintain process capability through self–regulation. Concerning the rail industry, it can be recognised that primarily reactive or preventive maintenance strategies are currently applied for rail vehicles. Preventive maintenance has been established in recent years, which leads to increased reliability of rail vehicles, but at the same time increases costs. Current trends in rail vehicle maintenance are therefore directed towards CBM and predictive maintenance. The rail industry clearly sees the advantages but has difficulties in fully integrating them.

Second secondary research question

Which Industry 4.0 technologies are generally possible to apply and suited for maintenance processes?

Fundamentally, many different technologies are mentioned with respect to Industrial 4.0 technologies. However, regarding emerging technologies which are suitable for application in maintenance, the nine most important ones were identified: big data, IoT, cloud computing, AR, VR, cyber security, CPS, AI and additive manufacturing. These differ significantly in their functionality and complexity of application as well as in their current maturity and development in research. The results from Section 2.4.3 prove that especially big data, IoT, cloud computing and VR are suitable for application in maintenance. These four technologies have been mentioned most frequently relating to maintenance. This is due to the varying degrees of maturity of the technologies as well as to the varying degrees of application of these technologies in other industries.

The use of these technologies creates positive synergies for companies. The results from Section 2.4.4 reveal that there are seven main benefits. First, there are benefits in terms of the reliability and transparency of assets. Furthermore, processes can be optimised, which saves time and improves quality. The overall company benefits can include cost savings, competitive advantages and increased safety of personnel in the maintenance processes. The benefits of the technologies thus underpin the rationale for implementing the nine identified Industry 4.0 in the rail industry.

Stellenbosch University https://scholar.sun.ac.za

Third secondary research question

How can the potential benefits from implementing Industry 4.0 technologies be quantified?

For the quantification of the potential benefits of implementing Industry 4.0 technologies, a survey was conducted. The seven identified benefits are quantified to assess whether they also correspond to rolling stock maintenance. The online survey has confirmed all seven benefits, which implies that all benefits also occur in rolling stock maintenance. The results reveal that improvements are particularly noticeable in the area of system reliability. Consequently, the increase in reliability contributes to higher availability of the rolling stock. According to the results from the subject matter experts, all other benefits also have a positive influence on rolling stock maintenance.

Fourth secondary research question

How does a rail operator's technological maturity affect the implementation of Industry 4.0 technologies in maintenance?

To answer this research question, an online survey was conducted with subject matter experts. The results confirm that digitalisation is generally dependent on the level of maturity of the rail industry. Thus, digitalisation is already an integral part of the industry at a high maturity level, whereas at a medium or low maturity level, only individual projects are implemented or are still in the planning phase. Further differences can be observed in the assessment of the importance of the technologies, the advantages, the challenges and the application of the technologies in certain maintenance areas. Concerning the assessment of the effects and impacts of the implementation of the technologies, it is worth noting that these have a predominantly positive impact on maintenance. No differences in the degree of maturity can be ascertained.

Fifth secondary research question

How can the developed model be consolidated?

For the consolidation of the developed model, face validation is chosen as an approach. The results of the validation prove that the I4.0TIM exactly fulfils the current relevance. Besides, the applicability and logical description are predominantly assessed positively. Furthermore, the results display that the predominantly positive characteristics of the model outweigh and convince any others. These include the selection of the maintenance strategy, the good explanation of the model as well as the easy decision–making. The few points of concern stated by the participants are mentioned and critically reviewed by the researcher.

Stellenbosch University https://scholar.sun.ac.za

6.3 Contributions of the Research

This work has contributed by generating diverse added value. This is partially sustained by the feedback from the face validation.

1. Industry 4.0 technologies beneficial for rolling stock maintenance are identified.
   "[. . .] Further advantages are: Defining the technologies and evaluating their applicability [. . .]"

2. The seven main benefits of Industry 4.0 technologies suitable for rolling stock maintenance are identified and quantified.

3. A questionnaire for determining the technological maturity level of a rail operator is developed.

4. Criticality criteria for prioritisation of rolling stock systems are established.
   "The strengths of this model are to select the maintenance strategy for the components per criticality."

5. A range of characteristics for the categorisation of emerging technologies contributes to the decision of the implementation possibility.

6. The I4.0TIM is developed, which incorporates the research results, allowing the model user to support the decision for implementing Industry 4.0 technologies in rolling stock maintenance.
   "The model is comprehensive and resulted in valves which makes the decision–making easy."
   "The model considers all the rolling stock components and ties them in logical relation with maintenance strategies and Industry 4.0 technologies [. . .]"

6.4 Concluding Remarks

Intermodal change necessitates that traditional industries such as railways remain competitive. This can be achieved by optimising the maintenance process in rolling stock maintenance by integrating Industry 4.0 technologies. So far, there are no uniform approaches that allow the implementation of Industry 4.0 technologies by rail operators taking into account their level of maturity. To ensure a successful selection and implementation of these emerging technologies, the I4.0TIM was developed in this study.

An extensive literature review and an online survey are used to develop the I4.0TIM. The research background and the necessity for this research are justified in the introduction of this study. The results of the online survey have confirmed that there is currently a lack of information for the implementation of Industry 4.0 technologies in rolling stock

Stellenbosch University https://scholar.sun.ac.za

maintenance. This is also reaffirmed in the validation of the I4.0TIM that the transformation from the current technologies to the Industry 4.0 technologies is occurring. Finally, the validation of the I4.0TIM with subject matter experts substantiated that the model assists rail operators in their decision to implement Industry 4.0 technologies and is a very effective solution for the industry. The limitations of this study are presented in the following section.

6.5 Limitations

It is essential in research to acknowledge the unavoidable limitations. The online survey was carried out only once for a limited period of time. Besides, due to the limited scope of the survey, only three questions could be asked in response to each of the technology prerequisites. Furthermore, the sample is mainly characterised by participants with experience in the European region. It is critical to note that in the evaluation concerning the degree of maturity and regions the sample size is partly low and thus only a tendency can be derived. Finally, the survey is limited by the fact that the subject matter experts are mainly identified through online networks. It was not possible to verify in advance the accuracy of the data about the existing knowledge in the field of rolling stock maintenance.

Face validation is carried out to provide internal validity and to ensure that the formulated problem comprises the entire actual problem and is appropriately structured so that a respectable solution is achieved before the actual implementation occurs. However, no practical application of the I4.0TIM is performed. This should be carried out to consider its suitability in practice.

The model is designed for all levels of maturity. However, the face validation revealed that a validation is essential for a very low level of maturity. This implies whether the model can also be applied for rail operators with a very low degree of maturity. In addition, the online survey identified a shortage of qualified personnel in maintenance. The I4.0TIM takes into account that external services are obtainable, but it cannot counteract the lack of qualified personnel. Furthermore, the model is developed for maintenance in general. It does not refer to the area in which some Industry 4.0 technologies are more suitable than others. Finally, it should be noted that the I4.0TIM is developed theoretically. Thus, it has not yet been converted into a computer–aided programme.

To address the mentioned limitations, recommendations for future research are proposed in the next section.

Stellenbosch University https://scholar.sun.ac.za

6.6 Recommendations and Future Research

The research contributions fully achieve the research objectives, but recommendations for further development and improvement of this research are possible. The following topics constitute these additional proposals, which are recommendations for the further development of the research:

1. The results of the face validation demonstrate that it is necessary to test the model practically in the next step. Consequently, it would be reasonable to carry out a case study with a rail operator. For this purpose, different systems and different emerging technologies should be selected and run through the model. This would reveal the practicability of the model and possible improvements.

2. The I4.0TIM is designed for application by rail operators with different levels of maturity. The second phase of the concept determines the maturity level and verifies whether the selected technology t_i can be used with the current maturity level. Further research is needed to validate whether the model is also suitable for use by rail operators with a very low level of maturity. It is therefore recommended to apply the model in practice to rail operators with different levels of maturity and to subsequently evaluate whether phase 2 is suitable for different levels of maturity.

3. The I4.0TIM considers, among other things, the selection of rolling stock systems and the corresponding technologies. It is possible by means of further research, to investigate which technologies are most appropriate for which measure. This implies whether there are technologies which are more suitable for service, inspection, repair or improvement.

4. The results of the online survey proved that the biggest challenge for Industry 4.0 technologies is to have qualified personnel with the necessary competencies. The I4.0TIM serves to support the implementation of Industry 4.0 technologies. However, the implementation can only be accomplished by qualified personnel. To overcome this challenge, further research is required.

5. The I4.0TIM is developed and theoretically presented in this work. A computer–aided programme can be developed on this basis, which facilitates the application of the model. It is proposed that future research will examine how the I4.0TIM can be implemented digitally to facilitate the application for rail operators.

In summary, these five recommendations offer further opportunities to extend and intensify the research in this field.

Stellenbosch University https://scholar.sun.ac.za

6.7 Chapter Summary

This research work concludes with a summary of the chapters and the research results. The results revealed that six major contributions are accomplished by this study. The limitations of this study demonstrate that there is further potential for future research in this field. This is required to enable rail operators improved application of Industry 4.0 technologies in rolling stock maintenance.

Stellenbosch University https://scholar.sun.ac.za

References

Akkermans, H., Besselink, L., Van Dongen, L. and Schouten, R. (2016). *Smart moves for smart maintenance. Findings from a Delphi study on "Maintenance innovation priorities" for the Netherlands*. URL: https://pdfs.semanticscholar.org/2bd7/53952261520bdccbeb026675245a77ca400a.pdf [Accessed 13th Aug. 2020].

Allianz pro Schiene e. V. (2018). *Ein Überblick: Innovative Antriebe auf der Schiene*. URL: https://www.allianz-pro-schiene.de/themen/aktuell/innovative-antriebe-auf-der-schiene/ [Accessed 18th Aug. 2020].

Asekun, O. O. and Fourie, C. J. (2015). "Selection of a decision model for rolling stock maintenance scheduling". In: *South African Journal of Industrial Engineering*, vol. 26 (1), pp. 135–149. URL: http://www.scielo.org.za/pdf/sajie/v26n1/11.pdf.

Ashjaei, M. and Bengtsson, M. (2017). "Enhancing smart maintenance management using fog computing technology". In: *2017 IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 1561–1565. URL: https://ieeexplore.ieee.org/abstract/document/8290155.

Balci, O. and Sargent, R. G. (1981). "A methodology for cost–risk analysis in the statistical validation of simulation models". In: *Communications of the ACM*, vol. 24 (11), pp. 190–197. URL: https://dl.acm.org/doi/abs/10.1145/358598.358609.

Bem, D. (1995). "Writing a review article for psychological bulletin". In: *Psychological Bulletin*, vol. 118 (2), pp. 172–177. URL: http://www2.psych.utoronto.ca/users/reingold/courses/resources/handouts_apa/Bem-WritingReviewArticle.pdf.

Berger, P. (2014). "Bremse". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung*. Ed. by C. Schindler. Hamburg: Eurailpress, pp. 420–435.

Bokrantz, J., Skoogh, A., Berlin, C., Wuest, T. and Stahre, J. (2020a). "Smart maintenance: A research agenda for industrial maintenance management". In: *International Journal of Production Economics*, vol. 224 (107547), pp. 1–14. URL: https://www.sciencedirect.com/science/article/pii/S0925527319303731.

Stellenbosch University https://scholar.sun.ac.za

Bokrantz, J., Skoogh, A., Berlin, C., Wuest, T. and Stahre, J. (2020b). “Smart maintenance: An empirically grounded conceptualization”. In: *International Journal of Production Economics*, vol. 223 (107534), pp. 1–17. URL: https://journals.sagepub.com/doi/abs/10.1177/0954405415601640.

Booth, A., Sutton, A. and Papaioannou, D. (2016). *Systematic approaches to a successful literature review*. 2nd ed. Los Angeles: Sage.

Borenstein, D. (1998). “Towards a practical method to validate decision support systems”. In: *Decision Support Systems*, vol. 23 (3), pp. 227–239. URL: https://www.sciencedirect.com/science/article/pii/S0167923698000463.

Bramauer, J. (2014). “Türsysteme”. In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung*. Ed. by C. Schindler. Hamburg: Eurailpress, pp. 457–467.

Bundesnetzagentur (2017). *Marktuntersuchung Eisenbahnen 2017*. URL: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Eisenbahn/Unternehmen_Institutionen/Veroeffentlichungen/Marktuntersuchungen/MarktuntersuchungEisenbahnen/MarktuntersuchungEisenbahn2017.pdf?__blob=publicationFile&v=3 [Accessed 16th Oct. 2020].

Cachada, A., Barbosa, J., Leitão, P., Geraldes, C. A. S., Deusdado, L., Costa, J., Teixeira, C., Teixeira, J., Moreira, A. H. J., Moreira, P. M. and Romero, L. (2018). “Maintenance 4.0: Intelligent and predictive maintenance system architecture”. In: *2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation*, pp. 139–146. URL: https://ieeexplore.ieee.org/abstract/document/8502489.

Cachada, A., Costa, D., Badikyan, H., Barbosa, J., Leitão, P., Moraisx, O., Teixeira, C., Azevedo, J., Moreira, P. M. and Romero, L. (2019). “Using AR interfaces to support industrial maintenance procedures”. In: *2019 45th Annual Conference of the IEEE Industrial Electronics Society*, pp. 3795–3800. URL: https://ieeexplore.ieee.org/abstract/document/8927815.

Campbell, J. D. and Reyes-Picknell, J. V. (2016). *Uptime. Strategies for excellence in maintenance management*. 3rd ed. Boca Raton: CRC Press.

Ceruti, A., Marzocca, P., Liverani, A. and Bil, C. (2019). “Maintenance in aeronautics in an Industry 4.0 context: The role of augmented reality and additive manufacturing”. In: *Journal of Computational Design and Engineering*, vol. 6 (4), pp. 516–526. URL: https://academic.oup.com/jcde/article/6/4/516/5732347.

Stellenbosch University https://scholar.sun.ac.za

Cheng, Y.-H. and Tsao, H.-L. (2015). “Rolling stock maintenance strategy selection, spares parts’ estimation, and replacements’ interval calculation”. In: *International Journal of Production Economics*, vol. 128 (1), pp. 404–412. URL: http://scinet.dost.gov.ph/union/Downloads/science_039_314005.pdf.

Creswell, J. W. (2012). *Educational research. Planning, conducting and evaluating quantitative and qualitative research.* 4th ed. Boston: Pearson.

Creswell, J. W. and Creswell, J. D. (2018). *Research design. Qualitative, quantiative, and mixed methods approaches.* 5th ed. Los Angeles: SAGE.

De León Hijes, F. C. G. and Cartagena, J. J. R. (2006). “Maintenance strategy based on a multicriterion classification of equipments”. In: *Reliability Engineering & System Safety*, vol. 91 (4), pp. 444–451. URL: https://www.sciencedirect.com/science/article/pii/S0951832005000803.

Dellmann, T. (2014). “Grundbegriffe”. In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung.* Ed. by C. Schindler. Hamburg: Eurailpress, p. 15.

Deutsches Institut für Normung e. V. (2011a). *Systematik der Schienenfahrzeuge. Übersicht, Benennungen, Definitionen.* DIN 25003. Berlin: Beuth.

Deutsches Institut für Normung e. V. (2011b). *Zusand der Eisenbahnfahrzeuge. Grundsätze und Begriffe für den betriebssicheren Zustand.* DIN 27200. Berlin: Beuth.

Deutsches Institut für Normung e. V. (2017). *Instandhaltung – Begriffe der Instandhaltung.* DIN EN 13306. Berlin: Beuth.

Deutsches Institut für Normung e. V. (2019a). *Bahnanwendungen. Bremsen. Anforderungen an die Bremsausrüstung lokbespannter Züge.* DIN EN 14198. Berlin: Beuth.

Deutsches Institut für Normung e. V. (2019b). *Grundlagen der Instandhaltung.* DIN 31051. Berlin: Beuth.

Dinmohammadi, F. (2019). “A risk–based modelling approach to maintenance optimization of railway rolling stock”. In: *Journal of Quality in Maintenance Engineering*, vol. 25 (2), pp. 272–293. URL: https://www.emerald.com/insight/content/doi/10.1108/JQME-11-2016-0070/full/html.

Stellenbosch University https://scholar.sun.ac.za

European Commission (2016). “Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 On Railway Safety (2016)”. In: *Official Journal of the European Union*, vol. 138. URL: https://eur-lex.europa.eu/eli/dir/2016/798/oj.

European Environment Agency (1999). “Environmental indicators: Typology and overview”. In: *Technical Report No 25/1999*. URL: https://www.eea.europa.eu/publications/TEC25.

Fedele, L. (2011). *Methodologies and techniques for advanced maintenance*. London: Springer.

Filipović, Ž. (2015). *Elektrische Bahnen: Grundlagen, Triebfahrzeuge, Stromversorgung*. 5th ed. Berlin Heidelberg: Springer.

Fink, A. (2014). *Conducting research literature reviews. From the internet to paper*. 4th ed. Los Angeles: Sage.

Fisher, M. (1991). *The millionaire's book of quotations*. London: HarperCollins.

Franzen, J. and Kuhlenkötter, B. (2018). “Präskriptive Analyse im Kontext der Instandhaltung von Schienenfahrzeugen”. In: *Eisenbahntechnische Rundschau*, vol. 12, pp. 64–66. URL: https://www.researchgate.net/publication/330292932_Praskriptive_Analyse_im_Kontext_der_Instandhaltung_von_Schienenfahrzeugen.

Frey, S. (2012). *Railway electrification. Systems & Engineering*. Delhi: White Word Publications.

Gaber, J. (2010). “Face validity”. In: *Encyclopedia of research design*. Ed. by N. J. Salkind. California: SAGE Publications, pp. 471–474.

Gashi, M. and Thalmann, S. (2019). “Taking complexity into account: A structured literature review on multi–component systems in the context of predictive maintenance”. In: *Information Systems. 16th European, Mediterranean, and Middle Eastern Conference*. Ed. by M. Themistocleous and M. Papadaki. Cham: Springer, pp. 31–44.

Gfatter, G., Berger, P., Krause, G. and Vohla, G. (2007). *Grundlagen der Bremstechnik*. 2nd ed. München: Knorr–Bremse Systeme für Schienenfahrzeuge.

Gohres, H. W. and Reichel, J. (2018). “Chronik der Instandhaltung – Schlaglichter einer Entwicklung”. In: *Betriebliche Instandhaltung. Methoden und Werkzeuge zur Gewähr-*

Stellenbosch University https://scholar.sun.ac.za

leistung eines sicheren und wirtschaftlichen Anlagenbetriebs. Ed. by J. Reichel, G. Müller and J. Haeffs. 2nd ed. Berlin: Springer, pp. 3–14.

Gratzfeld, P. (2014). "Elektrische Antriebe". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung*. Ed. by C. Schindler. Hamburg: Eurailpress, pp. 388–403.

Gray, B. H. (1989). *Urban public transportation glossary*. Washington D.C.: Transportation Research Board.

Greenhalgh, T. and Peacock, R. (2005). "Effectiveness and efficiency of search methods in systematic reviews of complex evidence: Audit of primary sources". In: *The BMJ*, vol. 331, pp. 1064–1065. URL: `https://doi.org/10.1136/bmj.38636.593461.68`.

Guo, Z., Zhou, D., Zhou, Q., Zhang, X., Geng, J., Zeng, S., Lv, C. and Hao, A. (2020). "Applications of virtual reality in maintenance during the industrial product lifecycle: A systematic review". In: *Journal of Manufacturing Systems*, vol. 56, pp. 525–538. URL: `https://www.sciencedirect.com/science/article/pii/S0278612520301175`.

Hecht, M. (2014). "Einleitung". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung*. Ed. by C. Schindler. Hamburg: Eurailpress, p. 11.

Henke, M., Heller, T. and Stich, V. (2019). *Smart Maintenance – Der Weg vom Status quo zur Zielvision*. URL: `https://www.acatech.de/wp-content/uploads/2019/09/acatech_STUDIE_Smart_Maintenance_final.pdf` [Accessed 11th Aug. 2020].

Hofer, R. (2014). "Heizung, Lüftung, Klimatisierung". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung*. Ed. by C. Schindler. Hamburg: Eurailpress, pp. 475–487.

Holzbaur, U. (2007). *Entwicklungsmanagement. Mit hervorragenden Produkten zum Markterfolg*. Berlin Heidelberg: Springer.

Hornby, A. S. (2005). *Oxford advanced learner's dicitionary*. 7th ed. London: Oxford University Press.

Ihme, J. (2016). *Schienenfahrzeugtechnik*. 2nd ed. Wiesbaden: Springer.

International Energy Agency (2019). *The future of rail*. URL: `https://www.iea.org/reports/the-future-of-rail` [Accessed 16th Oct. 2020].

Stellenbosch University https://scholar.sun.ac.za

Janicki, J., Reinhard, H. and Rüffler, M. (2020). *Schienenfahrzeugtechnik*. 4th ed. Berlin: Bahn Fachverlag.

Jantunen, E., Campos, J., Sharma, P. and Baglee, D. (2017). "Digitalisation of maintenance". In: *2017 2nd International Conference on System Reliability and Safety*, pp. 343–347. URL: https://ieeexplore.ieee.org/abstract/document/8272846.

Jardine, A. K. S., Lin, D. and Banjevic, D. (2006). "A review on machinery diagnostics and prognostics implementing condition–based maintenance". In: *Mechanical Systems and Signal Processing*, vol. 20 (7), pp. 1483–1510. URL: https://www.sciencedirect.com/science/article/pii/S0888327005001512.

Jasiulewicz-Kaczmarek, M. and Gola, A. (2019). "Maintenance 4.0 technologies for sustainable manufacturing – an overview". In: *IFAC PapersOnLine*, vol. 52 (10), pp. 91–96. URL: https://www.sciencedirect.com/science/article/pii/S2405896319308468.

Jimenez, J. J. M., Schwartz, S., Vingerhoeds, R., Grabot, B. and Salaün, M. (2020). "Towards multi–model approaches to predictive maintenance: A systematic literature survey on diagnostics and prognostics". In: *Journal of Manufacturing Systems*, vol. 56, pp. 539–557. URL: https://www.sciencedirect.com/science/article/pii/S0278612520301187.

Karch, S. (2014). "Antrieb". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung*. Ed. by C. Schindler. Hamburg: Eurailpress, p. 378.

Kitchenham, B., Brereton, P., Budgen, D., Turner, M., Bailey, J. and Linkman, S. (2009). "Systematic literature reviews in software engineering – A systematic literature review". In: *Information and Software Technology*, vol. 51 (1), pp. 7–15. URL: https://www.cin.ufpe.br/~in1037/leitura/meta-systematic-reviews-kitchenham-jan09ist.pdf.

Kobert, S. and Busch, D. (2014). "Zug– und Stoßeinrichtungen". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion-Instandhaltung*. Ed. by C. Schindler. Hamburg: Eurailpress, pp. 436–444.

Kohlegger, M., Thalmann, S. and Maier, R. (2009). "Understanding maturity models results of structured content analysis". In: *Proceedings of I–KNOW '09 and Proceedings of I–SEMANTICS '09*, pp. 51–61. URL: https://www.econstor.eu/handle/10419/44444.

Stellenbosch University https://scholar.sun.ac.za

Kostoláni, M., Murín, J. and Kozák, Š. (2019). "Intelligent predictive maintenance control using augmented reality". In: *22nd International Conference on Process Control*, pp. 131–135. URL: https://ieeexplore.ieee.org/document/8815042.

Kumar, U., Galar, D., Aditya, P., Stenström, C. and Berges, L. (2013). "Maintenance performance metrics: A state–of-the–art review". In: *Journal of Quality in Maintenance Engineering*, vol. 19 (3), pp. 233–277. URL: https://www.emerald.com/insight/content/doi/10.1108/JQME-05-2013-0029/full/html.

Kurz, M. (2016). *Digitaler Schatten, Zustandsprognose und Hochfrequenzsynchronisation – Industrie – orientierte Forschung zu Smart Maintenance*. URL: https://www.easyfairs.com/fileadmin/groups/9/maintenance/Schweiz_2016/Vortraege_2016/Michael-Kurz_20160211_FIR_Vortrag_Zuerich_final_Download.pdf [Accessed 10th Aug. 2020].

Kwasnicki, E. (2014). "Fahrwerk". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung.* Ed. by C. Schindler. Hamburg: Eurailpress, pp. 349–377.

Lämmli, B. (2020). *Zug–/ Stossvorrichtungen.* URL: https://www.lokifahrer.ch/Lukmanier/Rollmaterial/Kupplung/Zug-Druck.htm [Accessed 28th Aug. 2020].

Lang, H. P., Fürstenau, F. and Heerdegen, B. (2016). *Herausforderungen der Deutschen Bahn.* URL: http://www.schienenfahrzeugtagung.at/download/PDF2016/MoV02_Lang.pdf [Accessed 12th Oct. 2019].

Leboeuf, M. (2018). *High speed rail. Fast track to sustainable mobility.* URL: https://uic.org/IMG/pdf/uic_high_speed_2018_ph08_web.pdf [Accessed 21st Aug. 2020].

Linke, P., Jaroszewski, D. and Hocke, C. (2018). "Ausfallprognose als Baustein der Condition Based Maintenance im Instandhaltungssystem eines EMU". In: *ETR — Eisenbahntechnische Rundschau*, vol. 11, pp. 56–60. URL: https://frankfurtconsultingengineers.de/wp-content/uploads/2018/11/ETR_11_2018_Jaroszewski.pdf.

Linn, C., Bender, S., Prosser, J., Schmitt, K. and Werth, D. (2017). "Virtual remote inspection – A new concept for virtual reality enhanced real–time maintenance". In: *2017 23rd International Conference on Virtual System & Multimedia*, pp. 1–6. URL: https://ieeexplore.ieee.org/abstract/document/8346304.

Lucke, D., Görzig, D., Kacir, M., Volkmann, J., Haist, C., Sachsenmaier, M. and Rentschler, H. (2014). "Strukturstudie "Industrie 4.0 für Baden–Württemberg". Baden–Württemberg auf dem Weg zur Industrie 4.0". In: URL: https://wm.baden-wuerttemberg.de/

Stellenbosch University https://scholar.sun.ac.za

fileadmin/redaktion/m-wm/intern/Dateien_Downloads/Innovation/IPA_Strukturstudie_Industrie_4.0_BW.pdf.

Lucke, D., Defranceski, M. and Adolf, T. (2017). "Cyberphysische Systeme für die prädikative Instandhaltung". In: *Handbuch Industrie 4.0 Bd. 1. Produktion*. Ed. by B. Vogel-Heuser, T. Bauernhansl and M. Ten Hompel. 2nd ed. Berlin: Springer, pp. 75–91.

Manirajan, N., Gargama, H., Guhe, S. and Prabhakaran, M. (2018). "Approach for demonstrating reliability targets for rail transport during low mileage accumulation in the field: Methodology and case study". In: *International Journal of Transport and Vehicle Engineering*, vol. 12 (8), pp. 788–792. URL: https://publications.waset.org/10009411/approach-for-demonstrating-reliability-targets-for-rail-transport-during-low-mileage-accumulation-in-the-field-methodology-and-case-study.

Matyas, K. (2002). "Ganzheitliche Optimierung durch individuelle Instandhaltungsstrategien". In: *Industrie Management*, vol. 18 (2), pp. 13–16. URL: http://www.imme2000.de/dokumente/FachspezifischerTeil/Technik/Foerdertechnik/Instandhaltungsstrategien_e.pdf.

Matyas, K. (2016). *Instandhaltungslogistik. Qualität und Produktivität steigern.* 6th ed. München: Hanser.

Mergenthaler, W. and Käser, H. (2014). "Verfahren der Mustererkennung in der Instandhaltung von Schienenfahrzeugen". In: *Schweizer Eisenbahn–Revue*, pp. 2520–2523. URL: https://frankfurtconsultingengineers.de/wp-content/uploads/2018/06/Eisenbahn-Revue-201407.pdf.

Miluchev, M. (2014). "Innenbeleuchtung". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung*. Ed. by C. Schindler. Hamburg: Eurailpress, pp. 471–475.

Miser, H. J. (1993). "A foundational concept of science appropriate for validation in operational research". In: *European Journal of Operational Research*, vol. 66 (2), pp. 204–215. URL: https://www.sciencedirect.com/science/article/pii/037722179390313C.

Mish, F. (2004). *The Merriam–Webster dictionary*. 11th ed. Springfield, MA: Merriam–Webster Incorporated.

Mitchell, T. M. (1997). *Machine Learning*. New York: McGraw–Hill.

Stellenbosch University https://scholar.sun.ac.za

Montero-Jiménez, J. J. and Vingerhoeds, R. A. (2018). “Enhancing operational fault diagnosis by assessing multiple operational modes”. In: *12e Conférence Internationale de Modélisation, Optimisation et SIMulation*, pp. 237–244. URL: https://oatao.univ-toulouse.fr/23822/.

Mühlnickel, H., Maria, K. C., Jussen, P. and Emonts-Holley, R. (2018). “Smart Maintenance. Instandhaltung im Kontext der Industrie 4.0”. In: *Betriebliche Instandhaltung. Methoden und Werkzeuge zur Gewährleistung eines sicheren und wirtschaftlichen Anlagenbetriebs.* Ed. by J. Reichel, G. Müller and J. Haeffs. 2nd ed. Berlin: Springer, pp. 349–360.

Mulrow, C. (1994). “Rationale for systematic reviews”. In: *The BMJ*, vol. 304, pp. 597–599. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2541393.

Neumann, L. and Krippendorf, W. (2016). *Branchenanalyse Bahnindustrie. Industrielle und betriebliche Herausforderungen und Entwicklungskorridore.* Hans–Böckler–Stiftung. URL: https://www.econstor.eu/handle/10419/146408.

Nomad Digital (2015). *Rail industry survey.* URL: http://nomad-digital.com/uploads/ND_A4_Industry_White_Paper_240315_high-res.pdf [Accessed 22nd Oct. 2019].

Ochella, S. and Shafiee, M. (2019). “Artificial intelligence in prognostic maintenance”. In: *Proceedings of the 29th European Safety and Reliability Conference*, pp. 3424–3431. URL: http://rpsonline.com.sg/proceedings/9789811127243/pdf/0188.pdf.

Office of Rail Regulation (2013). “Rail value for money study: Rolling stock whole life costs”. In: *Arup’s Final Report.* URL: https://www.orr.gov.uk/media/18658.

O’Leary, T. J., Goul, M., Moffitt, K. E. and Essam, R. A. (1990). “Validating expert systems”. In: *IEEE Expert*, vol. 5 (3), pp. 51–58. URL: https://ieeexplore.ieee.org/document/54673.

Pacchini, A. P. T., Lucato, W. C., Facchini, F. and Mummolo, G. (2019). “The degree of readiness for the implementation of Industry 4.0”. In: *Computers in Industry*, vol. 113, pp. 1–8. URL: https://www.sciencedirect.com/science/article/pii/S0166361519303835.

Page, B. (1991). *Diskrete Simulation. Eine Einführung mit Modula–2.* Berlin Heidelberg: Springer.

Stellenbosch University https://scholar.sun.ac.za

Palmarini, R., Erkoyuncua, J. A., Roya, R. and Torabmostaedi, H. (2018). "A systematic review of augmented reality applications in maintenance". In: *Robotics and Computer–Integrated Manufacturing*, vol. 49, pp. 215–228. URL: `https://www.sciencedirect.com/science/article/abs/pii/S0736584517300686`.

Pawellek, G. (2016). *Integrierte Instandhaltung und Ersatzteillogistik. Vorgehensweisen, Methoden, Tools.* 2nd ed. Berlin Heidelberg: Springer.

Pieriegud, J. (2018). *Digital transformation of railways.* URL: `https://shift2rail.org/wp-content/uploads/2018/04/DIGITAL_TRANSFORMATION_RAILWAYS_2018_web.pdf` [Accessed 12th Oct. 2019].

Puntis, R. and Walley, D. (1986). "The use of reliability techniques on traction and rolling stock". In: *Proceedings of the Institution of Mechanical Engineers, Part D: Transport Engineering*, vol. 200 (4), pp. 295–304. URL: `http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.921.6482&rep=rep1&type=pdf`.

Rezvanizaniani, S. M., Valibeigloo, M, Asghari, M, Barabady, J and Kumar, U (2008). "Reliability centered maintenance for rolling stock. A case study in coaches' wheel sets of passenger trains of Iranian railway". In: *2008 IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 516–520. URL: `https://ieeexplore.ieee.org/document/4737922`.

Rösch, W. (2014). "Instandhaltung". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung.* Ed. by C. Schindler. Hamburg: Eurailpress, pp. 529–558.

Roy, R., Stark, R., Tracht, K., Takata, S. and Mori, M. (2016). "Continuous maintenance and the future – Foundations and technological challenges". In: *CIRP Annals*, vol. 65 (2), pp. 667–688. URL: `http://www.sciencedirect.com/science/article/pii/S0007850616301986`.

Ryll, F. and Freund, C. (2010). "Grundlagen der Instandhaltung". In: *Instandhaltung technischer Systeme. Methoden und Werkzeuge zur Gewährleistung eines sicheren und wirtschaftlichen Anlagenbetriebs.* Ed. by M. Schenk. Berlin Heidelberg: Springer, pp. 23–101.

Sahal, R., Breslin, J. G. and Ali, M. I. (2020). "Big data and stream processing platforms for Industry 4.0 requirements mapping for a predictive maintenance use case". In: *Journal of Manufacturing Systems*, vol. 54, pp. 138–151. URL: `https://www.sciencedirect.com/science/article/pii/S0278612519300937`.

Stellenbosch University https://scholar.sun.ac.za

Sakib, N. and Wuest, T. (2018). "Challenges and opportunities of condition–based predictive maintenance: A review". In: *Procedia CIRP*, vol. 78, pp. 267–272. URL: https://www.sciencedirect.com/science/article/pii/S2212827118312344.

Schindler, C. (2014). "Fahrzeugarten und Zugkonfigurationen". In: *Handbuch Schienenfahrzeuge. Entwicklung–Produktion–Instandhaltung.* Ed. by C. Schindler. Hamburg: Eurailpress, pp. 183–206.

Schuh, G., Anderl, R., Gausemeier, J., Hompel, M. ten and Wahlster, W. (2020). *Industrie 4.0 maturity index. Managing the digital transformation of companies – Update 2020.* URL: https://en.acatech.de/wp-content/uploads/sites/6/2020/04/aca_STU_MatInd_2020_en_Web-1.pdf [Accessed 15th May 2020].

Schumacher, A., Erol, S. and Sihn, W. (2016). "A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises". In: *Procedia Cirp*, vol. 52 (1), pp. 161–166. URL: https://publik.tuwien.ac.at/files/publik_255445.pdf.

Schunk Carbon Technology (2020). *Stromabnehmer Nahverkehr.* URL: https://www.schunk-carbontechnology.com/de/produkte/produkte-detail/stromabnehmer-nahverkehr [Accessed 27th Aug. 2020].

Schwilling, A., Guénard, F. and Nölling, K. (2016). *On the digital track. Leveraging digitization in rolling stock maintenance.* URL: https://www.rolandberger.com/publications/publication_pdf/roland_berger_tab_on_the_digital_track_3.pdf [Accessed 1st Sept. 2020].

Selcuk, S. (2017). "Predictive maintenance, its implementation and latest trends". In: *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 231 (9), pp. 1670–1679. URL: https://journals.sagepub.com/doi/abs/10.1177/0954405415601640.

Sharda, R., Delen, D., Turban, E., Aronson, J. E., Liang, T.-P. and King, D. (2014). *Business intelligence and analytics. System for decesion support.* 10th ed. New Jersey: Pearson.

Snyder, H. (2019). "Literature review as a research methodology: An overview and guidelines". In: *Journal of Business Research*, vol. 104, pp. 333–339. URL: https://doi.org/10.1016/j.jbusres.2019.07.039.

Stachowiak, H. (1973). *Allgemeine Modelltheorie.* Wien: Springer.

Stellenbosch University https://scholar.sun.ac.za

Statista (2019). *Öffentlicher Personenverkehr.* URL: https://de.statista.com/statistik/studie/id/6958/dokument/oeffentlicher-personenverkehr-statista-dossier/ [Accessed 22nd Oct. 2019].

Statistics South Africa (2013). *National Household Travel Survey 2013. Statistical release P0320.* URL: http://www.statssa.gov.za/publications/P0320/P03202013.pdf [Accessed 21st Oct. 2019].

Stefanovic, M., Nestic, S., Djordjevic, A., Djurovic, D., Macuzic, I., Tadic, D. and Gacic, M. (2015). "An assessment of maintenance performance indicators using the fuzzy sets approach and genetic algorithms". In: *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 231 (1), pp. 15–27. URL: https://journals-sagepub-com.ez.sun.ac.za/doi/full/10.1177/0954405415572641.

Stern, S., Behrendt, A., Eisenschmidt, E., Reimig, S., Schirmers, L. and Schwerdt, I. (2017). "The rail sector's changing maintenance game". McKinsey & Company.

Strunz, M. (2012). *Instandhaltung. Grundlagen–Strategien–Werkstätten.* Berlin Heidelberg: Springer.

Stuhr, H. J. (2013). "Untersuchung von Einsatzszenarien einer automatischen Mittelpufferkupplung". Dissertation. Technische Universität Berlin. URL: https://depositonce.tu-berlin.de/bitstream/11303/3833/1/Dokument_4.pdf.

Sue, V. M. and Ritter, L. A. (2012). *Conducting online surveys.* 2nd ed. Thousand Oaks: SAGE Publications.

Szkoda, M. (2014). "Analysis of reliability, availability and maintainability (RAM) of SM48 diesel locomotive". In: *22nd International Symposium EURO–ZEL*, pp. 1–10. URL: http://m8.mech.pk.edu.pl/szkoda/pdf/33_ZU_ZEL%20MSzkoda.pdf.

The World Bank (2020). *World Bank Country and Lending Groups.* URL: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups [Accessed 1st Oct. 2020].

Tsang, A. H. (2002). "Strategic dimensions of maintenance management". In: *Journal of Quality in Maintenance Engineering*, vol. 8 (1), pp. 7–39. URL: https://www.emerald.com/insight/content/doi/10.1108/13552510210420577/full/html.

Stellenbosch University https://scholar.sun.ac.za

Tuptuk, N. and Hailes, S. (2018). "Security of smart manufacturing systems". In: *Journal of Manufacturing Systems*, vol. 47, pp. 93–106. URL: https://www.sciencedirect.com/science/article/pii/S0278612518300463.

Umiliacchi, P., Lane, D. and Romano, F. (2011). "Predictive maintenance of railway subsystems using an ontology based modelling approach". In: *Proceedings of 9th World Conference on Railway Research*, pp. 1–10. URL: http://www.railway-research.org/IMG/pdf/copie_de_f4_umiliacchi_paolo.pdf.

Verband der Bahnindustrie in Deutschland (2013). *VDB–Positionspapier Nr. 02/2013: Obsoleszenzmanagement im Eisenbahnsektor–die Perspektive der Hersteller*. URL: https://www.yumpu.com/de/document/read/22397721/download-verband-der-bahnindustrie-in-deutschland-vdb [Accessed 25th Aug. 2020].

Wang, K. and Wang, Y. (2017). "How AI affects the future predictive maintenance: A primer of deep learning". In: *Advanced Manufacturing and Automation VII (IWAMA 2017)*. Ed. by K. Wagn, Y. Wang, J. O. Strandhagen and T. Yu. Singapore: Springer, pp. 1–9.

Wegener, D. (2020). *DIN and DKE ROADMAP. German Standardization Roadmap Industrie 4.0*. URL: https://www.din.de/blob/65354/57218767bd6da1927b181b9f2a0d5b39/roadmap-i4-0-e-data.pdff [Accessed 11th Aug. 2020].

Wikipedia (2015). *Reisezugwagen Drehgestell*. URL: https://de.wikipedia.org/wiki/Drehgestell [Accessed 25th Aug. 2020].

Winchester, C. and Salji, M. (2016). "Writing a literature review". In: *Journal of Clinical Urology*, vol. 9 (5), pp. 308–312. URL: https://doi.org/10.1177/2051415816650133.

Yang, F.-N. and Lin, H.-Y. (2019). "Development of a predictive maintenance platform for cyber–physical systems". In: *2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS)*, pp. 331–335. URL: https://ieeexplore.ieee.org/document/8780144.

Zhang, W., Yang, D. and Wang, H. (2019). "Data–driven methods for predictive maintenance of industrial equipment: A survey". In: *IEEE Systems Journal*, vol. 13 (3), pp. 2213–2227. URL: https://ieeexplore.ieee.org/document/8707108.

Zullig Jr, W. E. and Phraner, S. D. (2000). "North American commuter rail". In: *Transportation in the New Millennium*, pp. 1–6. URL: http://onlinepubs.trb.org/onlinepubs/millennium/00080.pdf.

Stellenbosch University https://scholar.sun.ac.za

Appendices

Stellenbosch University https://scholar.sun.ac.za

Appendix A

Survey Data

Stellenbosch University https://scholar.sun.ac.za

A.1 Research Ethics Committee Approval

UNIVERSITEIT
STELLENBOSCH
UNIVERSITY

NOTICE OF APPROVAL

REC: Social, Behavioural and Education Research (SBER) - Initial Application Form

9 June 2020

Project number: 15048

Project Title: Development of a Model for the Implementation of Industry 4.0 Technologies in Rail Rolling Stock Maintenance

Dear Mr Marius Wippel

Your REC: Social, Behavioural and Education Research (SBER) - Initial Application Form submitted on 23 April 2020 was reviewed and approved by the REC: Social, Behavioural and Education Research (REC: SBE).

Please note below expiration date of this approved submission:

Ethics approval period:

Protocol approval date (Humanities)	Protocol expiration date (Humanities)
9 June 2020	8 June 2023

SUSPENSION OF PHYSICAL CONTACT RESEARCH DURING THE COVID-19 PANDEMIC

Due to the Covid-19 pandemic and resulting lockdown measures, all research activities requiring physical contact or being in undue physical proximity to human participants has been suspended by Stellenbosch University. Please refer to a formal statement issued by the REC: SBE on 20 March for more information on this.

This suspension will remain in force until such time as the social distancing requirements are relaxed by the national authorities to such an extent that in-person data collection from participants will be allowed. This will be confirmed by a new statement from the REC: SBE on the university's dedicated Covid-19 webpage.

Until such time online or virtual data collection activities, individual or group interviews conducted via online meeting or web conferencing tools, such as Skype or Microsoft Teams are strongly encouraged in all SU research environments.

If you are required to amend your research methods due to this suspension, please submit an amendment to the REC: SBE as soon as possible. The instructions on how to submit an amendment to the REC can be found on this webpage: [instructions], or you can contact the REC Helpdesk for instructions on how to submit an amendment: applyethics@sun.ac.za.

GENERAL REC COMMENTS PERTAINING TO THIS PROJECT:

1) It may be necessary to obtain institutional permission from relevant organizations should the researcher obtain contact details of participants (experts) from an organisation directly. [ACTION REQUIRED]

INVESTIGATOR RESPONSIBILITIES

Please take note of the General Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

If the researcher deviates in any way from the proposal approved by the REC: SBE, the researcher must notify the REC of these changes.

Please use your SU project number (15048) on any documents or correspondence with the REC concerning your project.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

CONTINUATION OF PROJECTS AFTER REC APPROVAL PERIOD

You are required to submit a progress report to the REC: SBE before the approval period has expired if a continuation of ethics approval is required. The Committee will then consider the continuation of the project for a further year (if necessary).

Once you have completed your research, you are required to submit a final report to the REC: SBE for review.

Stellenbosch University https://scholar.sun.ac.za

Included Documents:

Document Type	File Name	Date	Version
Research Protocol/Proposal	01_Proposal_V2	20/04/2020	V2
Informed Consent Form	02_Electronic Consent_V2	20/04/2020	V2
Default	03_Covid19_V1	20/04/2020	V1
Data collection tool	02_Survey_Questions_EC	23/04/2020	V2

If you have any questions or need further help, please contact the REC office at cgraham@sun.ac.za.

Sincerely,

Clarissa Graham

REC Coordinator: Research Ethics Committee: Social, Behavioral and Education Research

National Health Research Ethics Committee (NHREC) registration number: REC-050411-032.
The Research Ethics Committee: Social, Behavioural and Education Research complies with the SA National Health Act No.61 2003 as it pertains to health research. In addition, this committee abides by the ethical norms and principles for research established by the Declaration of Helsinki (2013) and the Department of Health Guidelines for Ethical Research: Principles Structures and Processes (2^{nd} Ed.) 2015. Annually a number of projects may be selected randomly for an external audit.

Stellenbosch University https://scholar.sun.ac.za

Principal Investigator Responsibilities

Protection of Human Research Participants

As soon as Research Ethics Committee approval is confirmed by the REC, the principal investigator (PI) is responsible for the following:

Conducting the Research: The PI is responsible for making sure that the research is conducted according to the REC-approved research protocol. The PI is jointly responsible for the conduct of co-investigators and any research staff involved with this research. The PI must ensure that the research is conducted according to the recognised standards of their research field/discipline and according to the principles and standards of ethical research and responsible research conduct.

Participant Enrolment: The PI may not recruit or enrol participants unless the protocol for recruitment is approved by the REC. Recruitment and data collection activities must cease after the expiration date of REC approval. All recruitment materials must be approved by the REC prior to their use.

Informed Consent: The PI is responsible for obtaining and documenting affirmative informed consent using **only** the REC-approved consent documents/process, and for ensuring that no participants are involved in research prior to obtaining their affirmative informed consent. The PI must give all participants copies of the signed informed consent documents, where required. The PI must keep the originals in a secured, REC-approved location for at least five (5) years after the research is complete.

Continuing Review: The REC must review and approve all REC-approved research proposals at intervals appropriate to the degree of risk but not less than once per year. There is **no grace period.** Prior to the date on which the REC approval of the research expires, **it is the PI's responsibility to submit the progress report in a timely fashion to ensure a lapse in REC approval does not occur.** Once REC approval of your research lapses, all research activities must cease, and contact must be made with the REC immediately.

Amendments and Changes: Any planned changes to any aspect of the research (such as research design, procedures, participant population, informed consent document, instruments, surveys or recruiting material, etc.), must be submitted to the REC for review and approval before implementation. Amendments may not be initiated without first obtaining written REC approval. The **only exception** is when it is necessary to eliminate apparent immediate hazards to participants and the REC should be immediately informed of this necessity.

Adverse or Unanticipated Events: Any serious adverse events, participant complaints, and all unanticipated problems that involve risks to participants or others, as well as any research-related injuries, occurring at this institution or at other performance sites must be reported to the REC within **five (5) days** of discovery of the incident. The PI must also report any instances of serious or continuing problems, or non-compliance with the RECs requirements for protecting human research participants.

Research Record Keeping: The PI must keep the following research-related records, at a minimum, in a secure location for a minimum of five years: the REC approved research proposal and all amendments; all informed consent documents; recruiting materials; continuing review reports; adverse or unanticipated events; and all correspondence and approvals from the REC.

Provision of Counselling or emergency support: When a dedicated counsellor or a psychologist provides support to a participant without prior REC review and approval, to the extent permitted by law, such activities will not be recognised as research nor the data used in support of research. Such cases should be indicated in the progress report or final report.

Final reports: When the research is completed (no further participant enrolment, interactions or interventions), the PI must submit a Final Report to the REC to close the study.

On-Site Evaluations, Inspections, or Audits: If the researcher is notified that the research will be reviewed or audited by the sponsor or any other external agency or any internal group, the PI must inform the REC immediately of the impending audit/evaluation.

Stellenbosch University https://scholar.sun.ac.za

A.2 Letter of Electronic Consent

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY
ELECTRONIC CONSENT TO PARTICIPATE IN RESEARCH

TITLE OF RESEARCH PROJECT:	Development of a Model for the Implementation of Industry 4.0 Technologies in Rail Rolling Stock Maintenance
REFERENCE NUMBER:	ING-2020-15048
PRINCIPAL INVESTIGATOR:	Marius Wippel
ADDRESS:	Industrial Engineering Building Faculty of Engineering Banghoek Rd University of Stellenbosch 7600 Stellenbosch
CONTACT NUMBER:	+4917661597933
E-MAIL:	marius_tim.wippel@student.reutlingen-university.de

Dear Sir or Madam,

Kindly note that I am an MEng student at the Department of Industrial Engineering at Stellenbosch University, and I would like to invite you to participate in a research project entitled "Development of a Model for the Implementation of Industry 4.0 Technologies in Rail Rolling Stock Maintenance".

Please take some time to read the information presented here, which will explain the details of this project and contact me if you require further explanation or clarification of any aspect of the study. This study has been approved by the Research Ethics Committee (REC) at Stellenbosch University and will be conducted according to accepted and applicable national and international ethical guidelines and principles.

1. **INTRODUCTION:** Maintenance is fundamental for public transport to guarantee safety. Therefore, it is essential to have a working maintenance process and adapt to emerging technologies. But at the moment the industry is unaware of how to use Industry 4.0 technologies and there is no model for the companies which can support and guide their path for implementation. The objective is to develop a model, which will support the rail operators in their decision for implementing Industry 4.0 technologies for rail rolling stock maintenance.
2. **PURPOSE:** The purpose of this study is to identify in which maintenance areas emerging technologies are used and where there is still a need to catch up. Your feedback will help us to support you in implementing Industry 4.0 technologies in maintenance processes.
3. **PROCEDURES:** The survey contains open and closed questions. The questions relate to digitalisation in general, digitalisation in maintenance for rail rolling stock and the current level of maturity.
4. **TIME:** The questionnaire will take approximately 15 minutes to complete.
5. **RISKS:** There are not any potential risks or inconveniences regarding the participants.
6. **BENEFITS:** The result of this survey supports the design of a model for the implementation of Industry 4.0 technologies in rail rolling stock. The model can be used and applied by the participant in his maintenance environment.
7. **PARTICIPATION & WITHDRAWAL:** The prospective participants will do the survey on their own in private. If the need arises for them to withdraw from participating, they can close and end the survey whenever they want. The collected data and information will be destroyed.
8. **CONFIDENTIALITY:** The survey will be conducted anonymously. This ensures that no conclusions can be drawn about the participants. The research report will contain no direct quotes or links to any personal identifiers.
9. **RECORDINGS:** Regarding this survey, there will not be any voice, video, screen etc. recordings.

Stellenbosch University https://scholar.sun.ac.za

10. **DATA STORAGE:** The data is stored in a survey tool provided by the university and there is only one account for access regarding this survey. The prospective participant's personal data that they've shared with the primary investigator (e.g. email addresses) will be stored on a laptop that is password protected. Only the primary investigator and his supervisors will have access to the personal data of prospective participants, and/ or to the information that these participants have shared with the primary investigator.

If you have any questions or concerns about this research project, please feel free to Marius Wippel (marius_tim.wippel@student.reutlingen-university.de) and/or the Supervisor, Dr. Johannes Jooste (wyhan@sun.ac.za) and/or Supervisor, Prof. Dr.-Ing. Dominik Lucke (dominik.lucke@reutlingen-university.de).

RIGHTS OF RESEARCH PARTICPANTS: You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché (mfouche@sun.ac.za / 021 808 4622) at the Division for Research Development. You have the right to receive a copy of this Consent form.

If you are willing to participate in this research project, please select the relevant box in the Declaration of Consent below. You confirm that you have read and understood the information provided for the current study and agree to take part in this survey.

Stellenbosch University https://scholar.sun.ac.za

DECLARATION BY THE PARTICIPANT

As the **participant** I hereby declare that:

- I have read the above information and it is written in a language with which I am fluent and comfortable.
- I have had a chance to ask questions and all my questions have been adequately answered.
- I understand that taking part in this study is voluntary and I have not been pressurised to take part.
- I may choose to leave the study at any time and will not be penalised or prejudiced in any way.
- If the principal investigator feels that it is in my best interest, or if I do not follow the study plan as agreed to, then I may be asked to leave the study before it has finished.
- All issues related to privacy, and the confidentiality and use of the information I provide, have been explained to my satisfaction.

As the **participant** I hereby select the following option:

	I accept the invitation to participate in your research project, and if I decide to be interviewed it would automatically mean that I have given consent for my responses to be used confidentially and anonymously.
	I accept the invitation to participate in your research project, and if I decide to complete the questionnaire it would automatically mean that I have given consent for my responses to be used confidentially and anonymously.
	I decline the invitation to participate in your research project.

DECLARATION BY THE PRINCIPAL INVESTIGATOR

As the **principal investigator** I hereby declare that the information contained in this document has been thoroughly explained to the participant. I also declare that the participant has been encouraged (and has been given ample time) to ask any questions. In addition I would like to select the following option:

	The conversation with the participant was conducted in a language in which the participant is fluent.
	The conversation with the participant was conducted with the assistance of a translator, and this "Consent Form" is available to the participant in a language in which the participant is fluent.

____
Signed at *(place)*

____
Date

____
Signature of Principal Investigator

Stellenbosch University https://scholar.sun.ac.za

A.3 Survey Questionnaire

Welcome,

I am pleased that you are taking the time to take part in the survey as part of my master's thesis. Your personal opinion is important to me! My name is Marius Wippel and I study Digital Industrial Management and Engineering at Reutlingen University and Stellenbosch University in South Africa as part of a double degree programm.

Maintenance is fundamental for public transport. Therefore, it is essential to have working maintenance practices. The purpose of this survey is to identify if emerging technologies are applied in maintenance processes depending on the rail industries maturity level.

You will need about 15 minutes to answer the questions. Your answers will be collected, stored and evaluated anonymously.

Thank you very much for your time and assistance. If you have any questions please do not hesitate to contact me (marius_tim.wippel@student.reutlingen-university.de).

I am looking forward to your feedback!

Section A: A - Digitalisation in Respect to the Rail Industry

A1. **How strongly is the topic of digitalisation currently discussed in the rail industry?**

- Very strong ☐
- Strong ☐
- Less ☐
- Not at all ☐

Stellenbosch University https://scholar.sun.ac.za

A2. What is the current status regarding digitalisation in the rail industry?

- Digitalisation is an integral part in the rail industry. ☐
- The rail industry works on the implementation of individual digital projects. ☐
- The rail industry is still in the planning phase. ☐
- Digitalisation is not important for the rail industry. ☐

A3. Which areas or processes have already been digitalised in the rail industry?

- Purchase ☐
- Sales ☐
- Maintenance ☐
- Research & Development ☐
- Customer Service ☐
- IT ☐
- Production ☐
- Logistics ☐
- Marketing ☐
- Quality Assurance ☐
- None ☐
- Other ☐

Other

Section B: B - Implementation and Application of Industry 4.0 enabling Technologies in Maintenance

B1. Which of the following Industry 4.0 enabling technologies will be of greatest importance in rail rolling stock maintenance?

- Internet of Things ☐
- Big Data & Analytics ☐
- Additive Manufacturing (3D-Printing) ☐
- Cloud Computing ☐

Stellenbosch University https://scholar.sun.ac.za

- Augmented & Virtual Reality ☐
- Artificial Intelligence ☐
- Cyber-Physical Systems ☐
- Autonomous Robots ☐
- Cyber Security ☐
- None ☐
- Other ☐

Other

B2. Why do you think the above indicated technologies are important in rail rolling stock maintenance?

- Create competitive advantages ☐
- Increase safety for employees ☐
- Increase system reliability ☐
- Increase quality assurance ☐
- Cut costs ☐
- Increase transparency of the assets ☐
- Save time ☐
- Other ☐

Other

Stellenbosch University https://scholar.sun.ac.za

B3. What is the current status in the rail industry regarding the implementation of Industry 4.0 enabling technologies in rail rolling stock maintenance?

- Implemented and continuously updated ☐
- Implemented ☐
- In planning ☐
- Currently nothing planned ☐

B4. In which area of rail rolling stock maintenance does the rail industry apply these Industry 4.0 enabling technologies?

- Planning and organisation of maintenance ☐
- Execution of maintenance ☐
- Monitoring of the systems ☐
- Data acquisition ☐
- Process flow ☐
- Production of spare parts ☐
- Other ☐

Other

B5. Does the rail industry encounter any challenges related to Industry 4.0 enabling technologies in rail rolling stock maintenance?

- Yes ☐
- No ☐

B6. What challenges does the rail industry face regarding Industry 4.0 technologies in rail rolling stock maintenance?

- Lack of information regarding implementation ☐
- Lack of qualified personnel and competences ☐
- Limited access to technologies ☐
- Lack of technological prerequisites ☐
- Limited financial resources ☐
- Lack of corporate strategy ☐
- The industry does not face any challenges ☐

Stellenbosch University https://scholar.sun.ac.za

Other

Other

B7. For which rail rolling stock systems/components does the rail industry apply Industry 4.0 enabling technologies in maintenance?

- Traction motor
- Pantograph
- Wheels
- Spring system
- Damper
- Compressors
- Braking unit
- Coupling system
- Door unit
- HVAC (Heating ventilation and air conditioning)
- Light system
- Sanitary facilities
- None
- Other

Other

Stellenbosch University https://scholar.sun.ac.za

B8. **What impacts or effects have resulted from the implementation of Industry 4.0 enabling technologies for the above selected systems/components?**

Section C: C - Technological Maturity Level (Part1)

The following four sections are about the maturity level that you have experienced in the rail industry, especially for rolling stock. The following questions have a scale from 1 to 5:

The value 1 indicates that no realisation has occured in the rail industry. The value 5 indicates that a complete realisation has occured in the rail industry.

C1. **To what extent does the rail industry have the possibility to connect with resources on the network or among each other to share or use data?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

C2. **To what extent is the rail industry able to collect information with sensors and then transform it into mechanical work by using actuators?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Stellenbosch University https://scholar.sun.ac.za

C3. **To what extent are embedded systems for information processing in the rail industry implemented?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

C4. **To what extent does the rail industry have an infrastructure to collect and store data?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

C5. **To what extent is the rail industries data organised in digital secure systems?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

C6. **To what extent does the rail industry know how to deal with obtained data?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Stellenbosch University https://scholar.sun.ac.za

Section D: C - Technological Maturity Level (Part2)

The following four sections are about the maturity level that you have experienced in the rail industry, especially for rolling stock. The following questions have a scale from 1 to 5:

The value 1 indicates that no realisation has occured in the rail industry. The value 5 indicates that a complete realisation has occured in the rail industry.

D1. How high is the degree of process standardisation in the rail industry?

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

D2. To what extent are 3D models of technical components or spare parts in the rail industry available?

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

D3. To what extent does the rail industry have internal knowledge regarding the utilization of additive manufacturing?

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

D4. To what extent does the rail industry have broadband internet access?

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Stellenbosch University https://scholar.sun.ac.za

D5. **To what extent is the IT infrastructure in the rail industry provided via cloud computing?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

D6. **To what extent does the rail industry use cloud services for software or data?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Section E: C - Technological Maturity Level (Part3)

The following four sections are about the maturity level that you have experienced in the rail industry, especially for rolling stock. The following questions have a scale from 1 to 5:

The value 1 indicates that no realisation has occured in the rail industry. The value 5 indicates that a complete realisation has occured in the rail industry.

E1. **To what extent does the rail industry use self-learning systems to solve complex application problems?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

E2. **To what extent does the rail industry use virtual assistants?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Stellenbosch University https://scholar.sun.ac.za

E3. **To what extent does the rail industry train machines, systems or equipment with data?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

E4. **To what extent are machines, systems or equipment in the rail industry capable of communicating with each other?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

E5. **To what extent are machines, systems or equipment in the rail industry capable of independently assessing situations and taking decisions?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

E6. **To what extent can the rail industry create a virtual image of machines, systems or equipment?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Stellenbosch University https://scholar.sun.ac.za

Section F: C - Technological Maturity Level (Part4)

The following four sections are about the maturity level that you have experienced in the rail industry, especially for rolling stock. The following questions have a scale from 1 to 5:

The value 1 indicates that no realisation has occured in the rail industry. The value 5 indicates that a complete realisation has occured in the rail industry.

F1. To what extent is the rail industry able to display virtual objects in the real world?

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

F2. To what extent does the rail industry use supporting hardware technologies (e.g. tablets, smartphones or smartglasses)?

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

F3. To what extent can the rail industry perform remote tasks with supporting hardware technologies (e.g. tablets, smartphones or smartglasses)?

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Stellenbosch University https://scholar.sun.ac.za

F4. **How advanced is the rail industry regarding the security of internal data storage?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

F5. **How advanced is the rail industry regarding the data protection in cloud services?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

F6. **How advanced is the rail industry in terms of the communication security of internal and external data exchange?**

1 ☐
2 ☐
3 ☐
4 ☐
5 ☐

Section G: E - Demographic Data

You have now reached the end of the survey. By clicking on the "Submit" button, you can transfer your answers!

G1. **In which region did you mainly work in the rail industry?**

G2. **What is the average percentage of employees working in the maintenance department in the rail industry?**

less than 5 percent ☐
up to 10 percent ☐
over 10 percent ☐

Stellenbosch University https://scholar.sun.ac.za

G3. In which industrial sector are you experienced?

- Operation of rail rolling stock ☐
- Manufacturing of rail rolling stock ☐
- Both (operation and manufacturing of rail rolling stock) ☐
- Other ☐

Other

G4. In which field of transport are you experienced?

- Passenger transport ☐
- Freight transport ☐
- Both (passenger and freight transport) ☐

Thank you very much for participating in the survey!

The results will help to create a model which supports the rail industry in the implementation of Industry 4.0 technologies. If you have further questions please do not hesitate to contact me (marius_tim.wippel@student.reutlingen-university.de).

Stellenbosch University https://scholar.sun.ac.za

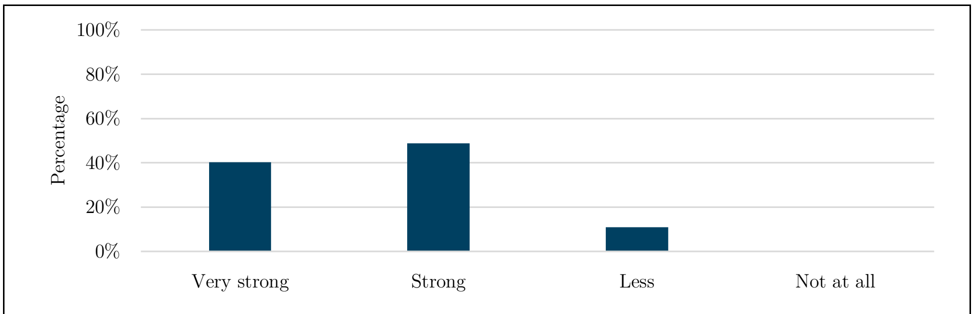
A.4 Survey Results Direct Analysis

Direct Analysis

General Information	
Sample size	82
Abbreviation	Q: Question
Question	For questions 3, 4, 5, 7, 9 and 10 multiple answers were possible. For question 11 the summary of the participants answers is provided. Questions 12 to 35 are answered from a scale from 1 to 5: • The value 1 indicates that no realisation has occurred in the rail industry. • The value 5 indicates that a complete realisation has occurred in the rail industry.
Structure of the Analysis	
Question 1 – 3	Digitalisation in the rail industry
Question 4 – 11	Implementation and application of Industry 4.0 enabling technologies in maintenance
Question 12 – 35	Technological maturity level
Question 36 – 39	Demographic data

Stellenbosch University https://scholar.sun.ac.za

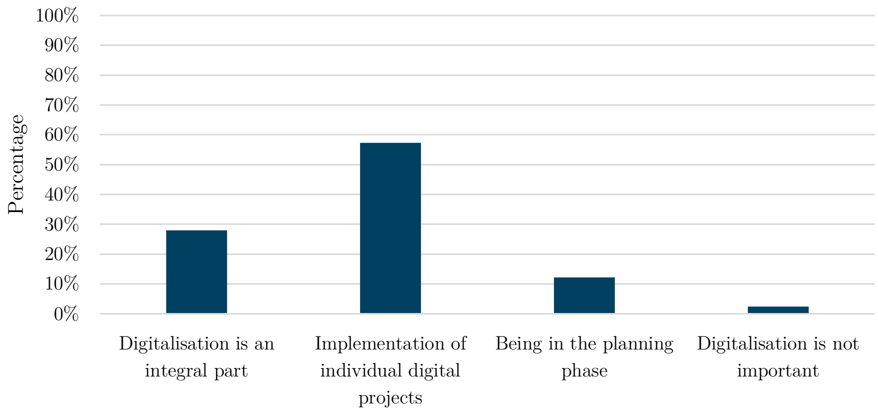
Q1
How strongly is the topic of digitalisation currently discussed in the rail industry



Answer	**Quantity**	**Percentage**
Very strong	33	40.24%
Strong	40	48.78%
Less	9	10.98%
Not at all	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q2
What is the current status regarding digitalisation in the rail industry?

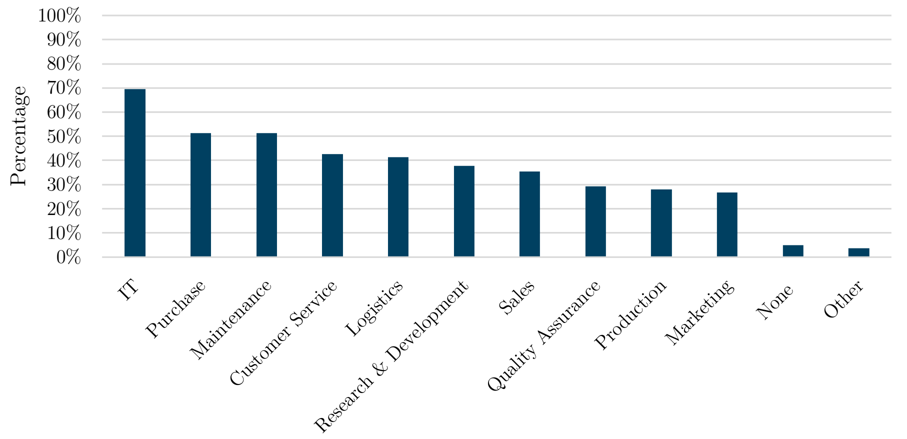


Answer	**Quantity**	**Percentage**
Digitalisation is an integral part in the rail industry	23	28.05%
The rail industry works on the implementation of individual digital projects	47	57.32%
The rail industry is still in the planning phase	10	12.20%
Digitalisation is not important for the rail industry	2	2.44%

Stellenbosch University https://scholar.sun.ac.za

Q3

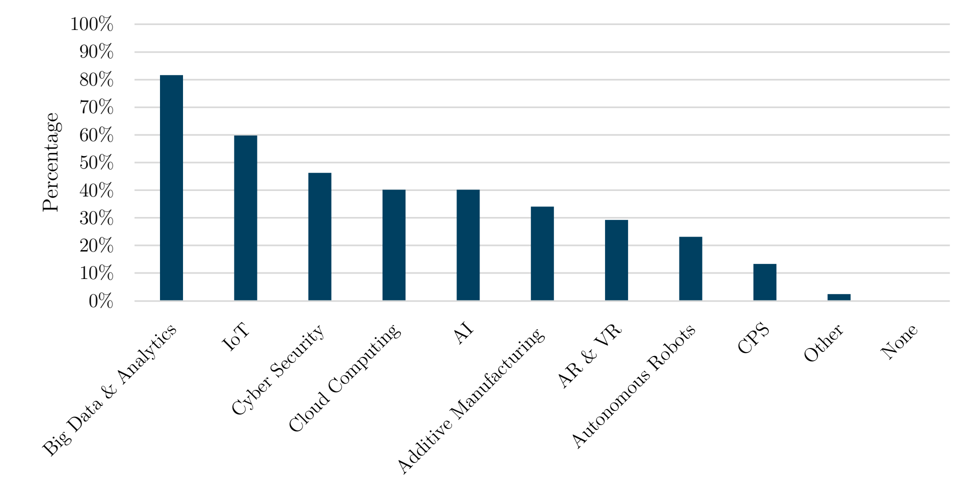
Which areas or processes have already been digitalised in the rail industry?



Answer	Quantity	Percentage
IT	57	69.51%
Purchase	42	51.22%
Maintenance	42	51.22%
Customer Service	35	42.68%
Logistics	34	41.46%
Research & Development	31	37.80%
Sales	29	35.37%
Quality Assurance	24	29.27%
Production	23	28.05%
Marketing	22	26.83%
None	4	4.88%
Other	3	3.66%

Stellenbosch University https://scholar.sun.ac.za

Q4
Which of the following Industry 4.0 enabling technologies will be of greatest importance in rail rolling stock maintenance?

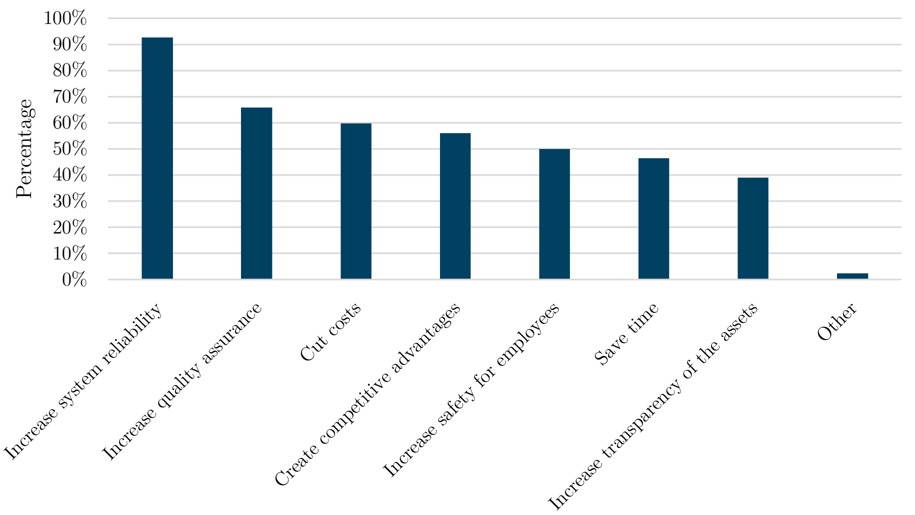


Answer	Quantity	Percentage
Big Data & Analytics	67	81.71%
Internet of Things (IoT)	49	59.76%
Cyber Security	38	46.34%
Cloud Computing	33	40.24%
Artificial Intelligence (AI)	33	40.24%
Additive Manufacturing	28	34.15%
Augmented & Virtual Reality (AR & VR)	24	29.27%
Autonomous Robots	19	23.17%
Cyber-Physical System (CPS)	11	13.41%
Other	2	2.44%
None	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q5

Why do you think the above indicated technologies are important in rail rolling stock maintenance?

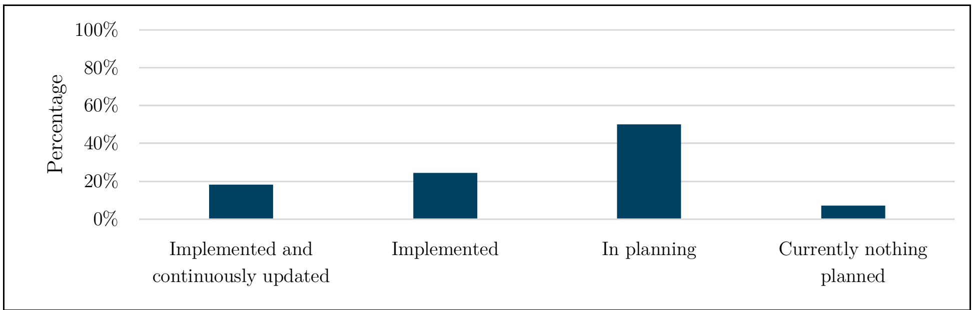


Answer	**Quantity**	**Percentage**
Increase system reliability	76	92.68%
Increase quality assurance	54	65.85%
Cut costs	49	59.76%
Create competitive advantages	46	56.10%
Increase safety for employees	41	50.00%
Save time	38	46.34%
Increase transparency of the assets	32	39.02%
Other	2	2.44%

Stellenbosch University https://scholar.sun.ac.za

Q6

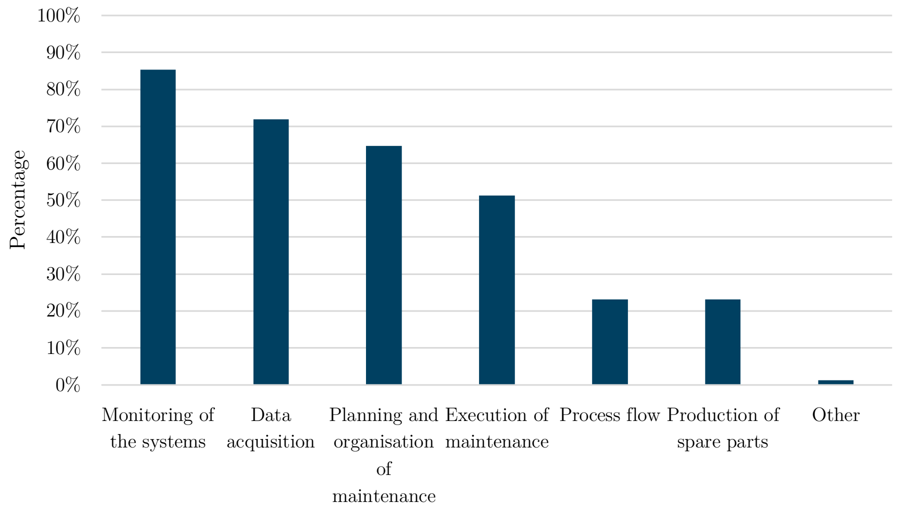
What is the current status in the rail industry regarding the implementation of Industry 4.0 enabling technologies in rail rolling stock maintenance?



Answer	Quantity	Percentage
Implemented and continuously updated	15	18.29%
Implemented	20	24.39%
In planning	41	50.00%
Currently nothing planned	6	7.32%

Stellenbosch University https://scholar.sun.ac.za

Q7
In which area of rail rolling stock maintenance does the rail industry apply these Industry 4.0 enabling technologies?

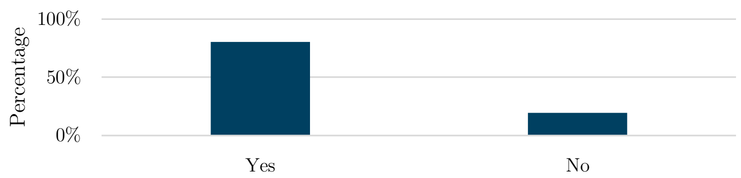


Answer	Quantity	Percentage
Monitoring of the systems	70	85.37%
Data acquisition	59	71.95%
Planning and organisation of maintenance	53	64.63%
Execution of maintenance	42	51.22%
Process flow	19	23.17%
Production of spare parts	19	23.17%
Other	1	1.22%

Stellenbosch University https://scholar.sun.ac.za

Q8

Does the rail industry encounter any challenges related to Industry 4.0 enabling technologies in rail rolling stock maintenance?

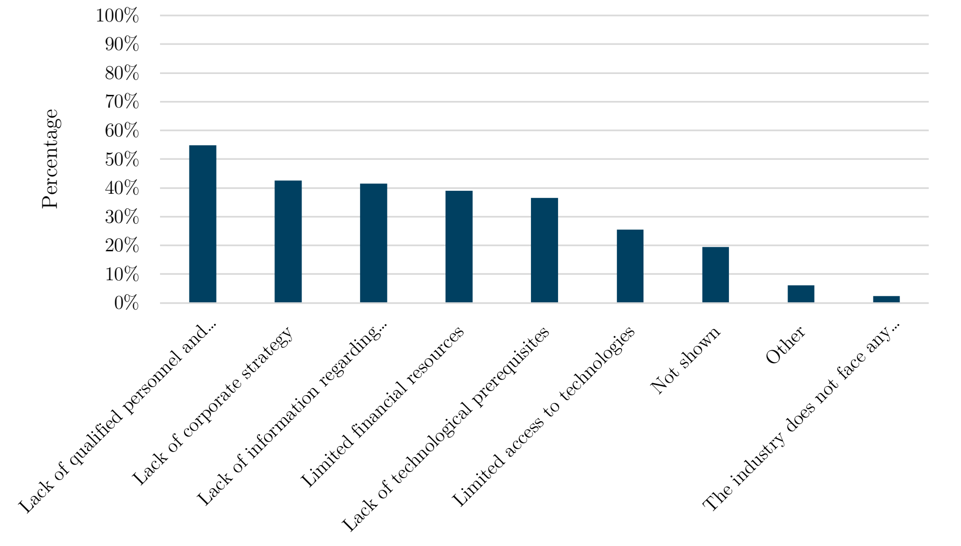


Answer	Quantity	Percentage
Yes	66	80.49%
No	16	19.51%

Stellenbosch University https://scholar.sun.ac.za

Q9

What challenges does the rail industry face regarding Industry 4.0 technologies in rail rolling stock maintenance?

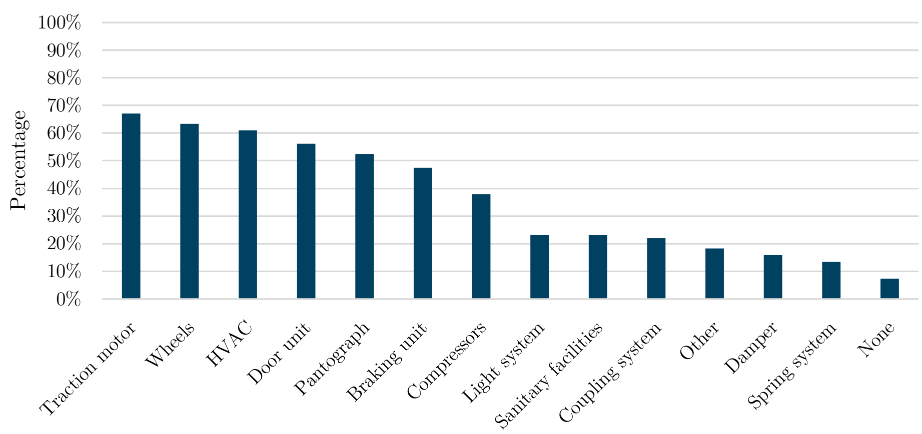


Answer	Quantity	Percentage
Lack of qualified personnel and competences	45	54.88%
Lack of corporate strategy	35	42.68%
Lack of information regarding implementation	34	41.46%
Limited financial resources	32	39.02%
Lack of technological prerequisites	30	36.59%
Limited access to technologies	21	25.61%
Not shown	16	19.51%
Other	5	6.10%
The industry does not face any challenges	2	2.44%

Stellenbosch University https://scholar.sun.ac.za

Q10

For which rail rolling stock systems/components does the rail industry apply Industry 4.0 enabling technologies in maintenance?



Answer	**Quantity**	**Percentage**
Traction motor	55	67.07%
Wheels	52	63.41%
HVAC	50	60.98%
Door unit	46	56.10%
Pantograph	43	52.44%
Braking unit	39	47.56%
Compressors	31	37.80%
Light system	19	23.17%
Sanitary facilities	19	23.17%
Coupling system	18	21.95%
Other	15	18.29%
Damper	13	15.85%
Spring system	11	13.41%
None	6	7.32%

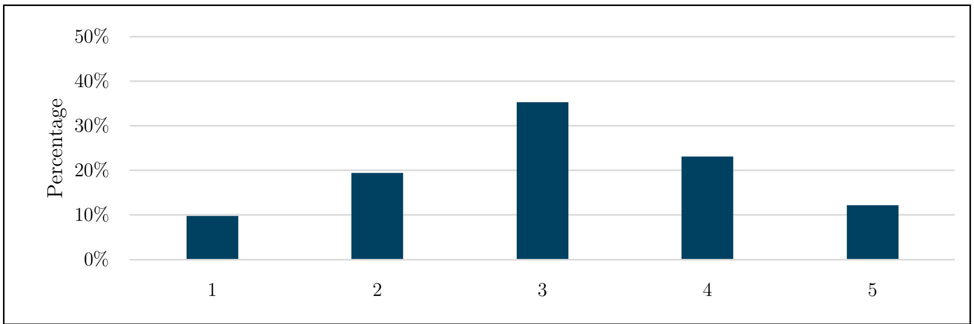
Stellenbosch University https://scholar.sun.ac.za

Q11
What impacts or effects have resulted from the implementation of Industry 4.0 enabling technologies for the above selected systems/components?

Answer Summary
• Maintenance optimisation in general • Higher reliability of rolling stock systems and of maintenance planning • Improved troubleshooting • Higher efficiency • Reduction in maintenance costs • Reduction of downtime • Difficulties in implementation of emerging technologies

Stellenbosch University https://scholar.sun.ac.za

Q12
To what extent does the rail industry have the possibility to connect with resources on the network or among each other to share or use data?

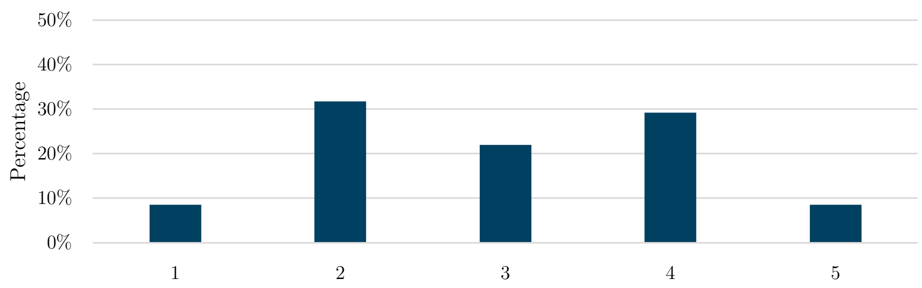


Answer	Quantity	Percentage
1	8	9.76%
2	16	19.51%
3	29	35.37%
4	19	23.17%
5	10	12.20%

Stellenbosch University https://scholar.sun.ac.za

Q13

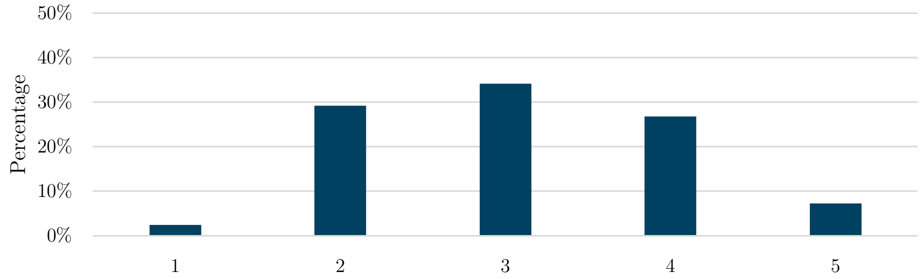
To what extent is the rail industry able to collect information with sensors and then transform it into mechanical work by using actuators?



Answer	Quantity	Percentage
1	7	8.54%
2	26	31.71%
3	18	21.95%
4	24	29.27%
5	7	8.54%

Stellenbosch University https://scholar.sun.ac.za

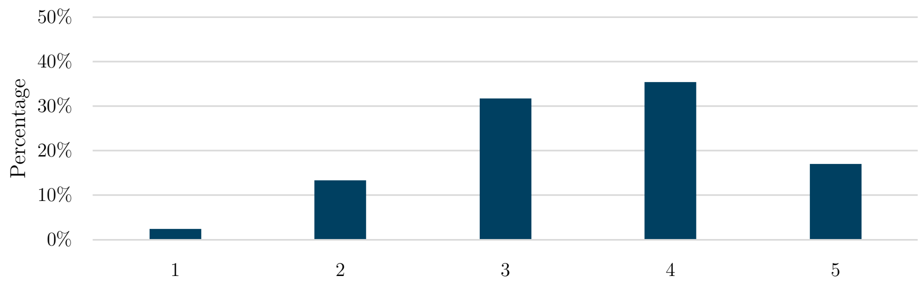
Q14
To what extent are embedded systems for information processing in the rail industry implemented?



Answer	Quantity	Percentage
1	2	2.44%
2	24	29.27%
3	28	34.15%
4	22	26.83%
5	6	7.32%

Stellenbosch University https://scholar.sun.ac.za

Q15
To what extent does the rail industry have an infrastructure to collect and store data?

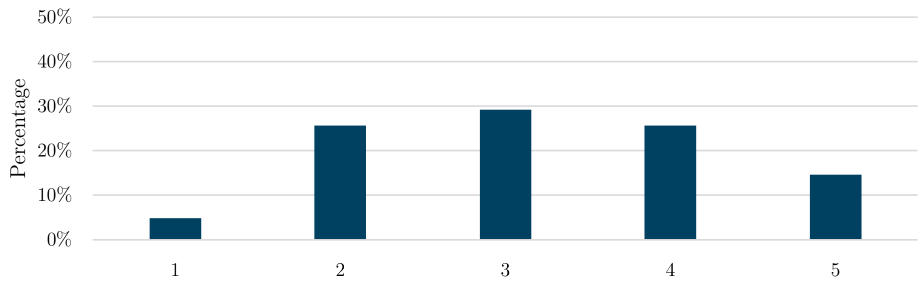


Answer	Quantity	Percentage
1	2	2.44%
2	11	13.41%
3	26	31.71%
4	29	35.37%
5	14	17.07%

Stellenbosch University https://scholar.sun.ac.za

Q16

To what extent is the rail industries data organised in digital secure systems?

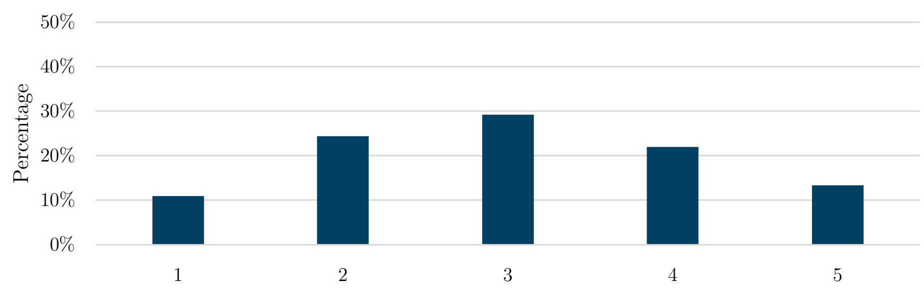


Answer	Quantity	Percentage
1	4	4.88%
2	21	25.61%
3	24	29.27%
4	21	25.61%
5	12	14.63%

Stellenbosch University https://scholar.sun.ac.za

Q17

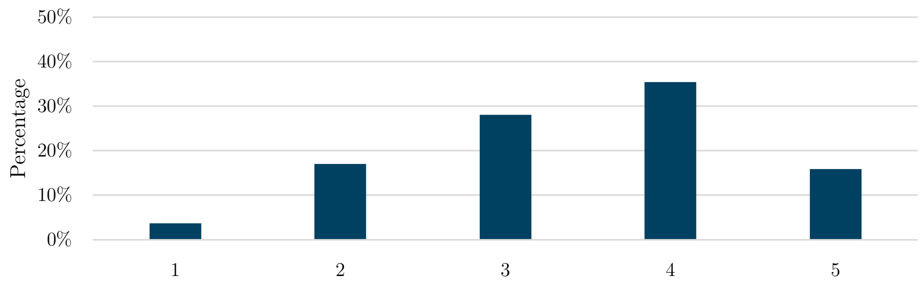
To what extent does the rail industry know how to deal with the obtained data?



Answer	Quantity	Percentage
1	9	10.98%
2	20	24.39%
3	24	29.27%
4	18	21.95%
5	11	13.41%

Stellenbosch University https://scholar.sun.ac.za

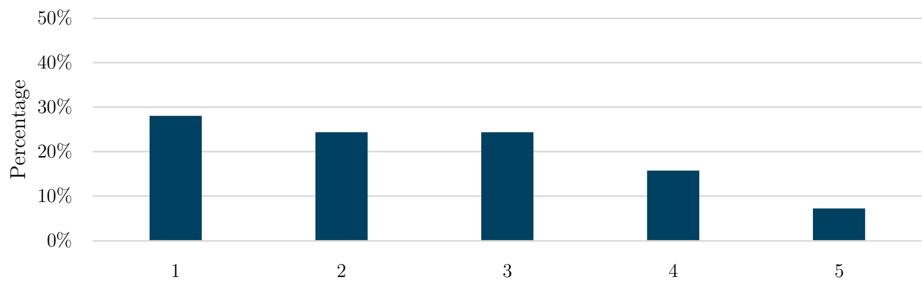
Q18
How high is the degree of process standardisation in the rail industry?



Answer	Quantity	Percentage
1	3	3.66%
2	14	17.07%
3	23	28.05%
4	29	35.37%
5	13	15.85%

Stellenbosch University https://scholar.sun.ac.za

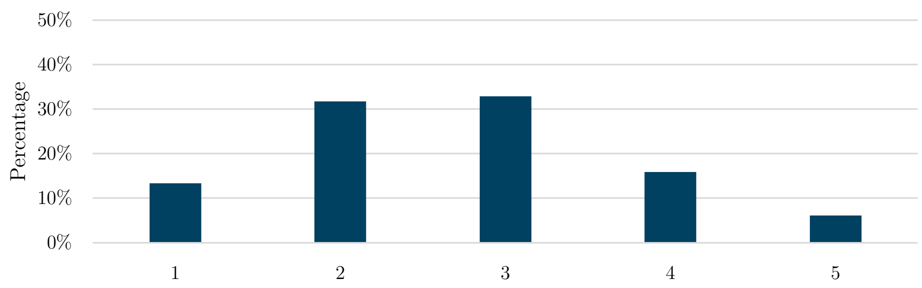
Q19:
To what extent are 3D models of technical components or spare parts in the rail industry available?



Answer	Quantity	Percentage
1	23	28.05%
2	20	24.39%
3	20	24.39%
4	13	15.85%
5	6	7.32%

Stellenbosch University https://scholar.sun.ac.za

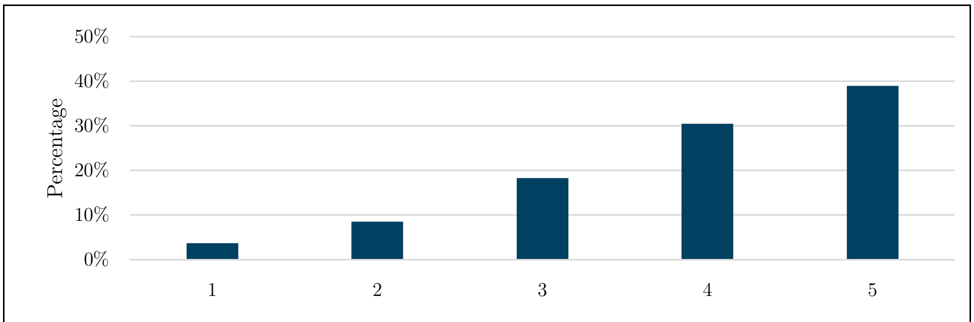
Q20
To what extent does the rail industry have internal knowledge regarding the utilisation of additive manufacturing?



Answer	Quantity	Percentage
1	11	13.41%
2	26	31.71%
3	27	32.93%
4	13	15.85%
5	5	6.10%

Stellenbosch University https://scholar.sun.ac.za

Q21
To what extent does the rail industry have broadband internet access?

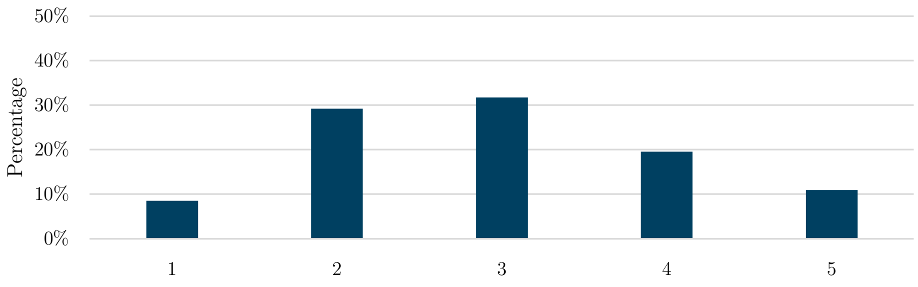


Answer	Quantity	Percentage
1	3	3.66%
2	7	8.54%
3	15	18.29%
4	25	30.49%
5	32	39.02%

Stellenbosch University https://scholar.sun.ac.za

Q22

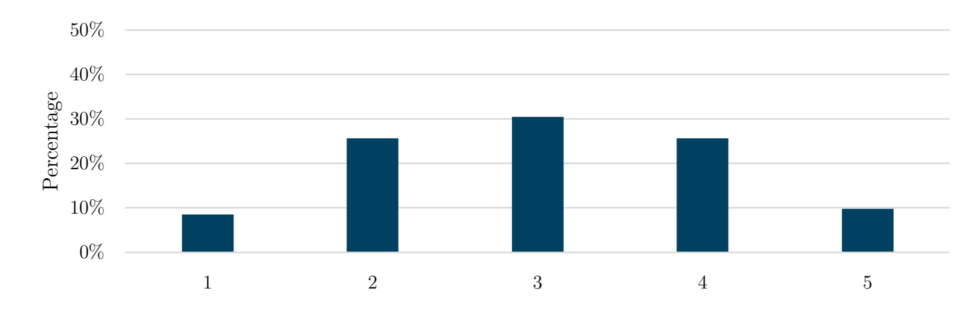
To what extent is the IT infrastructure in the rail industry provided via cloud computing?



Answer	Quantity	Percentage
1	7	8.54%
2	24	29.27%
3	26	31.71%
4	16	19.51%
5	9	10.98%

Stellenbosch University https://scholar.sun.ac.za

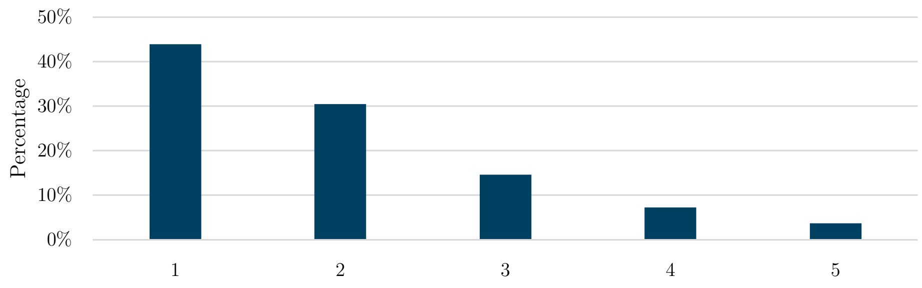
Q23
To what extent does the rail industry use cloud services for software or data?



Answer	Quantity	Percentage
1	7	8.54%
2	21	25.61%
3	25	30.49%
4	21	25.61%
5	8	9.76%

Stellenbosch University https://scholar.sun.ac.za

Q24
To what extent does the rail industry use self-learning systems to solve complex application problems?

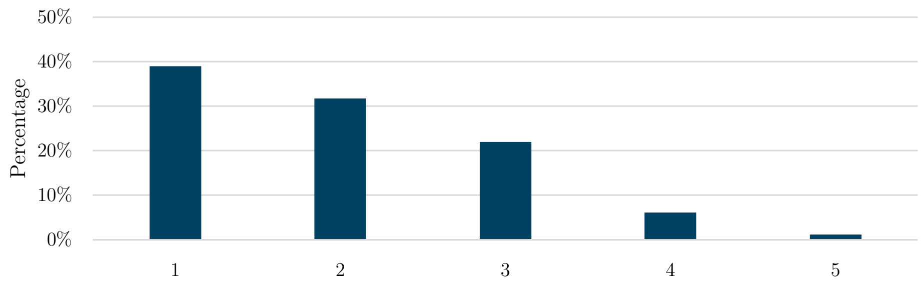


Answer	Quantity	Percentage
1	36	43.90%
2	25	30.49%
3	12	14.63%
4	6	7.32%
5	3	3.66%

Stellenbosch University https://scholar.sun.ac.za

Q25

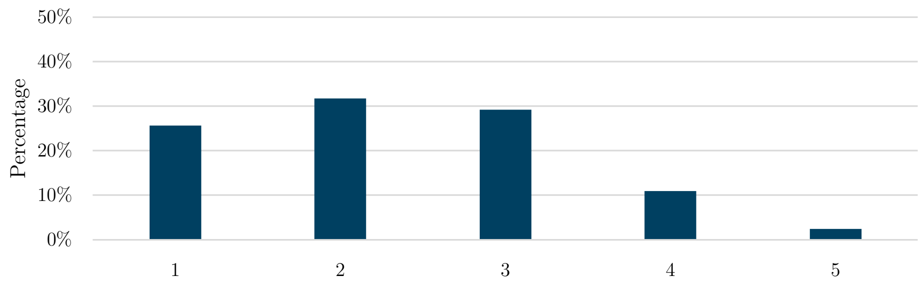
To what extent does the rail industry use virtual assistants?



Answer	Quantity	Percentage
1	32	39.02%
2	26	31.71%
3	18	21.95%
4	5	6.10%
5	1	1.22%

Stellenbosch University https://scholar.sun.ac.za

Q26
To what extent does the rail industry train machines, systems or equipment with data?

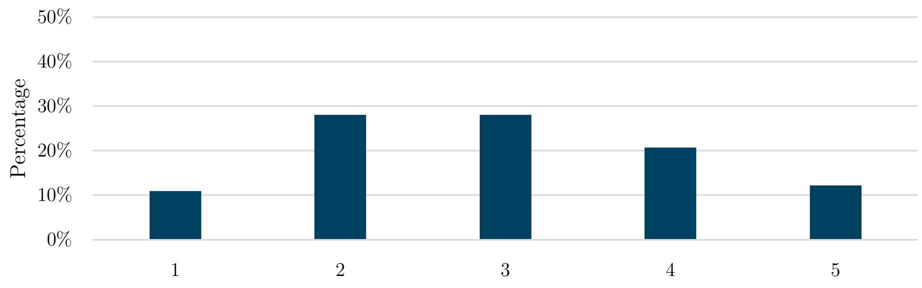


Answer	Quantity	Percentage
1	21	25.61%
2	26	31.71%
3	24	29.27%
4	9	10.98%
5	2	2.44%

Stellenbosch University https://scholar.sun.ac.za

Q27

To what extent are machines, systems or equipment in the rail industry capable of communicating with each other?

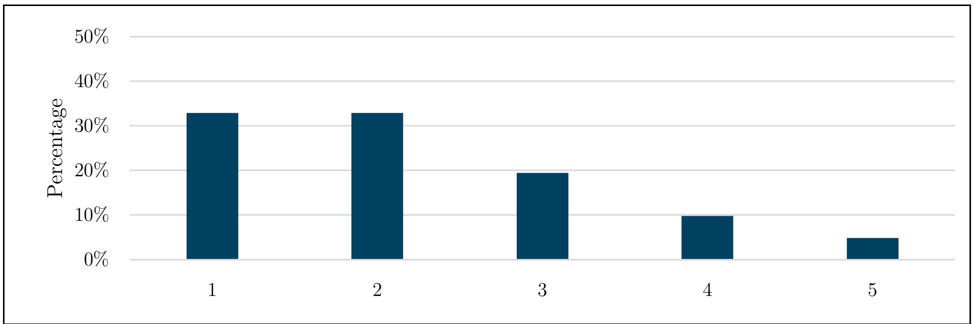


Answer	Quantity	Percentage
1	9	10.98%
2	23	28.05%
3	23	28.05%
4	17	20.73%
5	10	12.20%

Stellenbosch University https://scholar.sun.ac.za

Q28

To what extent are machines, systems or equipment in the rail industry capable of independently assessing situations and taking decisions?

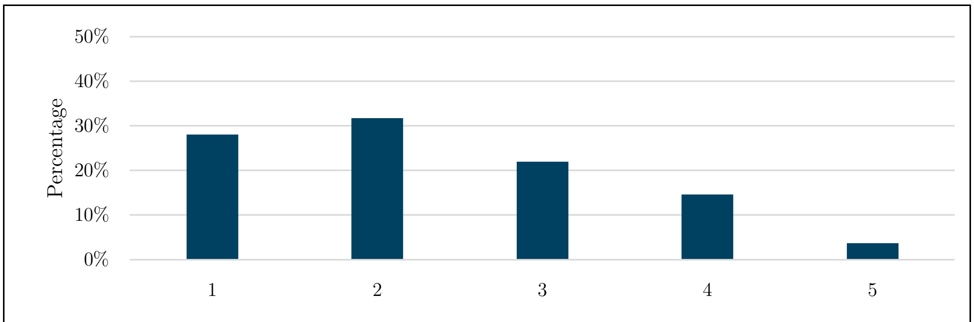


Answer	Quantity	Percentage
1	27	32.93%
2	27	32.93%
3	16	19.51%
4	8	9.76%
5	4	4.88%

Stellenbosch University https://scholar.sun.ac.za

Q29

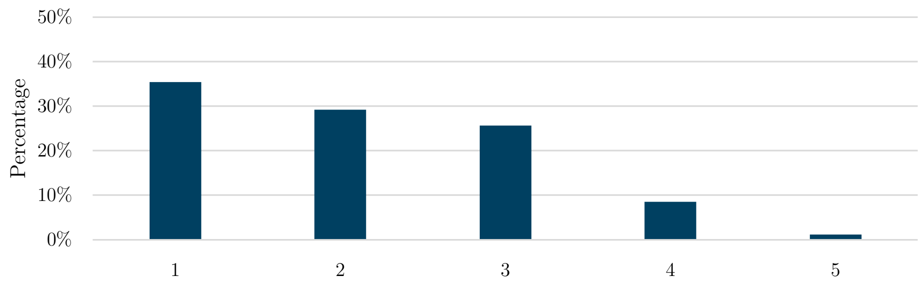
To what extent can the rail industry create a virtual image of machines, systems or equipment?



Answer	Quantity	Percentage
1	23	28.05%
2	26	31.71%
3	18	21.95%
4	12	14.63%
5	3	3.66%

Stellenbosch University https://scholar.sun.ac.za

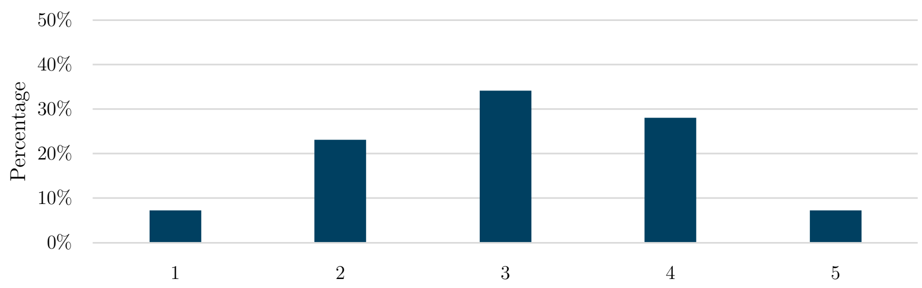
Q30
To what extent is the rail industry able to display virtual objects in the real world?



Answer	Quantity	Percentage
1	29	35.37%
2	24	29.27%
3	21	25.61%
4	7	8.54%
5	1	1.22%

Stellenbosch University https://scholar.sun.ac.za

Q31
To what extent does the rail industry use supporting hardware technologies (e.g. tablets, smartphones or smartglasses)?

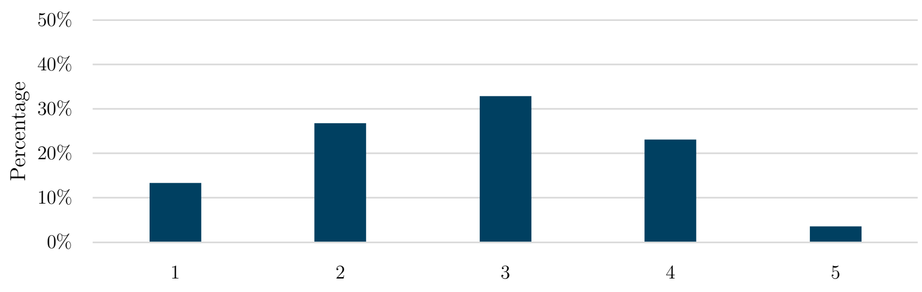


Answer	Quantity	Percentage
1	6	7.32%
2	19	23.17%
3	28	34.15%
4	23	28.05%
5	6	7.32%

Stellenbosch University https://scholar.sun.ac.za

Q32

To what extent can the rail industry perform remote tasks with supporting hardware technologies (e.g. tablets, smartphones or smartglasses)?

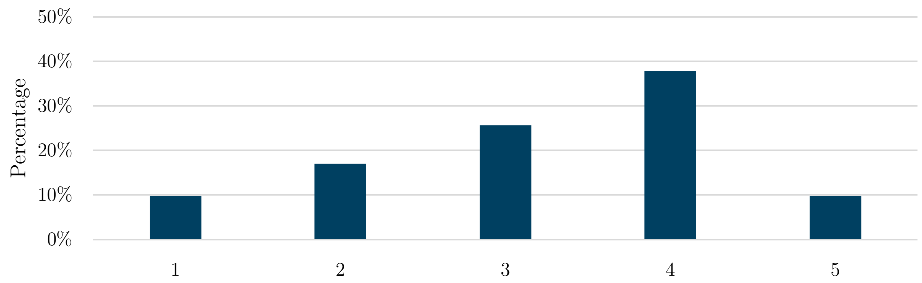


Answer	Quantity	Percentage
1	11	13.41%
2	22	26.83%
3	27	32.93%
4	19	23.17%
5	3	3.66%

Stellenbosch University https://scholar.sun.ac.za

Q33

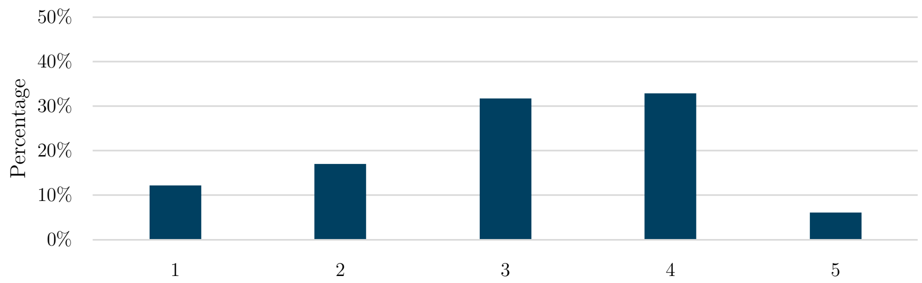
How advanced is the rail industry regarding the security of internal data storage?



Answer	Quantity	Percentage
1	8	9.76%
2	14	17.07%
3	21	25.61%
4	31	37.80%
5	8	9.76%

Stellenbosch University https://scholar.sun.ac.za

Q34
How advanced is the rail industry regarding the data protection in cloud services?

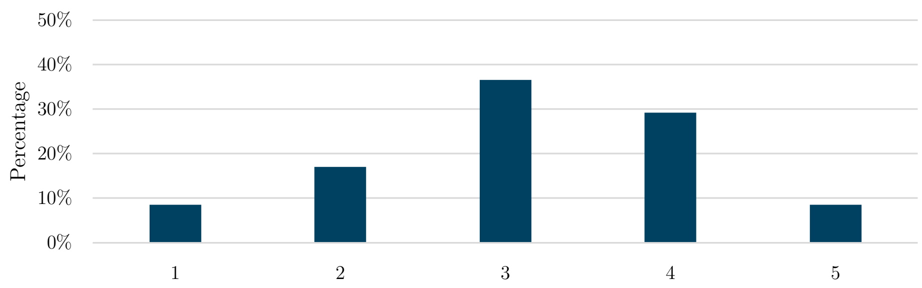


Answer	Quantity	Percentage
1	10	12.20%
2	14	17.07%
3	26	31.71%
4	27	32.93%
5	5	6.10%

Stellenbosch University https://scholar.sun.ac.za

Q35

How advanced is the rail industry in terms of the communication security of internal and external data exchange?

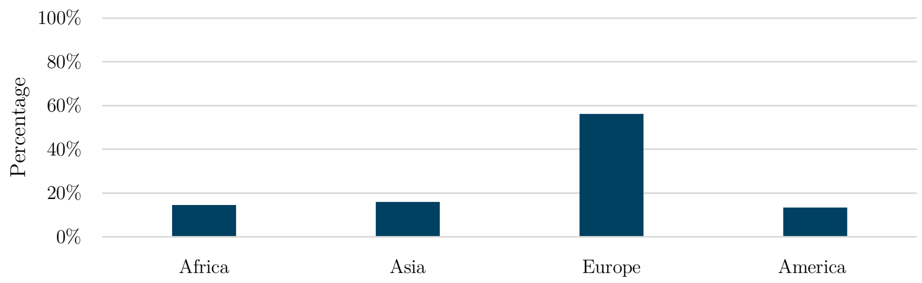


Answer	Quantity	Percentage
1	7	8.54%
2	14	17.07%
3	30	36.59%
4	24	29.27%
5	7	8.54%

Stellenbosch University https://scholar.sun.ac.za

Q36

In which region did you mainly work in the rail industry?

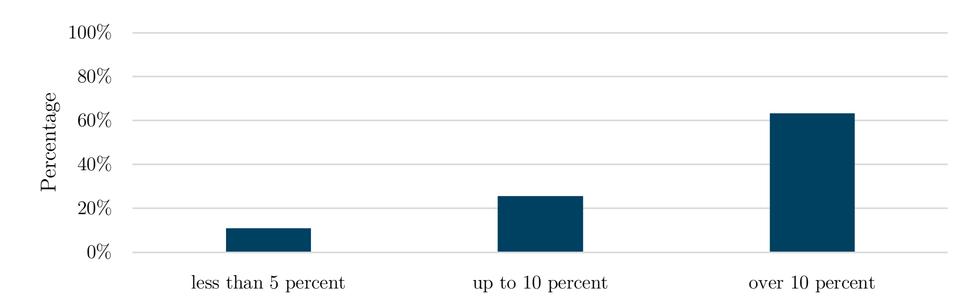


Answer	Quantity	Percentage
Africa	12	14.63%
Asia	13	15.85%
Europe	46	56.10%
America	11	13.41%

Stellenbosch University https://scholar.sun.ac.za

Q37

What is the average percentage of employees working in the maintenance department in the rail industry?

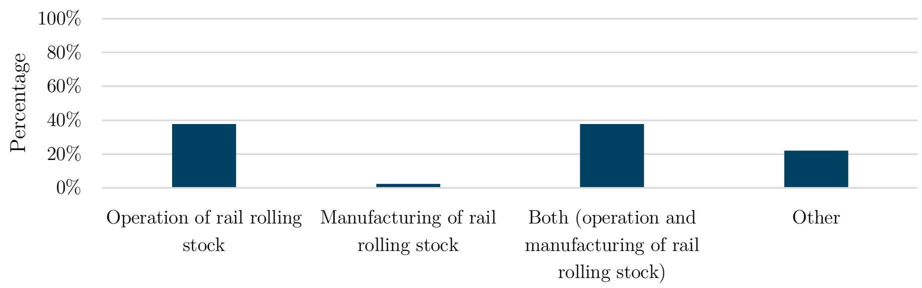


Answer	Quantity	Percentage
less than 5 percent	9	10.98%
up to 10 percent	21	25.61%
over 10 percent	52	63.41%

Stellenbosch University https://scholar.sun.ac.za

Q38

In which industrial sector are you experienced?



Answer	Quantity	Percentage
Operation of rail rolling stock	31	37.80%
Manufacturing of rail rolling stock	2	2.44%
Both (operation and manufacturing of rail rolling stock)	31	37.80%
Other	18	21.95%

Stellenbosch University https://scholar.sun.ac.za

Q39

In which field of transport are you experienced?

Answer	Quantity	Percentage
Passenger transport	48	58.54%
Freight transport	5	6.10%
Both (passenger and freight transport)	29	35.37%

Stellenbosch University https://scholar.sun.ac.za

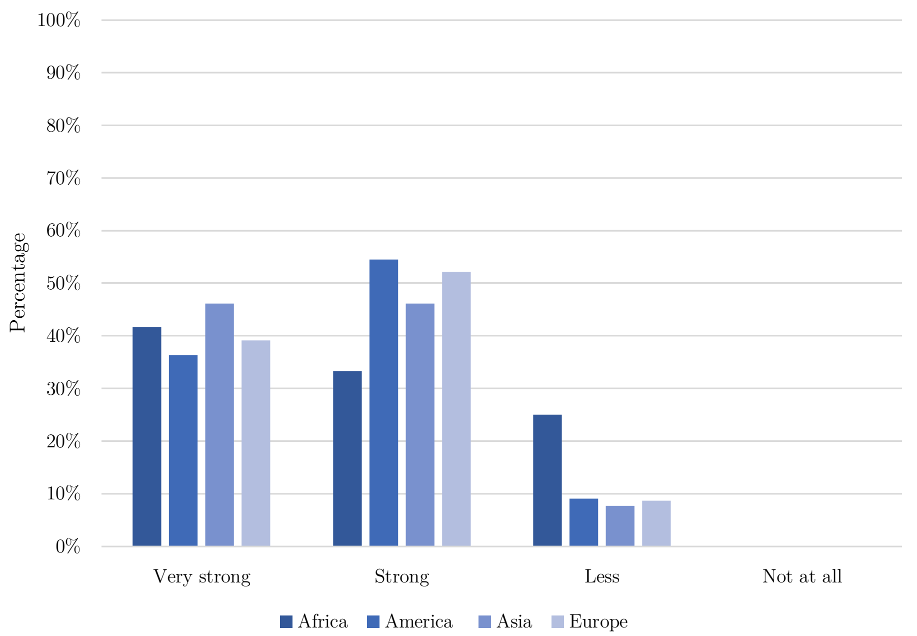
A.5 Survey Results Indirect Analysis – Region

Indirect Analysis Region

General Information	
Sample size	Africa: 12 America: 11 Asia: 13 Europe: 46
Abbreviation	Q: Question Qty: Quantity
Question	• For questions 3, 4, 5, 7, 9 and 10 multiple answers were possible. • The term "not shown" indicates that the question did not appear due to the previous answer of the question.
Structure of the Analysis	
Question 1 – 3	Digitalisation in the rail industry
Question 4 – 10	Implementation and application of Industry 4.0 enabling technologies in maintenance

Stellenbosch University https://scholar.sun.ac.za

Q1
How strongly is the topic of digitalisation currently discussed in the rail industry

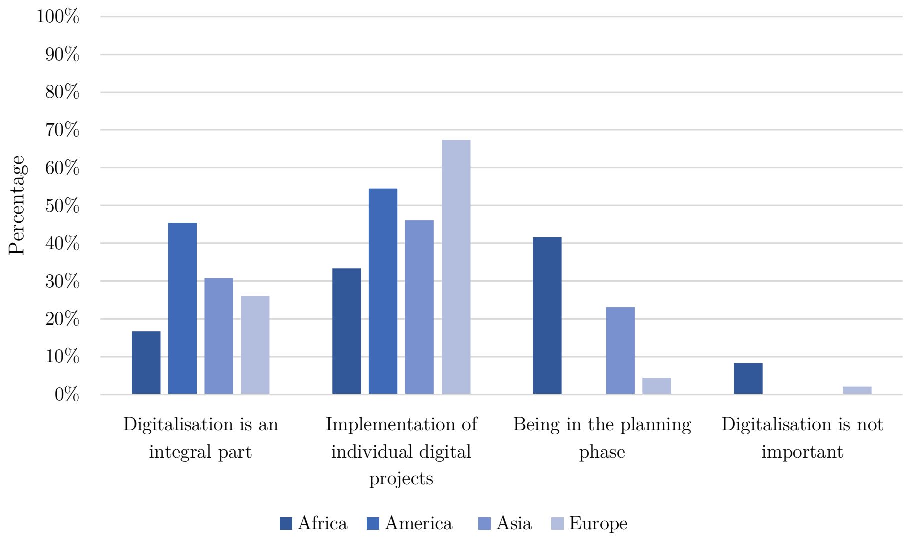


Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Very strong	5	41.67%	4	36.36%	6	46.15%	18	39.13%
Strong	4	33.33%	6	54.55%	6	46.15%	24	52.17%
Less	3	25.00%	1	9.09%	1	7.69%	4	8.70%
Not at all	0	0.00%	0	0.00%	0	0.00%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q2

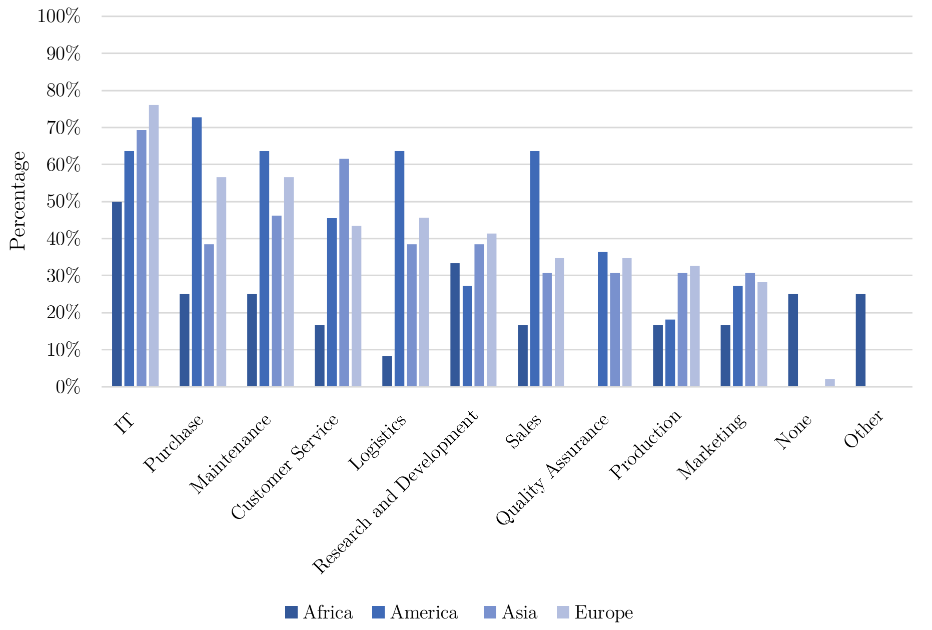
What is the current status regarding digitalisation in the rail industry?



Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Digitalisation is an integral part in the rail industry	2	16.67%	5	45.45%	4	30.77%	12	26.09%
The rail industry works on the implementation of individual digital projects	4	33.33%	6	54.55%	6	46.15%	31	67.39%
The rail industry is still in the planning phase	5	41.67%	0	0.00%	3	23.08%	2	4.35%
Digitalisation is not important for the rail industry	1	8.33%	0	0.00%	0	0.00%	1	2.17%

Stellenbosch University https://scholar.sun.ac.za

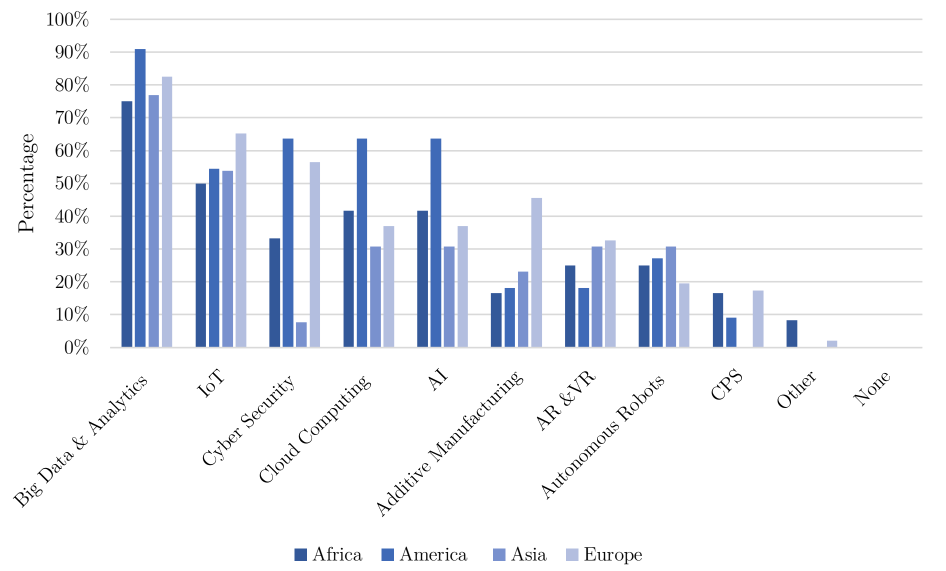
Q3
Which areas or processes have already been digitalised in the rail industry?



Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
IT	6	50.00%	7	63.64%	9	69.23%	35	76.09%
Purchase	3	25.00%	8	72.73%	5	38.46%	26	56.52%
Maintenance	3	25.00%	7	63.64%	6	46.15%	26	56.52%
Customer Service	2	16.67%	5	45.45%	8	61.54%	20	43.48%
Logistics	1	8.33%	7	63.64%	5	38.46%	21	45.65%
Research & Development	4	33.33%	3	27.27%	5	38.46%	19	41.30%
Sales	2	16.67%	7	63.64%	4	30.77%	16	34.78%
Quality Assurance	0	0.00%	4	36.36%	4	30.77%	16	34.78%
Production	2	16.67%	2	18.18%	4	30.77%	15	32.61%
Marketing	2	16.67%	3	27.27%	4	30.77%	13	28.26%
None	3	25.00%	0	0.00%	0	0.00%	1	2.17%
Other	3	25.00%	0	0.00%	0	0.00%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q4
Which of the following Industry 4.0 enabling technologies will be of greatest importance in rail rolling stock maintenance?

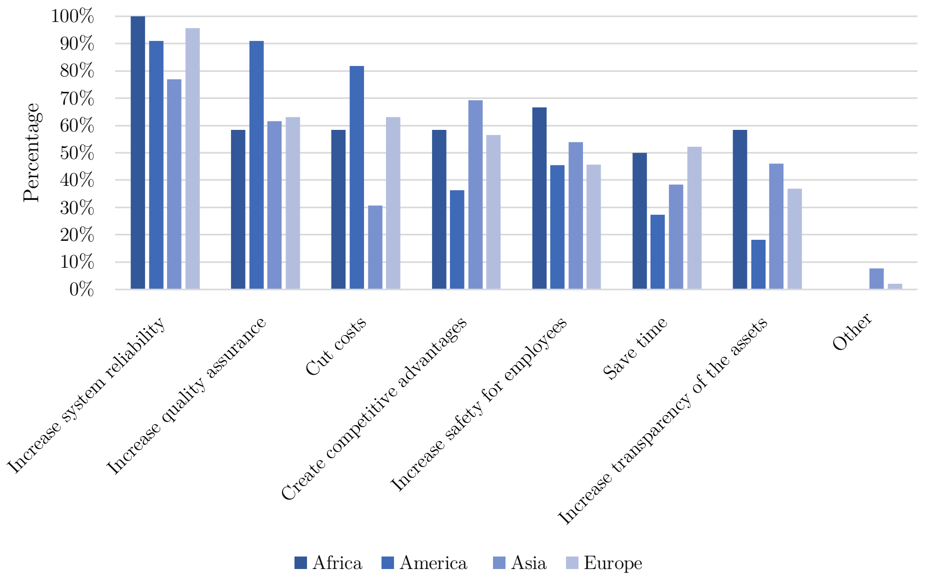


Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Big Data & Analytics	9	75.00%	10	90.91%	10	76.92%	38	82.61%
Internet of Things (IoT)	6	50.00%	6	54.55%	7	53.85%	30	65.22%
Cyber Security	4	33.33%	7	63.64%	1	7.69%	26	56.52%
Cloud Computing	5	41.67%	7	63.64%	4	30.77%	17	36.96%
Artificial Intelligence (AI)	5	41.67%	7	63.64%	4	30.77%	17	36.96%
Additive Manufacturing (3D-Printing)	2	16.67%	2	18.18%	3	23.08%	21	45.65%
Augmented & Virtual Reality (AR & VR)	3	25.00%	2	18.18%	4	30.77%	15	32.61%
Autonomous Robots	3	25.00%	3	27.27%	4	30.77%	9	19.57%
Cyber-Physical System (CPS)	2	16.67%	1	9.09%	0	0.00%	8	17.39%
Other	1	8.33%	0	0.00%	0	0.00%	1	2.17%
None	0	0.00%	0	0.00%	0	0.00%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q5

Why do you think the above indicated technologies are important in rail rolling stock maintenance?

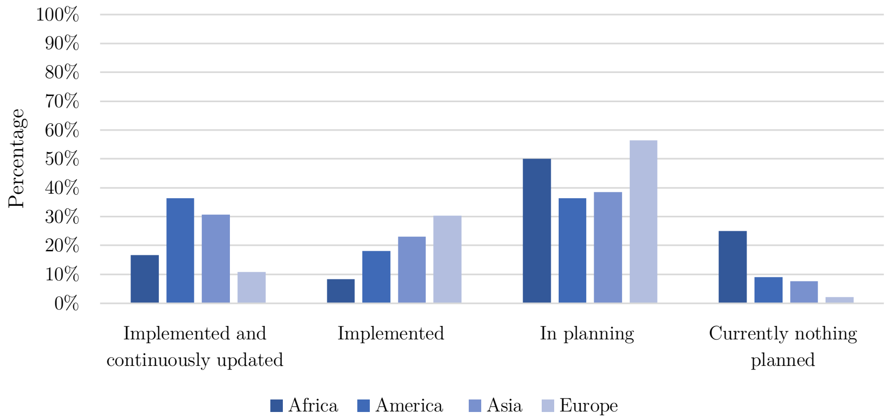


Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Increase system reliability	12	100.00%	10	90.91%	10	76.92%	44	95.65%
Increase quality assurance	7	58.33%	10	90.91%	8	61.54%	29	63.04%
Cut costs	7	58.33%	9	81.82%	4	30.77%	29	63.04%
Create competitive advantages	7	58.33%	4	36.36%	9	69.23%	26	56.52%
Increase safety for employees	8	66.67%	5	45.45%	7	53.85%	21	45.65%
Save time	6	50.00%	3	27.27%	5	38.46%	24	52.17%
Increase transparency of the assets	7	58.33%	2	18.18%	6	46.15%	17	36.96%
Other	0	0.00%	0	0.00%	1	7.69%	1	2.17%

Stellenbosch University https://scholar.sun.ac.za

Q6

What is the current status in the rail industry regarding the implementation of Industry 4.0 enabling technologies in rail rolling stock maintenance?

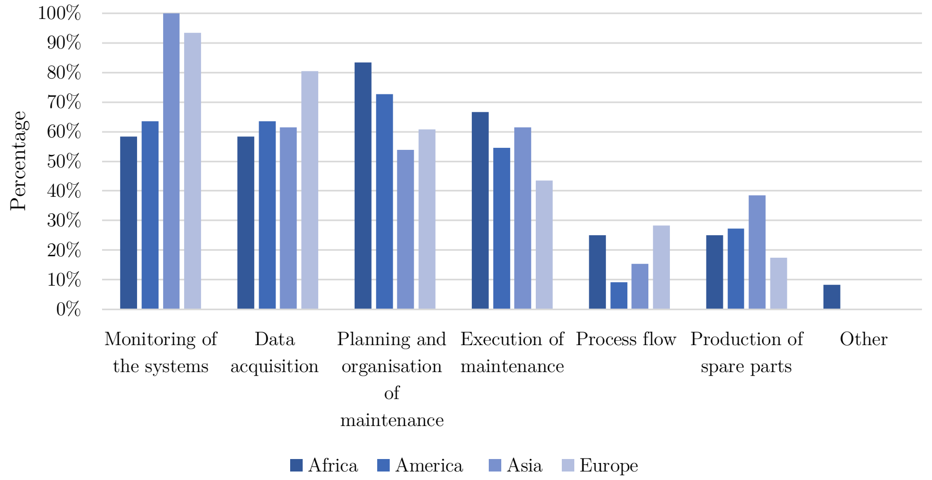


Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Implemented and continuously updated	2	16.67%	4	36.36%	4	30.77%	5	10.87%
Implemented	1	8.33%	2	18.18%	3	23.08%	14	30.43%
In planning	6	50.00%	4	36.36%	5	38.46%	26	56.52%
Currently nothing planned	3	25.00%	1	9.09%	1	7.69%	1	2.17%

Stellenbosch University https://scholar.sun.ac.za

Q7

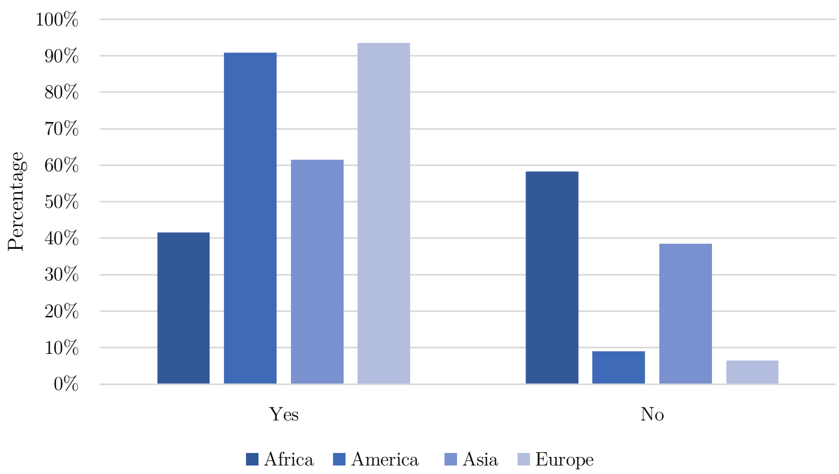
In which area of rail rolling stock maintenance does the rail industry apply these Industry 4.0 enabling technologies?



Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Monitoring of the systems	7	58.33%	7	63.64%	13	100.00%	43	93.48%
Data acquisition	7	58.33%	7	63.64%	8	61.54%	37	80.43%
Planning and organisation of maintenance	10	83.33%	8	72.73%	7	53.85%	28	60.87%
Execution of maintenance	8	66.67%	6	54.55%	8	61.54%	20	43.48%
Process flow	3	25.00%	1	9.09%	2	15.38%	13	28.26%
Production of spare parts	3	25.00%	3	27.27%	5	38.46%	8	17.39%
Other	1	8.33%	0	0.00%	0	0.00%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q8
Does the rail industry encounter any challenges related to Industry 4.0 enabling technologies in rail rolling stock maintenance?

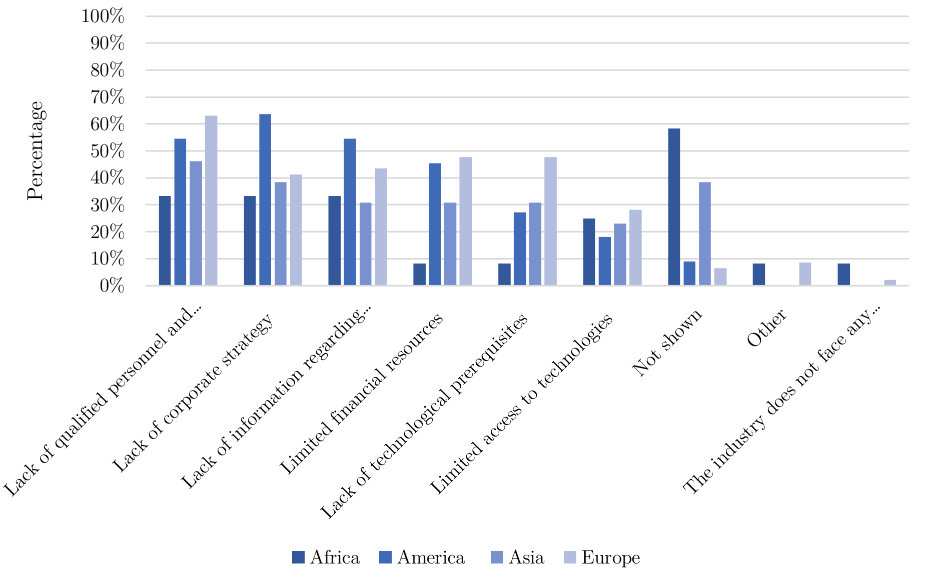


Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Yes	5	41.67%	10	90.91%	8	61.54%	43	93.48%
No	7	58.33%	1	9.09%	5	38.46%	3	6.52%

Stellenbosch University https://scholar.sun.ac.za

Q9

What challenges does the rail industry face regarding Industry 4.0 technologies in rail rolling stock maintenance?

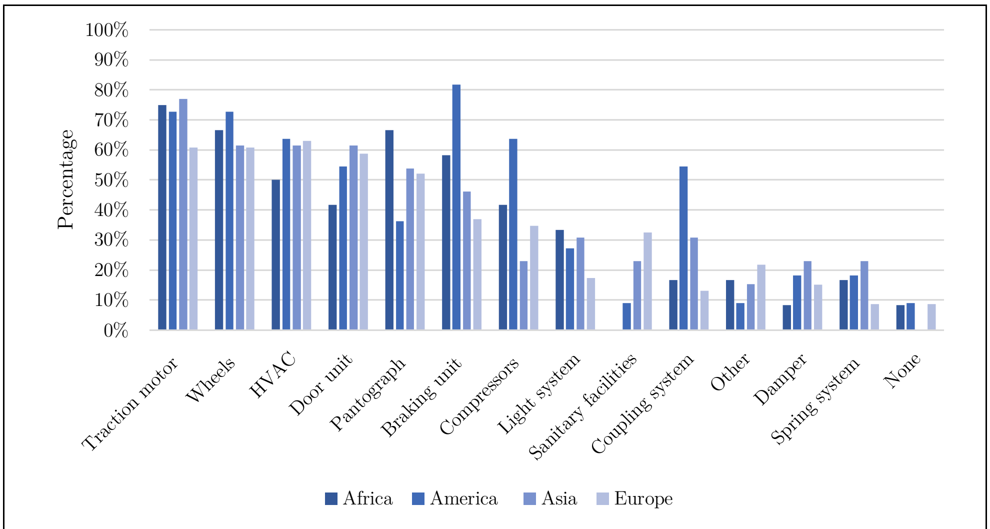


Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Lack of qualified personnel and competences	4	33.33%	6	54.55%	6	46.15%	29	63.04%
Lack of corporate strategy	4	33.33%	7	63.64%	5	38.46%	19	41.30%
Lack of information regarding implementation	4	33.33%	6	54.55%	4	30.77%	20	43.48%
Limited financial resources	1	8.33%	5	45.45%	4	30.77%	22	47.83%
Lack of technological prerequisites	1	8.33%	3	27.27%	4	30.77%	22	47.83%
Limited access to technologies	3	25.00%	2	18.18%	3	23.08%	13	28.26%
Not shown	7	58.33%	1	9.09%	5	38.46%	3	6.52%
Other	1	8.33%	0	0.00%	0	0.00%	4	8.70%
The industry does not face any challenges	1	8.33%	0	0.00%	0	0.00%	1	2.17%

Stellenbosch University https://scholar.sun.ac.za

Q10

For which rail rolling stock systems/components does the rail industry apply Industry 4.0 enabling technologies in maintenance?



Answer	Africa		America		Asia		Europe	
	Qty	%	Qty	%	Qty	%	Qty	%
Traction motor	9	75.00%	8	72.73%	10	76.92%	28	60.87%
Wheels	8	66.67%	8	72.73%	8	61.54%	28	60.87%
HVAC	6	50.00%	7	63.64%	8	61.54%	29	63.04%
Door unit	5	41.67%	6	54.55%	8	61.54%	27	58.70%
Pantograph	8	66.67%	4	36.36%	7	53.85%	24	52.17%
Braking unit	7	58.33%	9	81.82%	6	46.15%	17	36.96%
Compressors	5	41.67%	7	63.64%	3	23.08%	16	34.78%
Light system	4	33.33%	3	27.27%	4	30.77%	8	17.39%
Sanitary facilities	0	0.00%	1	9.09%	3	23.08%	15	32.61%
Coupling system	2	16.67%	6	54.55%	4	30.77%	6	13.04%
Other	2	16.67%	1	9.09%	2	15.38%	10	21.74%
Damper	1	8.33%	2	18.18%	3	23.08%	7	15.22%
Spring system	2	16.67%	2	18.18%	3	23.08%	4	8.70%
None	1	8.33%	1	9.09%	0	0.00%	4	8.70%

Stellenbosch University https://scholar.sun.ac.za

A.6 Survey Results Indirect Analysis – Maturity Level

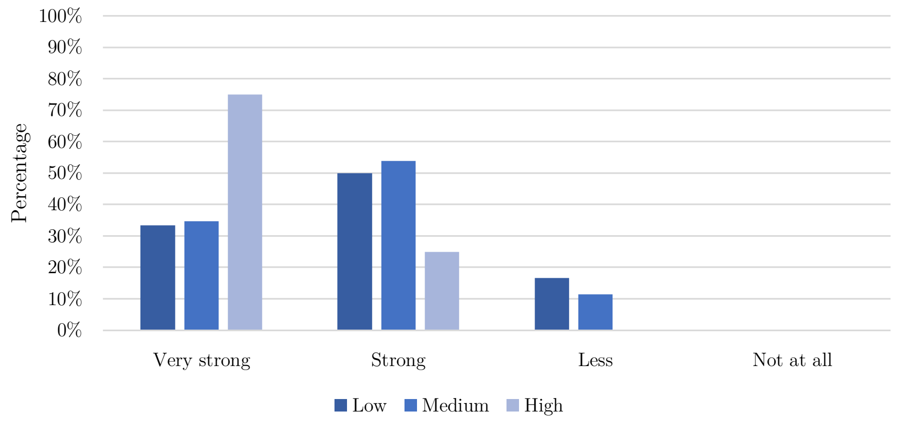
Indirect Analysis Maturity Level

General Information	
Sample size	Low Maturity Level: 18 Medium Maturity Level: 52 High Maturity Level: 12
Abbreviation	Q: Question Qty: Quantity
Question	• For questions 3, 4, 5, 7, 9 and 10 multiple answers were possible. • The term "not shown" indicates that the question did not appear due to the previous answer of the question.
Structure of the Analysis	
Question 1 – 3	Digitalisation in the rail industry
Question 4 – 10	Implementation and application of Industry 4.0 enabling technologies in maintenance

Stellenbosch University https://scholar.sun.ac.za

Q1

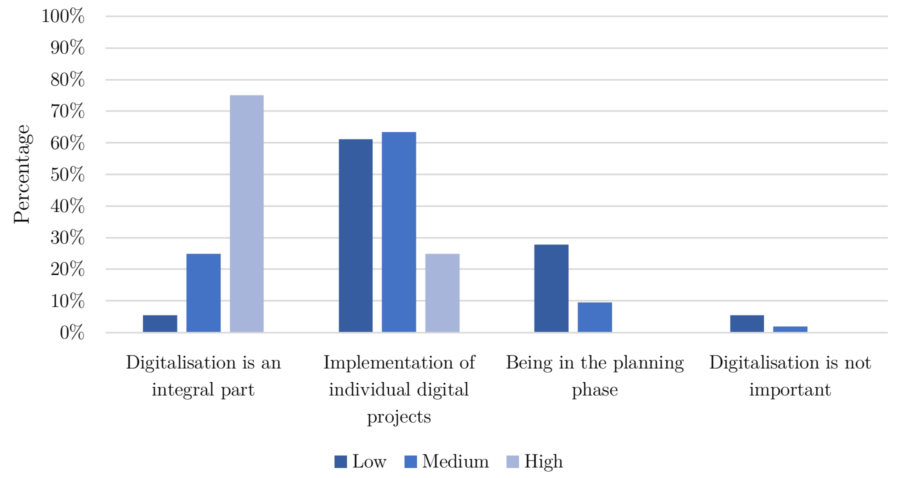
How strongly is the topic of digitalisation currently discussed in the rail industry



Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Very strong	6	33.33%	18	34.62%	9	75.00%
Strong	9	50.00%	28	53.85%	3	25.00%
Less	3	16.67%	6	11.54%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

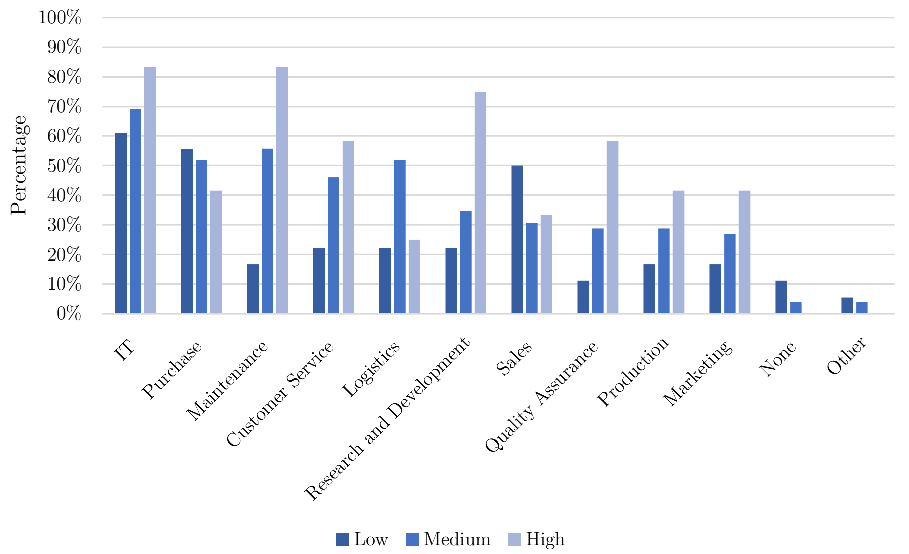
Q2
What is the current status regarding digitalisation in the rail industry?



Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Digitalisation is an integral part in the rail industry	1	5.56%	13	25.00%	9	75.00%
The rail industry works on the implementation of individual digital projects	11	61.11%	33	63.46%	3	25.00%
The rail industry is still in the planning phase	5	27.78%	5	9.62%	0	0.00%
Digitalisation is not important for the rail industry	1	5.56%	1	1.92%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

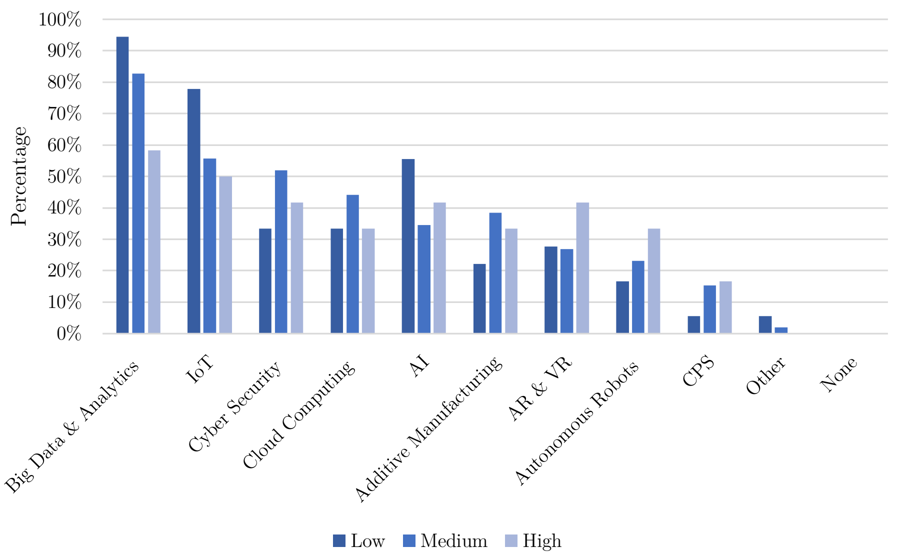
Q3
Which areas or processes have already been digitalised in the rail industry?



Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
IT	11	61.11%	36	69.23%	10	83.33%
Purchase	10	55.56%	27	51.92%	5	41.67%
Maintenance	3	16.67%	29	55.77%	10	83.33%
Customer Service	4	22.22%	24	46.15%	7	58.33%
Logistics	4	22.22%	27	51.92%	3	25.00%
Research & Development	4	22.22%	18	34.62%	9	75.00%
Sales	9	50.00%	16	30.77%	4	33.33%
Quality Assurance	2	11.11%	15	28.85%	7	58.33%
Production	3	16.67%	15	28.85%	5	41.67%
Marketing	3	16.67%	14	26.92%	5	41.67%
None	2	11.11%	2	3.85%	0	0.00%
Other	1	5.56%	2	3.85%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

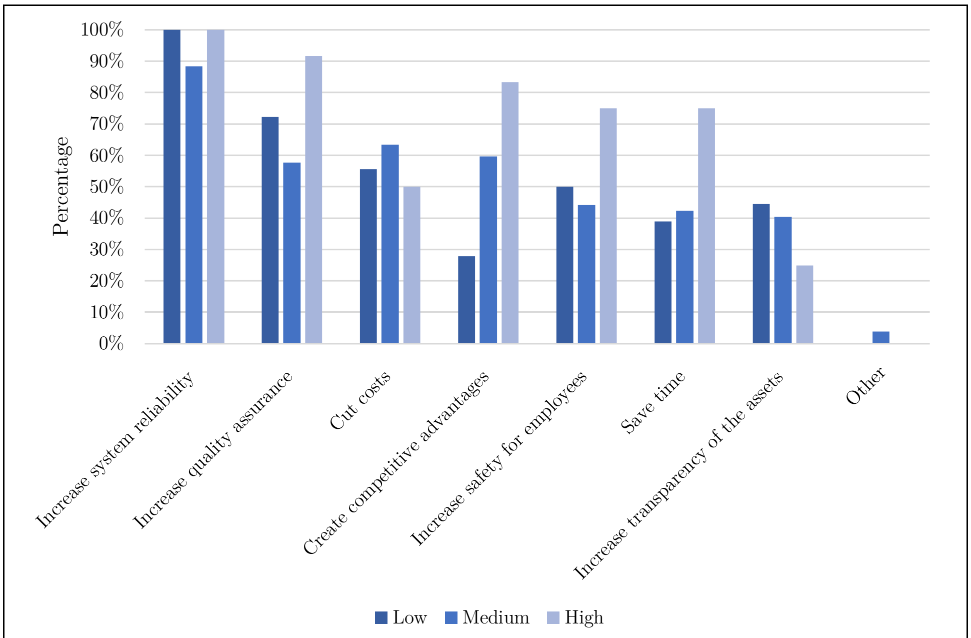
Q4
Which of the following Industry 4.0 enabling technologies will be of greatest importance in rail rolling stock maintenance?



Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Big Data & Analytics	17	94.44%	43	82.69%	7	58.33%
Internet of Things (IoT)	14	77.78%	29	55.77%	6	50.00%
Cyber Security	6	33.33%	27	51.92%	5	41.67%
Cloud Computing	6	33.33%	23	44.23%	4	33.33%
Artificial Intelligence (AI)	10	55.56%	18	34.62%	5	41.67%
Additive Manufacturing (3D-Printing)	4	22.22%	20	38.46%	4	33.33%
Augmented &Virtual Reality (AR & VR)	5	27.78%	14	26.92%	5	41.67%
Autonomous Robots	3	16.67%	12	23.08%	4	33.33%
Cyber-Physical System (CPS)	1	5.56%	8	15.38%	2	16.67%
Other	1	5.56%	1	1.92%	0	0.00%
None	0	0.00%	0	0.00%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

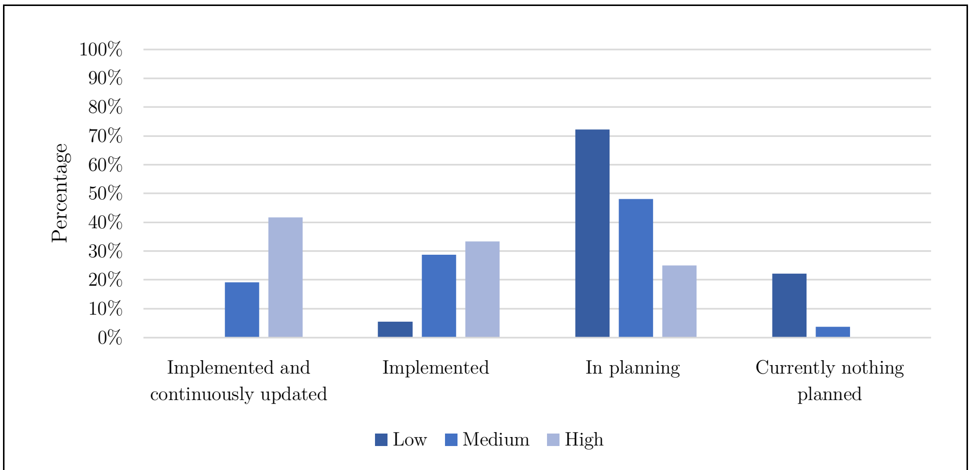
Q5
Why do you think the above indicated technologies are important in rail rolling stock maintenance?



Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Increase system reliability	18	100.00%	46	88.46%	12	100.00%
Increase quality assurance	13	72.22%	30	57.69%	11	91.67%
Cut costs	10	55.56%	33	63.46%	6	50.00%
Create competitive advantages	5	27.78%	31	59.62%	10	83.33%
Increase safety for employees	9	50.00%	23	44.23%	9	75.00%
Save time	7	38.89%	22	42.31%	9	75.00%
Increase transparency of the assets	8	44.44%	21	40.38%	3	25.00%
Other	0	0.00%	2	3.85%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q6
What is the current status in the rail industry regarding the implementation of Industry 4.0 enabling technologies in rail rolling stock maintenance?

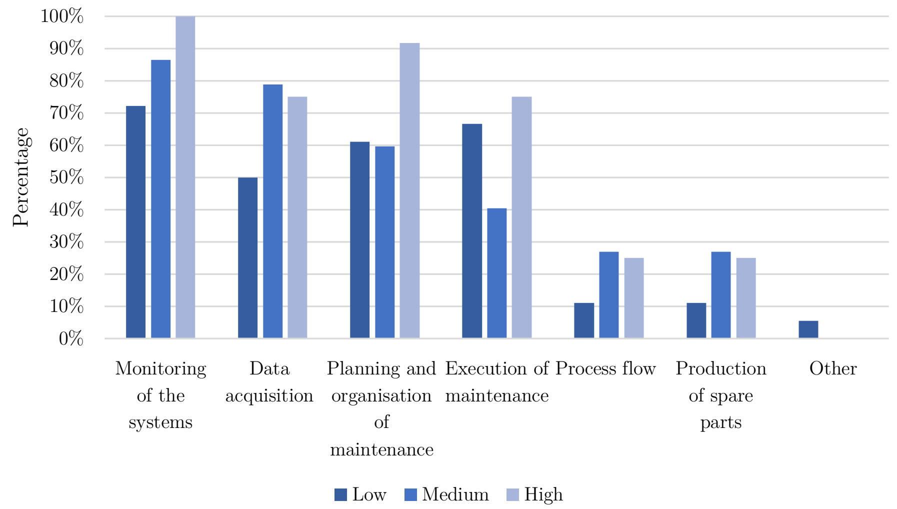


Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Implemented and continuously updated	0	0.00%	10	19.23%	5	41.67%
Implemented	1	5.56%	15	28.85%	4	33.33%
In planning	13	72.22%	25	48.08%	3	25.00%
Currently nothing planned	4	22.22%	2	3.85%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q7

In which area of rail rolling stock maintenance does the rail industry apply these Industry 4.0 enabling technologies?

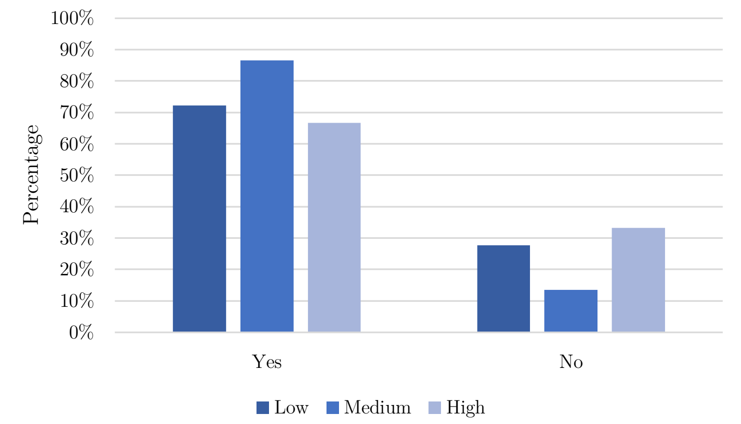


Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Monitoring of the systems	13	72.22%	45	86.54%	12	100.00%
Data acquisition	9	50.00%	41	78.85%	9	75.00%
Planning and organisation of maintenance	11	61.11%	31	59.62%	11	91.67%
Execution of maintenance	12	66.67%	21	40.38%	9	75.00%
Process flow	2	11.11%	14	26.92%	3	25.00%
Production of spare parts	2	11.11%	14	26.92%	3	25.00%
Other	1	5.56%	0	0.00%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q8

Does the rail industry encounter any challenges related to Industry 4.0 enabling technologies in rail rolling stock maintenance?

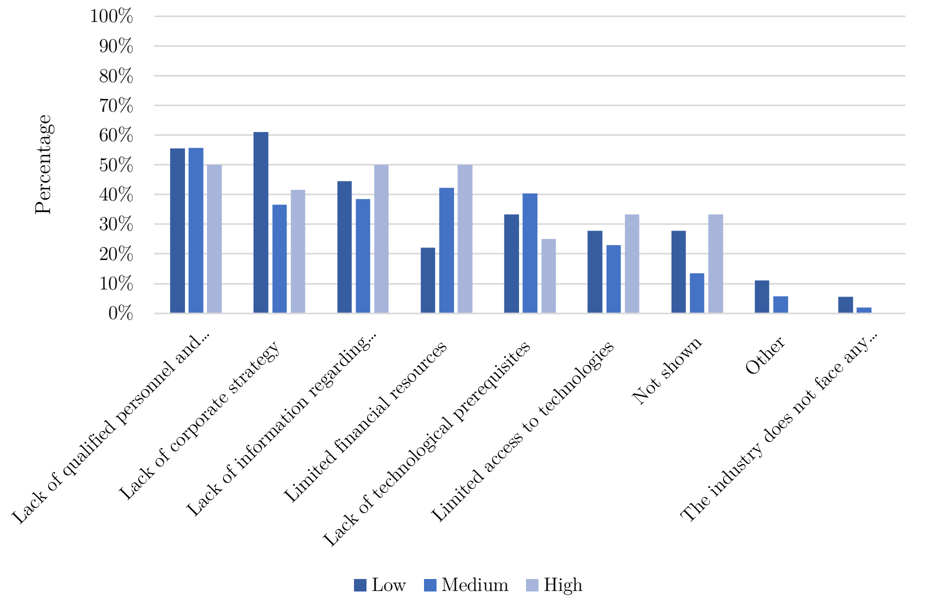


Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Yes	13	72.22%	45	86.54%	8	66.67%
No	5	27.78%	7	13.46%	4	33.33%

Stellenbosch University https://scholar.sun.ac.za

Q9

What challenges does the rail industry face regarding Industry 4.0 technologies in rail rolling stock maintenance?

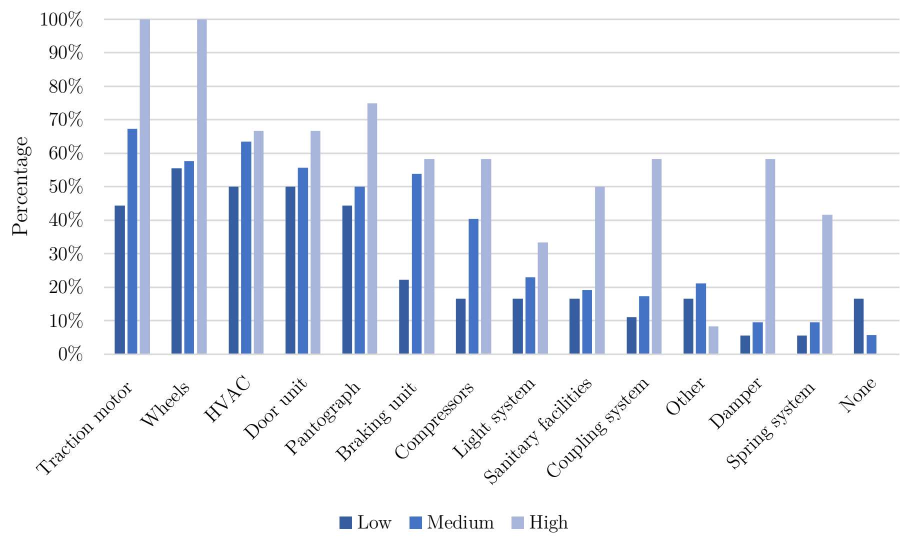


Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Lack of qualified personnel and competences	10	55.56%	29	55.77%	6	50.00%
Lack of corporate strategy	11	61.11%	19	36.54%	5	41.67%
Lack of information regarding implementation	8	44.44%	20	38.46%	6	50.00%
Limited financial resources	4	22.22%	22	42.31%	6	50.00%
Lack of technological prerequisites	6	33.33%	21	40.38%	3	25.00%
Limited access to technologies	5	27.78%	12	23.08%	4	33.33%
Not shown	5	27.78%	7	13.46%	4	33.33%
Other	2	11.11%	3	5.77%	0	0.00%
The industry does not face any challenges	1	5.56%	1	1.92%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Q10

For which rail rolling stock systems/components does the rail industry apply Industry 4.0 enabling technologies in maintenance?



Answer	Low		Medium		High	
	Qty	%	Qty	%	Qty	%
Traction motor	8	44.44%	35	67.31%	12	100.00%
Wheels	10	55.56%	30	57.69%	12	100.00%
HVAC	9	50.00%	33	63.46%	8	66.67%
Door unit	9	50.00%	29	55.77%	8	66.67%
Pantograph	8	44.44%	26	50.00%	9	75.00%
Braking unit	4	22.22%	28	53.85%	7	58.33%
Compressors	3	16.67%	21	40.38%	7	58.33%
Light system	3	16.67%	12	23.08%	4	33.33%
Sanitary facilities	3	16.67%	10	19.23%	6	50.00%
Coupling system	2	11.11%	9	17.31%	7	58.33%
Other	3	16.67%	11	21.15%	1	8.33%
Damper	1	5.56%	5	9.62%	7	58.33%
Spring system	1	5.56%	5	9.62%	5	41.67%
None	3	16.67%	3	5.77%	0	0.00%

Stellenbosch University https://scholar.sun.ac.za

Appendix B

Details of I4.0TIM

B.1 Direct Insertion Method

The performance of the individual steps of the direct insertion method are provided below.

Step 1: adding c_1

$$c_1 \tag{B.1}$$

Step 2: adding c_2

$$\begin{matrix} c_1 \\ c_2 \end{matrix} \tag{B.2}$$

Step 3: adding c_3

$$\begin{matrix} c_1 \\ c_2,\ c_3 \end{matrix} \tag{B.3}$$

Step 4: adding c_4

$$\begin{matrix} c_1,\ c_4 \\ c_2,\ c_3 \end{matrix} \tag{B.4}$$

Stellenbosch University https://scholar.sun.ac.za

Step 5: adding c_5

$$\begin{array}{l} c_1,\ c_4 \\ c_5 \\ c_2,\ c_3 \end{array} \tag{B.5}$$

Step 6: adding c_6

$$\begin{array}{l} c_1,\ c_4 \\ c_6 \\ c_5 \\ c_2,\ c_3 \end{array} \tag{B.6}$$

Step 7: adding c_7

$$\begin{array}{l} c_1,\ c_4 \\ c_6,\ c_7 \\ c_5 \\ c_2,\ c_3 \end{array} \tag{B.7}$$

Step 8: adding c_8

$$\begin{array}{l} c_1,\ c_4 \\ c_6,\ c_7 \\ c_5,\ c_8 \\ c_2,\ c_3 \end{array} \tag{B.8}$$

Step 9: adding c_9

$$\begin{array}{l} c_1,\ c_4 \\ c_6,\ c_7 \\ c_5,\ c_8,\ c_9 \\ c_2,\ c_3 \end{array} \tag{B.9}$$

Stellenbosch University https://scholar.sun.ac.za

B.2 Overview of Degrees of Criticality

Table B.1: Degrees of criticality of criterion c_i

Criterion c_i	Value	Degrees of criticality
c_1	4	Irreversible impact on health & safety
	3	Enormous impact on health & safety
	2	Reversible impact on health & safety
	1	Low impact on health & safety
	0	Negligible impact on health & safety
c_2	4	Total failure for rolling stock, recovery required
	3	Able to proceed to termination station
	2	Failed in service and a delay of more than five minutes
	1	Failed in service and a delay of less than five minutes
	0	No restrictions for operational use of rolling stock
c_3	4	MTTR more than a week
	3	MTTR from four to seven days
	2	MTTR from one to three days
	1	MTTR less than one day
	0	MTTR is negligible
c_4	4	Extreme environmental harm
	3	Major environmental harm
	2	Serious environmental harm
	1	Minimal environmental harm
	0	Negligible impact on environment
c_5	4	Very high maintenance costs
	3	High maintenance costs
	2	Normal maintenance costs
	1	Low maintenance costs
	0	Very low maintenance costs
c_6	4	No redundant component
	3	Possible to provide alternative component shortly after failure
	2	Inferior component in reserve
	1	Similar component in reserve
	0	Redundant component available
c_7	4	Extreme negative impact for customer satisfaction
	3	Major negative impact for customer satisfaction
	2	Serious negative impact for customer satisfaction
	1	Minimal impact for customers satisfaction
	0	Negligible impact for customer satisfaction
c_8	4	System fails very frequently ($>$ 25 failures per month)
	3	System fails frequently (10 – 25 failures per month)
	2	System fails with some frequently (5 – 10 failures per month)
	1	System fails occasionally (1 – 5 failures per month)
	0	System fails rarely ($<$ 1 failures per month)
c_9	4	Extreme restriction for rail operation
	3	Major restriction for rail operation
	2	Serious restriction for rail operation
	1	Minimal restriction for rail operation
	0	Negligible restriction for rail operation

Stellenbosch University https://scholar.sun.ac.za

B.3 Maturity Level Questionnaire

1. To what extent does your company have the possibility to connect with resources on the network or among each other to share or use data?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

2. To what extent is your company able to collect information with sensors and then transform it into mechanical work by using actuators?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

3. To what extent are embedded systems for information processing in the your company implemented?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

4. To what extent does your company have an infrastructure to collect and store data?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

5. To what extent is your company's data organised in digital secure systems?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

6. To what extent does your company know how to deal with obtained data?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

7. How high is the degree of process standardisation in your company?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

8. To what extent are 3D models of technical components or spare parts in your company available?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

9. To what extent does your company have internal knowledge regarding the utilisation of additive manufacturing?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

10. To what extent does your company have broadband internet access?

    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

11. To what extent is the IT infrastructure in your company provided via cloud computing?

    ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Stellenbosch University https://scholar.sun.ac.za

12. To what extent does your company use cloud services for software or data?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

13. To what extent does your company use self–learning systems to solve complex application problems?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

14. To what extent does your company use virtual assistants?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

15. To what extent does your company train machines, systems or equipment with data?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

16. To what extent are machines, systems or equipment in your company capable of communicating with each other?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

17. To what extent are machines, systems or equipment in your company capable of independently assessing situations and taking decisions?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

18. To what extent can your company create a virtual image of machines, systems or equipment?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

19. To what extent is your company able to display virtual objects in the real world?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

20. To what extent does your company use supporting hardware technologies (e.g. tablets, smartphones or smartglasses)?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

21. To what extent can your company perform remote tasks with supporting hardware technologies (e.g. tablets, smartphones or smartglasses)?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

22. How advanced is your company regarding the security of internal data storage?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Stellenbosch University https://scholar.sun.ac.za

23. How advanced is your company regarding the data protection in cloud services?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

24. How advanced is your company in terms of the communication security of internal and external data exchange?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

B.4 Maturity Level Calculation

Calculation of the technological maturity level M_i for each technology:

$$M_i = \frac{\sum rating}{max\ points\ possible} \cdot 100 \tag{B.10}$$

Calculation of the total technological maturity level M_T:

$$M_T = \frac{\sum M_i}{\sum number\ of\ technologies} \tag{B.11}$$

The Maturity level scale for the classification of the calculated total technological maturity level M_T is presented in Table B.2.

Table B.2: Maturity level scale

Technological maturity level	**Classification in [%]**
Maturity level 1	$0 \leq M_T < 20$
Maturity level 2	$20 \leq M_T < 40$
Maturity level 3	$40 \leq M_T < 70$
Maturity level 4	$70 \leq M_T < 90$
Maturity level 5	$90 \leq M_T \leq 100$

Stellenbosch University https://scholar.sun.ac.za

B.5 Industry 4.0 Prerequisites

Table B.3: Industry 4.0 technologies and their main prerequisites

Technologies	**Main prerequisites**
Big data & analytics	Infrastructure to collect and store data Digital secure systems for data organisation Know–how for data handling
Internet of Things	Network to share and use data Creation of virtual image of the equipment Embedded systems for information processing
Cloud computing	Broadband internet access Cloud capable IT infrastructure Software and data compatible for the cloud
Augmented Reality & Virtual Reality	Display virtual objects Supporting hardware Performance of remote tasks
Cyber security	Security of internal data storage Data protection in cloud services Secure internal and external data exchange
Cyber–physical System	Systems communication Independent situation assessment and decision–making by the equipment Sensors and actuators to collect information
Artificial Intelligence	Self–learning systems Virtual assistants Training of equipment with data
Additive manufacturing	High process standardisation 3D models of components Expertise of 3D printing

Stellenbosch University https://scholar.sun.ac.za

B.6 Calculations for the Performance Indicators

Equipment performance:

$$Availability = \frac{Scheduled\ uptime - all\ downtime}{Scheduled\ uptime} \tag{B.12}$$

$$Reliability = \frac{Total\ operating\ time}{Number\ of\ failures} \tag{B.13}$$

$$Maintainability = \frac{Total\ downtime\ from\ failures}{Number\ of\ failures} \tag{B.14}$$

$$Process\ rate = \frac{Ideal\ cycle\ time}{Actual\ cycle\ time} \tag{B.15}$$

$$Quality\ rate = \frac{Quality\ product\ produced}{Total\ product\ produced} \tag{B.16}$$

$$\begin{aligned} Overall\ equipment\ effectiveness = {} & Availability \cdot Process\ rate \\ & \cdot Quality\ rate \end{aligned} \tag{B.17}$$

Process performance:

$$Planning\ rate = \frac{Planned\ work}{Total\ work\ done} \tag{B.18}$$

$$Schedule\ compliance\ rate = \frac{Total\ labour\ hours\ completed}{Total\ labourhours\ scheduled} \tag{B.19}$$

$$Work\ order\ rate = \frac{Number\ of\ completed\ tasks}{Number\ of\ received\ tasks} \tag{B.20}$$

$$Stores\ inventory\ turnover = \frac{Total\ value\ of\ stores\ issued\ to\ maintenance}{End\ of\ year\ stores\ value} \tag{B.21}$$

Cost performance:

$$\begin{aligned} Direct\ maintenance\ costs = {} & Corrective\ maintenance\ costs \\ & + Preventive\ maintenance\ costs \end{aligned} \tag{B.22}$$

$$Breakdown\ severity = \frac{Breakdown\ costs}{Direct\ maintenance\ costs} \tag{B.23}$$

$$Percentage\ cost\ of\ personnel = \frac{Staff\ costs}{Maintenance\ costs} \tag{B.24}$$

Stellenbosch University https://scholar.sun.ac.za

Appendix C

Validation Data

Stellenbosch University https://scholar.sun.ac.za

C.1 Validation Questionnaire

Validation of the Industry 4.0 Technology Implementation Model

1. What is your opinion about the model as a potential solution to support the rail industry for the implementation of Industry 4.0 technologies in maintenance?

2. What are the strengths of the model in your opinion?

3. What are the weaknesses of the model in your opinion?

4. Please comment on the following aspects:

Aspect	Very good	Good	Fair	Poor
Logical description of the model	☐	☐	☐	☐
Applicability of the model	☐	☐	☐	☐
Relevance of the model (does the model represent the real problem and addresses it effectively?)	☐	☐	☐	☐

5. Based on your previous comments, how would you improve the model?

Stellenbosch University https://scholar.sun.ac.za

C.2 Questions and Feedback

1. **What is your opinion about the model as a potential solution to support the rail industry for the implementation of Industry 4.0 technologies in maintenance?**

   P1 *"This model is going to remodel the maintenance of the rolling stock, it will streamline the approach of doing maintenance per criticality of the components. This is the best tool that can be used for rolling stock."*

   P2 *"I like the model. The maturity level I have experienced is quite low and don't believe that we have fully embraced Industry 4.0 technologies. So the model could support the industry."*

   P3 *"It is understandable."*

   P4 *"The model covers almost all the areas and could be considered as a potential solution for the implementation of Industry 4.0."*

   P5 *"The model could turn out to be practical. The 4.0 technology is still under development and hopefully in future we can see that in reality especially in railways. It is good to mention smart maintenance which would be really interesting if implemented. Smart maintenance could help in reducing the corrective downtime. At last my suggestion would be to get the model reviewed from RAMS expert or reliability engineer. They can help in boosting your model."*

   P6 *"I think that the model is very well constructed and takes into account all the elements which are in correlation with rolling stock maintenance tasks as well as all maintenance strategies."*

   P7 *"The applicability of the technologies that the fourth industrial revolution could bring to the rail industry was discussed in boardrooms before, but the implication of this was never really investigated. This model will definitely be able to assist in this regard."*

   P8 *"In my opinion this model will improve a lot in rolling stock maintenance industries. As presently seen, specially in rolling stock sector there is no such improvements in regards of new technologies. This model will support a lot in improving maintenance of rolling stock."*

2. **What are the strengths of the model in your opinion?**

   P1 *"The strengths of this model is to select the maintenance strategy for the components per criticality."*

Stellenbosch University https://scholar.sun.ac.za

P2 *"Many people talk about technologies 4.0 but not come up with a model or solution that bring us to industry 4.0. It is the first time I see a model that seeks to take us from third technologies to fourth technologies."*

P3 *"The theory part is well explained."*

P4 *"The model is comprehensive and resulted in valves which makes the decision making easy."*

P5 *"Well organised with each aspect defined. It covers every aspect of maintenance."*

P6 *"The model considers all the rolling stock components and ties them in logical relation with maintenance strategies and Industry 4.0 technologies (still not easy to understand by a large number of labors). It is a very big challenge to represent it in one model and conduct the evaluation in one model. It is very wanted for all managers in rolling stock. The strengths of the model are considered as a very good interesting idea and deals with a very important needs for rolling stock operators."*

P7 *"The step by step process of assessing the applicability of introducing these new technologies. Further advantages are: Defining the technologies and evaluating their applicability. Could works on all components and systems. Adaptability and flexibility of the model in terms of number of technologies, uniqueness of the components and weighting of the criteria."*

P8 *"At this moment as far as I know rolling stock industry is only a little bit away from new technologies so the model is perfect. With time it will be improved."*

3. **What are the weaknesses of the model in your opinion?**

P1 *"Now the weaknesses are that you need to implement this model in the rolling stock industry which will normally take a long time to see the benefits of the model."*

P2 *"I don't see any fundamental weaknesses. I only have concerns of the maturity level, because that the maturity level I have experienced is very low. Maybe different scales regarding the regions should be established to receive a more degree of details."*

P3 *"There is no practical sample provided."*

P4 *"No weaknesses found, though in more practical approach, a lot need to be added in calculations."*

Stellenbosch University https://scholar.sun.ac.za

P5 *"The model could be hypothetical for present as 4.0 technology has just begin to enter in railway field. The practicality of this model can turn out to be much expensive."*

P6 *"No weakness in the model but I think the criticality criteria* c_i *need to reevaluate or give more attention to* c_3 *and* c_6*."*

P7 *"Nothing that I could identify but the flexibility could easily accommodate any potential shortcomings."*

P8 *"For the moment no weakness but in my opinion this model should be introduced with the rolling stock industry from the beginning so that these industries can implement this model in future."*

5. **Based on your previous comments, how would you improve the model?**

P1 *"Train this model to the maintenance personnel and management of the rail industry to receive the benefits of using the tool for the rolling stock."*

P2 *"I would define the scale regarding the different maturity levels differently based on the regions. The scales should be be different for example in Europe or Africa."*

P3 *"Rolling stock producers (Siemens, Alstom, Bombardier, etc.) use already IoT and offer this as an extra service for the maintenance contracts or as additional equipment (data are streamed to the server and AI algorithms determine the presence/predict the failure and plan repair or facility availability. Upper approach allows planning of the lower level of the capital spare parts for a higher quantity of the vehicles, because of the increased reliability. All OEMs make planned maintenance "golden plated" and sell additional services or spare parts when there is no need for this. The transport agencies in the USA still do not implement completely asset maintenance and lifecycle support. The agencies use public funds for the support of the fleets and still, IoT is classified as extra, no matter that you increase reliability and availability, parallel with money savings in long term. You can include Covid 19 effect over the transportation efficiency in the model (how low-level ridership will affect financial parameters of the transportation agencies like Washington Metropolitan Area Transit Authority, Chicago Transit Authority, Massachusetts Bay Transportation Authority, etc.)."*

P4 *"To apply it as a ultimate solution for the maintenance digitalisation of rolling stock fleet, the model need to be arranged accordingly."*

Stellenbosch University https://scholar.sun.ac.za

P5 *"The model can be improved by describing what competency would be needed in order to attain that 4.0 level technology. How the skills and qualification of a person can help in achieving that level. As mentioned previously do get the model reviewed by RAMS expert. My experience is more onto the site of operations and execution rather than on design and engineering side."*

P6 *"I think the rolling stock components are very different in function, in nature, cost and have a different impact in daily railways operation. So, I think it is better to build one model for each component against the Industry 4.0 technologies to be more accurate and be able to define the critical scientific problems for it. For example, the wheels fracture problems are very more dangerous in comparison of a door unit. So, you take it into consideration when you classified them between smart maintenance and corrective maintenance, because in practical experience the maintenance cost, the component related directly to safety is given more attention than others."*

P7 *"Noting to add but the logical next step would be to test it."*

P8 *"I think for this moment it is fine. The improvements will be made after implementation. As this is a new thing for the industry and a lot of practical feedbacks are required for improvement."*