A Framework for Selecting Data Acquisition Technologies in Support of Railway Infrastructure Predictive Maintenance

by

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Declaration

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Abstract

Digital technological advancements is a product of the continuous changes experienced by the technology sector, whereas the advancements are represented as new and emerging technologies. However, to utilise these emerging technologies, new management strategies must be adopted. This is the case for the emergence of a predictive maintenance strategy due to the improved capabilities of the maintenance equipment.

Against the background of railway infrastructure maintenance, the problem is that maintenance managers have not leveraged the full potential of emerging data acquisition technologies to support a predictive maintenance approach. This research investigates railway infrastructure maintenance and the technologies capable of acquiring the condition monitoring data to determine why the full potential of the technologies have not been leveraged. It is found that the slow adoption is largely attributed to uncertainty based on technological capabilities, potential barriers and challenges experienced throughout the process. To address the problem in this research, it is decided to develop a framework that supports railway operators with the process of data acquisition technology identification, evaluation, and acquisition. The framework ultimately aids railway operators with the shift towards a predictive maintenance approach.

This research is based on a *mixed method exploratory sequential design* methodology, as described by Creswell. The first phase of this research is responsible for contextualising the problem, and in the second phase, the framework is developed. The completion of the two phases relied on *systematic literature reviews*, railway industry expert feedback obtained from *survey questionnaires*, and *face validation interviews* conducted with railway industry practitioners.

Utilising the research approach, as described previously, the Railway Infrastructure Technology Selection Support (RITSS) framework is developed. The RITSS framework consists of three stages namely; Stage 1 – *mapping assets and technology*, Stage 2 – *technology evaluation*, and Stage 3 *acquisition mode guide*. These stages try and support railway operators to leverage the full potential of emerging data acquisition technologies. Face validations are used to test the real-world

applicability of the RITSS framework; in other words, the frameworks feasibility, usability, and utility are assessed by railway industry practitioners.

The thesis concludes with a summary of the research conducted, the research objectives achieved, the expected research contributions, the research limitations identified, and the recommendations for future research. The overall opinion is that the RITSS framework has enormous potential in the railway infrastructure maintenance sector; however, certain aspects are identified that require refinement, such as the acquisition mode guide (Stage 3).

Opsomming

Digitale tegnologiese vooruitgang is 'n produk van die voortdurende veranderinge wat die tegnologie sektor ervaar, terwyl die vooruitgang as nuwe en opkomende tegnologieë voorgestel word. Om hierdie opkomende tegnologieë te benut, moet daar egter nuwe bestuurstrategieë aanvaar word. Dit is die geval met die ontstaan van 'n voorspellende instandhoudingstrategie as gevolg van die verbeterde vermoëns van die instandhoudingstoerusting.

Teen die agtergrond van die instandhouding van die spoorweginfrastruktuur is die probleem dat instandhoudingsbestuurders nie die volle potensiaal van opkomende tegnieke vir die verkryging van data benut om 'n voorspellende instandhoudingsbenadering te ondersteun nie. Hierdie navorsing ondersoek instandhouding van spoorweginfrastruktuur en die tegnologieë wat die toestandmoniteringsdata kan bekom om te bepaal waarom die volle potensiaal van die tegnologieë nie benut word nie. Daar word bevind dat die stadige aanvaarding grotendeels toegeskryf word aan onsekerheid gebaseer op tegnologiese vermoëns, potensiële hindernisse en uitdagings wat gedurende die proses ervaar word. Om die probleem in hierdie navorsing aan te spreek, word daar 'n raamwerk ontwikkel wat spoorwegoperateurs ondersteun met die proses van identifisering, evaluering en verkryging van data-verkrygings tegnologieë. Die raamwerk help spoorwegoperateurs met die skuif na 'n voorspellende instandhoudingsbenadering.

Hierdie navorsing is gebaseer op 'n *mixed method exploratory sequential design* metodologie, soos beskryf deur Creswell. Die eerste fase van hierdie navorsing is verantwoordelik vir die kontekstualisering van die probleem, en in die tweede fase word die raamwerk ontwikkel. Die voltooïng van die twee fases was afhanklik van *sistematiese literatuurstudies*, terugvoering van kundige spoorwegbedrywe verkry uit *vraelyste* en *Gesigsvalidasies* onderhoude wat met spoorwegondernemings gevoer is.

Met behulp van die navorsingsbenadering, soos voorheen beskryf, word die RITSS-raamwerk (Railway Infrastructure Technology Selection Support) ontwikkel. Die RITSS-raamwerk bestaan uit drie fases naamlik; Fase 1 – *kartering van bates en tegnologie*, Fase 2 – *tegnologiese evaluering* en Fase 3 – *gids vir verkrygingsmodus.*

Hierdie fases probeer spoorwegoperateurs ondersteun om die volle potensiaal van opkomende data-verkrygingstegnologieë te benut. Gesigsvalidasies word gebruik om die toepaslikheid van die RITSS-raamwerk te toets; Met ander woorde, die raamwerk se haalbaarheid, bruikbaarheid en nut word deur die spoorwegbedryf beoordeel.

Die proefskrif word afgesluit met 'n samevatting van die navorsing wat gedoen is, die navorsingsdoelstellings wat bereik is, die verwagte bydraes, die navorsingsbeperkings wat geïdentifiseer is en die aanbevelings vir toekomstige navorsing. Die algemene tendens is dat die RITSS-raamwerk enorme potensiaal het in die onderhoudsektor vir spoorweginfrastruktuur; sekere aspekte word egter geïdentifiseer wat verfyning vereis, soos die gids vir die verkrygingsmodus (fase 3).

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Papers and Publications

A conference paper is submitted and presented (virtually) at the 29th international conference of the Internation Association for Management of Technology (IAMOT), hosted by Nile University in Cairo, Egypt. The paper made use of extracts from research presented in Chapter 2 and Chapter 4 of this thesis.

- Van Schalkwyk, J.W. and Jooste, J.L. (2020). Emerging Data Acquisition Technologies in Railway Infrastructure Condition Monitoring and the Adoption Challenges. In: *29th International Conference of the International Association for Management of Technology. (IAMOT 2020)*, pp. 414-426. Graduate School of Technology Management, University of Pretoria & Media Chef CC., Nile University, Cairo, Egypt. ISBN 9781775921950.

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Acronyms

ACRG	Asset Care and Research Group
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AM	Asset Management
ANP	analytic network process
AREMA	American Railway Engineering and Maintenance-of-Way Association
AUAV	Autonomous Unmanned Aerial Vehicle
AV	Autonomous Vehicle
CBM	Condition Based Maintenance
CI	Consistency Index
CM	Corrective Maintenance
CR	Consistency Ratio
CSIR	Council for Scientific and Industrial Research
CWR	Continuous Welded Rail
DAQ	Data Acquisition
DAS	Data Acquisition System
DGPS	Differential Global Positioning System
DMI	Distance Measuring Indicator
DR	Design Requirements
ESD	Exploratory Sequential Design
FAHP	Fuzzy Analytic Hierarchy Process
IBWM	Interval Best-Worst Method
IBWP	Interval Best-Worst Projection
ICT	Information and Communication Technology
IET	Interval Entropy Technique
IMU	Inertial Measurement Unit
IoT	Internet of Things
M&A	Mergers and Acquisitions
MCA	Multi-Criteria Assessment
MCDA	Multi-Criteria Decision Analysis
OEE	Original Equipment Effectiveness
OGMS	Optical Gauge Measuring System

OHE	Overhead Electrification System
OHTE	Overhead traction equipment
PAM	Physical Asset Management
PAS 55	Publicly Available Specifications 55
PdM	Predictive Maintenance
PM	Preventive Maintenance
POS/TG	Position and Orientation System for Track Geometry
PRASA ERC	PRASA Engineering Research Chair
PRASA	Passenger Rail Agency of South Africa
R&D	Research and Development
RAMAS	Reliable, Available, Maintainable, Affordable and Safe
RCM	Reliability Centred Maintenance
RI	Random Index
RITSS	Railway Infrastructure Technology Selection Support
RU	Reutlingen University
SACAA	South African Civil Aviation Authority
Sid	Survey Inspection Device
SMEs	Subject Matter Experts
SU	Stellenbosch University
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UIC	Union of International Railways
UST	Unmanned Systems Technology
USV	Unmanned Surface Vehicle
UT	Unmanned Technology
UUV	Unmanned Underwater Vehicle
UV	Unmanned Vehicle

Chapter 1

Introduction

This chapter gives the context of this research. It serves as an introduction to the project and provides the background for the research. The research problem, questions, objectives, and the methodology are developed. The chapter concludes with an outline of chapters for the thesis giving the reader a holistic view of the research. Figure 1.1 presents how and where Chapter 1 fits into the thesis.

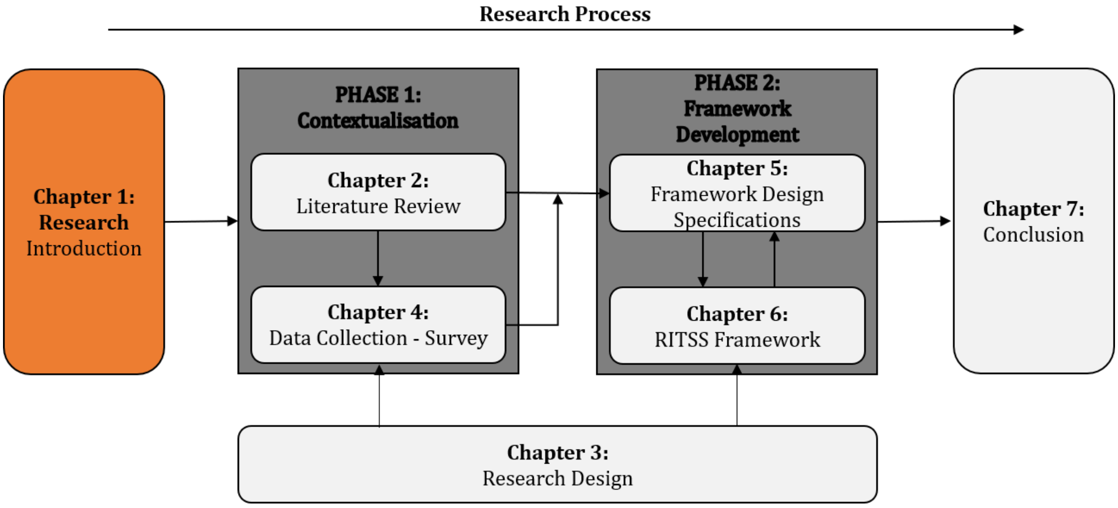


Figure 1.1: Research design: Chapter 1

1.1 Research Background and Overview

Transport is fundamental to economic activities, and thus it is important to ensure a functional and efficient transportation system. Transportation systems are divided into private and public transport (PT) with railway being a significant sub-system of public transportation in South Africa, with the primary function to transport freight and people.

Motor-driven railway transportation originated in the early 1800s and still plays an essential role in driving sustainable economic growth as transportation of passengers between major economic centres is a fundamental link in the global economic supply chain (Yin *et al.*, 2017). Developments in the rail industry have resulted in a variety of operational categories for both freight and passenger transportation. As freight rail transportation mostly shares mainline tracks with passenger trains, the focus of this research is on the passenger rail industry. According to Marinov *et al.* (2013), passenger rail transportation can be categorised as: high-speed, international passenger, intercity, interregional, regional multi-stopping, suburban and urban rail transport.

According to Pan *et al.* (2018) performance improvements of urban rail transport systems regarding energy saving and consumption reduction are topical in current railway research. Therefore, improvements in railway operations, especially in urban rail transport, are highly relevant and justify further investigation. Urban rail is subdivided into commuter rail, tram, light rail, 'streetcar', trolley and cable car – with commuter rail being the most prevalent category (American Public Transport Association, 2013).

Commuter or suburban rail is a passenger rail transport service that operates primarily between city centres, surrounding suburbs and commuter towns. Commuter rail services provide transport for people on a daily basis. Urban rail transport is seen as a preferred mode for green and convenient transport, since it could alleviate traffic congestion in large cities which is more beneficial to the environment (Wang *et al.*, 2015). For urban transportation to be a viable transport mode, its performance must be adequate. Performance indices are used to track and manage performance levels of urban rail transit systems. For these indices to be accurate, they must be adaptable for changes in urban transit demand and must reflect the passengers' demands for safety, comfort, rapidity; and should reflect the "service-oriented" marketing philosophy employed by rail transportation enterprises (Pan *et al.*, 2018). To ensure an efficient railway system and levels of appropriate functionality, effective implementation of railway operations are imperative.

In the past decade, railway transport has changed and progressed in terms of technological development, the lengths of train sets, infrastructure requirements, travel speeds, and service quality (Yin *et al.*, 2017). These changes and performance requirements highlight the need for efficient railway operations in support of the overall rail system. Railway operations, according to RailNetEurope (2019), are defined as the processes involved with rail infrastructure and rolling stock for the rail service. Such operations include: the operation and movement of rolling stock; the construction of rolling stock and rail infrastructure; the management, commissioning, operations of decommissioning of rail infrastructure and rolling stock; and the maintenance, repair, modification, and installation of rail infrastructure and rolling stock. Other operations of importance excluded in this definition, are the safety and security of both infrastructure and rolling stock (Marinov *et al.*, 2013; Barmpounakis and Golias, 2016). Other literature shows the occurrence of other aspects of railway operations that includes planning and construction, maintenance work, safety and security.

Implementation of railway maintenance practices is vital in ensuring constant delivery of system peak performance in the rail industry. Effective maintenance work prolongs the operational life of an asset and warrants operation as stipulated by design specifications and also minimises downtime. However, due to the technical focus of proper maintenance activities, a proclivity to neglect economic considerations exists (Gaudry *et al.*, 2016). The two main reasons for wastage of resources regarding maintenance inspection, identified by Garambaki *et al.* (2016) are, underuse of assets due to inaccurate failure predictions, and overuse due to the capture of faulty operational data.

Effective implementation of railway planning can help ensure that operations run efficiently. Planning pertains to decision-making over both the long-term and day-to-day bases of operations. According to Lusby *et al.* (2018), a typical sequence of planning in descending order of timespan are: network design, line planning, timetabling, rolling stock planning, crew scheduling and recovery. Railway construction entails all the modifications and repairs to existing infrastructure, and the building of new infrastructure. Whether planning consists of scheduling or how to survey proposed land for expansions, the challenge is presented in the collection of accurate and useful data. Inaccurate data can lead to timetable inefficiencies, wasteful expenditure, and operational downtime.

Railway safety and security are affected by technological development. Trains are becoming faster and artificially more intelligent, which results in more uncertainty and thus increased safety and security risks. Railway safety and security incorporate the well-being of both people and the rail assets (Evans, 2013). While technological advancements have the potential to improve overall rail operations, they are difficult to adapt to existing systems used by operators as uncertainty is introduced to the systems.

Railway industry assets include two distinct groups: rolling stock and infrastructure, the characteristic difference being that rolling stock is mobile while infrastructure is fixed to a specific location. Rolling stock has various operational challenges according to Lai *et al.* (2015), and Canca and Barrena (2018). One of these is that the availability of rolling stock does not meet the demand of the utilisation path, which can lead to penalties. Other difficulties include minimising the "buffer-time" of rolling stock stationed at depots when switching paths; constraints of maintenance depot capacity and the maintenance depots' locations. The primary rail infrastructure challenge is attributed to it being fixed in location. Rail networks span vast areas and also connect remote regions. Therefore, regular maintenance on railway infrastructure is labour intensive and costly. Therefore, the monitoring of railway infrastructure is challenging, as assets cannot be moved to secure depots as with rolling stock.

As technology develops and with adoption of newer technologies, it is more viable for industries to consider automating systems that are prone to human error or that are too labour intensive. Unmanned Technology (UT) has been adopted successfully and shows high commercial use after being introduced to the public years ago. UT can operate without a user's continuous instructions and already exists in the railway industry in the form of sensors and mechatronics (Yin *et al.*, 2017). Another application of UT is the implementation of control systems that automate the driving of trains (Evans, 2013).

Another related technology that is impacting on the transportation industry is Unmanned Vehicles (UVs). A UV is a vehicle that operates without an on-board human presence (Lam Loong Man *et al.*, 2018). This type of vehicle is controlled remotely. An Automated Vehicle (AV) is able to navigate without human intervention (Lam Loong Man *et al.*, 2018). Fagnant and Kockelman (2015) state that AVs have the potential to reduce the risk and uncertainty imposed by human error. By implementing UVs and AVs in rail transportation, more optimised transport is attainable. The improvement implies a greater degree of sustainable economic growth. Currently five types of UVs exist; namely, unmanned ground vehicle (UGV) (Lam Loong Man *et al.*, 2018), unmanned aerial vehicle (UAV) (Barmpounakis and Golias, 2016), unmanned surface vehicle (USV) (Lv *et al.*, 2019), unmanned underwater vehicle (UUV) (Wu *et al.*, 2019) and unmanned spacecraft (Lacombe and Berger, 1983). Each of these UVs has the potential to be automated. Various researchers are focusing on potential commercial applications of AVs (Lam Loong Man *et al.*, 2018).

UAVs, commonly referred to as "drones", have the potential for solving real-world problems (Barmpounakis and Golias, 2016), and this technology has peaked recently on the Gartner Hype Cycle as it is seeing more adoption into real-life applications on a commercial level (Gartner, 2018). The rise of UAV technology is further seen in the growth within the UAV market, which is estimated to have grown from $2 billion in 2016 to nearly $127 billion in 2020 (Moskwa, 2016). This market growth stems from the fact that UAV technology endured commercial adoption and is seeing increased application and usage in both private and commercial sectors.

The drive for technological change is ever-present. Innovation gives rise to numerous new and emerging technologies, but not every new innovation sees large commercial adoption and success. However, condition monitoring technologies have been refined through the course of many years and have reached the point where they can be adopted in all railway sectors. Transportation, of which railway transport is a large constituent, plays a pivotal role in major economic sectors. In a growing economy, constant innovation is vital. Therefore, data acquisition technologies supplemented by technological carriers are worthy of investigation, as they have the potential to dramatically improve railway operations. Drone technology is uniquely suited to combat challenges presented in maintenance of railway infrastructure – as networks of railways connect regions both widespread and remote. Drones would eliminate much of the challenge, as they could traverse complex territory and reach any point close to their station to monitor railway infrastructure. The same can be said for other possible carriers and emerging data acquisition technologies, each possessing features that would benefit the condition monitoring of railway infrastructures.

The implementation of these technologies is deemed to be advantageous in the railway sector; however, for this to happen the correct technology must be selected. Technology selection can be seen as a form of predicting or forecasting which technology would best suit an organisation's needs. This is, however, no simple task. Niels Bohr, the Noble laureate in Physics and father of the atomic model gives the following quote, "Prediction is very difficult, especially if it is about the future!". Thus, the complex decision-making problem of technology selection must be addressed through the help of various tools, techniques, and processes to ensure a favourable result is obtained.

1.2 Problem Statement

Due to the continuous changes and advancements in technologies, new management strategies need to be developed to utilise these technologies. A predictive maintenance strategy has emerged due to the improvement in the technological capabilities of the maintenance equipment. Against the background of railway infrastructure maintenance, the problem is that maintenance managers have not evolved to leverage the full potential of emerging data acquisition technologies to support a predictive maintenance approach. The slow adoption of predictive maintenance can be largely attributed to uncertainty based on technological capabilities, challenges throughout the process, and potential benefits the approach may present. Consequently, there is a growing need amongst railway companies for identifying emerging data acquisition technologies, barriers that slow adoption and implementation, and finally identifying possible strategies to overcome the implementation challenges of emerging technologies.

1.3 Research Questions and Objectives

To address the research problem the following research questions are posed.

Primary Research Question

How can railway operators be assisted with the selection and implementation of emerging data acquisition (DAQ) technologies for predictive maintenance of railway infrastructure assets?

Secondary Research Questions

From the primary research question, the following secondary research questions are derived:

1. What are the fundamental aspects of railway infrastructure maintenance?
2. What does the data acquisition technology landscape look like for performing predictive maintenance on railway infrastructure?
3. What are the barriers and promoters for the selection and implementation of new technology into a company's current structures (technologies and processes currently employed by railway companies)?
4. What should a framework consist of to assist railway managers with the selection of new data acquisition technologies for condition monitoring in support of railway infrastructure predictive maintenance?

Research Objectives

The ultimate goal of the research is to develop a DAQ technology selection framework to aid railway operators with the adoption of emerging DAQ technologies in support of predictive maintenance. To address the research questions, the following objectives must be achieved:

RO1 **Investigate the context surrounding railway infrastructure maintenance, more specifically, the failure modes identifiable through emerging data acquisition technologies and the capabilities of the technologies itself.**

(i) To identify the critical railway infrastructure components that require maintenance for ensuring reliable and safe transportation.

(ii) To identify the failure modes at each of the infrastructure components identified in RO1(i), as well as the possible signs to detect imminent failures for prevention.

(iii) To identify suitable emerging data acquisition technologies for monitoring the condition of railway infrastructure.

(iv) To establish what the factors are that promote and slow the adoption of new data acquisition technology in the railway environment.

(v) To determine potential strategies for ensuring the successful adoption of new technology by a railway company.

RO2 **Develop a framework to guide the selection of emerging data acquisition technologies to promote successful adoption.**

(i) To establish a set of design requirements, to which the technology selection framework must adhere.

(ii) To evaluate existing technology selection frameworks against the set of design requirements established in RO2(i).

(iii) To develop a framework for the selection of data acquisition technologies incorporating the design requirements.

(iv) To refine the framework and transform it into a practical selection framework railway operators can use.

RO3 **Determine the validity and feasibility of a technology selection framework in the railway industry.**

(i) To validate the DAQ technology monitoring capabilities mapped to their respective failure modes by means of subject matter experts.

(ii) To validate the technology selection criteria and their relative importance through judgements from subject matter experts.

(iii) To validate the refined framework through real-world application.

1.4 Research Design and Methodology

This study follows a mixed method research approach. According to Bryman and Bell (2018), the mixed method approach has the capability to capitalise on the strengths and offset the weaknesses of only using qualitative or quantitative methods.

A exploratory design best fits this type of study. Thus, a two-phase *mixed method exploratory sequential design (ESD)* is chosen (Creswell *et al.*, 2005). The first phase starts with qualitative methods to explore a certain phenomenon, and then develops into a second phase consisting of quantitative methods. Interpretations are made based on the findings of both qualitative and quantitative data. For an exploratory design the qualitative data collection takes priority over the quantitative data, with the quantitative data being used for supplementation purposes. Figure 1.2 represents the research methodology followed from start to finish.

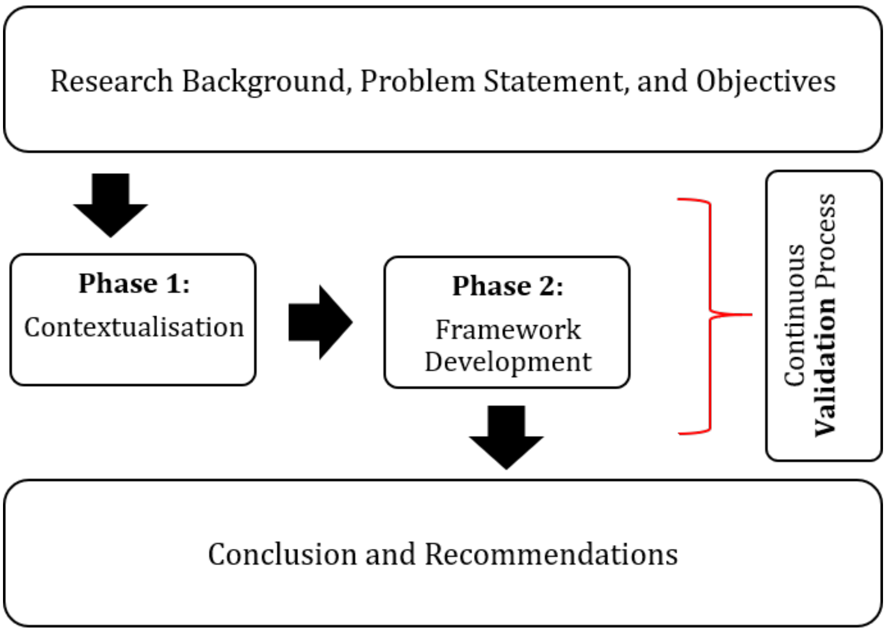


Figure 1.2: Research design and methodology

The first phase of the methodology commences once the research background and problem statement are defined. The first phase of the research is aimed at contextualising the research problem. It starts with a comprehensive literature review which identifies critical railway infrastructure components and their functions, failures, defects, and maintenance-related activities. This is followed by a structured review of the literature. The purpose of the review is to identify data acquisition technologies that can be used for predictive maintenance and their respective technological capabilities. This phase further builds on the literature findings by gathering inputs from railway industry experts. Questionnaires completed by subject matter experts are used to support the findings of the structured literature review and to identify barriers and promoters of current and emerging data acquisition technologies. Quantitative data is also collected at the same time, focusing on aspects of maintenance-related activities of a railway company. The quantitative findings merely support the qualitative research conducted up to this point.

In phase two the DAQ technology selection framework is developed. This phase is responsible for integrating all the research findings from the literature review and questionnaires completed by subject matter experts to construct the framework design requirements. After this, existing frameworks are analysed to aid with the complex problem. This merger of the findings creates the key concepts and ideas for the selection framework. The framework is then further refined for practical use by railway operators.

Validation is achieved by the literature findings and the feedback from subject matter experts throughout the research process. Experts are used three times in this research to validate findings; (i) to validate the DAQ technologies identified in the structured review and their individual monitoring capabilities, (ii) to validate parts of the framework development, and finally (iii) to validate the DAQ technology selection framework.

The final step for the research methodology is to conclude the research and recommend alterations or improvements to future studies.

1.5 Research Delimitations and Limitations

This investigation is bound to the following delimitations and limitations:

Delimitations:

- Various types of technologies with possible benefits for solving the problem are researched during the literature review and fieldwork. The information and communication technologies which support predictive condition monitoring are mentioned but not fully explored, due to the focus being on data acquisition technologies.
- The assets being investigated are limited to railway infrastructure and its operational challenges and do not include rolling stock. Furthermore, rail infrastructure scope is narrowed down even more to include only the infrastructure along the railway track.
- The framework validation through real-world implementation occurs at one railway operator, which is the Passenger Rail Agency of South Africa (PRASA).

Limitations:

- The time constraints associated with the structured review to identify data acquisition technologies limits the amount of different technologies explored.

1.6 Ethical Considerations

This research gathers data and valuable inputs from questionnaires completed by subject matter experts, based on their knowledge of the subject and opinions. Thus, as in all research, ethical considerations play a role when using the data collected. This thesis followed the ethical procedures as requested by Stellenbosch University. See Chapter 4, Section 4.2.5, and Chapter 6, Section 6.2.2.2 and 6.3, for which ethical approval is required. Approval is granted by the *Research Ethics Committee (REC)* for all the afore-mentioned instances and is classified as low risk in accordance with Stellenbosch University's guidelines (project reference: *ING-11672-2019 & -2020*).

1.7 Chapter Outline

This section summarises the thesis document outline, with a look into what each chapter contributes to the final document. The report's structure guides the reader through the research process. It shows how each chapter builds on the previous, finally leading to a conclusion. Figure 1.3 shows an overview of the structure.

Chapter 1 sets the stage by providing an introduction to the research topic. The background of the study is emphasised, along with the problem statement, research question, research objectives, and the methodology followed to complete the study.

Chapter 2 provides a comprehensive literature study of maintenance in the railway infrastructure landscape. The literature identifies the importance of maintenance regarding physical asset management and the evolution of it through the years. The literature is further analysed to identify critical railway infrastructure components and their functions, failures, defects, and maintenance-related activities. Following the railway landscape, a structured review is conducted. The purpose of the review is to identify data acquisition technologies (current and emerging) capable of condition monitoring, in support of railway infrastructure predictive maintenance. Furthermore, the review highlights popular carriers to supplement the efficiency of the data acquisition technologies.

Chapter 3 covers the methodology employed in each step of the research process to deliver a solution to the research problem. It explores different possible methodologies and expands on the approach followed, based on the requirements of this research. This chapter shows the scientific approach used to draw up viable conclusions and recommendations.

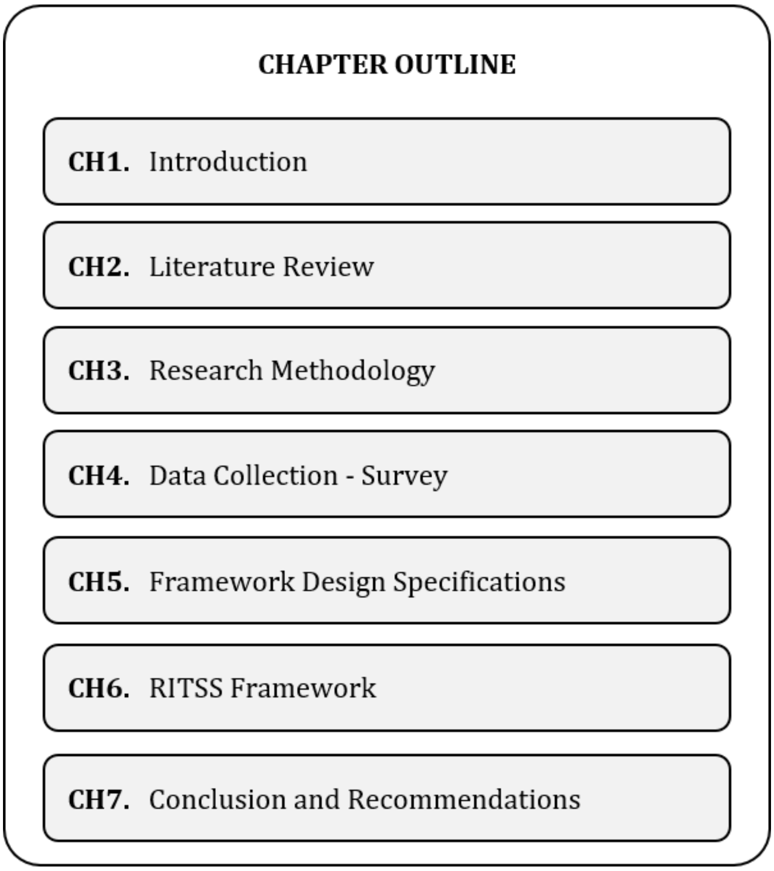


Figure 1.3: Thesis structure

Chapter 4 covers the collection of additional data from subject matter experts to build on and validate the research that has been conducted in Chapter 2. This chapter explores the reasoning behind the selection of a questionnaire as a viable means of collecting valuable data from subject matter experts. The subject matter experts included in the study are participants from Austria, the Netherlands, South Africa and Slovakia. Their input assisted with the exploration of specific railway infrastructure's criticality as well as the factors which affect the criticality, validating the DAQ technologies and their respective monitoring capabilities, and highlighting key barriers and promoters for the adoption of new technologies in railways as well as possible strategies for overcoming these challenges.

Chapter 5 covers the design specifications definition for the DAQ technology selection framework. This chapter merges the findings from both Chapter 2 and Chapter 4. In this chapter various technology selection frameworks are explored to determine what the framework needs to include in order to achieve all the research requirements. All the steps and justifications for the framework are stipulated throughout, ending with the multi-criteria decision analysis technique and evaluation criteria development.

Chapter 6 builds on the key aspects described in Chapter 5 by developing and refining the framework to present railway operators with a practical selection framework. Refinement is based on the integration of all the findings in a manner that is structured and logical. The practical selection framework is tested for validity by applying it in a real-world environment with the assistance of a railway operator.

Chapter 7 concludes the findings of the previous chapters and discusses the core findings of each chapter. The significance of the contributions each chapter makes to achieving the objectives is discussed. A final recommendation delivers possible improvements or opportunities for further studies.

1.8 Conclusion

This chapter presents the background and overview of the research, placing it in context. Then the research problem is discussed along with the objectives of the study. The study's delimitations and limitations are laid out and lastly the research methodology and structure of the report follow. The chapter to follow includes a comprehensive literature review of railway infrastructure maintenance and failure methods, DAQ technologies utilised for condition monitoring, and all the challenges presented with adopting and implementing new technologies.

Chapter 2

Literature Review

2.1 Introduction

This chapter covers the contextualisation (Phase 1) of the research. It is achieved by providing all the necessary knowledge and background information with regard to railway infrastructure maintenance and the data acquisition (DAQ) technology available for condition monitoring. Figure 2.1, represents the position of this chapter in relation to the entire research process.

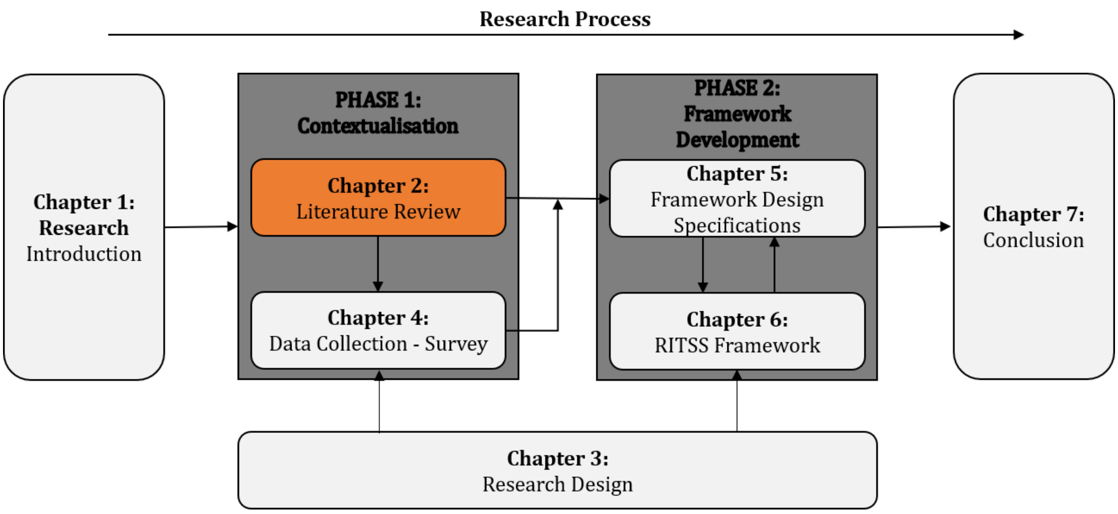


Figure 2.1: Research design: Chapter 2

The two themes explored in this chapter, as mentioned in the previous paragraph, consist firstly of a comprehensive analysis of the existing literature to explore railway infrastructure maintenance, in Section 2.2. This is done to highlight major failure modes that occur on or to the specified infrastructure in the scope of this study. Furthermore, the research aims at understanding the cause of the failures and warning signs and to potentially prevent them. The second theme, discussed in Section 2.3, is explored by means of a structured literature review to identify new and emerging technologies that can be used for condition monitoring of railway infrastructure.

2.2 Railway Infrastructure Maintenance

Railway as a form of transport has become a major contributor to economic growth and sustainability as mentioned in Chapter 1, research background and overview. Thus, an in-depth look is required into the working principles of railway activities that ensure for an efficient railway system. This section provides the necessary information on railway activities for drawing certain conclusions. Furthermore, the characteristics of importance unique to each activity is highlighted.

Railways have changed considerably over the course of time from the first forms used until now. The first form of a type of rail transport can be traced back to the 6th century BC in Greece when boats were transported on rails. However, it was only in the early 1550s that people started using 'wagonways' in German mines (Zaayman, 2017). These wagonways, where carts with unflanged wheels ran on wooden rails, were the first means of transport to come close to the perception people currently have of railways. The history of rail since the fifteenth century can be divided into several discrete periods defined by the locomotive power and type of track used. The distinct periods are: pre-steam; steam-powered; electricity-powered; diesel-powered and high-speed rail as known at the present time. The railway sector has experienced extensive development over the past decade. In China, passenger traffic has grown at an average annual rate of 7.6% between 2007 and 2016 (Li *et al.*, 2019*b*). This increased flow of passenger traffic has increased the need for improved railway activities.

The goal of a railway is to perform its primary function, which is to transport freight and people from one place to another safely, rapidly, comfortably and on time (Zaayman, 2017). Railway systems also need to be efficient. This is achieved by performing a railway's primary function at cost-effective rates while ensuring railway infrastructure is reliable, available, maintainable, affordable and safe (RAMAS). Railway operational activities are therefore the means by which a railway system can achieve its goal.

Railway operational activities include all the service provided in, on and around railway assets. The two types of overseeing assets identified in previous sections are infrastructure and rolling stock. In Section 1.1, the following railway operational activities of importance are identified: maintenance; planning; construction;

safety and security (Marinov *et al.*, 2013; Barmpounakis and Golias, 2016; RailNetEurope, 2019). Railway maintenance is the most frequently discussed topic in the literature studied. Zaayman (2017), focuses the attention on track infrastructure and the department in charge of ensuring the infrastructure is RAMAS. This literature analysis covers the maintenance strategies and methods that play large roles in the RAMAS of the railway.

2.2.1 Rail Infrastructure Management

The goal of most companies is to achieve the best possible outcome when implementing their strategy. One means of doing this is by focusing on Asset Management (AM). This section helps identify where rail track operational activities, such as maintenance, and safety and security, fit into the *bigger picture* in terms of an organisation's strategy. However, to do this, the basics of AM need to be understood.

2.2.1.1 The Scope of Asset Management

The rapidly changing economic climate and technological developments around the world have forced industries to adapt their strategies and way of thinking to best suit the new environment. This is the case for AM as an alternative method of managing industry assets. AM is a vast field globally and therefore the British Standards Institution initially published the Publicly Available Specifications 55 (PAS 55), in 2004, to help standardise the management of physical assets. A revised version was launched later in 2008. This standard comprises of two parts (British Standards Institution, 2008*a*,*b*):

- Part 1: Specification for the optimised management of physical assets.
- Part 2: Guidelines for the application of PAS 55-1.

The term AM has been used by people and organisations for a long time. It was only in the 1980s that AM transitioned from being only connoted to the management of investments and finances, but also to the field of physical asset management (The Institute of Asset Management, 2015). According to the ISO 55000:2014 standard the definition of AM is:

> *"the coordinated activity of an organisation to realise value from assets"*,

whereas the standards also state the definition of an asset as an:

> *"item, thing or entity that has the potential or actual value to an organisation"*

The goal of asset management, according to The Institute of Asset Management (2015), is to ensure that assets deliver value, and to help achieve an organisation's objectives. The value which assets can contribute to the overall success of an organisation depends on the type and purpose of the organisation, its operating context, financial constraints and regulations, and the needs and expectations of the stakeholders (ISO 55000, 2014). Part of the AM process is finding ways of achieving the organisation's objectives while at the same time managing to balance costs, risks, opportunities, and performance benefits. The British Standards Institution (2008*a*) identified five categories of assets in an organisation in the PAS 55; however, focus is placed only on physical assets. The categories of assets are financial, human, information, intangible, and physical assets. Seeing as emphasis is placed on physical assets this concept requires exploring. Its definition according to Basson (2016) is:

> *"...is an entity that creates, sustains or has the potential to create value and includes, but is not limited to, equipment, infrastructure, valuables, inventory, information, and employees."*

The IAM makes use of the AM model shown in Figure 2.2, to show a high-level scope of the activities that fall under AM, how the activities are linked, how they are integrated, and how the role of AM aligns with an organisation's strategic plan. The research conducted in this thesis includes mainly aspects of the life cycle delivery activities related to assets. This is where the majority of expenditures are incurred (The Institute of Asset Management, 2015). However, the research is not limited to life cycle delivery only. Life cycle delivery activities focusses on the effective management of assets and all possible influences throughout their life cycle.

2.2.1.2 The Role of Maintenance in AM

Maintenance has always been an important part of life cycle delivery of assets, and thus is instrumental for effective asset management. According to Tsang (2000), the scope of maintenance management should include every stage in the life cycle delivery of physical assets such as specifications, acquisitions, planning, operation, performance evaluation, improvement and disposal. A definition of maintenance, in the context of asset management, summarised from the literature is: (Tsang, 2000, 2002; Zuashkiani *et al.*, 2011; Manickam, 2012; Zaayman, 2017)

> *"Maintenance is the combination of all the technical and administrative actions intended to ensure physical assets are RAMAS."*

Refer to Section 2.2.1.3 for explanations of RAMAS.

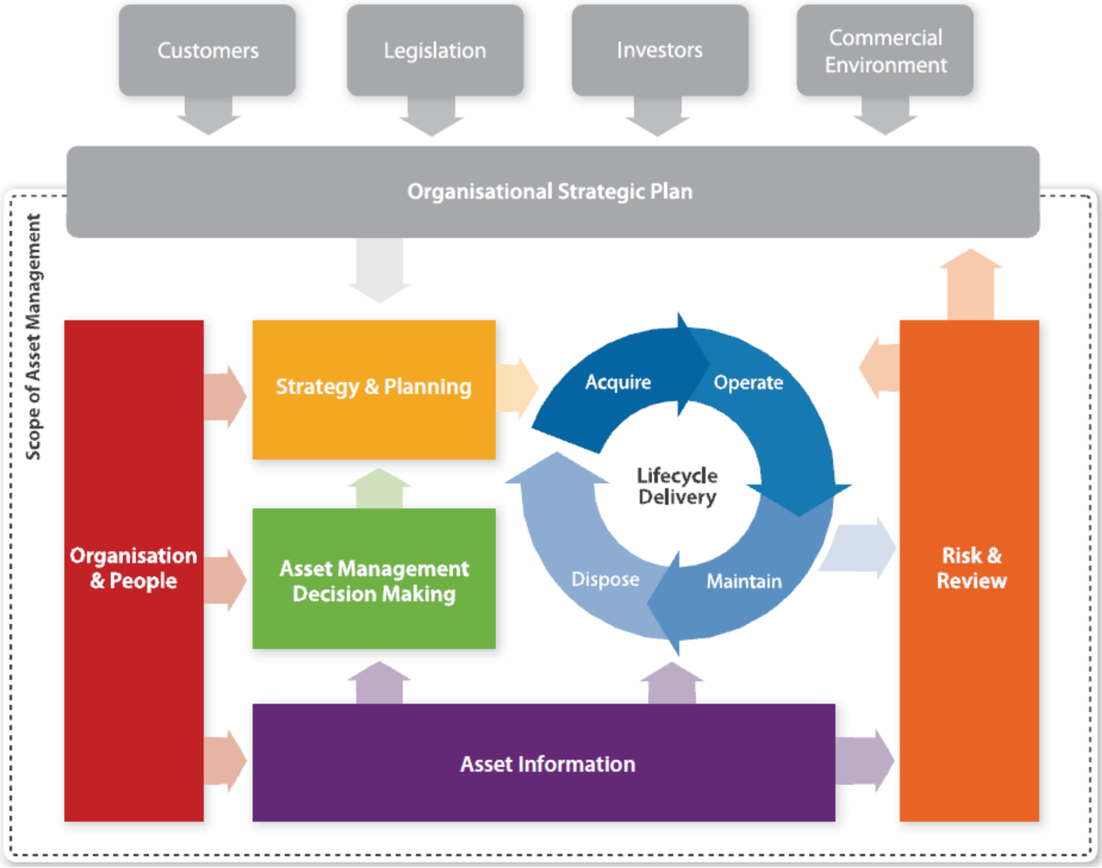


Figure 2.2: The Asset Management model as depicted by IAM (The Institute of Asset Management, 2015)

Over the past decade more attention has been directed towards asset management (Basson, 2016), mainly due to the advancements in technology. Seeing as maintenance has become a crucial factor in the success of an organisation, according to Zuashkiani *et al.* (2011), an increasing number of companies are making the shift over to a more mechanised and automated approach to their activities.

Previous views of maintenance identified it as a "necessary evil" to repair broken equipment (Tsang, 2000, 2002). Maintenance was usually regarded as the first target for cutting costs. However, the use of maintenance is of strategic importance to an organisation for increasing their capabilities in terms of creating value and cost effectiveness of their operations (Tsang, 2002). Maintenance and how it is implemented has progressed dramatically over the years. These changes are contributing to the vast variety of assets that require maintaining, new maintenance techniques, complexity of designs, and organisations' changing view of maintenance and their responsibilities (Moubray, 1997). With the changing landscape of maintenance, certain challenges occur when addressing the growing performance demands of organisations. According to Tsang (2002), the factors that bring about the challenges are:

- **Emerging trends of operations:** Organisations shifted their emphasis from volume creation to fast response, defect prevention, and elimination of waste.
- **Toughening societal expectations:** Society is becoming more focused on the effects that activities have on the environment, and health and safety of people.
- **Technological changes:** Technology advances at a rapid pace, creating demands for maintenance and the application of emerging technologies.
- **Changes in the people and organisational systems:** As times have changed so has the knowledge of people and organisations increased.

The developments in the field of maintenance can be traced back to the challenges mentioned above, emerging trends of operations, toughening societal expectations, technological changes, and changes in the people and organisational systems. Moubray (1997) identified the developments in the maintenance field and described it as three distinct generations of maintenance. John Moubray's view of maintenance philosophies was adapted over time by other researchers and a fourth generation was added. The four generations of maintenance approaches are seen in Figure 2.3, according to Arunraj and Maiti (2007).

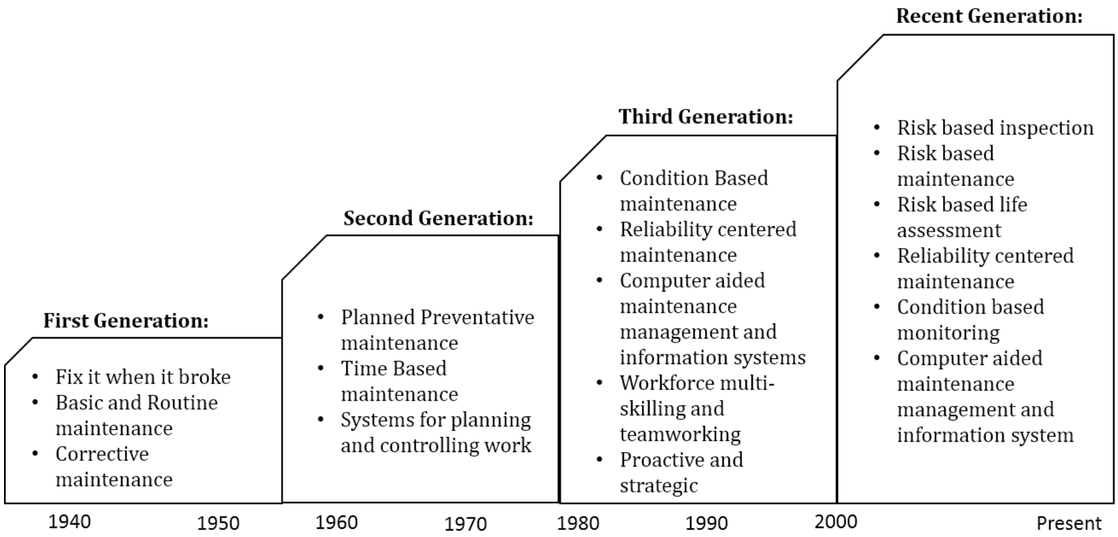


Figure 2.3: Evolution of maintenance philosophies (Moubray, 1997; Arunraj and Maiti, 2007)

First Generation:
The first generation occurred in the time period before World War II. Back then, industry processes and activities were not highly mechanised. The equipment was simple and mostly over-designed, leading to reliable equipment. Breakdowns were also relatively easy to repair. Managers in those times did not prioritise preventive techniques seeing as downtime due to equipment failure did not have a major impact on processes. The maintenance philosophies followed in this generation were corrective maintenance, reactive maintenance ("fix it when it broke"), and basic routine maintenance.

Second Generation:
The second generation presented itself during the World War II. The pressure from the war increased the demand on goods. Industries became more mechanised to meet the new demands. Decreasing the down time of equipment became a priority in this stage, because industries became more dependent on them. This paved the way for 'preventative' maintenance. Industries also realised that maintenance costs rose with respect to the operating costs of a company and therefore efforts were allocated to maintenance planning and control systems. Maintenance philosophies adopted in this era were 'preventative' maintenance, time-based maintenance, and planning and controlling systems (Arunraj and Maiti, 2007).

Third Generation:
The change in industry expectations continued to grow rapidly at an exponential rate in this era. Thus, the third generation of maintenance philosophies appeared, driven by the need for higher plant availability and reliability, greater safety, increased product quality, elimination of environmental impact, increased equipment life, and increased cost effectiveness (Moubray, 1997). The adoption of this philosophy included the rise of Condition Based Maintenance (CBM), Reliability Centred Maintenance (RCM), and computer aided maintenance management.

Recent Generation:
The fourth generation that is currently in practice was adopted since the end of the 1990s to 2000. This generation started due to the adoption of safety-orientated approaches by maintenance practitioners (Arunraj and Maiti, 2007). Therefore, in addition to RCM and CBM approaches, risk-based inspection and maintenance methodologies became popular. The desired outcome of the new methodologies are to ensure profitability and optimise life cycle costs while at the same time trying to minimise safety and environmental effects.

Huang *et al.* (2012) identify four different maintenance strategies that are currently in practice and fits into the fourth generation of maintenance. The four types of maintenance strategies are; reactive-, preventive-, predictive-, and proactive maintenance. See Figure 2.4 for the different maintenance strategies.

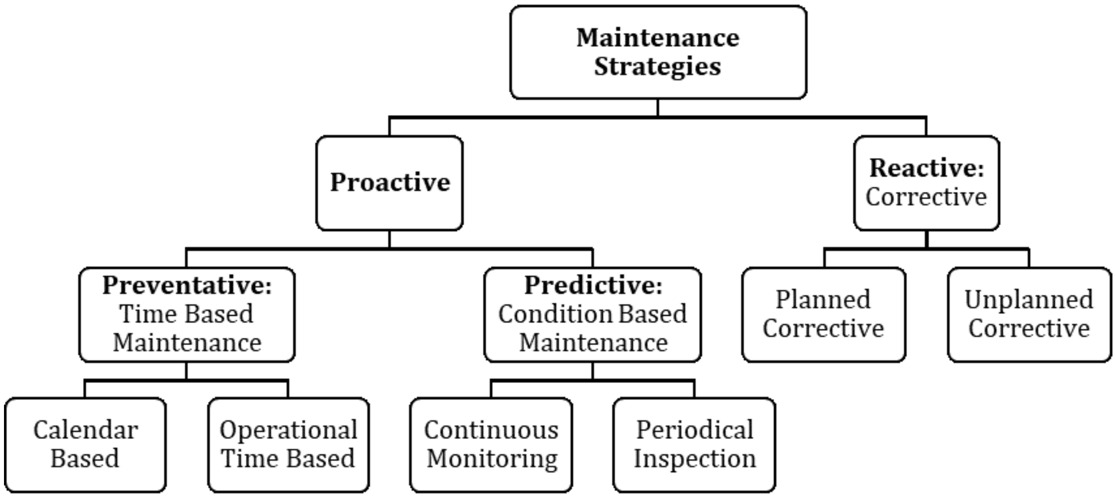


Figure 2.4: Maintenance strategies (Huang *et al.*, 2012)

Reactive maintenance, also called Corrective Maintenance (CM), can be either planned or unplanned. CM includes activities that are performed to rectify defects, damages or address shortfalls in performance with the goal of restoring assets to perform intended functions to a set standard (The Institute of Asset Management, 2015). This type of maintenance is only implemented when equipment or system failure occurs. The use of CM is best suited in situations where predicting failures is difficult (Manickam, 2012). According to Huang *et al.* (2012) the implementation of CM requires minimal special knowledge and equipment, but the costs due to repairs after failure and downtime are extremely high.

Preventive Maintenance (PM) is planned activities that are performed on a set time schedule. The activities are performed to prevent or reduce the impact of failures, faults, or excessive deterioration of assets (The Institute of Asset Management, 2015). Huang *et al.* (2012) describes the knowledge required to implement PM is extensive, and the specialised equipment required is moderate. The cost of PM is high, keeping the costs related to repairs and downtime at a moderate level.

Predictive Maintenance (PdM) requires regular inspection and monitoring of equipment, following CBM strategy. This ensures that PM can be performed at the optimal time intervals before failure occurs (Manickam, 2012). PdM thus requires appropriate condition data to select the maximum allowable period between repairs while at the same time minimising the number and cost of unscheduled breakdowns (Basson, 2016). PdM requires moderate to extensive amounts of specialised knowledge and equipment. However, the costs of maintenance and corrective actions are minimal (Huang *et al.*, 2012). The advancements in technology have led to digital technology becoming less costly and more widely available. Coupled with the growth of the digital supply network, it sets the stage for PdM to be implemented across a variety of organisations (Colemen *et al.*, 2017).

Proactive maintenance strategies incorporate the tactics of both PM and PdM. The combination of the two strategies is used to supplement each other's shortcomings. Huang *et al.* (2012) states that RCM is not classified as a specific maintenance strategy, but rather a decision-making process which determines the optimal combination of different types of maintenance strategies, seen in Figure 2.4, in order to meet the asset's requirements based on a reliability analysis. Moubray (1997) supports the statement by calling RCM a process. The definition of RCM according to Moubray (1997):

> *"...a process used to determine the maintenance requirements of any physical asset in its operating context."*

Figure 2.5 shows a typical cost vs effectiveness graph of each of the identified maintenance types mentioned in this section. An increase in the effectiveness of a strategy will lead to a decrease in the cost involved. From Figure 2.5 it is seen that RCM is the most effective strategy in terms of minimising the cost.

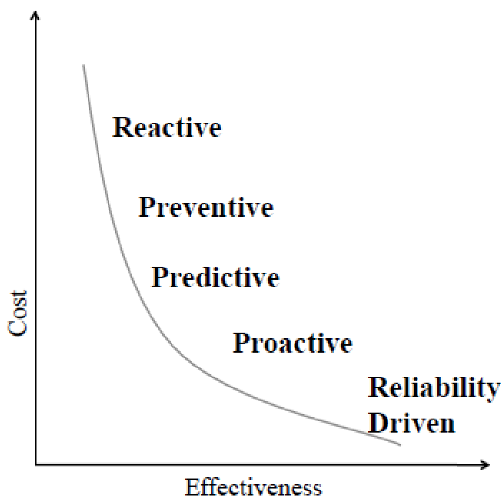


Figure 2.5: Cost vs Effectiveness strategies (Mitchell and Hickman, 2013)

Although proactive maintenance is a more cost-effective strategy than PdM according to Mitchell and Hickman (2013), in the "Deloitte series on digital manufacturing enterprises", Colemen *et al.* (2017) sees PdM as the most reliable strategy. See Figure 2.6 for the maintenance strategies identified and their relative Original Equipment Effectiveness (OEE).

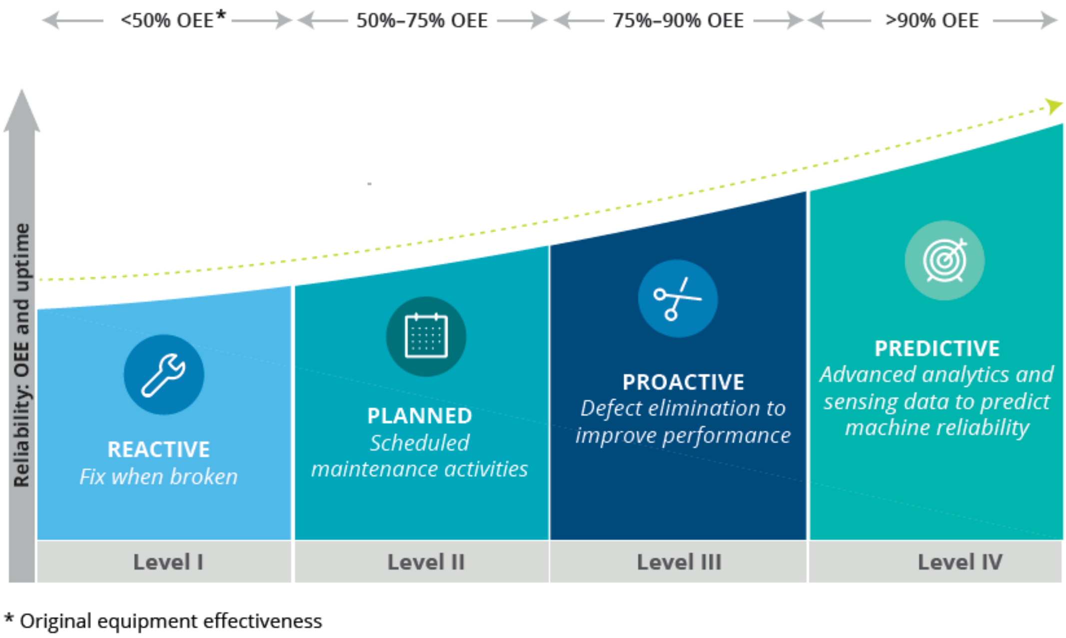


Figure 2.6: Reliability of maintenance strategies (Colemen *et al.*, 2017)

Maintenance plays a critical role in the life cycle delivery of a physical asset and therefore also contributes to the overall effectiveness of AM. Thus, maintenance strategies and practices should be continuously evaluated. This is to ensure that assets provide value while at the same balancing the risks, costs, and the performance measurement associated with the maintenance activities. Refer to the definition of asset management in the previous section. This section also identified that emerging digital technologies favours PdM by providing means of monitoring assets' condition and predicting failures. This form of "Technology Push" by digital technologies and also the growing expectations of maintenance, lead the way for this research.

2.2.1.3 Maintenance in Rail Infrastructure Management

Railway infrastructure management assumes a vital role in the effective and efficient operation of a railway organisation. As mentioned in Section 2.2.1.2, maintenance activities form part of an asset's life cycle management phase and thus also form part of AM. On the one hand, railway infrastructure is a costly investment in terms of resource allocation. However, regular and effective maintenance activities applied to infrastructure can help an organisation reap the benefits of their investment (Odolinski and Wheat, 2018). The benefits of an effective rail transport system include economic growth, development, and the prosperity of a country (Zaayman, 2017). The maintenance of railway infrastructure is not a simple task. This is mainly due to the complexity associated with maintaining infrastructure, but also due to the fact that infrastructure spans over a large area (Al-Douri *et al.*, 2016). Railway infrastructure consists of various components with the track being a focus area. Therefore, excellent maintenance to the track is fundamental. Negligent maintenance can lead to rail tracks breaking down. Breakdowns can then lead to the possible loss of service, property, and life, which will then result in high maintenance costs, decreased overall track performance, dissatisfied passengers, and damaged goods (Al-Douri *et al.*, 2016).

Rail track maintenance requires specific attention to a few areas of importance. Attention to these areas will help the infrastructure manager reach the goals set out by the organisation. According to the European Standard (EN 50126) the ultimate goal for rail track infrastructure is to be RAMS (reliable, available, maintainable, and safe). Zaayman (2017) added to the EN 50126 standard by creating a new acronym, RAMAS (reliable, available, maintainable, **affordable**, and safe). Zaayman's acronym RAMAS incorporates the aspect of cost-effectiveness to both the railway organisation and passengers. The areas of the rail track maintenance process that require special attention for reaching the end goal are shown in Figure 2.7.

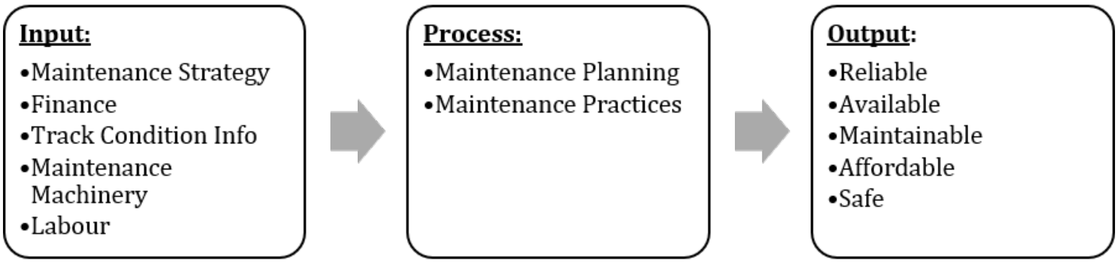


Figure 2.7: Approach of track maintenance (Zaayman, 2017)

Various factors influence the application of a maintenance strategy followed by a railway company. These can differ from strategy to strategy. On a high level, railway maintenance strategies include both reactive and proactive characteristics (Al-Douri *et al.*, 2016), (Figure 2.4). The input characteristics seen in Figure 2.7, are prioritised based on the specific maintenance strategy implemented. Sufficient financial support is a necessity when implementing maintenance activities determined by the maintenance strategy. The capital allocated to maintenance determines the amount and quality of infrastructure condition rectifying activities, maintenance machinery, and skilled labour force (Zaayman, 2017).

Track life is directly related to the amount and consistency of financial input a company invests into track maintenance. As mentioned previously, companies, in general, want to cut costs where they can while maintaining their performance or capabilities (Tsang, 2002). In the case of rail, track maintenance forms a large part of the company's operational cost. Thus, if managers are under pressure to minimise costs, they will, in most cases, address track maintenance first (Basson, 2016). Problems experienced with cutting back on financial support for maintenance are that the condition of tracks deteriorates faster, leading to higher probabilities of failures. To rectify these failures is more costly than having invested in maintenance activities to prevent them. It is important to try to balance maintenance and intervention costs to find a form of equilibrium (Zaayman, 2017).

The cost tied to intervention activities depends on when the interventions take place. Intervention should occur before the tracks deteriorate below a certain threshold. To prevent this happening, track condition information is required regularly (The Institute of Asset Management, 2015; Al-Douri *et al.*, 2016). There are various methods of gathering track condition data. Using them in combination to create a big picture of the overall track condition is valuable. Track data acquisition can be visual observations or measurements made with specific equipment and technologies (Al-Douri *et al.*, 2016; Colemen *et al.*, 2017). The condition information is valuable in the sense that it can help in planning effective maintenance activities.

Currently, skilled labour forces are still a necessity for track maintenance, and technology has yet to develop all the capabilities of completely replacing skilled workers (Huang *et al.*, 2012). A labour force is another large operational expenditure of a company and this requires effective management. When managing a labour force, it is important to consider factors that can affect them directly, which will, in return, affect their work performance. This is where maintenance planning and scheduling come into play to create an effective maintenance system.

Railways are expensive and valuable assets, and when managed properly, they can be vital for sustainable social development in developing countries. The railway can be the most reliable and economical means of transporting passengers and freight if the track infrastructure is maintained and managed well. The outcome of the entire track maintenance process is finally for the track infrastructure to be RAMAS.

2.2.2 Rail Infrastructure Components Overview

In Chapter 1 railway assets were identified and categorised into two distinct groups, namely rolling stock and infrastructure. It is decided for the purpose of this study to focus only on infrastructure. Infrastructure itself consists of a large variety of different components. Thus, the literature that is analysed regarding the railway industry is further directed towards a selected few critical components. The book *The basic principles of mechanised track maintenance*, authored by Dr. Leon Zaayman, has guided the selection of infrastructure components for further study (Zaayman, 2017). Zaayman is an expert in the field of rail track infrastructure maintenance with 23 years of experience. His book is referenced multiple times throughout this chapter for being extensive and aligned with the goal of this research. Furthermore, the references to Zaayman's book in this research are supplemented by other reputable sources. The selection of the infrastructure components to be included is based on two criteria; (i) components most affected by maintenance, and (ii) components that form part of the rail track or are situated alongside the track. The railway infrastructure components explored in this research are shown in Figure 2.8.

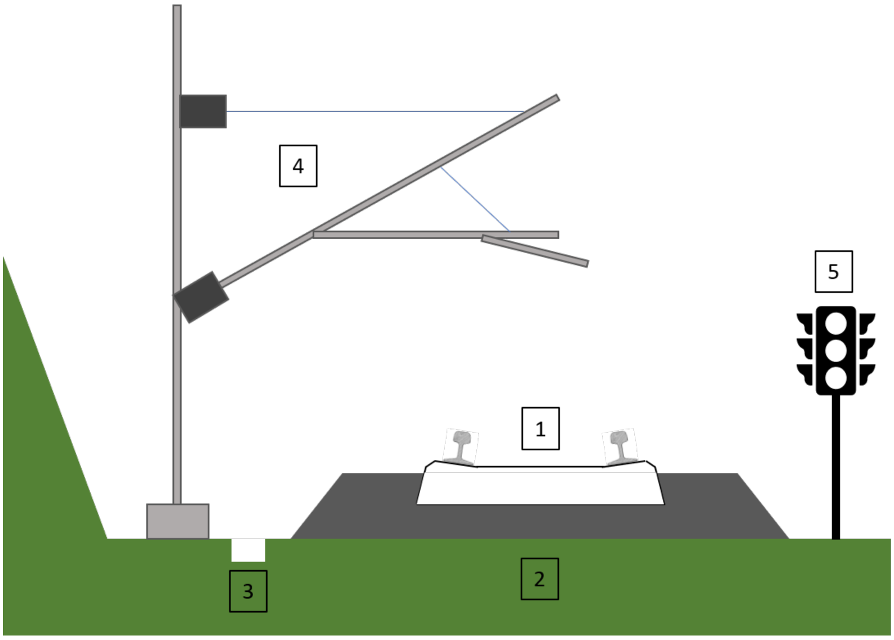


Figure 2.8: Typical rail track infrastructure (adapted from Zaayman (2017))

Legend:	
1. Rail track	4. Overhead traction equipment (OHTE)
2. Formation	5. Signalling and telecommunications
3. Drains	

Refer to the legend on the different rail track components mentioned to help illustrate the components' positions with respect to each other. Item 1 and item 2 refer to more than one component and the further breakdown of the rail track components is seen in Figure 2.9.

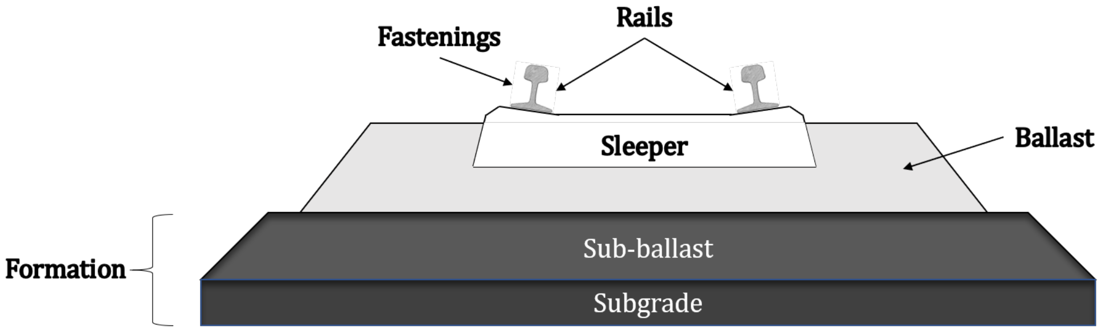


Figure 2.9: Railway track components

2.2.3 Functionality of Rail Infrastructure Components

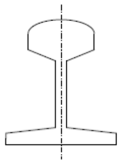
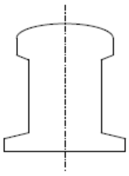
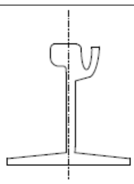
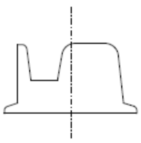
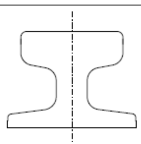
This section elaborates on the rail track components identified, with the goal of defining the function of each component and emphasising the importance of maintaining each component. The rail track and its components are discussed separately to gain insight about each component.

2.2.3.1 Rail

Rails have the most important function of the track components. They are responsible for guiding the train along the track by being directly in contact with the train wheels (Kaewunruen and Remennikov, 2008). This direct contact of metal on metal exposes the rails to very harsh conditions. If the rail were to fail, countless lives and/or freight cargo can be put in danger and thus it is of utmost importance to maintain the rails. Of all the track components, rails are the most costly component in the asset register (Zaayman, 2017). Therefore, to deliver an optimal life cycle cost management plan, it is essential to understand rail deterioration and maintenance.

Different types of rail are identified by the weight per running metre. Rails that generally fall into the category of 30 kg/m to approximately 75 kg/m are available for freight and passenger railways. Depending on the application of specific rails or even the country in which they are used, railway companies need to comply with certain industry standards such as Union of International Railways (UIC), American Railway Engineering and Maintenance-of-Way Association (AREMA), or others. These standards provide details for the different types of rails. These details include the profiles, steel grades, composition, and other characteristics. The vast majority of rail profiles used in current times are flat-bottom rail, also referred to as broad-footed rail (Kaewunruen and Remennikov, 2008). There are other forms of rail profiles based on each of their applications. The most commonly used profiles and their applications can be seen in Table 2.1.

Table 2.1: Rail profiles and applications (Kaewunruen and Remennikov, 2008)

Shape	**Profile Type**	**Applications**
	Flat-bottom rail	Standard rail track
	Construction rail	Manufacturing of auto mobiles and switch parts.
	Grooved rail	Railway track embedded in pavements, roads, yards.
	Block rail	Railway track used in concrete slab as part of Nikex-structure.
	Crane rail	Heavy load hoisting cranes with high wheel loads.

The train wheels make contact with the 'head', also called the crown, of the rail profile. This interaction between the profiles of the wheels and track is important in the fact that it is responsible for tracking of the rail wheels. This interaction over time causes the rails to deteriorate and can increase the risk of failure. A way of prolonging or mitigating the inevitable is to apply preventive maintenance on the rails. Part of the preventive maintenance plan for rails is rail profiling. This profiling consists of rail planing, rail grinding or rail milling, which in effect can extend the rail lifespan. A more in-depth look into the strategy can be seen in Section 2.2.1.3, on railway maintenance strategies.

To simplify the manufacture, transportation, and installation of rails, they are limited to certain lengths. These lengths are usually the same as the cars used to transport them. The single rails need to be connected for creating a continuous track on which trains run. Thus, the method of joining two rails forms part of the functionality of the rails. This is the reason they are considered as part of the rail. Zaayman (2017) identified the following methods for joining rails:

- Fish-plate, splice bar or joint bar
- Temporary rail joints
- Insulating joints/block joints
- Compromise joints
- continuous welded rail (CWR)

A fish-plated joint is a metal bar that joins two rails by bolting them at their ends. This method is commonly used and ensures that there is no lateral or vertical movement between the rail ends, while at the same time allowing longitudinal movement along the rail track for expansion and contraction of the rails due to temperature changes. Temporary joints are two fish-plates held in place by screw clamps. These joints are used for short time spans for either track renewal, or rail breakages, or as safety measures for when internal rail defects are detected. Insulating joints are used to insulate one rail from the next. This is for signalling or splitting electrified track from the non-electrified track. When joining rail track of different profiles, compromised joints are used to ensure that the running surfaces of the two rails are flush and aligned. Rail joints are a continuous recurrence in rail track maintenance and thus for eliminating this, it is better to join two rails by welding them into a CWR.

2.2.3.2 Sleepers

The sleepers, as with the rails, form part of the superstructure of railway track components and are visible to the eye (Zaayman, 2017). The main functions of sleepers contributes to the overall effectiveness of the railway tracks. As they are responsible for distributing the load from the rails onto the supporting ballast, they provide resiliency and absorption for some of the impact; they hold the fastening systems to connect the rails to the sleepers; insulate rails electrically; and they are responsible for maintaining the rail's track gauge (Kaewunruen and Remennikov, 2008; Yella *et al.*, 2009). Sleepers come in various types and designs, each type being unique and used for a specific purpose. The literature has identified five different types of sleepers (Yella *et al.*, 2009; Kaewunruen and Remennikov, 2009; Ferdous *et al.*, 2015; Jing *et al.*, 2018), namely:

- Steel sleepers
- Timber sleepers
- Monolithic prestressed concrete sleepers
- Twin-block concrete sleepers
- Composite material sleepers

Timber was the first material used for producing railroad sleepers. The use of timber is justified by its adaptability and having phenomenal dynamic, electrical, and sound-insulating properties (Ferdous *et al.*, 2015). The need for steel sleepers was introduced in the 1880s due to a shortage of timber, and the use of monolithic prestressed concrete sleepers was applied in 1943 (Kaewunruen and Remennikov, 2009; Ferdous *et al.*, 2015). Although concrete sleepers are able to resist the highest amount of lateral forces, they are not always the preferred material. For instance, steel sleepers are used extensively throughout Africa, India, and the UK (Jing *et al.*, 2018). The reasoning behind the use of steel sleepers is due to technical and economically based decisions. Based on performance and application efficiency, the steel sleepers are manufactured in different sizes and forms. They distribute loads efficiently on ballast layer; reduce ballast depth; installation and transportation are simple; and lastly, they consist of 100% recycled materials (Jing *et al.*, 2018). From an economic perspective it makes sense, due to the 40% reduction in railroad construction costs compared to concrete (Jing *et al.*, 2018). Recent developments in the field of materials science has led to the manufacturing of composite material sleepers. What makes these sleepers special is the fact that they are able to mimic the properties of timber sleepers, unlike steel and concrete, without the setback timber has due to degradation from the environment (Ferdous *et al.*, 2015).

2.2.3.3 Ballast

Track ballast is a critical component that forms part of a typical rail track, seen in Figure 2.9. The ballast forms the bed on which the sleepers rest and has various functions. However, these functions can only be utilised if the ballast conforms to specified characteristics and profiles. The major functions a ballast has are firstly, resisting forces applied to the track in the vertical, lateral, and longitudinal directions to secure the track in its position. Secondly, the ballast reduces the pressure the sleepers exert on the formation by providing elasticity to the sleeper-bearing areas. Thirdly, drainage is an important function ballast has, to ensure that water saturation does not take place in the ballast, which impacts the load-carrying capabilities and the life expectancy of the formation. Lastly, the ballast can be adjusted to correct misalignments of the track geometry (Lam *et al.*, 2014; Sadeghi *et al.*, 2019).

For the ballast to perform its function optimally it needs to conform to the following ballast stone specifications (Zaayman, 2017):

- **Cubic and angular:** Ballast stones must have many sides, high particle angularity, to ensure they stay in position due to high shear strength between particles.
- **Abrasion and wear-resistant:** Must be hard and wear-resistant to prevent it from breaking down due to the impact loads caused by traffic. Examples of hard rocks are granite, basalt, and diabase.
- **Broadly graded and free of fine materials:** Must consist of large and small stones to increase the interlocking strength. Stones have a maximum and minimum size limit.

See Figure 2.10 for visual explanation of ballast profile, the bed profile specifications required for functionality are (Zaayman, 2017):

- Sleepers should rest within the ballast bed and must have a shoulder of roughly between 250 to 300 mm.
- Ballast depth must be between 200 to 300 mm, measured from under the sleeper.
- The ballast slope must be approximately at 1:1.5.
- The formations should have a cross fall slope of 1:25, to ensure water moves through the ballast to the drain.

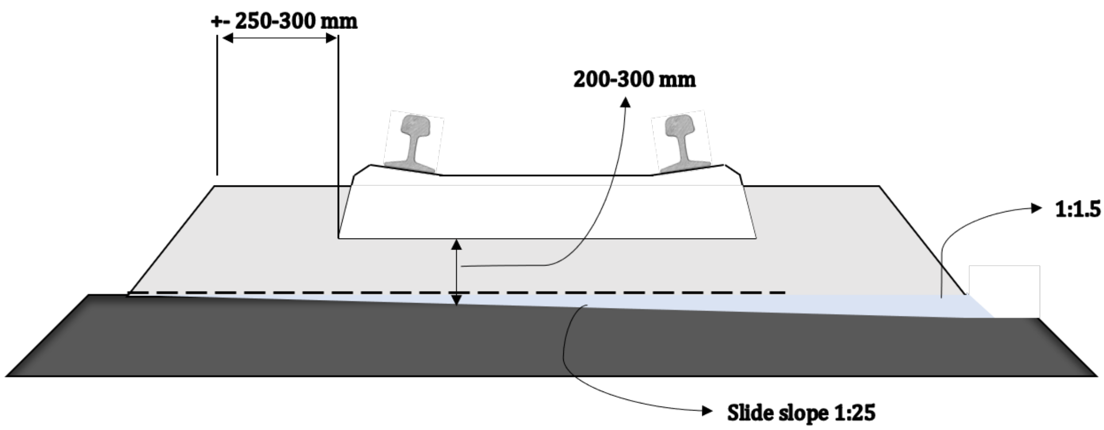


Figure 2.10: Ballast bed profile (adapted from Zaayman (2017))

2.2.3.4 Formations

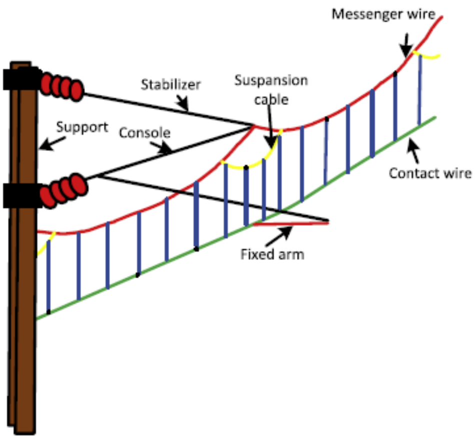
The lower layers of the rail track are called the formation and consist of the sub-ballast and subgrade (Figure 2.9). The sub-ballast is formed from soil that is placed on top of the subgrade, that contains a mixture of broadly-graded naturally occurring or processed sand-gravel (Jiang *et al.*, 2016). The subgrade is the base on which the rail track is constructed, usually local soil but soil can be transported in. The formation has two functions specific to the two layers. First, the sub-ballast is responsible for creating a barrier to prevent fine materials from migrating upwards to the ballast from the subgrade and also helps with water drainage away from the subgrade. The subgrade's function is purely to be a solid and stable platform for the rail track to be constructed upon. In some cases the subgrade is used to level the track structures (Jiang *et al.*, 2016; Schulz-poblete *et al.*, 2019).

2.2.3.5 Surface Drains

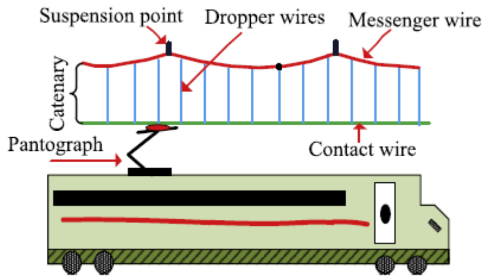
Surface drains are vital components to the overall functionality of the rail track infrastructure, but in most cases they are neglected. The drains are responsible for diverting water trying to enter the track substructure and also water that seeps out of the track (Chen *et al.*, 2019; Sañudo *et al.*, 2019). Drains can be constructed from concrete or even be cleared areas alongside rail tracks. Drain defects come in the form of blockages due to build-up of soil or other forms of obstruction that can prevent water flow along the drain (Sañudo *et al.*, 2019). Drain monitoring and maintenance needs to be implemented on a preventive basis. Part of the maintenance includes drain cleaning which can be labour intensive or done using mechanised equipment (Zaayman, 2017).

2.2.3.6 Overhead Traction Equipment (OHTE)

Overhead traction equipment (OHTE) also known as overhead contact system, overhead line equipment, and Catenary. The OHTE is responsible for delivering power to electric trains through sliding contact between the overhead contact line and the pantograph (Aydin *et al.*, 2015). The components of OHTE are seen in Figure 2.11a. In an ideal situation the pantograph and contact line are permanently connected by means of low contact forces (Liudvinavičius and Dailydka, 2016; Aydin *et al.*, 2018). The pantograph and contact wire interaction is seen in Figure 2.11b. Methods of maintaining the permanent contact are sufficient tensioning of the contact wire and regular maintenance to rectify defects (Liudvinavičius and Dailydka, 2016). Negligent maintenance leads to the loss of contact between the pantograph and the contact wire, creating an electric arc, and this can lead to catastrophic failures of the OHTE and even derailments (Barmada *et al.*, 2016).



(a) OHTE



(b) Pantograph and contact wire

Figure 2.11: Overhead traction equipment (Aydin *et al.*, 2015)

As with other railway infrastructure components regular inspections and maintenance activities are required. Due to OHTE having numerous small and large components, and being suspended over the track, the use of mechanised methods rather than labour-intensive methods are limited (Aydin *et al.*, 2015; Barmada *et al.*, 2016; Aydin *et al.*, 2018). That is why labour is still required for inspection, cleaning, repairs, and replacement of components. The maintenance activities of OHTE are not only the most challenging; they are also the most dangerous of all the rail track components.

2.2.3.7 Signalling

Railway signals are instrumental in ensuring the safety of railway transportation (Mou, 2012). This study focuses on physical railway signalling and not the signals situated along roadways at level crossings. Railway signalling mainly has two categories of technologies; (i) fixed block sections, and (ii) moving block sections (Bersani *et al.*, 2015). According to European Union Agency for Railways (2019) the definition of a railway signal is:

> *"...a visual display device that conveys instructions or provides advance warning of instructions regarding the driver's authority to proceed"*

Railway signals were originally used only to indicate to train operators when they needed to stop or go. With the increase in rail traffic, more and more additions were made to indicate a number of required actions such as speed of the train and which waypoints are set. Signalling is placed at various locations along railroad tracks, dependent on the purpose of the signal. These locations include the start of a track section, on approach to a movable item or infrastructure, in advance of other signals, before level crossings, switch or turnout, ahead of stoppage zones (platforms and depots), and train order stations. Four different categories of rail signals are identified and they are;

- **Mechanical signals:** Signals that require parts to be moved physically for displaying required actions, movement is actuated by means of electrical or hydraulic motor.
- **Colour light signals:** Indications are different coloured electric light bulbs, similar to street traffic lights.
- **Position light signals:** Signals where the colour of the light is not the indicator but rather the positioning of the different lights.
- **Colour-position signals:** These signals combine both aspects of the colour of the light as well as the position to indicate intended actions.

Signalling defects include faulty electrical systems and damaged signalling equipment (Mou, 2012). These defects are caused either by degradation due to extreme weather conditions, damages due to operations, or vandalism.

2.2.4 Rail Infrastructure Failure Modes

This section identifies the different defects and failures of the rail infrastructure components that form part of the scope. The causes are also identified, where applicable. However, the defects of the surface drains and signalling are included in the previous section.

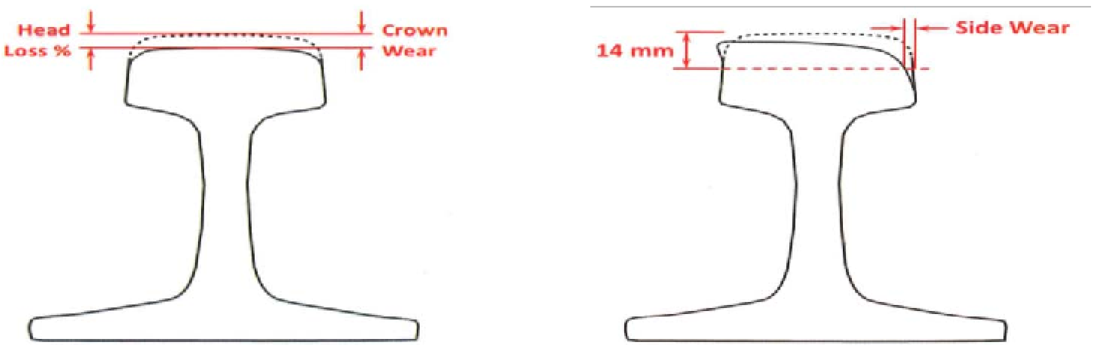
2.2.4.1 Rail

Rail defects and flaws are abnormalities that can affect the lifespan of the rail negative. Thus, regular maintenance is required to mitigate the risks of failures and prolong the life of the assets. To ensure effective maintenance planning and procedures the rail defects need to be placed into categories (UIC 712, 2004). This, however, is no easy task as it is not always possible to establish these categories based only on visual inspections. Based on the literature that was analysed, rail defects for this research are categorised as either rail wear, cracked rail, rail damage, and broken rail (UIC 712, 2004; ARTC, 2006; Zaayman, 2017). The different defects are defined as follows:

- **Rail Wear:** The loss of material from either wheel, or rail, or both due to the relative motion between the two components.
- **Cracked Rail:** Rail material with gaps in between them. This can be visible or not, and holds the possibility of a rail fracture if gap increases with in length.

- **Rail Damage:** Rail defects that cannot be classified as rail wear or cracks. This is mostly caused due to dynamic loading.
- **Broken Rail:** When a rail is separated into two or more pieces, or a part of the rail becomes detached creating a gap of more than 50 mm in length and 10 mm in depth.

Rail wear can be observed as one of three types; crown wear, side wear, or rail corrugations (Zaayman, 2017). Crown wear, also referred to as rail head wear and vertical wear are measured in the centre of the running surface of the rail. Specific standards need to be followed depending on the type and profile of the rail, stipulating the maximum amount of wear allowable before the rail must be replaced. Figure 2.12a, gives a fair representation of how crown wear affects the profile of a rail. Side wear, also referred to as lateral wear and bevelling takes place where centrifugal forces push the flange of the wheel against the side of the outside rail. This happens when gauge widening has not been implemented correctly, the contact band of the rails and wheels are not well defined, or check rails are not in place. Side wear is measured 14 mm below the crown of the rail and how it affects the rail profiles can be seen in Figure 2.12b. The gauge side of the rail that is damaged during side wear increases the risk of train derailment and should not be taken lightly.



(a) Crown Wear (b) Side Wear

Figure 2.12: Effect of rail wear on profile (Zaayman, 2017)

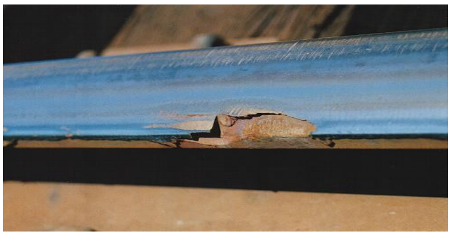
Another form of wear is rail corrugation, but this can also sometimes involve plastic flow in severe cases. In Figure 2.13 short wave marks can be seen on the rail crown. This is an indication of corrugation and is the reason for loud noises and increased stress on all track components. Rail corrugation has numerous possible causes and all of them must be investigated to determine the root cause. These causes include high contact stresses between wheel and rail, poor wheel and rail profiles, differential wheel diameters, and others. The most common area to find corrugation is where the sleepers are severely fouled, decreasing their elasticity.

Figure 2.13: Rail corrugation (MORI *et al.*, 2010)

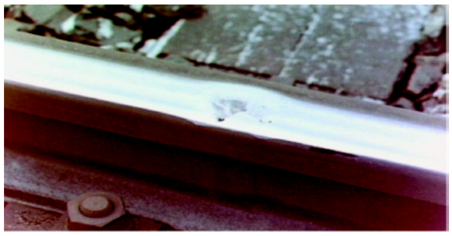
Rail cracks form two distinct groups, which are surface cracks and internal cracks. Surface cracks are defects that can be traced back to excessive shear stresses between the wheels and rails because of rolling contact fatigue (ARTC, 2006). If preventive maintenance practices such as rail grinding do not take place, a platform is created for surface cracks to develop on the crown. These cracks can grow further into the crown as time goes on and finally turn into a rail break with possible dire risks. Another risk associated with leaving surface cracks unattended for too long includes ultrasonic detection equipment not being able to detect internal rail defects (Zaayman, 2017). It is important to note that internal rail defects pose a greater risk for potential rail breaks. Visual representations of both surface and internal rail cracks can be observed in Figure 2.14 and Figure 2.15 respectively. Surface cracks include head checks and running surface checking. Internal rail cracks include shelling/spalling, squat defects, transverse fatigue cracking, vertical split head, horizontal split head, head/web crack, vertical split web (piping), fish-bolt hole crack, and web/foot crack (UIC 712, 2004).

(a) Head checks (b) Running surface checking

Figure 2.14: Rail surface cracks (Popović *et al.*, 2015)



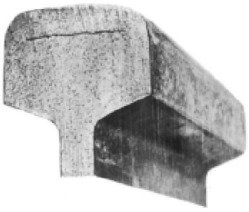
(a) Shelling/Spalling



(b) Squat defects

(c) Transverse fatigue cracking

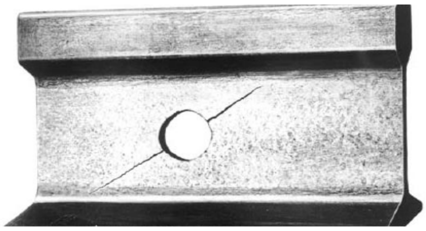
(d) Vertical split head



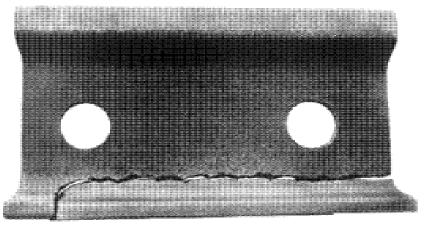
(e) Horizontal split head

(f) Head/Web crack

(g) Vertical split web (Piping)



(h) Fish-bolt hole crack



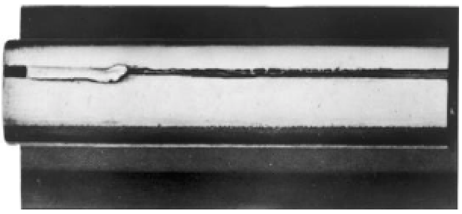
(i) Web/Foot crack

Figure 2.15: Internal rail cracks (UIC 712, 2004)

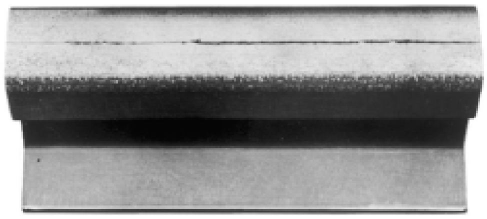
As mentioned before, rail damage is not caused by rail wear and cracks but rather due to impact loads. It can also be as a result of defects that occurred during the manufacturing process. According to Zaayman (2017), the following different types of rail damage are identified. These include long groove and line defects, battered rail ends and dipped joints, metal flow, wheel burn, and crushing. Refer to Figure 2.16 for graphical representations of the different types of rail damage investigated. Long groove and line defects are manufacturing defects, with depths into the rail surface of no more than a few millimetres. These longitudinal defects are only picked up shortly after the rail is laid. Battered rail ends and dipped joints develop at rail joints when rail continuity is compromised. This can be due to the lack of effective joint maintenance and dynamic wheel loads working in on the compromised joints (Zaayman, 2017). Metal flow is a common occurrence when the crown of the rail profile flattens. The crown is flattened by the wheels hunting across the rails due to the contact area between the wheel and rail becoming obscure. Wheel burn is caused by train wheels continuously slipping when they exceed their adhesion limit. This spinning of the wheels forms martensite on the rail due to rapid temperature changes. This crystalline substance is brittle and can lead to cracks and transverse defects. Lastly, crushing of rails is identified. This form of damage can be identified by a depression of the rail surface and a widening of the thread. The main cause of rail crushing is traffic loading, but can also be due cracks underneath the rail running surface.

Rail breaks or broken rails tend to be the most dangerous defects a rail can have. This is a known cause of derailment, leading to possible serious harm of its passengers. The cause of rail breaks can be traced back to the rail defects mentioned previously in this section. Thus, if identified, steps must be taken to rectify the break.

As mentioned, rail joints form part of the rails and thus failures or defects require identification. Indications of defects at rail joints include bolts that are missing, wide gaps between two separate rails, battered rail ends, and geometrical irregularities in all directions (Wang and Markine, 2018). Another issue with rail joints is that they can lose stiffness under dynamic loads, increasing the chances of derailments or other dangerous failures (Kaewunruen *et al.*, 2017).



(a) Long groove defect



(b) Line defect

(c) Battered rail ends

(d) Dipped joints

(e) Metal flow

(f) Wheel burn

(g) Crushing

Figure 2.16: Rail damage (UIC 712, 2004; ARTC, 2006)

2.2.4.2 Sleepers

Sleepers on the one hand require little to no maintenance, thus making sure sleepers are initially installed correctly is important for ensuring that they do not affect the overall effectiveness of the rail track. They are very durable and have relatively long life expectancies, up to 50 years, if the rest of the rail lines are well maintained (Ferdous *et al.*, 2015). However they are very susceptible to damages caused by other rail component defects. Three causes for sleeper failures or damage, highlighted by Zaayman (2017), are rail surface defects creating higher impact loads, shock waves returned when ballast is very fouled, and fines in the ballast bed becoming hard after being saturated causing centre binding.

The different characteristics of each type of material that is used in sleepers are the reasons different types of sleepers will have different failures and defects. Timber sleepers have the potential of rotting, splitting, and insect attacks degrading the material. Steel is susceptible to corrosion and fatigue cracking in the rail seat region. Concrete is also not perfect as it is vulnerable to chemical attacks (Kaewunruen and Remennikov, 2009; Ferdous *et al.*, 2015). Composite sleepers have similar defects or failures to the other materials; however, their long-term performance is unknown due to it being a recent development and little information on the fact is available (Ferdous *et al.*, 2015).

2.2.4.3 Ballast

Ballast is constantly subjected to certain factors that cause defects either to the material characteristics or the ballast bed profile. Contamination and fouling are the types of defects that can affect the material characteristics and for the ballast profile, a shortage or excess of ballast rocks (Lam *et al.*, 2014; Sadeghi *et al.*, 2019). Effective maintenance requires maintenance managers to obtain the right condition-monitoring data (Sadeghi *et al.*, 2019). Thus, before data collection takes place, the manager must know what to look out for and what the cause of the defects was.

Fouling is caused by operational loads of the train being transferred to the ballast via the sleepers, then the load rearranges the stones, splinters the stones, and creates a rise in the fines due to friction. Secondly, internal degradation of the ballast bed is caused by ballast fracture and abrasions relating to dynamic loading, rail surface defects, tamping, and chemical wear. Also fouling occurs because of external infiltration of alien fines by wind or washed in during heavy rain, and also contaminated due to dropping from freight trains carrying products such as coal. Lastly, fouling occurs due to infiltration from underlying granular layers (Lam *et al.*, 2014; Zaayman, 2017; Ciotlaus and Kollo, 2018).

Deviation or misalignments in the rail profile can be corrected through adjustments of the ballast as mentioned in Section 2.2.3.3. Adjustments are required to correct too little or too much ballast. The reason behind ballast not having enough rocks under and around the sleepers, and on the shoulders are because of external factors. Factors include non-existent or neglected ballast maintenance activities, people and animal interference spreading ballast around and away from shoulders, theft of ballast, dynamic loading of traffic crushing ballast, and the tamping process (Ciotlaus and Kollo, 2018).

2.2.4.4 Formations

Failure of the formation is usually as an effect of poor maintenance to other rail track components. One way of ensuring a long lifespan for the formation is maintaining other components diligently. The initial quality of the construction also factors into the life expectancy and life cycle cost of the formation. Formation failure (defect) is caused by (Jiang *et al.*, 2016; Zaayman, 2017; Mamou *et al.*, 2019; Schulz-poblete *et al.*, 2019):

- **Water:** The precipitation can lead to formation failure when the ballast bed retains moisture, due to fouling, for longer than the period of absorption of the formations saturating it. Surface flow entering the subgrade due to neglected drain maintenance and subsurface seepage prevented by a subsurface drain causing water to seep upwards into the subgrade.

- **Clay:** In the case of clay, swelling decreases the capillary space between particles; this reduces the water absorption of the soil and so the soil gets saturated faster, creating a slurry.

- **Water and clay combination:** A mixture of the two above causes can also take place, leading to failure of the formation.

2.2.4.5 Overhead Traction Equipment (OHTE)

As mentioned in Section 2.2.3.6, the OHTE are critical for transferring electricity to trains to ensure they operate at optimal speeds. Thus, the failures and defects regarding OHTE are identified. The literature that is analysed identified that electric arcs occurring between the contact wire and pantograph are indications of OHTE defects (Aydin *et al.*, 2015, 2018). The cause of electrical arcing is due to the following reasons (Aydin *et al.*, 2015):

- Incorrect static contact forces,
- Excess friction,
- Incorrectly set aerodynamics,
- Worn components, and
- Poor geometric adjustments.

Zaayman (2017) also identified that the defects of OHTE include anything from corrosion of the wires, shortages, breaks, obstruction of components due to birds building nests. These defects are linked to the causes of electrical arcing which in return can lead to OHTE becoming more damaged.

2.2.5 Railway Infrastructure Inspections and Monitoring

The condition monitoring of rail track infrastructure to obtain real-time data is critical to limit the risks involved with rail and ensure the safety of railways (MORI *et al.*, 2010). In many cases maintenance managers strive to follow preventive maintenance procedures as far as possible. To achieve effective preventive maintenance it is desirable to monitor rail track conditions continuously or on a regular basis. Monitoring methods that are currently in practice include manual inspections by maintenance crew, and also the use of special measuring vehicles. In the current landscape these monitoring methods are highly accurate. However, factors such as cost and sustainability controls curtail the frequency at which monitoring can be employed (Tsunashima *et al.*, 2015). Most railway companies face the same dilemma, their infrastructures are deteriorating due to age, and at the same time they struggle to keep up with the developments of new technologies. The dilemma prevents railway operators from performing adequate condition monitoring of infrastructure.

Infrastructure monitoring can, as mentioned, be done manually, which is time-consuming and cost-intensive, or by means of special measuring vehicles. Plasser and Theurer are the largest manufacturer of rail track condition monitoring vehicles. They can customise a vehicle with a variety of combinations of monitoring systems to suit a railway company's needs. Their vehicles are capable of speeds up to 160 km/h (Zaayman, 2017) whilst monitoring, depending on the type of measuring equipment attached. The following measuring technologies can be installed on Plasser and Theurer monitoring vehicles:

- Axle box acceleration measuring system
- Catenary parameter measuring system (voltage, pantograph pressure)
- Contactless inertial navigational track geometry measuring system
- Corrugation measuring system
- Contact wire geometry measuring system with mast pole detection system
- Rail profile measuring system
- Tunnel clearance, ballast profile, track centre distance measuring system.
- Monitoring system for contact wire wear
- Traction plate position measuring system
- Ultrasonic rail flaw detection system

Video monitoring systems can be used in conjunction with the above measuring systems to supplement the effectiveness of monitoring. The video systems currently used in rail include driver's view video system, contact wire position monitoring, rail component monitoring, third rail video system, thermal imaging, and head check monitoring systems.

This section only serves the purpose of an introduction regarding rail infrastructure monitoring and inspections. A structured review of the literature is conducted in Section 2.3, to identify the technologies that are currently used and emerging in the field of data acquisition, data transfer, data storage, and data processing with the task of condition monitoring.

2.3 Condition Monitoring Landscape - DAQ Technology

The intent of this section is to provide the necessary knowledge and background of railway infrastructure condition monitoring and processing technologies. First of all the background is discussed, followed by the fundamentals of a Data Acquisition System (DAS) which includes the key enabling technologies. This section also highlights another important aspect of the data acquisition (DAQ) landscape which is the carriers and devices that are used for implementing the sensor technology.

2.3.1 Background

Advancements in technology are the driving force behind organisations in various industries, resulting in them having to change their operations in order to stay competitive. This is seen by the rise of Industry 4.0 and how it impacts industries worldwide. Industry 4.0, and its technologies such as Internet of Things (IoT), is becoming a talking point for manufacturers and asset managers when addressing maintenance (Seebo, 2019).

As mentioned in Section 2.2.1.2, maintenance has evolved over the years creating different expectations for each generation, and this is mainly due to technological advancements (Moubray, 1997; Arunraj and Maiti, 2007; Zuashkiani *et al.*, 2011). PdM is the desired maintenance strategy asset managers would like to implement due to its benefits identified in Section 2.2.1.2. However, a PdM strategy can only be implemented via the use of an IoT approach. A IoT approach to maintenance involves the continuous monitoring and transmission of assets' condition data, storing of the data in a central repository, and the use of big data analysing techniques for sorting the data and identifying critical patterns (Seebo, 2019). James Manyika *et al.* (2015) of the McKinsey Global Institute, state the following:

> *"Better predictive maintenance using IoT can reduce equipment downtime by up to 50 percent and reduce equipment capital investment by 3 to 5 percent...In manufacturing, these savings have a potential economic impact of nearly $630 Billion per year in 2015"*

Emerging trends and technologies in DAQ, data sharing, and data processing have the potential of adding value to society and the economy. McKinsey & company identified nine areas, or as they call it "settings", to which IoT can add value. The nine areas of value addition by IoT are human, home, retail environment, offices, factories, worksites, vehicles, cities, and outside (James Manyika *et al.*, 2015). The areas obtain value by means of optimisation and prediction, with the help of emerging technologies. The benefits obtained from the implementation of IoT technologies has already presented itself in manufacturing companies, oil and gas companies, and other businesses. IoT consists of a vast network of technologies, thus, these underlying technologies are instrumental in the success of IoT (Dahlqvist *et al.*, 2019).

It is evident that with the advancement of technology, IoT technologies will become easier to implement. This can be seen from the increase of businesses that make use of IoT technologies from 13% in 2014 to about 25% currently. Dahlqvist *et al.* (2019) predicts that by the year 2023 there will be 43 billion IoT devices around the world, which is almost a threefold increase from 2018.

IoT technology is almost just as valuable to developing economies as it is to advanced economies. The amount of value that is generated by an advanced economy will be more due to the higher value associated with each deployment. However, the probability is higher that a developing country will have more possible applications for the technology. A contributing factor which supports the implementation of emerging technologies in developing countries is the fact that in some cases there is no technology that needs to be replaced by the new technology. This creates a shortcut for implementing the technologies in developing countries (James Manyika *et al.*, 2015).

It is noted from the literature that most of the studies conducted on IoT take place in industries related to manufacturing, supply chains, and customer service. The opportunities that arise with emerging technologies in railways is that it can transform business processes such as PdM, optimal asset utilisation, and higher productivity. These opportunities create a space for further research into interconnected condition monitoring networks or data acquisition systems for implementing PdM strategies on railway infrastructure assets.

2.3.2 Structured Literature Review

Railway infrastructure condition monitoring is an extremely large field, especially when looking at all the DAQ technologies available to acquire the condition monitoring data. Based on this reason it is decided that the use of a systematic review process will be best suited to identify the DAQ technologies that are relevant to this research and which align with its scope. The structured literature review enables the identification of relevant DAQ technologies that are utilised in railway infrastructure condition monitoring as well as the characteristics and capabilities of each. Ultimately by successfully completing this review, the **second** research objective in Section 1.3 is achieved.

2.3.2.1 Methodology

The strategy of this structured review utilised keywords or key search terms to guide the selection of appropriate literature from a scientific database. For this study the Stellenbosch University's library database is chosen as the scientific database for initial selection, which gives access to both *ScienceDirect* and *SCOPUS*. The keywords have a connection to railway infrastructure maintenance and the keywords used are: railway AND infrastructure AND condition AND monitoring; OR infrastructure AND condition AND monitoring AND IoT; OR condition AND monitoring AND IoT. The keyword IoT is included to incorporate the Industry 4.0 technologies used as part of the emerging condition monitoring practices by guiding the literature in a more digital orientated manner that is currently relevant. Figure 2.17 represents the systematic review process followed.

The initial database search (iteration 1) using the keywords, identified 65 papers as relevant. Iteration 2 assessed these 65 papers according to a set of predefined evaluation criteria, (see Table 2.2). The assessment included their respective titles, abstracts, and keywords. According to the assessment criteria, 45 of the initial papers were excluded. Iteration 3 is also based on the same evaluation principles as iteration 2, with the difference being that the full text of the 20 remaining papers was assessed. Due to iteration 3, 4 full text papers were excluded. The last step, iteration 4, added 10 fortuitous papers to be included in this study. These 10 papers were identified using the same database as initial selection or were extracted from reference lists of the initial papers.

The findings from the 26 reviewed papers were able to highlight key enabling technologies required in the condition monitoring landscape as well as valuable characteristics to take into consideration. From these findings the rest of this Section 2.3 can be categorised as follows: (i) data acquisition system, (ii) DAQ

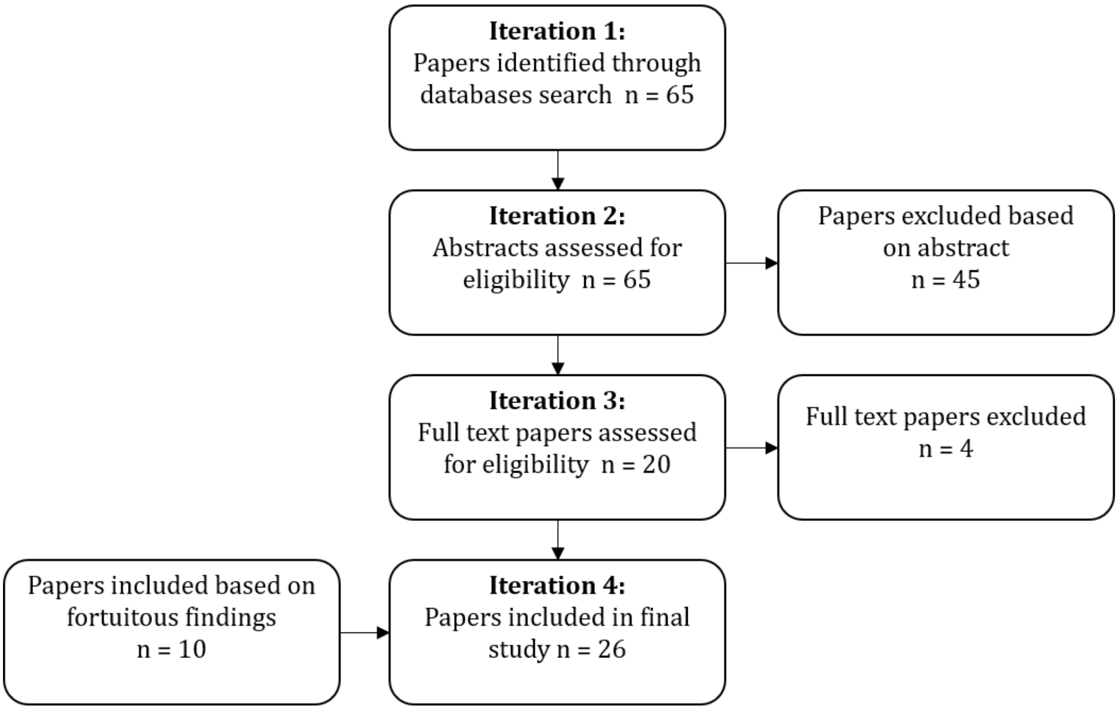


Figure 2.17: Systematic review process for identifying suitable documents

Table 2.2: Structured review inclusion/exclusion criteria

Criteria	**Justification**
Research published between 2009 and 2019	The rapid rate of technological developments creates the possibility for technologies to become irrelevant faster and faster. Thus, the decision is made to include papers from 10 years ago up until now to address only current and emerging DAQ technologies.
English publications	Only papers that are published in English are included.
Type of publication	Journal articles, conference proceedings, books, and research articles are accepted so as to not limit or be biased with the identification of potential DAQ technologies.
Technology related to infrastructure condition monitoring	The technologies identified during this review must in some manner be able to help with or be able to gather condition monitoring data of railway infrastructures – specifically infrastructure components mentioned in the scope, Section 2.2.2 (Figure 2.8).

technology implementation devices, and (iii) performance metrics for DAQ technology in the rail industry.

2.3.2.2 Bibliometric Analysis

This bibliometric analysis is responsible for providing the reader with background context to the papers that were selected for this research. Furthermore, it is important to note that this analysis includes only the 26 papers that are part of the final study. For this analysis the papers will be categorised based on (i) the year they were published, (ii) publication source type, and (iii) the authors' country of operations.

Year of Publication: The papers included in the study were all published from 2009 and onwards, see Figure 2.18, with the vast majority published more recently, from 2016 onwards. The upward trend of the graph indicates that this research field has become more relevant over time. The relevance is further supported by the fact that 19 of the 26 papers (73%) included were published post 2016.

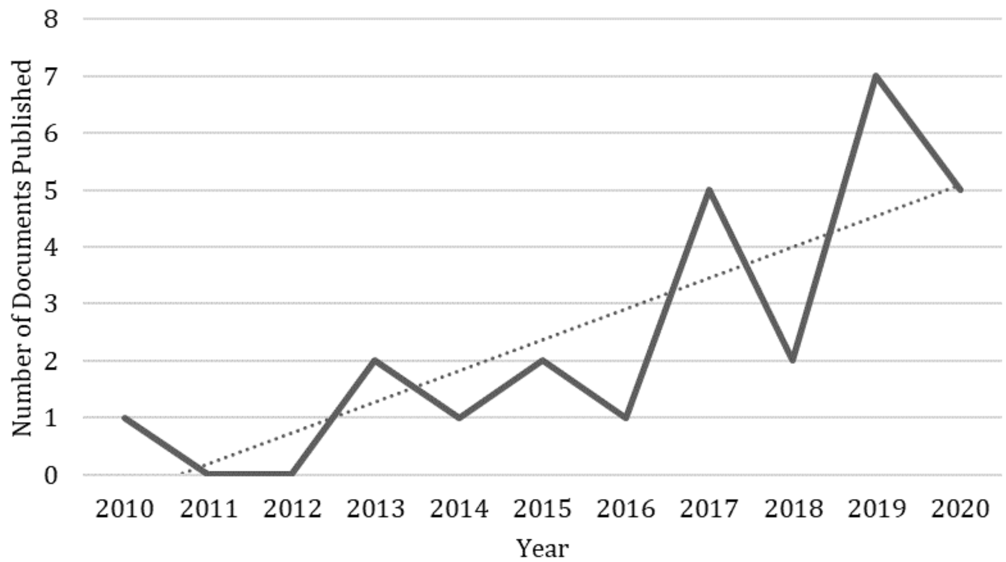


Figure 2.18: Papers published per year

Publication Source Type: As mentioned in Table 2.2, there were no stringent restrictions on the specific type of publications that would be included in this study. Thus, the make-up of the papers could have included various source types. However, only three different source types are included in this study, see

Figure 2.19, namely Journals (61.5%), Conference Proceedings (30.8%), and Books (7.7%). These three source types all are peer-reviewed, enhancing the scientific validity of this research. From the high percentage of conference proceedings, it can be said that this topic is still highly relevant as researchers are continuously discussing this topic at conferences as they are new.

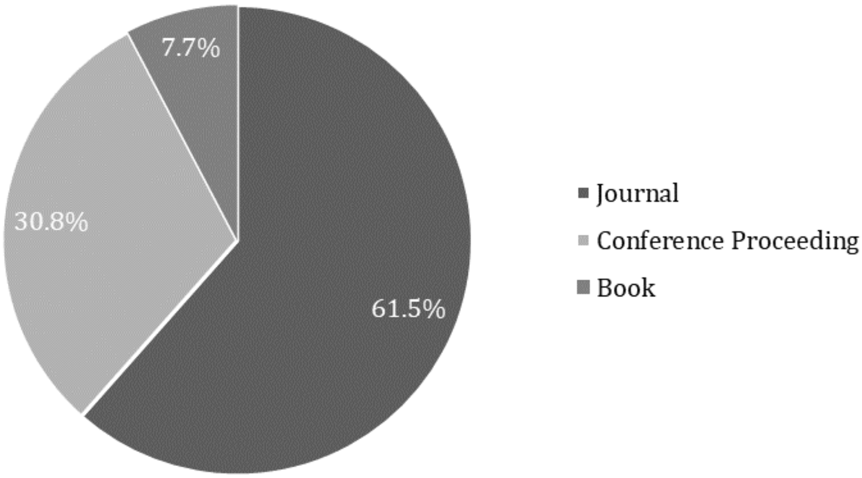


Figure 2.19: Publication type

Researcher Origins: Taking into account the geographical location of the main authors as well as the co-authors, it is possible to gather an idea of where this research can be more applicable and relevant. From Figure 2.20, it can be seen that most of the research is conducted in European countries which are generally viewed as countries with traditionally strong railway industries. The United States of America (USA) is the only country not situated in Europe to also present more than one publication in this study. Though not having a railway industry as big as that of Europe, the USA railway industry is highly rated.

2.3.3 Data Acquisition System

Technological advancement is one of the driving forces behind the evolution of maintenance strategies and their growing dependency on effective condition monitoring practices. These developments are seen in the form of technologies becoming more digitised and more automated, the increase in capabilities, and the costs of

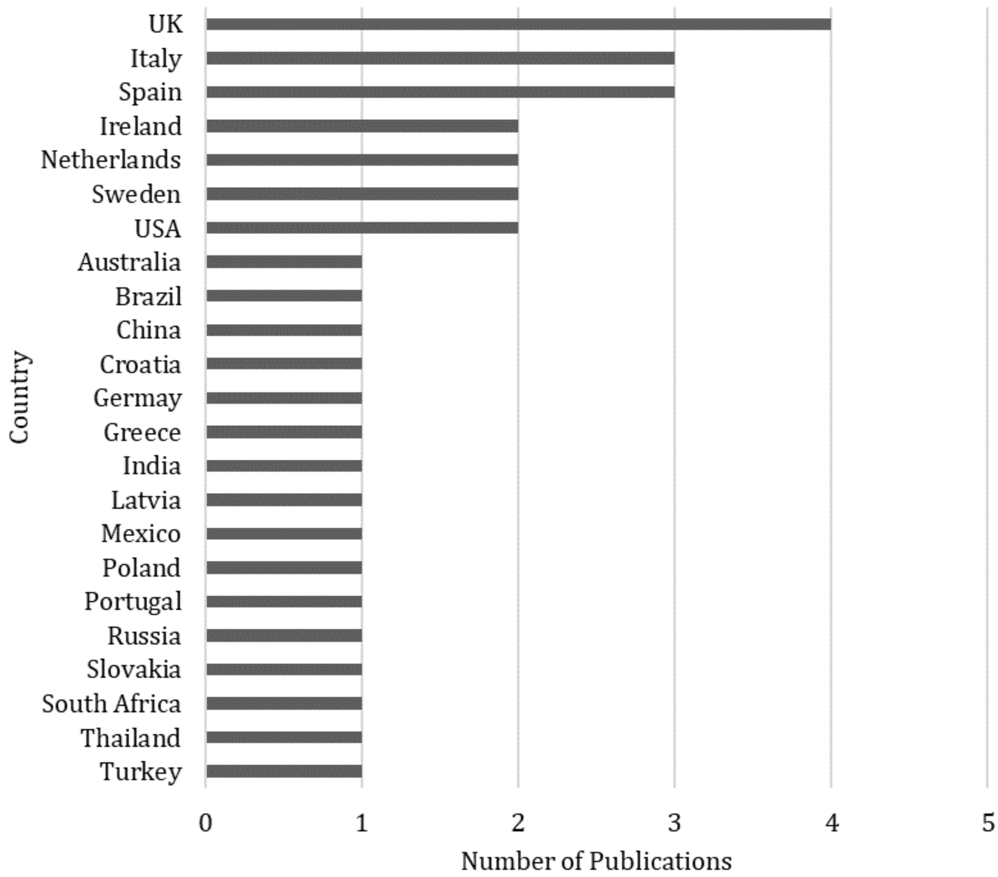


Figure 2.20: Authors' country of origin

technologies which are decreasing (Hodge *et al.*, 2015; Qian *et al.*, 2019). Furthermore, the improvement opportunities include reducing the human inspection requirements and the overall maintenance through early fault detection and prediction (Hodge *et al.*, 2015).

From the structured review it is found that with the advancement of technologies the landscape of infrastructure condition monitoring has become very complex. Thus, a complete systems perspective is required to understand the DAS used for condition monitoring. The success of a DAS is reliant on key enabling technologies. These key enabling technologies can be subdivided into two main categories, namely the DAQ technologies, and Information and Communication Technologies (ICTs). See Figure 2.21 for the overview of the key enabling technologies that form part of the complete DAS for condition monitoring in railways.

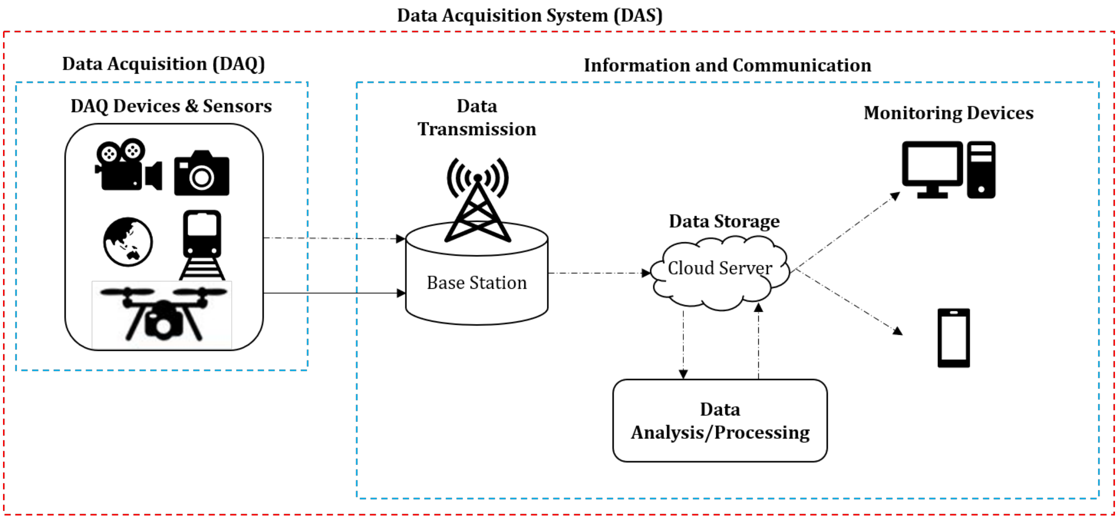


Figure 2.21: Data Acquisition System, adapted from Hodge *et al.* (2015)

Different characteristics which a railway condition monitoring DAS can include:

- Means of acquiring the relevant condition data can be automated (e.g. using an automated vehicle or carrier to monitor) or manual (e.g. labour force taking physical measurements or making visual observations).
- The analysis of the data can either be done in real time (e.g. machine learning methods or other algorithms) or the analysis can be performed once all the data is obtained (retrospective analysis).
- The results obtained from the data analysis can be monitored either on site, at the infrastructure component, or remotely using a network interactive device.

However, a desirable approach to railway infrastructure maintenance would include the following characteristics: real-time DAQ, analysis and processing, and decision-making activities. The success of such an approach relies mostly on the key enabling technologies mentioned previously.

Kilian *et al.* (2016), highlight that a basic DAQ technology system includes the following components: (i) sensor module, which interprets the physical factors; (ii) signal conditioning module, which converts the signal obtained from the sensor module which can be analogue functions and digital functions; (iii) output module, which provides the measurements in the appropriate form required; and (iv) control module, which is only present in active sensing systems and is responsible for interpreting the output and feeds the information back to an actuator that can manipulate the physical process.

ICTs are responsible for connecting and storing all the condition data obtained from the DAQ technologies system. The main components of ICTs are: (i) data transmission, which can be either be wired or wireless transmission of data from the DAQ technology to the storage; (ii) data storage or cloud server, which consists of hardware, networks, storages, services, and interfaces that enable the delivery of computing as a service; (iii) real-time analysis and processing, which is software that is able to interpret large amounts of data and provide suggested actions accordingly; and (iv) monitoring devices, that enable operators to interact with the information that is stored in the cloud (Morant *et al.*, 2012; Hodge *et al.*, 2015).

Current DAQ technologies incorporate numerous sensors with capabilities of monitoring infrastructure conditions (Milne et al., 2016). However, Hodge et al. (2015) state that a majority of these DAQ technologies have not utilised the full potential of advanced ICT. Emerging DAQ technologies do not require the full utilisation of ICTs. These technologies can be self-reliant and instrumental for improved condition monitoring. Section 2.3.4 and Section 2.3.5, which follow, highlight the important features and characteristics of current and emerging technologies in the railway infrastructure condition monitoring field.

2.3.4 Data Acquisition Technology

As mentioned in Section 2.3.2, the identification of suitable DAQ technologies utilised in railway infrastructure condition monitoring is the main goal of the structured review. The DAQ technologies are seen as the tools or equipment that physically measure or monitor the condition of the railway infrastructure. A simple description of what the actual purpose of DAQ technologies is that it:

> *"provides the link between the data-generating sensors and data-storing recording devices... can also provide the means for driving external actuators from a computer, by generation of external excitation signals." – (Efunda - Engineering Fundamentals)*

The information provided in this section is supplemented by Tables B.3 to B.6 which are presented in Appendix B.

The 26 papers that are reviewed led to the identification and final inclusion of 26 relevant DAQ technologies. These are all able to monitor one or more of the failure methods mentioned in Section 2.2.4. The identified technologies have different means of implementation, which can be fixed to a specific location, manually operated by a human, or attached to a vehicle (referred to as a 'carrier' in this research). More details on the implementation methods are presented in Section 2.3.5. The DAQ technologies of note are shown in Table 2.3.

Table 2.3: DAQ Technologies included in study

DAQ Technology	**Reference**
Acoustic emissions	Tatarinov *et al.* (2019)
Axle box measurements	De Rosa *et al.* (2019); Molodova *et al.* (2016); Kaewunruen (2014); Zaayman (2017)
Concrete surface strain gauge	Qian *et al.* (2019)
Corrugation measuring system	Zaayman (2017)
Differential global positioning system (DGPS)	Zaayman (2017)
Distance measuring indicator (DMI)	Zaayman (2017)
Eddy current	Molodova *et al.* (2016); Zaayman (2017); Campbell (2013)
Electrical resistivity tomographic (ERT) imaging	Gunn *et al.* (2018)
Global navigation satellite system (GNSS)	Chen *et al.* (2018)
Ground penetrating radar (GPR)	Kovacevic *et al.* (2016); Qian *et al.* (2019); Fontul *et al.* (2016); Zaayman (2017)
Hammer test	Molodova *et al.* (2016); Montiel-Varela *et al.* (2017)
Inertial measuring unit (IMU)	Chen *et al.* (2018); Zaayman (2017)
Infrared imaging	Garrido *et al.* (2018)
Laser scanning systems	Vagnoli and Remenyte-Prescott (2018); Gunn *et al.* (2018); De Rosa *et al.* (2019); Skibicki (2018); Chen *et al.* (2018); Zaayman (2017)
Matrix based tactile surface sensors (MBTSS)	Qian *et al.* (2019)
Micro electrical mechanical systems (MEMS)	Milne *et al.* (2016); Vagnoli and Remenyte-Prescott (2018)
Monochromatic line scan camera	Zaayman (2017)
Optical gauge measuring system (OGMS)	Zaayman (2017)
Piezo electrical systems	Milne *et al.* (2016)
Radiography	Campbell (2013)
Seismic refraction tomography and surface wave	Kovacevic *et al.* (2016); Gunn *et al.* (2018)
"SmartRock"	Qian *et al.* (2019)
Total station	Vagnoli and Remenyte-Prescott (2018); Gunn *et al.* (2018); Chen *et al.* (2018)
Ultrasound	Tatarinov *et al.* (2019); Molodova *et al.* (2016); Campbell (2013); Zaayman (2017)
Visual camera imaging	Kovacevic *et al.* (2016); Tatarinov *et al.* (2019); Gunn *et al.* (2018); Skibicki (2018); Chen *et al.* (2018); Campbell (2013); Zaayman (2017)
Wheel impact load detector (WILD)	Qian *et al.* (2019)

For clarity, not all DAQ technologies are fully explored in this section, only the technologies with the most occurrences in the 26 included papers. For more detail regarding the other technologies, see Appendix B. Figure 2.22, represents the number of times each of the identified DAQ technologies is mentioned and explored in the selected papers. The most referenced technologies are:

- **Visual camera imaging:** These methods are explored in 6 out of the 26 papers (23.1%). It is the method of using visual images obtained by a high-resolution camera in conjunction with video analysis software to measure and inspect objects. In combination with a UAV this technology is capable of operating at up to 20 km/h whilst observing the topography of railway embankments and trackbed structure. Topography is observable through measuring the 3D coordinates, geometry, and detection of settlement and soil movement (Kovacevic *et al.*, 2016). It is also capable of measuring the displacement of the OHTE contact wire in a 2D plane Skibicki (2018). Camera imaging is also used to detect defects or abnormalities of infrastructure and equipment. The possibilities of this technology are endless with the capability of substituting human operators for inspection purposes and the versatility of it being able to be attached to all of the carriers in Section 2.3.5 (Zaayman, 2017; Kovacevic *et al.*, 2016; Chen *et al.*, 2018).

- **Laser scanning systems:** These are explored in 6 out of the 26 papers (23.1%). 1D and 2D laser scanning technology makes use of the controlled deflection of laser beams, visible or invisible, combined with a laser rangefinder to survey objects. Similarly, LiDAR (light detection and ranging) is a laser scanning system that senses the 3D space by incorporating laser, scanners, and GPS for mapping 3D natural and man-made environments (Gunn *et al.*, 2018). Laser scanning technology is capable of monitoring displacement and wear of OHTE (Vagnoli and Remenyte-Prescott, 2018; Skibicki, 2018). It also possesses the capability of determining the geometry of a railway track (De Rosa *et al.*, 2019; Chen *et al.*, 2018). The versatility of this technology is similar to that of visual camera imaging as it is also compatible with almost all the carriers identified (Zaayman, 2017; Chen *et al.*, 2018; De Rosa *et al.*, 2019).

- **Ground penetrating radar (GPR):** This technology is explored in 4 out of the 26 papers (15.3%). It is an electromagnetic radar used to detect and define physical boundaries of shallow structures. GPR capable of monitoring up to 70 km/h with a custom-made cart, by observing the relative dielectric permittivity, electrical conductivity, magnetic permeability, and electromagnetic wave velocity of the trackbed structure. It identifies ballast depth variation, trackbed condition, fouling, intermixing between ballast and subgrade materials, and the relative degree of moisture in the ballast (Kovacevic *et al.*, 2016; Qian *et al.*, 2019). In basic terms, it records the subsurface profile and ballast particle distribution (Zaayman, 2017). According to Fontul *et al.* (2016), by utilising a designated track inspection vehicle (Plasser and Theurer EM120), GPR can be used at speeds of up to 120 km/h.

- **Ultrasound:** These monitoring methods are explored in 3 out of the 26 papers (11.5%). It utilises high-frequency sound energy to perform examinations and make measurements of internal cracks, non-bonds, and inclusions in materials, most commonly in metals (Campbell, 2013). It is capable of identifying internal cracks and their intensity in concrete sleepers as well (Tatarinov *et al.*, 2019). Furthermore, it can detect rail defects in proximity to insulated rail joints (Zaayman, 2017; Molodova *et al.*, 2016). The carriers that are compatible with ultrasound monitoring technologies need to be in contact with the rails which are rail track trolleys, in-service trains, and rail inspection vehicles (Molodova *et al.*, 2016; Zaayman, 2017). Zaayman (2017) identified ultrasonic transducers that are capable of detecting internal rail flaws at speeds of $60km/h$.

- **Total station:** This is explored in 3 out of the 26 papers (11.5%). It is an electronic / optical instrument used for surveying. It consists of an electronic transit theodolite integrated with electronic distance measuring, including angle encoder, automated target recognition sensor, tilt compensator, and electrical discharge machine (Gunn *et al.*, 2018). It can measure vertical as well as horizontal angles, and also the slope distance from the instrument to a particular point. The on-board computer is capable of performing triangulation calculations based on the collected data. Attached to a rail track measuring trolley it is able to help determine the track geometry (Chen *et al.*, 2018). Implementation method is either manually transported or fitted on a rail track measuring trolley.

- **Eddy current:** These technologies are explored in 3 out of 26 papers (11.5%). It is a non-destructive (NDT) method utilising electromagnetic induction to detect and characterise surface and subsurface flaws in conductive materials. It is capable of determining surface or near-surface rail defects when combined with a rail track measuring trolley (Campbell, 2013; Molodova *et al.*, 2016; Zaayman, 2017).

- **Axle box measurements:** These are explored in 3 out of the 26 papers (11.5%). Utilises accelerometers mounted to a train's axle box to measure the displacement of the train due to the track. The capabilities include measuring the absolute displacement of the train wheels to determine the vertical and lateral track irregularities, from which the track geometry can be obtained (Kaewunruen, 2014; Molodova *et al.*, 2016; Zaayman, 2017; De Rosa *et al.*, 2019). Defects include corrugation, inadequate welds, and squats. The designated railway inspection vehicle investigated by Kaewunruen (2014) is capable of measuring the railway track displacement at speeds of 60 km/h and the vehicle mentioned by Molodova *et al.* (2016) was capable of operating at speeds of 100 km/h.

Figure 2.23a and Figure 2.23b are created by analysing the technologies and what infrastructure components they monitor. From Figure 2.23a, it is seen that most of the papers investigate the monitoring of the rails and trackbed (ballast and formation), whereas the condition monitoring of surface drains are not so frequently researched. The number of identified technologies that monitor each of the respective infrastructure components, see Figure 2.23b, follows a similar pattern to the number of papers that address those specific infrastructure components. Based on these figures it can be assumed that it represents the criticality ranking of the railway infrastructure components in the scope and it can also be an indication of the availability of technology to monitor the respective railway infrastructures.

2.3.5 DAQ Technology Carriers

Recent developments in technology cannot eliminate the necessity of relying on manual labour for rail track maintenance. Rail track maintenance requires human beings to periodically perform visual inspections, due to it still being a requirement for prioritising a large portion of maintenance activities (Qian *et al.*, 2019). These manual inspections are time-consuming, and cost-intensive (Zaayman, 2017), as well as having limitations in its capability of sensory monitoring (Gunn *et al.*, 2018; Qian *et al.*, 2019).

As part of the structured literature review, a fundamental characteristic of DAQ technology came to light. The way in which the data is acquired differed from technology to technology; however it is noted that these technologies share similar means of implementation. Whereas, the means of implementation refers to the tool, human, or vehicle that enables or supplements the DAQ technology to acquire data to ultimately ensure more efficient condition monitoring these are finally referred to as the carriers of DAQ technology. From the reviewed papers the following categories of carriers are identified, (i) designated rail inspection vehicle, (ii) in-service trains, (iii) railway measuring trolleys, (iv) unmanned vehicles

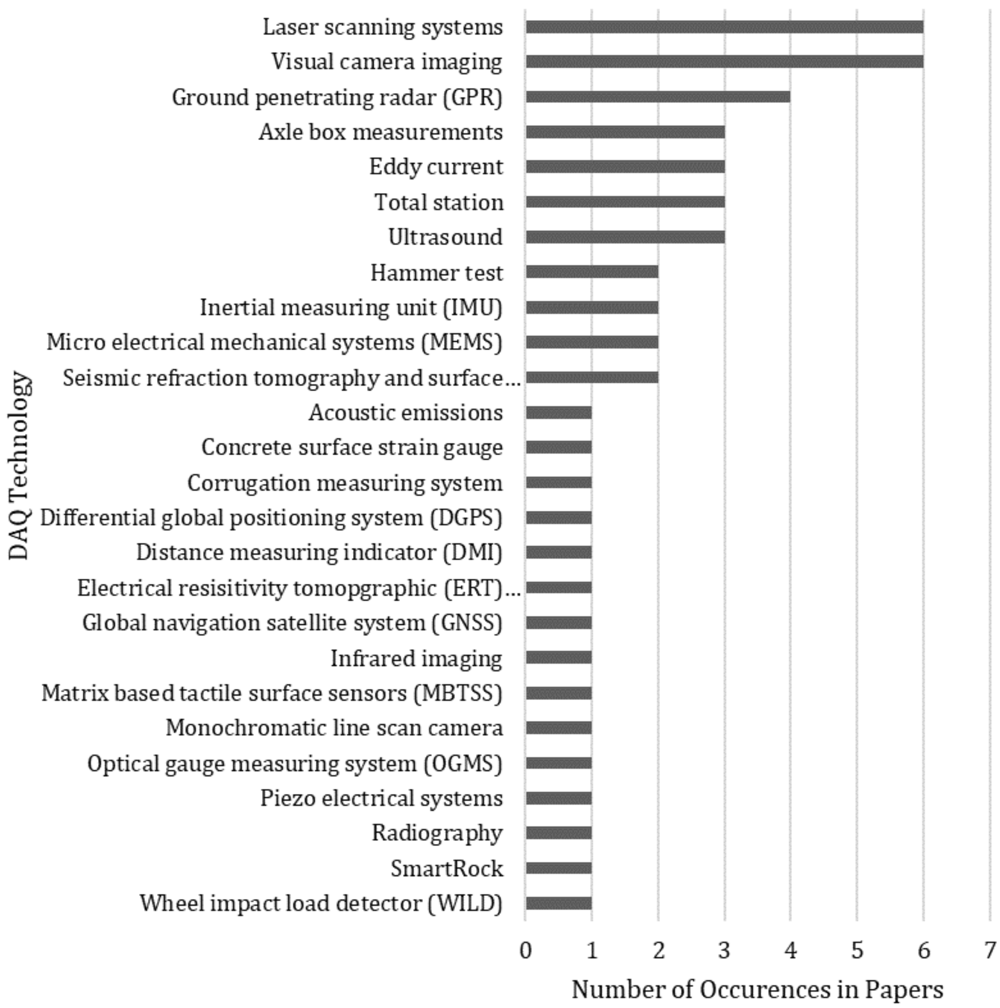
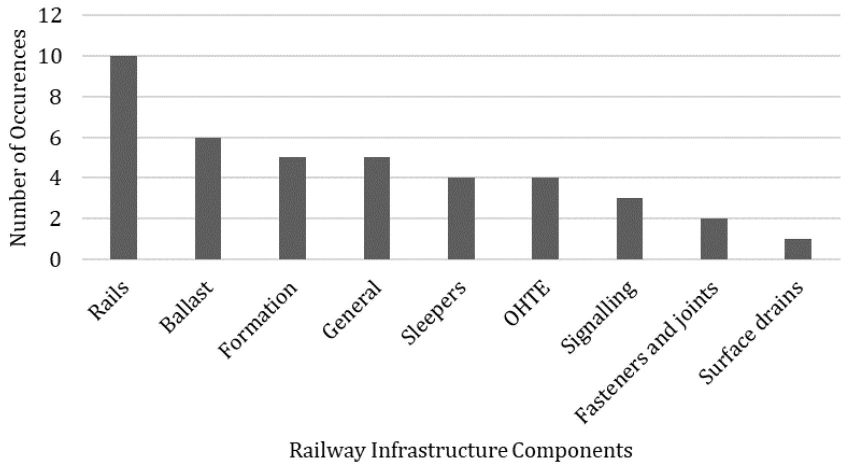


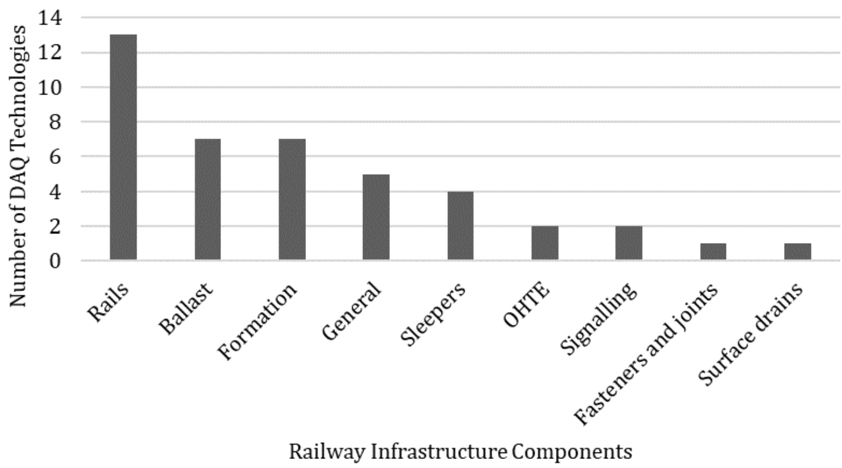
Figure 2.22: Most referenced DAQ technologies

(UAVs) or drones, and lastly (v) other carriers, which includes manual human operation and fixed location monitoring. See Figure 2.24, for the distribution of carriers across the 26 reviewed papers.

It is evident from the reviewed literature that in-service trains, specialised track inspection vehicles, measuring trolleys, and UAVs are the most frequently used carriers. Although these carriers can operate and measure accurately, the frequency at which monitoring can be done is determined by factors such as cost and sustainability controls (Tsunashima *et al.*, 2015). Each of the carriers features various combinations of attachments (DAQ technology) to monitor the condition of railway infrastructure, see Table B.7. The total number of technologies from the review that are attachable to the carriers are as follows: in-service trains 2 out



(a) in selected papers



(b) by DAQ technologies

Figure 2.23: Railway infrastructure components monitored

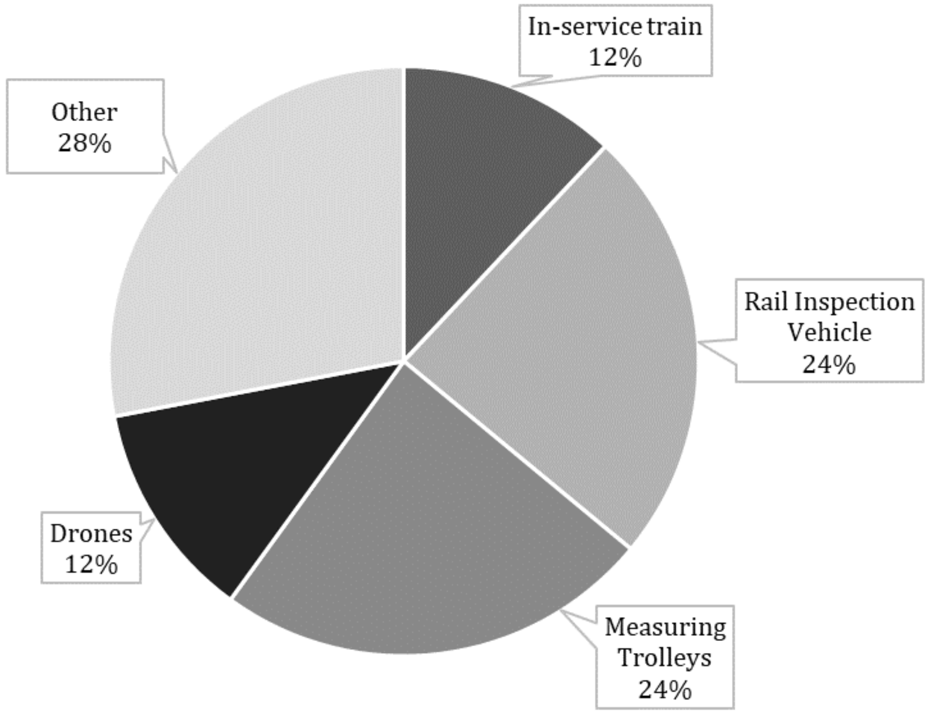


Figure 2.24: Implementation devices / carriers

of 26 (7.6%), rail inspection vehicles 11 out of 26 (42.3%), measuring trolleys 6 out of 26 (23.1%), UAVs 3 out of 26 (11.5%).

Although designated rail inspection vehicles are accurate, the problem is that these vehicles require significant capital investment, and are expensive to operate and maintain (Chen *et al.*, 2018; De Rosa *et al.*, 2019). Utilising in-service trains for monitoring infrastructure is therefore preferred. In-service trains also have the benefit of being able to monitor continuously in a cost-efficient way, while not posing a risk of traffic delays which could be the case with rail inspection vehicles (Fontul *et al.*, 2016; De Rosa *et al.*, 2019). However, not all DAQ technologies can be attached to in-service trains due to high maintenance costs of the technology and the lack of robustness (De Rosa *et al.*, 2019). For shorter track sections, the use of rail track measuring trolleys is preferred as they are less expensive and still capable of recording accurate data (Chen *et al.*, 2018). For visual inspection, UAVs are becoming increasingly popular due to the fast acquisition of data, ease of operability, and the capabilities of reaching hard-to-reach places (Kovacevic *et al.*, 2016; Garrido *et al.*, 2018; Gunn *et al.*, 2018).

2.3.6 Condition Monitoring Technology and Rail

Railway infrastructures demand real-time condition monitoring of their structural health over their life cycle, encompassing maintenance, restoration and renewal activities to enhance the performance of the railway network (Vagnoli and Remenyte-Prescott, 2018). The function of condition monitoring in rail as described by Hodge *et al.* (2015) is,

> *"Condition monitoring detects and identifies deterioration in structures and infrastructure before the deterioration causes a failure or prevents rail operations."*

Designated rail track inspection vehicles are highlighted as very accurate (Chen *et al.*, 2018), and in this review it is one of the most referenced carriers. The review also identified it as the carrier with the highest DAQ technology compatibility (attachments), see Table B.7. Thus, this section aims at exploring designated inspection vehicles.

2.3.6.1 Track Geometry Monitoring

Track geometry that does not conform to specific standards can cause a safety issue. Therefore, early detection of irregularities in the geometry of a track can mitigate potential issues. The overall geometry of existing railway tracks is monitored regularly by designated rail inspection vehicles which can survey the geometry at high speeds. These are not as accurate as measuring trolleys, and due to their cost and inflexibility they are deemed not ideal for short track section where precision is required (Chen *et al.*, 2018). Track monitoring vehicles manufactured by Plasser and Theurer come standard with two different types of measuring systems, which are Position and Orientation System for Track Geometry (POS/TG) and Optical Gauge Measuring System (OGMS). The POS/TG system measures track geometry in millimetres as well as calculating standard deviations of the track irregularities, and records navigational outputs at the measurements. The POS/TG system consists of a computer system which integrates data received from the Inertial Measurement Unit (IMU), Differential Global Positioning System (DGPS), and Distance Measuring Indicator (DMI) (Zaayman, 2017). Their features are:

- **IMU:** Senses three-dimensional acceleration and rotation to determine the track position in space. Track profile deviations can determined from the positional space map.
- **DGPS:** Adds the exact location data acquired to the other measured data. More accurate than normal GPS.

- **DMI:** External sensor which determines distance from the rotation of the train wheels.

The OGMS consists of a set of lasers, mirrors, and cameras mounted on the measuring frame. The OGMS sensors along with the IMU, through triangulation, can measure horizontal displacement of the rails. Track geometry is measured at 250 mm sampling intervals (Zaayman, 2017), and the parameters measured by the two systems include horizontal rail alignment, vertical rail alignment, cant, gauge, twist, curve radius, gradient, position, speed, distance, events (e.g. tunnels and bridges), and ambient temperatures (Zaayman, 2017; Chen *et al.*, 2018).

2.3.6.2 Rail Track Monitoring

Rail monitoring is split into five groups depending on the defects that require recording, be it rail wear, surface cracks, rail corrugation, internal rail defects, or geometry (Kaewunruen, 2014; Molodova *et al.*, 2016; Zaayman, 2017; De Rosa *et al.*, 2019). Each of the five groups makes use of different monitoring equipment. Surface cracks are identified using a monochromatic line scan camera mounted to the bogie frame of the monitoring vehicle. The images are acquired and stored to be evaluated alongside other forms of measurements to compare rail surface defects with geometry or rail defects (Zaayman, 2017). Eddy current technology can also be used to detect rail surface defects (Campbell, 2013; Molodova *et al.*, 2016).

Rail wear is monitored by an optical measuring system, consisting of lasers and cameras. The rail profile is captured by a high resolution camera which then converts the picture into a format which gives it coordinates. The captured image is digitally analysed, compared to a new rail profile, and the rail wear is calculated. The rail wear monitoring takes place at 250 mm sampling intervals, and calculates the wear at speeds up to 300 km/h with an accuracy of plus-minus 200 μm. This system is able to perform real-time analysis on the rail profiles determining the rail height and width wear to the rails, wear of the crown, side wear, and the gauge and field side over for both rails (Zaayman, 2017).

Rail corrugation can be measured by a system specifically designed to measure corrugations. The corrugation is analysed based on different wave lengths. The rail corrugation data can be collected at speeds of up to 300 km/h, with a sampling interval of every 5 mm travelled (Zaayman, 2017). Finally internal rail flaws are detected by means of ultrasonic transducers mounted on a telescopic axle. The ultrasonic detection system is able to detect internal flaws in all aspects of the rail profile (Molodova *et al.*, 2016). The system consists of fourteen transducers per rail to detect internal defects. These transducers are able to detect internal flaws up to speeds of 60 km/h. The data obtained from the ultrasonic signals is analysed inside of the measuring vehicle, and used to create a side profile of the rails (Zaayman, 2017).

2.3.6.3 Structure Clearance and Ballast Monitoring

The infrastructure monitoring vehicles can utilise laser mirror scanners to scan for the profiles of tunnels, platforms, adjacent lines, and other structures, to ensure that nothing obstructs the vehicle's structure gauge. If this were to happen the occurrence will be recorded along with the location information. This scanner is also capable of determining if there is an excess or a deficit in the amount of ballast on either shoulder (Zaayman, 2017; De Rosa *et al.*, 2019).

2.3.6.4 Monitoring Via Video Recording

Infrastructure monitoring vehicles sometimes come equipped with high resolution video recording systems. These are capable of operating at speeds of 100 km/h while taking 15 pictures every second. The pictures are uploaded to a central network to be analysed either on the vehicle, or on any computer with the correct analysis software. The two different video systems used are a driver's view system, and a system directed at taking pictures of the OHTE (Zaayman, 2017).

2.3.7 Technology Maturity

When investigating new and emerging technologies, it is good practice to determine where in terms of its life cycle a technology stands. Another word used for this technology life cycle assessment is maturity. Technology is mature when it starts to become highly competitive and has the option of being integrated into products and processes safely (Rodríguez Salvador *et al.*, 2019). Improvements for a technology at this stage in its life cycle is seen as *"evolutionary rather than revolutionary"* – Segen's Medical Dictionary (2011). Gao *et al.* (2013) describes two dimensions for measuring technological changes, one being the technology's competitive impact and two its integration in products and processes. To best describe the concept of the technology life cycle, the S-curve graph can be used, see Figure 2.25. Gao *et al.* (2013) further describes the two dimensions of measuring technological changes using the S-curve, where the technology performance is related to its competitiveness and adoption in other products and processes. A new technology's performance slowly progresses because it is in its early stages, meaning low levels of understanding, control, and rate of diffusion. Technology that is improving experiences exponential growth in its performance, a method of assessing this growth is the Technology Readiness Level (TRL) scale. Once a technology becomes mature, its growth starts to slow down due to all the knowledge about that technology has been exhausted. The last step in a technology's life cycle is the ageing process where the performance starts to decline because the technology becomes rendered obsolete as new technologies emerge that is more efficient and cheaper (Chisi, 2019).

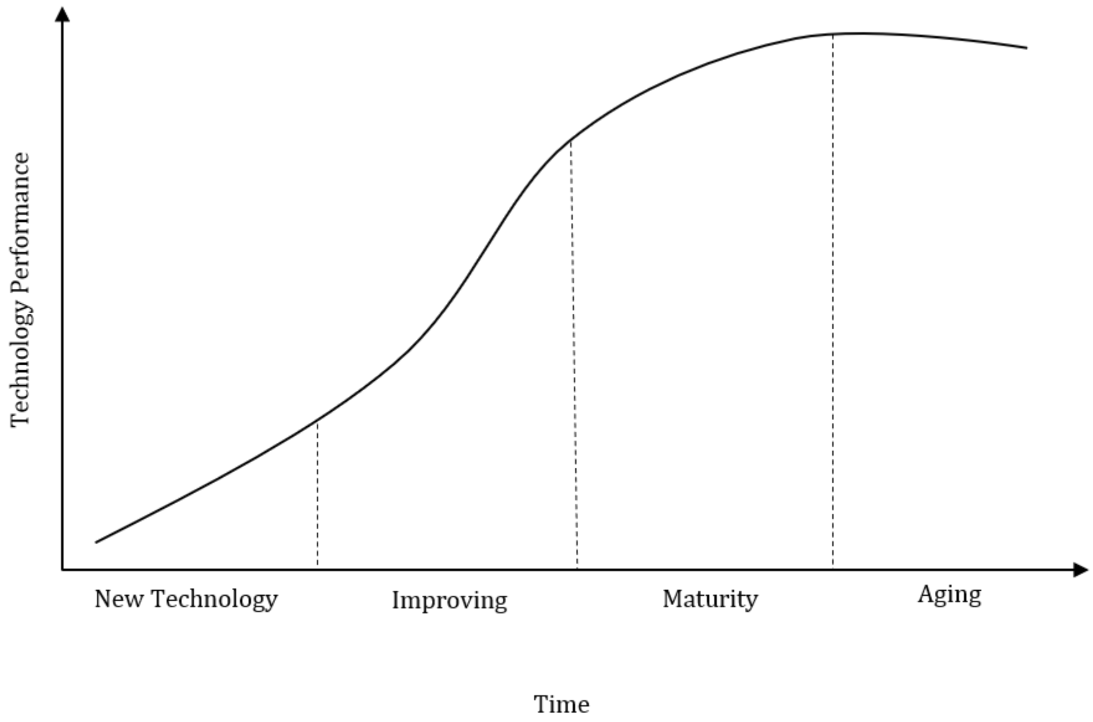


Figure 2.25: S-curve concept of technology life cycle, adapted from Chisi (2019)

As mentioned in the explanation of the different technology maturity stages (S-curve), technology readiness levels or TRLs can be used as a measurement system to assess the maturity of technology during its improving/growing stage (Chisi, 2019). The earliest TRL measurement systems were created by the National Aeronautics and Space Administration (NASA) in the late 1980s and ever since then updated versions were used (Engel *et al.*, 2012). TRL evaluates a technology according to its development process by subdividing it into several clearly defined steps that are the different levels. The TRL scale incorporates nine levels, whereas TRL 1 is the lowest and TRL 9 is the highest. Furthermore, TRL 1-3 is categorised as *research*, TRL 4-6 is categorised as *development*, and TRL 7-9 is categorised as *deployment*. Table 2.4 summarises the nine TRL levels.

Table 2.4: Technology readiness levels, adapted from Armstrong (2015)

TRL	**Definition**	**Description**
TRL 1	Basic research	Basic principles observed and reported

Continued on next page...

Table 2.4 – *continued from previous page*

TRL	Definition	Description
TRL 2	Technology formulation	Technology concept and/or application formulated
TRL 3	Applied research	Experimental proof of concept
TRL 4	Small-scale prototype	Technology validated in a laboratory
TRL 5	Large-scale prototype	Technology validated in a relevant environment
TRL 6	Prototype system	Technology demonstrated in a relevant environment
TRL 7	Demonstration system	Technology prototype demonstration in operation environment
TRL 8	First commercial scale system	Actual technology complete and qualified though test and demonstration
TRL 9	Full commercial application	Actual technology proven in operational environment

2.4 Chapter 2 Summary

This chapter started by deriving the foundation of maintenance from asset management to gather an understanding of maintenance and its purpose. The first section further discussed railway infrastructure maintenance, from which the infrastructure components included in the scope are investigated. This helped with understanding the functions of each of the components as well as their respective failure modes and causes – determining ways to detect and prevent failures with the help of condition monitoring. The second part of this chapter identified suitable current and emerging DAQ technologies to perform efficient condition monitoring. Various carriers that supplement the DAQ technologies' monitoring capabilities are also investigated. The chapter concludes by answering secondary research questions one and two from Section 1.3.

Chapter 3

Research Design and Methodology

3.1 Introduction

This chapter covers the methodology used for developing a decision support framework which enables the selection and adoption of emerging data acquisition (DAQ) technologies by railway operators. The methods used to address the research questions and objectives are presented, as stated in Section 1.3,. The methods are compared with each other to select the methods which will be best suited for the research requirements. Figure 2.1 shows the position of Chapter 3 in support of the other chapters.

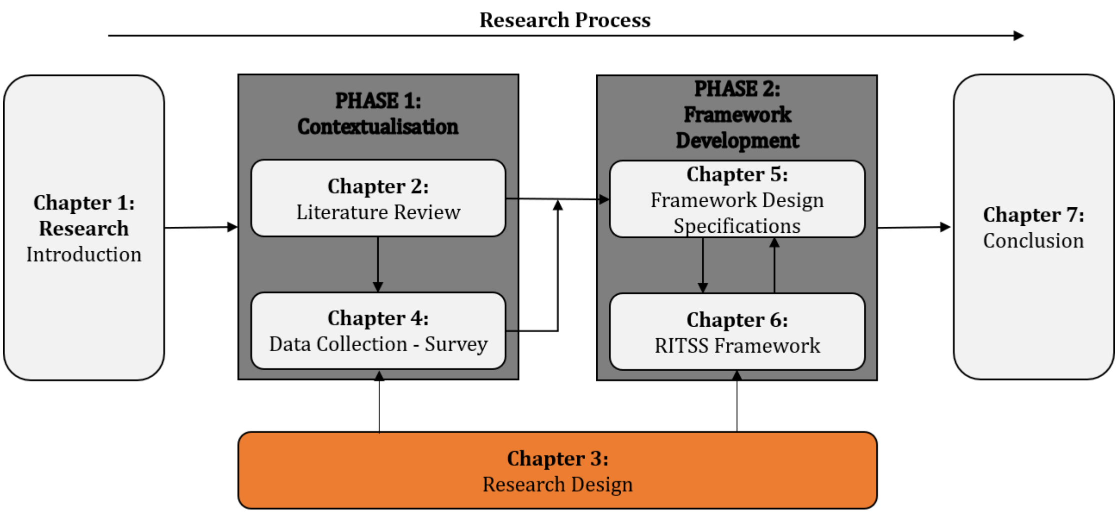


Figure 3.1: Research design: Chapter 3

3.2 Research Approach

It is essential at the outset to define the term 'research approach'. According to Creswell (2014), research approaches "are plans and procedures for research that span the steps from broad assumptions to detailed methods of data collection, analysis, and interpretation". Thus, it is the strategy to answer all of the research questions in this study systematically and scientifically. From the literature, three different research approaches are identified and considered for this study, these being (i) qualitative, (ii) quantitative, and (iii) mixed method (Creswell, 2014; Creswell and Creswell, 2017; Bryman and Bell, 2018). Furthermore, it is found that a research approach consists of three key components, according to Creswell and Creswell (2017), which are the philosophical worldviews (Section 3.2.1), the research design (Section 3.2.2), and the research methodology (Section 3.2.3). In Figure 3.2, the relationship between each of the components is illustrated.

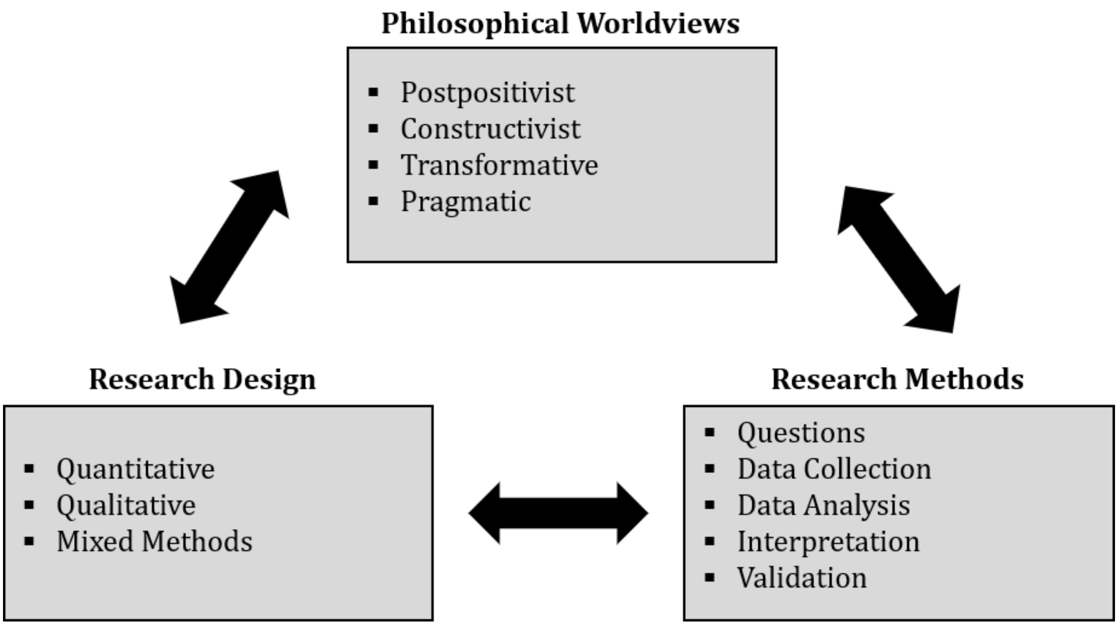


Figure 3.2: Research framework (Adapted from Creswell and Creswell (2017))

3.2.1 Philosophical Worldviews

Philosophy plays a significant role in research by being the foundation upon which all research is based. Thus, researchers need to be aware of the specific assumptions they make to gather knowledge during their respective studies. The particular assumption a researcher makes can shape the processes and conduct of inquiry (Creswell and Plano Clark, 2011). When articulating these philosophical assumptions in research, the following requires consideration:

1. The worldview(s) the research foundation is based on.
2. The elements of the worldview(s).
3. How these elements relate to specific procedures in the research process.

Creswell and Creswell (2017), further highlight that researchers must explicitly state all the philosophical assumptions in their research.

The term worldview is used to describe the philosophical assumptions made in research, whereas these assumptions consist of a basic set of beliefs or assumptions that guide inquiries. Another term used interchangeably with worldview is *paradigm*. From Figure 3.2, it is seen that four different worldviews are considered for this study and they are *postpositivist*, *constructivist*, *transformative*, and *pragmatic* (Creswell and Plano Clark, 2011; Creswell, 2014; Creswell and Creswell, 2017). A ***pragmatic worldview*** best describes and guides this study.

Creswell and Plano Clark (2011), state that a *pragmatic worldview* is seen by many mixed method researchers as the "best" worldview to be used as a foundation for mixed method research. The philosophy of pragmatism is derived from the early work of Pierce, James, Mead, and Dewey (Creswell and Creswell, 2017). This worldview is based on actions, situations, and consequences, rather than on antecedent conditions. The focus of this philosophical worldview is to address the research problem and questions through multiple available methods, rather than to focus on the methods themselves (Creswell and Creswell, 2017).

The foundation of this research is based on the *pragmatic worldview*. The research problem highlights the need for merging technology selection frameworks with those of the railway infrastructure maintenance equipment, exploring the benefits as well as the challenges of selecting and implementing new technologies into current business structures. This worldview gives this research the freedom and flexibility to utilise multiple methods of gathering and analysing data at each given point in the research process, to ensure the best possible outcome for answering the research questions and develop a working technology selection framework.

3.2.2 Research Design

This section explores the research design proposed for this study. It is the second key component of the research approach framework seen in Figure 3.2. The research design is not only responsible for selecting the type of study (i.e. qualitative and quantitative, or mixed method), but also the state of inquiry within each of the respective types of study. In some instances researchers have called it the *strategies of inquiry* (Creswell and Creswell, 2017), because it provides specific guidelines for the procedures in research.

Creswell (2014), describe qualitative research as an approach for exploring and understanding the meaning of individuals or groups assigned to specific social or human problems, and quantitative research as an approach that examines the relationship between variables for testing objective theories. Qualitative research is useful to gain insight into a problem or aid the development of ideas or hypotheses for potential research. Trends and other problems can also be explored by deconstructing thoughts and opinions. Quantitative research, on the other hand, creates useful statistics that are derived from numerical data to quantify a problem (DeFranzo, 2011). Lastly, mixed methods is the third type of research design identified. The construct of mixed method research is based on the combination or integration of both qualitative and quantitative research and data. Qualitative data tends to be open-ended, and the quantitative data tends to be closed-ended (Creswell, 2014). A definition of mixed method research is,

> *"...the collection and analysis of both quantitative and qualitative data in a single study in which the data is collected concurrently or sequentially, are given priority, and involve the integration of data at one or more stages in the process of research" (Creswell* et al.*, 2005).*

According to Bryman and Bell (2018), the mixed method approach can capitalise on the strengths and offset the weaknesses of only using qualitative or quantitative methods in a particular study. The study type selection is based on the capabilities each method has in addressing the research problem and questions. Thus, it is decided that this research will follow a *mixed method design*. Furthermore, each study type (method) possesses various strategies of inquiry that guide the research process, see Table 3.1.

According to Creswell and Plano Clark (2011), four critical decisions are involved when deciding on a specific mixed method strategy of inquiry. The decisions are: (i) the level of interaction between the different data strands, (ii) the relative priority of the data strands, (iii) the timing of the data strands, and (iv) the manner in which the data strands are mixed. This research utilises data strands which are *interactive*, as the strands have a direct interaction between them due to the nature of the quantitative data supplementing and building directly on the initial qualitative data. Furthermore, the priority is given to qualitative data over the quantitative data (QUAL > quan) seeing as the research is more exploratory in nature. Data collection and analysis occurs *sequentially*, qualitative leading the quantitative and lastly the mixing of the strands occurs at the *level of design* where the theoretical framework development takes place.

Table 3.1: Research design strategies of inquiries (Adapted from Creswell and Creswell (2017))

Design	Strategy
Quantitative	• Experimental design • Non-experimental design
Qualitative	• Case study • Ethnography • Grounded theory • Narrative research • Phenomenology
Mixed Methods	• Explanatory sequential • Exploratory sequential • Transformative, embedded

Using the four critical decisions as a guideline, this study follows a *mixed method exploratory sequential design*, which is the best strategy of inquiry to answer all of the research questions (Creswell *et al.*, 2005; Creswell and Plano Clark, 2011; Creswell and Creswell, 2017). It is a two-phased process. The initial phase is responsible for exploring a particular phenomenon using qualitative data collection and analysis techniques. Following the exploratory phase, phase two is responsible for building on the first phase through qualitative techniques to test or generalise the initial findings. The interpretations are made based on the findings of both qualitative and quantitative data. For an exploratory design, the qualitative data collection takes priority over the quantitative data, with the quantitative data being used for supplementation purposes (Creswell and Plano Clark, 2011).

3.2.3 Research Methodology

This section explores the research methodologies employed during each phase of this study and is the third component of the research framework seen in Figure 3.2. The research methodology states all the specific research methods involved with either the collection, analysis or interpretation of the data during this research (Creswell and Creswell, 2017).

The identification of an appropriate methodology for the selection and adoption of data acquisition technology in railway infrastructure maintenance is the one overarching concern that leads the direction for this study. Based on this assumption, it is decided to investigate various methods to determine an appropriate one which can best achieve answers to the research questions. The following methodologies are considered: framework, model, roadmap, and a tool. Table 3.2 presents the methodologies under consideration as well as a short description of each.

Table 3.2: Research methods

Research Tool	**Description**
Framework	Conceptual frameworks are used in research for outlining possible options or for presenting the preferred approach, namely defining the problem and purpose, conducting a literature review, devising a methodology, data collection and final analysis. (Suman, 2014)
	A network, or 'a plane', of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena. (Jabareen, 2009)
Model	A model is seen as a human construct which is able to help with a better understanding of real-world systems. Models contain some form of information input, information processor, and output obtained from the information processor. (Ford, 2009)
Roadmap	A detailed plan to guide progress toward a goal. (Merriam-Webster, 2009)
	A roadmap is capable of developing specific research programmes by outlining a research agenda. To answer scientific questions, reduce uncertainties, and provide a reliable scientific foundation for future policy development. (Nelson *et al.*, 2009)
Tool	Used to obtain, measure, and analyse data from subjects around the research topic (Editage Insights, 2020)
	Anything that becomes a means of collecting information for your study is called a research tool or a research instrument. (Civil Engineering Terms, 2015)

Based on the findings in the above table, it is concluded that a framework is the best-suited methodology for the selection and adoption of current and emerging data acquisition technologies for railway infrastructure maintenance. The selection framework will, however, include features from both a model and a roadmap. The detailed technology selection framework is constructed in Chapter 6.

Against the background of the research design, two main research phases are introduced in the research process to address the research questions, (Figure 3.3). Validation occurs continuously throughout the process.

3.2.3.1 Phase 1: Contextualisation

Phase 1 covers the contextualisation of the research problem. For this phase, the starting point is a *qualitative content analysis* of the existing literature, (Chap-

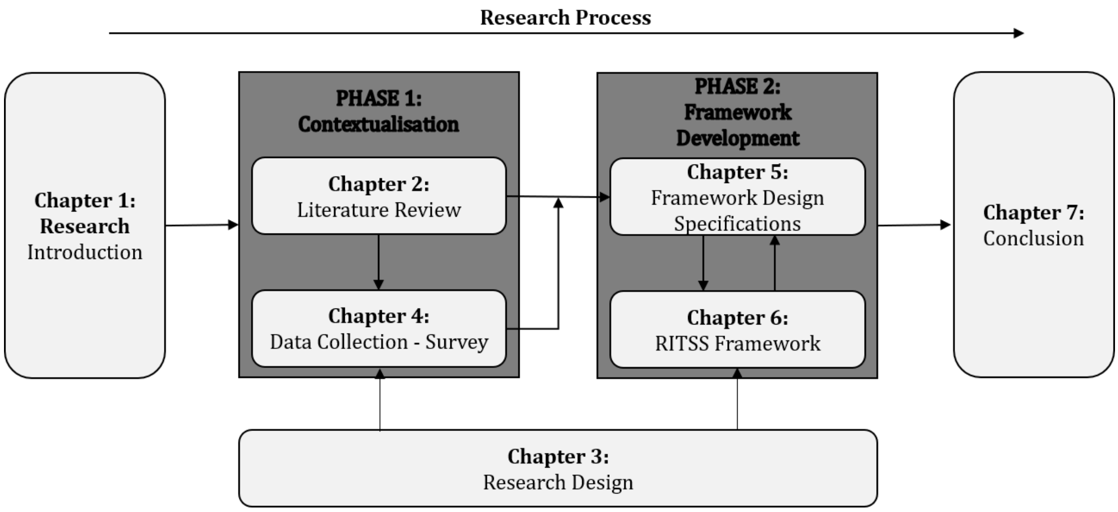


Figure 3.3: Research design

ter 2). The purpose of the content analysis is to set the background of railway infrastructure maintenance and identify railway infrastructure failure modes cross-linked to their respective infrastructure components.

A *structured literature review* is implemented in the latter part of Chapter 2. The purpose of the structured review is to identify current and emerging data acquisition technologies used for condition monitoring of railway infrastructures with the capabilities of monitoring the failure modes obtained from the content analysis. *Microsoft Excel*, is used to categorise the features and capabilities of the identified technologies.

This phase concludes with the inclusion of *survey responses* from subject matter experts (SMEs). The primary purpose of the survey is to supplement the findings from the structured review. The purpose can further be split into three subcategories namely (i) identifying what factors influence railway infrastructures' criticality, (ii) validating the identified data acquisition technologies monitoring capabilities from Chapter 2, and lastly (iii) gain insights into barriers and promoters of technology adoption. The data is collected from questionnaires through the web-based survey software, *SurveyMonkey*. Where applicable, statistical differences are calculated using *two-sample t-tests* for analysis purposes.

3.2.3.2 Phase 2: Framework Development

Phase 2 covers the technology selection framework's development. The initial step of phase 2 defines the requirements of the technology selection framework based on the findings from both the structured review and survey results. Against the framework requirements, multiple selection frameworks are evaluated to be used as the foundation for the framework. The last part of Chapter 5 covers the development of the *multi-criteria decision analysis (MCDA)* technique and the evaluation criteria itself.

The second part (Chapter 6) of phase 2 is aimed at refining the framework. It is responsible for integrating all of the research findings and turning it into a logically structured decision support framework for use in the railway industry. The refinement constitutes the development of multiple stages so as to provide guidance systematically for selecting new technology. The stages are responsible for mapping the assets and technology, evaluating and prioritising the most favourable technologies, and lastly providing decision support on how to acquire that technology. The purpose of the framework is to determine the priority of the technologies according to the criteria identified for each specified infrastructure failure mode and to assist with the acquisition process.

3.2.3.3 Research Validation

Throughout both phase one and two the research is validated, more specifically the technology selection framework. Validation is based on triangulation through literature findings, input from subject matter experts, and a case study. The validation of the research occurs at three points in the research process; (i) the validation of the data acquisition technologies' monitoring capabilities identified from the structured review through surveys completed by subject matter experts, (ii) a second subject matter expert survey to validate the evaluation criteria and its relative importance, and lastly (iii) a case study is implemented to test the validity of the refined framework in an industry case study.

3.3 Chapter 3 Summary

This chapter described the research approach to which this particular study conforms. The approach is based on the research framework created (Creswell and Creswell, 2017). This framework identifies three components required for a research approach; (i) philosophical worldviews, (ii) research design, and (iii) research methods. Therefore, the key components are explored in that particular order. In conclusion, it is decided to follow a *pragmatic worldview* philosophy and select a *mixed method exploratory sequential design* as the strategy of inquiry. Lastly, the methods used at each stage of research are presented (see Table 3.3 for the methodology summary).

Table 3.3: Methodology summary

Phase	**Chap.**	**Approach**	**Method**	**Instrument**
1	1	Qualitative	Content analysis; Structure review	*Microsoft Excel*
	4	Quantitative and qualitative (QUANT > qual)	SME Survey	*SurveyMonkey*
2	5	Qualitative	Structure review; Content analysis; Integration	Various
	6	Quantitative	'Failure pathways'; MCDA	*Microsoft Excel*
Cont.	Mult.	Qualitative	Triangulation	Various

Chapter 4

Data Collection – Survey

4.1 Introduction

Against the background of the research design, which employs an exploratory sequential design, it is stated that a second quantitative phase is required to supplement the first qualitative phase. This chapter resides in the second phase of the research design. The purpose of this chapter is to validate and build on the findings of Chapter 2 through the inputs of subject matter experts (SMEs). See Figure 4.1, for the position of this chapter in the research process.

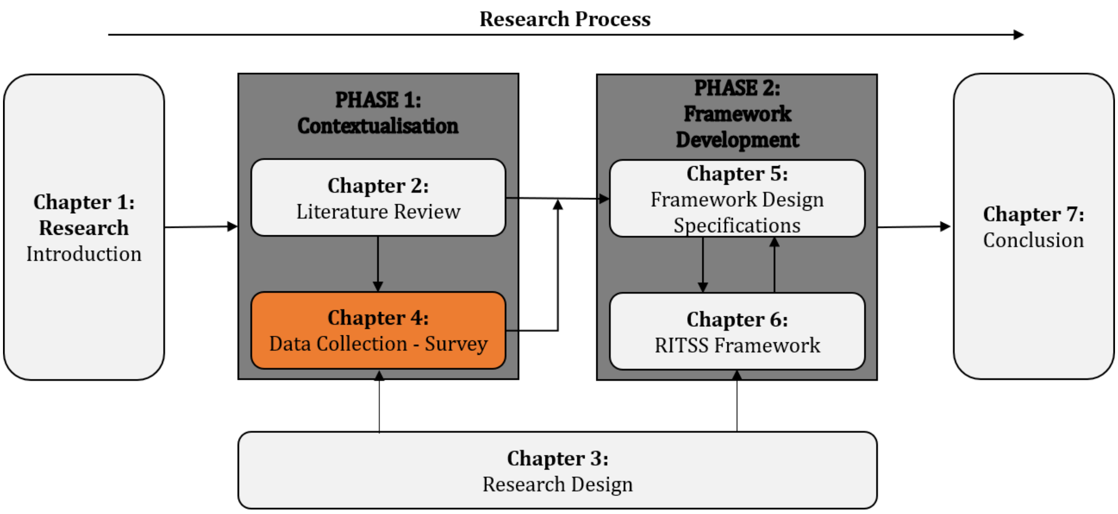


Figure 4.1: Research design: Chapter 4

This chapter describes the process undertaken to gather inputs from SMEs. The chapter starts with the methods considered for collecting data and the construction of the selected method (web-based survey), followed by the selection of the subject matter experts, and finally an analysis of the responses from the SMEs. Refer to Appendix C, for the detailed responses to the questionnaire.

4.2 Data Collection

As stated in Chapter 1 and Chapter 3, this chapter covers the data collection from SMEs. Thus, it is necessary to identify a data collection method which best fits the research design. This section provides the background information required for the development of the data collection tool and the analysis.

Three different methods of data collection are considered for gathering inputs from SMEs; namely, (i) interviews, (ii) focus groups, and (iii) surveys (Gill *et al.*, 2008). Based on the research design implemented for this study, the data collected during this phase of the research is quantitative. Therefore, interviews and focus groups are excluded from selection as these methods provide predominately qualitative data. The exclusion of both interviews and focus groups leaves only surveys left to be explored as a viable option for collecting the required data. A survey has the capability of providing a researcher with both qualitative and quantitative data depending on the survey's construction (Hines, 1993; Glik *et al.*, 2006; Ponto, 2015).

> *"The quality of a survey is best judged not by its size, scope, or prominence, but by how much attention is given to [preventing, measuring and] dealing with the many important problems that can arise."*
> – American Association for Public Opinion (2020)

To produce a good quality survey the construction of the survey is systematically considered. The main components that form part of a survey are explored in the following order:

1. Survey methodology
2. Questionnaire development
3. Administration modes
4. Participant sampling
5. Ethical considerations

4.2.1 Survey Methodology

Surveys are commonly used in research for collecting information about a specified population of interest, whether the population consists of a group of individuals or organisations. The administration mode of the survey and the sample selected can differ for the various types of surveys. Depending on the type of survey, the sample can either include all members of a population or only a small part of it. Nevertheless, all surveys must include the following two features; (i) a questionnaire, and (ii) sampling – the scientific technique used to identify a subgroup of the population (West, 2019).

It is important to note that a questionnaire and a survey are not the same. Check and Schutt (2011); Ponto (2015) identifies two specific distinctions between a survey and a questionnaire, which are; (i) a questionnaire is a set of written questions used for collecting information, and (ii) a questionnaire does not use aggregate data for statistical analysis, whereas, a survey aggregates the data gathered to draw a conclusion based on statistical analysis. Furthermore, it can be deduced that a questionnaire is a set of questions used to gather information, and a survey is a process of collecting and analysing the data. See Table 4.1 below for some of the advantages and disadvantages of using surveys in scientific research according to West (2019).

Table 4.1: Advantages and Disadvantages of surveys in research

Advantages	**Disadvantages**
• Cost-effective and efficient means of obtaining information. • Capable of collecting data from a large number of participants. • Probability sampling methods for participant selection leads to the possibility to approximate population characteristics without the need to collect data from the entire population. • Survey questionnaire are not limited to in-person administration – can be done remotely.	• Questions included in a survey tend to be broad in scope. • Respondents may be reluctant to share personal or sensitive information. • Respondents may provide responses which they deem more socially desirable (not their actual opinion). • The participation (response) rate of surveys is on a decline. • Often do not allow for the in-depth understanding of participants' circumstances.

Based on the advantaged and disadvantage of surveys in research, it decided that a survey is the best suited mode of obtaining the required knowledge from

SMEs during this phase of the research. The cost-effective capabilities of acquiring data from a large sample size remotely aligns well with the purposive probability sample identified (Section 4.2.4). The disadvantages do not affect this study as much, because the participants are not asked to share personal information. The SMEs are asked questions based on a specific topic which they are experts on.

4.2.2 Questionnaire Development

The goal of the questionnaire can be split into three subcategories; namely, (i) identifying what factors influence railway infrastructures' criticality, (ii) validating the identified data acquisition technologies' monitoring capabilities based on the research from Chapter 2, and lastly (iii) gain insights into the barriers and promoters of technology adoption.

The development of a questionnaire is not as simple as grouping a set of questions together. Before a researcher can start with the development of a questionnaire, key considerations (factors that affect the quality of the questionnaire) need to be addressed. Addressing the considerations assist with ensuring high participation rates and accurate responses from participants. The construction of the questionnaire included in this survey follows a transparent process. The questionnaire is built on the premise of its intended purpose. From this purpose, three subcategories of questions are derived. The order in which the categories are presented ensures the participants are introduced to questions in an order which tells a story starting from railway maintenance progressing towards the technology used, with the final step incorporating the adoption of the technology.

Various methods of presenting the questions are considered of which the type of questions include both open-ended and closed-ended questions. The majority of the questionnaire consists of closed-ended questions asking for participants to rate or choose one of the following options. The closed-ended and shorter questions are presented early so as to not discourage participants from completing the entire questionnaire, with the open-ended questions presented only as follow-up questions if deemed necessary. However, in the last category of questions, more open-ended questions are asked as their intended purpose is to explore rather than to validate previous findings. The first category included questions that incorporate rating scales ranging from not, slightly, moderately, very, to extremely (1 - 5 numerical values for analysing) and the second category asking only for participants to agree or disagree.

4.2.3 Administration Modes

As highlighted in the survey methodology (Section 4.2.1) an advantage of surveys in research is the fact that the administration is not limited only to an in-person contact session. Administration can occur remotely. Four different methods of administering surveys are highlighted; namely, (i) mail surveys, (ii) telephone surveys, (iii) in-person surveys, and (iv) online (web-based) surveys (Polaris Marketing Research, 2012).

Researchers are increasingly mixing the above methods to administer surveys. The mixing of the above methods is implemented to try to increase the participation rate of the surveys, which gives potential participants the option for completing the questionnaire via their preferred method (West, 2019). Millar and Dillman (2011), describes other techniques to ensure a higher participation rate such as, multiple contacts, token cash incentives, personalised communication, respondent-friendly construction, and other design features. These types of techniques can be more favourable for increasing the participation rate rather than mixing administrative methods. This is stated based on the research of Millar and Dillman (2011), where it is argued that providing potential participants with multiple options of how to respond to a questionnaire can harm the response rate. By giving potential participants two or more options, they automatically compare the methods identifying possible trade-offs, and this can make each method less appealing than when it is offered alone. This research selects a *web-based survey* for administering the questionnaire to SMEs. To collect the data a web-based survey software *SurveyMonkey* is used.

4.2.4 Participant Sampling

In Section 4.2.1 it is stated that all surveys must include a questionnaire and sampling. Questionnaires have already been addressed, and therefore, this section explains the sampling methods considered and the final sampling method used for identifying participants. The primary strength of sampling, according to West (2019), is its capability to estimate a population's characteristics based on a small proportion of the population. Various methods to sample a group of potential participants exist and the methods considered for this research are seen in Figure 4.2.

Participant sample criteria: The validity of the SMEs to participate in the survey is based on the following three criteria:

1. The participant is working or has worked in the railway maintenance sector.
2. The participant is part of a research team that investigates or consults on railway maintenance activities to improve the efficiency of these activities.

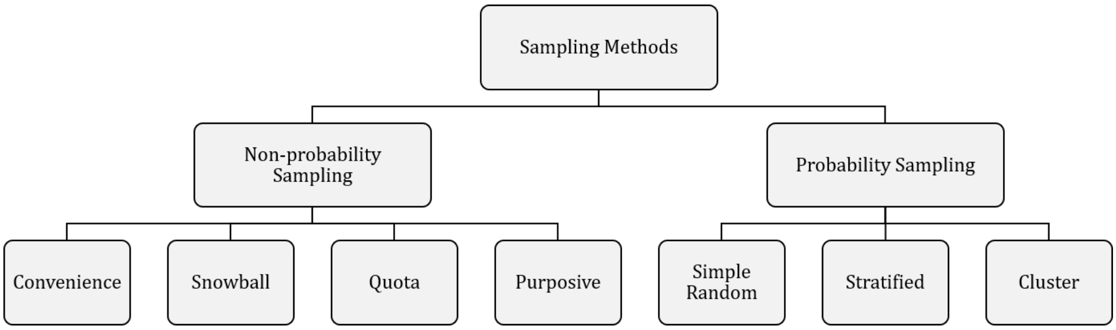


Figure 4.2: Different sampling methods

3. The participant is part of an organisation that specialises in railway condition monitoring technologies and equipment, either providing services or products.

Sampling method: Against the research design and the intended objective of this survey, *non-probability sampling* is an appropriate method. This type of sampling selects potential participants not by chance, but rather for a specific purpose. This is justifiable for this research as the intended purpose of the survey is to gather opinions from SMEs in the railway industry and not a diverse group of people. Furthermore, *purposive sampling* is the chosen non-probability sampling method intended for this particular survey, since participants can be traced back as experts in the railway field.

Sample size: Purposive non-probability sampling does not require a clear set number of participants due to the sample size not being determined by statistical power but rather data saturation. Guidelines for selecting a sample size is provided by researchers such as Creswell and Morse. Creswell (1998) recommends 5 - 25 participants and Morse (2000) suggests at least six. Using these two guidelines as the foundation for determining this survey's sample size, and further factors such as the narrow aim of the study and the selected sample is a specialised group of individuals, a sample size of 8 - 15 participants is assumed to be sufficient to achieve saturation.

4.2.5 Ethical Considerations

This research gathers data through questionnaires completed by SMEs, based on their knowledge of the subject and opinions. Thus, as in all research, certain ethical considerations must be addressed when using the data collected. This survey followed the ethical procedures according to Stellenbosch University requirements. Thus, ethical approval is required from the *Research Ethics Committee (REC)* before any form of data could be collected through this method. According to the guidelines scripted by Stellenbosch University, this research is classified as low risk and is granted ethical approval (project reference: *ING-11672-2020*).

Apart from the ethical approval process required by REC, the questionnaire includes a letter of consent. This letter is presented at the start of the questionnaire and gives participants background knowledge about the research it contributes towards. The letter includes an introduction to the research, its intended purpose, procedures, questionnaire time estimate, associated risk, participant benefits from participating, participation and withdrawal processes, confidentiality measures, and lastly how the data will be stored. Potential participants have the opportunity to accept the conditions of the letter and continue to the questionnaire or decline and be removed automatically from the web survey.

4.3 Survey Findings

This section provides the process followed and the summarised findings of the results obtained through the survey. See Appendix C for the detailed responses obtained from the SMEs. The following order presents the structure of this section; first, the background of the expert panel is provided, and how they are invited to participate in the survey study. Secondly, the first part of the feedback from the questionnaires is presented, followed by part two the data acquisition technology validation, and lastly part three, the adoption of new technology.

4.3.1 Expert Panel

Fourteen railway SMEs were invited to participate. Out of the 14 experts invited, 8 (57%) responded positively, achieving the desired number of participants.

The SMEs were identified through the network of the PRASA Engineering Research Chair (PRASA ERC), which also assisted with the initial contact between the potential participants and the researcher. Thereafter an invitation email with an attached web-link to the survey were sent to the participants. The survey duration lasted four weeks with a reminder sent out to the participants once a week until the required number of participants was reached.

The SMEs included in the survey come from different backgrounds of expertise in terms of job prescription and geographical location (see Table C.1). The expert panel included university researchers (five), an independent consultant (one), and employees of major railway operators (two). With the expert panel, including majority researchers, it is assumed that the SMEs are knowledgeable of the new and emerging technologies available in the railway industry. Further, it is found that the positive responses included experts from Austria (two), the Netherlands (one), South Africa (two), and Slovakia (three). This allowed for deductions from both developing and developed countries.

4.3.2 Part 1: Infrastructure Maintenance

This section summarises the findings from the first part of the questionnaire (refer to Appendix C.1.1 for detailed feedback). The main goal of this section in the questionnaire is to determine how to rank infrastructure components based on their respective criticality and what factors are able to influence the criticality. Most of the questions in part 1 enlist the use of a measuring scale which requires less effort from the participants, intended to capture their attention. The following questions require more effort to answer. As an initial opening question, the SMEs are asked to measure how critical they perceive inspections and condition monitoring as a means of preventing potential failures. The responses showed that all of the experts share the same opinion; that it is imperative.

The SMEs are asked to rate the infrastructure component's criticality, where the measure of criticality is based on the effect the failure of a component will have on everyday operations. In this research, a component's criticality is argued (refer to Section 2.2) to be directly related to its ability to affect everyday operations, because the focus of the research being on maintenance and the purpose of maintenance is to ensure continuous operations or to rectify assets to a level of operation (Zaayman, 2017). The rating scale used for the criticality and impact axis is: (1) not; (2) slightly; (3) moderately; (4) very; and (5)extremely (Figure 4.3 and Figure 4.4). From the responses, the rails are indicated as the most critical component with OHTE and signalling as second and third most important (see Figure 4.3). Another goal is to determine what factors influence the criticality ratings, based on SMEs' opinions. Thus, Figure 4.4 represents the SMEs' responses related to the factors affecting the criticality. The responses indicated that the three most important factors influencing the criticality ratings (Figure 4.3) are safety, downtime, and cost. Controlling these factors is, therefore, essential for ensuring successful rail infrastructure operations. The results highlighted in both these figures create a priority order guideline in which infrastructure components and criticality factors could be addressed when planning and executing maintenance and condition monitoring activities.

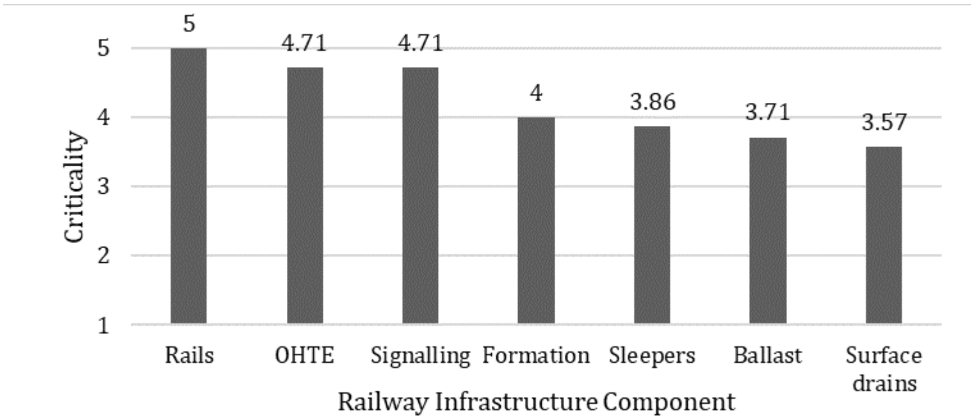


Figure 4.3: Infrastructure component criticality

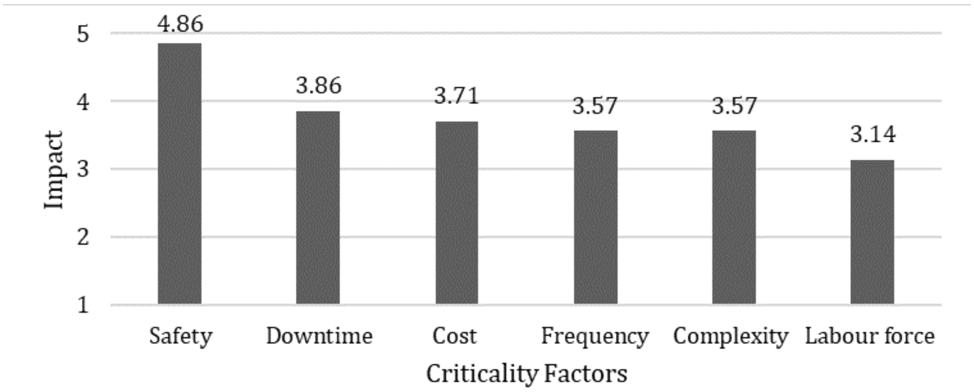


Figure 4.4: Criticality factors

To justify the deduction made regarding component criticality and criticality factors, a quantitative analysis of the data is required to determine if there are statistically significant differences in both the results from Figure 4.3 and Figure 4.4. Thus, a two-sample t-test is employed. Two-sample t-tests at 90% confidence, however, show that the criticality of rails is not significantly more than the OHTE and signalling. There is, however, a significant difference between the rails and the rest of the infrastructure components. The OHTE and signalling provide statistically significant results between the formation and lower average rating infrastructure components. The t-test supports the identification of the three most critical infrastructure components, although it does not lead to the specific order of priority between the top three. T-tests for the criticality factors highlight that the safety factor significantly differs from the other criticality factors and should, therefore, be a priority for minimising or mitigating failures.

The criticality factors that are provided in the questionnaire are based on the literature review in Chapter 2. Therefore, to determine if there are any other factors not identified from the literature, the SMEs are asked to supplement the factors presented. The most notable factor the SMEs think that are omitted is unusual schedules caused by deteriorated tracks slowing down train speeds which can have an adverse effect on normal operations and create traffic build-up. The SMEs also highlighted that a factor to consider is the failure location, since the severity of a locational failure is dependent on the traffic associated with that section and the locality (soil conditions) surrounding the failure.

During condition monitoring, certain obstacles are expected, and thus the SMEs are asked to provide obstacles they have encountered or have knowledge of. The obstacles mentioned in Appendix C.1.1 did not include any new obstacles not identified from the literature review, and thus they are not described here. To conclude the first part of the questionnaire and introduce the second, a final question is asked that shifts the focus to technology in rail. The last question illustrates that the SMEs opinions are diverse about the effectiveness of current technology to perform condition monitoring. Given the widespread opinions, it is assumed that the SMEs feel that current condition monitoring technologies still have room for improvement.

4.3.3 Part 2: DAQ Technology Validation

This section summarises the findings from the first part of the questionnaire (refer to Appendix C.1.2 for detailed feedback). The main goal of this section is to validate the data acquisition technologies (Section 2.3) mapped to their respective failure mode (Section 2.2) monitoring capabilities.

As part of the validation process, the SMEs were presented with the data acquisition technologies linked to their respective monitoring capabilities (see Table 4.2). The SMEs had the opportunity to agree or disagree with the combinations presented to them. If the majority of the SMEs agreed with a particular combination it is marked with an “X”. Furthermore, the technologies that did not reach a positive majority vote are then re-evaluated against the literature to determine if that particular technology should be included in the research going forward.

Table 4.2: DAQ Technologies monitoring capabilities validation

Component	**Monitoring**	**Capable Technology**	**Valid**
Rails	Wear	Axle box measurements	X
		Eddy current	-
		Corrugation measuring system	X
	Surface cracks	Ultrasound	X
		Eddy current	-
		Infrared thermography	X
		Monochromatic line scan cameras	X
	Internal cracks	Ultrasound	X
		Eddy current	X
		Hammer test	X
		Infrared thermography	X
	Damage	Infrared thermography	X
		Visual camera imaging	X
	Breakage	Visual camera imaging	X
	Geometry	1D and 2D Laser scanning systems	X
		Visual camera imaging	X
		Axle box measurements	-
		Inertial measuring unit (IMU)	X
		Optical gauge measuring system (OGMS)	X
		Micro-electrical-mechanical systems (MEMS)	X
		Piezo electrical systems	X
Rail fasteners	Damaged components	Visual camera imaging	X
	Missing components	Visual camera imaging	X
Sleepers	Flexural demand	Concrete surface strain gauges	X
	Internal defects	Acoustic emissions	X
		Infrared thermography	-
		Hammer test	-
Trackbed	Geometry	Visual camera imaging	X
		Ground penetrating radar (GPR)	X
		Seismic refraction	X
		Surface wave analysis	X
		Electrical resistivity tomographic (ERT) imaging	X
		Matrix based tactile surface sensors (MBTSS)	-
		SmartRock	X
Surface Drains	Obstructions	Visual camera imaging	X
OHTE	Geometry	1D and 2D Laser scanning systems	X
		Visual camera imaging	X
	Wear	Visual camera imaging	X
	Missing components	Visual camera imaging	X
Signalling	Damaged components	Infrared thermography	-

Continued on next page...

Table 4.2 – *continued from previous page*

Component	**Monitoring**	**Capable Technology**	**Valid**
		Visual camera imaging	X
	Missing components	Visual camera imaging	X
General	Ground and structural displacement	Robotic total stations	X
	Irregularities of rails, sleepers, and ballast	Wheel impact load detector (WILD)	X
	Positioning coordinates	Global navigation satellite system (GNSS)	X
		Differential global positioning system (DGPS)	X
	Track distance	Distance measuring indicator (DMI)	X

From the above table it is determined that the following technologies and their monitoring capabilities did not meet the requirements to be automatically included in the final research and require a second round of evaluation from the literature;

- **Eddy current:** Wear and surface cracks of rails. (Included)
- **Axle box measurements:** Geometry of rails. (Included)
- **Infrared imaging:** Internal defects of sleepers and damaged components of signalling. (Excluded)
- **Hammer test:** Internal defects of sleepers. (Excluded)
- **MBTSS:** Geometry of trackbed. (Included)

To eliminate the possibility of inaccurate results caused by SMEs that might not be familiar with all the latest technological developments or some experts using different terminologies as stated in the questionnaire, a second round of evaluation is required. The exclusions were therefore assessed against the available literature for justifiable evidence stating the technologies capabilities.

Following the second evaluation, Eddy current remains included in the study. It is justified by three sources (Ronald Krull *et al.*, 2002; Molodova *et al.*, 2016; R. Schalk *et al.*, 2018), where the capabilities of Eddy current include the monitoring of rolling contact fatigue which includes defects such as corrugation (falls under the scope of rail wear in Section 2.2.4.1) and surface defects such as cracks. Axle box measurements are remains included in the study for determining the geometry of rails. De Rosa *et al.* (2019), clearly state that it has the capability of measuring the displacement of the wheels, which is caused by the changes in track geometry and therefore the geometry can also be measured. Infrared imaging is excluded for both detecting sleeper internal defects and signalling damaged components. The hammer test is excluded for only detecting internal defects of sleepers. Montiel-Varela *et al.* (2017), mentions potentially using the hammer test to determine cracks in sleepers, but it has never proven to be a viable method. MBTSS is included after the second evaluation. Qian *et al.* (2019), highlights that MBTSS are capable of determining ballast pressure distribution underneath sleepers.

In concluding the validation of the data acquisition technology's capabilities, the SMEs are requested to provide technologies that are not included in the original study but should be explored. From this question the consensus from the participants was that the data acquisition technologies included in this study are sufficient. One expert suggested closer investigation into *infrared imaging* technology to monitor overhead traction equipment and another suggested the non-destructive testing method of *Barkhausen* noise for inspecting rails.

4.3.4 Part 3: Adoption of New Technologies

This section summarises the findings from the first part of the questionnaire (refer to Appendix C.1.3 for detailed feedback). The main goal of this section is to explore the barriers and promoters of the adoption of new technologies and to identify strategies to adopt these new and emerging technologies. This part of the questionnaire includes mostly open-ended questions which are deemed to be more qualitative in nature. This section is mostly responsible for building on and supplementing the literature findings in Chapter 2 rather than gaining a deeper understanding of what is found initially or validating it.

As described in Section 2.3.5, data acquisition technology can be improved in terms of its capabilities by using different carriers. To determine what type of carriers are currently being used, the SMEs are asked to choose the ones they use or know of in their locality. The two most frequently used carriers for performing condition monitoring are rail inspection vehicles (100%) and secondly, measuring trolleys (62.5%). The use of in-service trains (50%) is not that far behind. As for using UAVs (12.5%) for condition monitoring, only one participant acknowledged that they are being used. This can be attributed to the fact that it is a relatively new technology in this particular field.

The most notable contender for new technology (especially more automated) is the labour force which is currently performing the monitoring tasks. Thus, the panel is used to determine their point of view on the matter of when technology in condition monitoring becomes a substitute for manual labour. The experts have acknowledged that due to safety, downtime, effectiveness and cost reasons, the labour force has been experiencing reductions. However, the general indication amongst the railway experts is that the labour force is still an essential aspect of the rail environment. Furthermore, they highlighted that there is a growing need for highly skilled workers not to perform the actual physical monitoring but to be employed somewhat further down the line for interpreting the collected condition data and turning it into usable information, including the prioritising of defects and developing a preventive and corrective maintenance regime (including the funds to do the work).

The concerns of the labour force are not able to stop the development created by technological advancements, and more industries are following the trend. One such industry is the railway sector as the technological developments promote the shift towards predictive maintenance. According to the SMEs, in order to make the shift a company would need to consider the following: a company would need to collect data effectively and acquire the methods to analyse and quantify it; able to translate data into actions; and the means of acquiring condition data must be comprehensive and automated as far as possible. Also, the condition data must be combined with cost data into a structured database system. Other aspects that also affect the transformation would be a willingness to buy into twenty-first century solutions and act promptly on deficiencies highlighted by the monitoring equipment, the need for more skilled labour, and adequate finance allocated towards maintenance.

As deduced from this research, the shift towards predictive maintenance includes the adoption of new and emerging technologies into current structures. Therefore, the SMEs are utilised to group the barriers prohibiting adoption and the promoters advancing the adoption of technology. The benefits associated with technology adoption highlight the following. Firstly, there is the likelihood of increased customer satisfaction by ensuring 'peak' rail operations (normal 100 % operating capacity); then secondly, downtime is reduced due to early prevention. Furthermore, the cost of repairs is reduced by eliminating unneeded replacements and extending asset life. In addition, the implementation of automated or semi-automated DAQ technologies could alleviate labour and skills shortages, reduce human error in maintenance tasks, and increase the overall safety of operations. Emerging technologies also support more accurate life cycle costing, which can lead to improved investment decisions.

Specific barriers to adopting emerging technologies are also observed. Societal and government barriers are highlighted. In many cases, rail operators are subsidised by governments for the social and economic benefits public rail transport brings. Government involvement, therefore, can potentially influence the decision-making processes and priorities of rail operators. An example is the funding of capital expenditure projects, which could include the acquisition of new technologies. An example of a societal barrier experienced in South Africa is the unsocial behaviour of theft and vandalism of rail assets that shifts priorities from preventive and condition monitoring practices to rectifying damage and restoring infrastructure into service. There are various areas where a lack of knowledge and skills creates barriers for DAQ technology adoption. The first is the shortage of knowledge and skills to perform tasks to uphold the standards set by the rail operators. This includes a general lack of awareness about the benefits of predictive maintenance for long-term cost reduction and proper life cycle costing practices. Secondly, there is a lack of knowledge and skills for converting data into usable information for decision-making. Related to this barrier is the inability to select appropriate emerging technologies in support of operational and maintenance improvements. Thirdly, a lack of knowledge on management level results in the unwillingness to support the adoption of new technologies. Frequently, rail operator managers focus on rectifying short-term obstacles and lose sight of long-term planning for sustaining the success of the company. Also highlighted from the questionnaire results is the distrust of new technologies by managers, resulting in resistance to change current practices.

With both the barriers to and promoters of adoption, a good strategy is capable of utilising the benefits and decreasing challenges to ensure successful implementation of new technology. Every strategy must include all the relevant stakeholders in the design, implementation and operation of the technology. The business case for using new DAQ technologies also needs to be carried out, where a cost-benefit analysis and impact analysis on current work and communication process should be included. Three strategies are suggested by the SMEs for adopting emerging technologies for predictive maintenance. The strategies are:

1. **In-house:** Following a set process from; (i) identification of the requirements and application areas, (ii) determining the underlying decision processes, (iii) identifying the information content required, (iv) evaluating alternatives, (v) selecting and (vi) implementing the data acquisition technologies.

2. **Outsourcing:** Condition monitoring service providers install and own the monitoring equipment and sell diagnostic and prognostic information to railway infrastructure managers.

3. **Benchmarking:** Using the experiences and approaches of other countries' railway operators as a guide to aid with the adoption of data acquisition technologies.

4.4 Chapter 4 Summary

This chapter first explained the foundation upon which the survey is built, the methodology used to design the questionnaire, identify and invite participants, and also how to administer the survey. From the survey methodology a web-based survey using *SurveyMonkey* is used for data collection. The design decision also included the selection of a *purposive non-probability* sampling method to invite the SMEs to participate. The second part of this chapter provided a summary of the survey results highlighting information advantageous towards the research goals. In conclusion, this chapter has provided (i) criticality rankings of the specific infrastructure components and the factors influencing criticality, (ii) validated data acquisition technologies mapped to their respective monitoring capabilities, and (iii) strategies and considerations for adopting data acquisition technologies in support of predictive maintenance.

Chapter 5

Framework Design Specifications

5.1 Introduction

This chapter describes the design specifications of the framework which will aid railway operators with the selection of data acquisition technologies in support of railway predictive maintenance. Figure 5.1, represents the position of this chapter with regard to the entire research process. It shows that this chapter initiates phase 2 of the research which is the framework development.

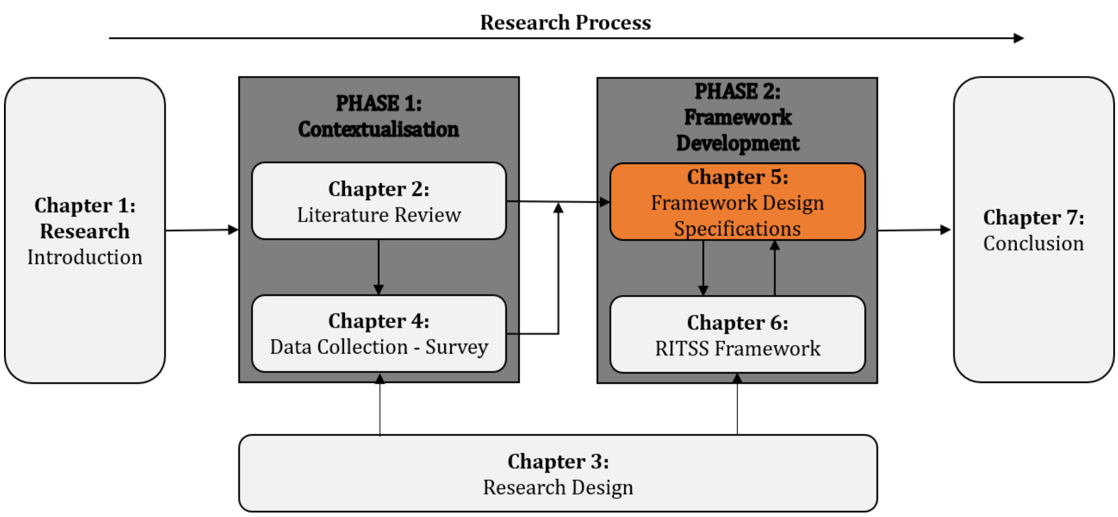


Figure 5.1: Research design: Chapter 5

The development starts by constructing a set of design requirements (features) the framework must include, based on knowledge obtained from Chapters 2, 4, 5, and 6 (multiple iterations), after which existing technology selection frameworks are reviewed through a structured process. As part of the review process the existing technology selection frameworks are evaluated against the set of design requirements to determine their applicability. The evaluation helps select the existing frameworks that can aid with the development of the framework for this thesis. This chapter further investigates different multi-criteria decision analysis (MCDA) techniques to aid with the selection problem and the development of the evaluation criteria. Finally this chapter explores different technology acquisition strategies. In short, this chapter provides the final tools required by the framework in Chapter 6.

5.2 Framework Design Requirements

Against the background of Chapter 2 and 4, this section aims to highlight the important requirements to consider when selecting emerging technologies. The focus is on the background of railway infrastructure maintenance, data acquisition technologies used for condition monitoring of the asset, the challenges faced when combining the maintenance and technologies, and the challenges of technology adoption. As the development of a framework is an iterative approach, the requirements are subjected to minor modifications and additions, based on the conclusions of both Chapter 5 and 6. This is seen in the research design, Figure 5.1.

It is decided to develop a set of requirements that the technology selection framework needs to address. These requirements are developed for a framework that selects a particular technology where the technology is seen as an asset to an organisation (e.g. used for condition monitoring) and not as a product to sell. Based on the relevant conclusions from all the chapters in this thesis the following set of *Design Requirements (DR)* is created:

DR1: The framework must enable organisations to define a specific set of assets for further investigation.

DR2: The framework must assist organisations to identify the failure modes and monitoring parameters of the assets in question.

DR3: The framework must aid organisations with the identification of suitable technologies for monitoring the parameters of each asset to detect or prevent potential failures.

DR4: The framework must allow organisations to investigate different implementation methods for the potential technologies identified.

DR5: The framework must enable organisations to map the potential technologies to their respective assets, by linking the technological capabilities with those of the asset monitoring parameters.

DR6: The framework must aid organisations to determine the potential benefits, challenges and risks associated with the selection, acquisition, and adoption of new technologies.

DR7: The framework must incorporate a multi-criteria decision analysis stage to evaluate and prioritise the potential technologies for each asset, based on a predefined criterion.

DR8: The framework must present the prioritised technologies to organisations along with suggestions for implementing them.

DR9: The framework must present organisations with multiple methods to acquire the technologies from the prioritised list.

DR10: The framework must enable an organisation to evaluate their strategic position, to determine the best-suited method of acquiring the technology.

5.3 Existing Framework Analysis

This section describes the methodology followed and knowledge gathered from the analysis of existing technology selection frameworks. The analysis is implemented through a structured literature review similar to that of the review in Chapter 2, Section 2.3.

5.3.1 Methodology

The structured review again uses keywords and key search terms to guide the selection of appropriate literature. *ScienceDirect* is chosen as the scientific database for initial selection. The keywords that were used are: technology AND selection AND framework; OR technology AND adoption AND framework; OR technology AND selection AND framework AND condition AND monitoring AND technologies. Figure 5.2 represents the systematic review process followed.

The initial database search (iteration 1) using the keywords, identified 27 papers as relevant. Iteration 2 assessed these 27 papers according to a set of predefined evaluation criteria, see Table 5.1. The assessment included their respective titles, abstracts, and keywords. According to the assessment criteria, 13 of the initial papers were excluded. Iteration 3 is also based on the same evaluation principles as iteration 2, the difference being that the full text of the 12 remaining papers was assessed. Due to iteration 3, 4 full-text papers were excluded. The last step, iteration 4, added 0 fortuitous papers to be included in this study, bringing the final number of papers to 8.

The findings from the 8 reviewed papers were able to provide valuable insights into the field of technology selection. The frameworks are investigated later in Section 5.3.3 and are then used as a starting point for developing the data acquisition technology selection framework (the output of this thesis).

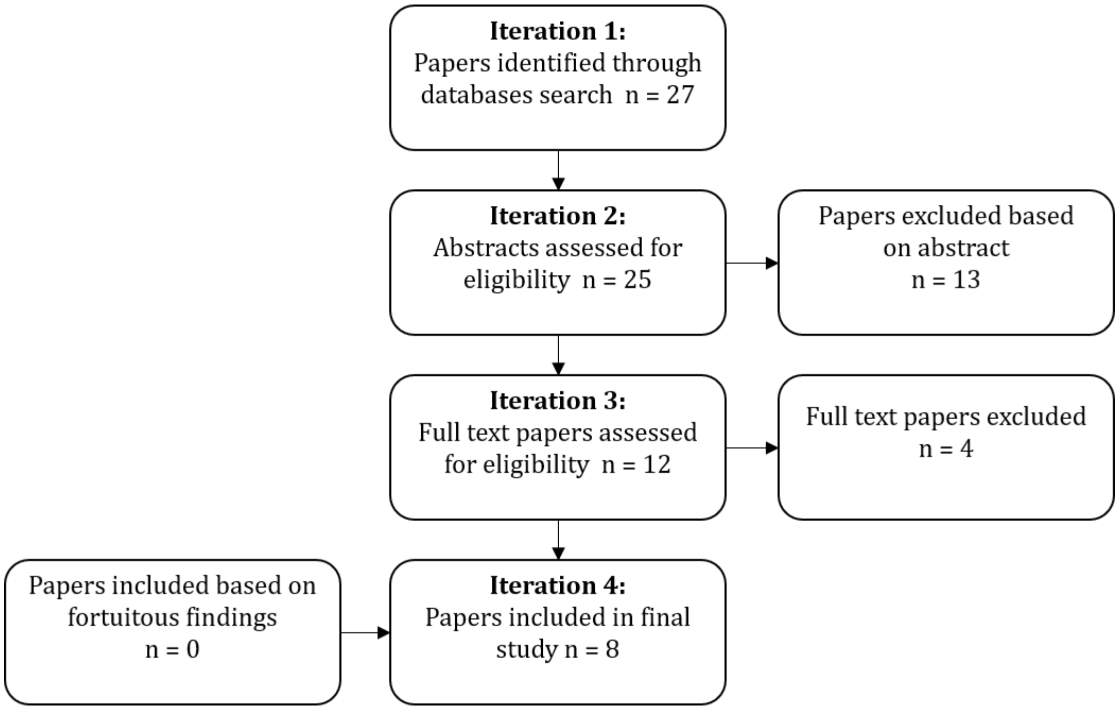


Figure 5.2: Systematic review process for identifying suitable documents

Table 5.1: Structured review inclusion/exclusion criteria

Criteria	**Justification**
Research published between 2010 and 2020	The rapid rate of technological developments creates the possibility for technologies to become irrelevant faster and faster. Thus, the decision is made to include papers from 10 years ago up until now to address only current and emerging DAQ technologies.
English publications	Only papers that are published in English are included.
Type of publication	Journal articles, conference proceedings, books, and research articles are accepted so as to not limit or be biased with the identification of potential DAQ technologies.
Technology selection and/or adoption frameworks	The papers must elaborate on frameworks that address the process of technology selection along with challenges faced when evaluating and adopting technologies.

5.3.2 Bibliometric Analysis

The bibliometric analysis is responsible for providing the reader with the background context of the papers that were selected in this research. Furthermore, it is important to note that this analysis is based only on the eight papers included in the final study. For this analysis, the papers will be categorised based on (i) the year they were published, (ii) publication source type, (iii) the authors' country of operations.

Year of Publication: The papers included in the study were all published from 2012 and onwards, see Figure 5.3, with the majority being published in the last five years. The graph shows no clear trend as to how technology selection frameworks have increased in popularity or not. This can be attributed to the fact that such types of frameworks have always been sought after due to their addressing an issue applicable to almost any industry throughout time. These frameworks might become more complex over time, but the core essence stays the same.

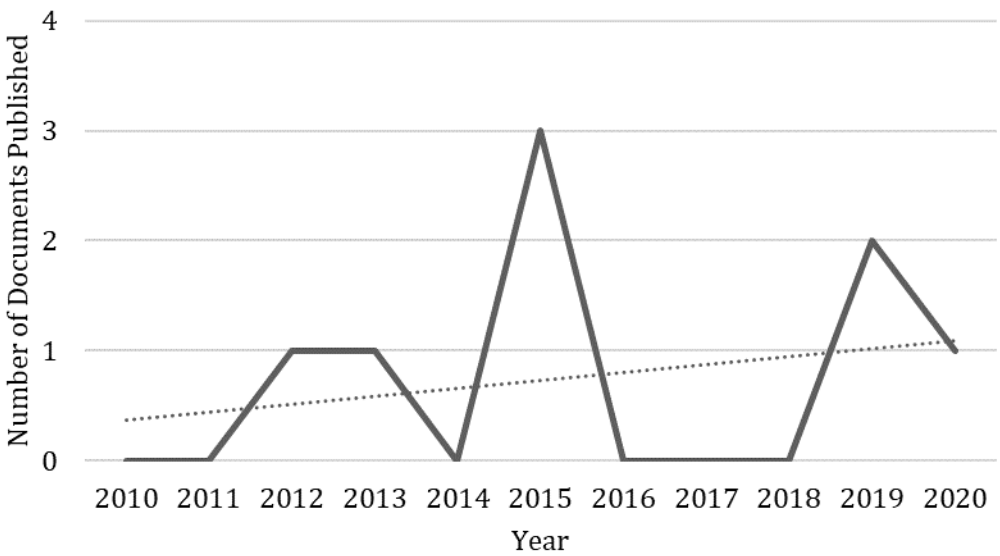


Figure 5.3: Papers published per year

Publication Source Type: As mentioned in Table 5.1, there were no stringent restrictions on the type of publication that needed to be included in the study. Thus, the make-up of the papers could have included various source types. However, only two different source types are included in this study, see Figure 5.4, namely journals (87.5%) and conference proceedings (12.5%). These two source types are all peer-reviewed, enhancing the scientific validity of this research.

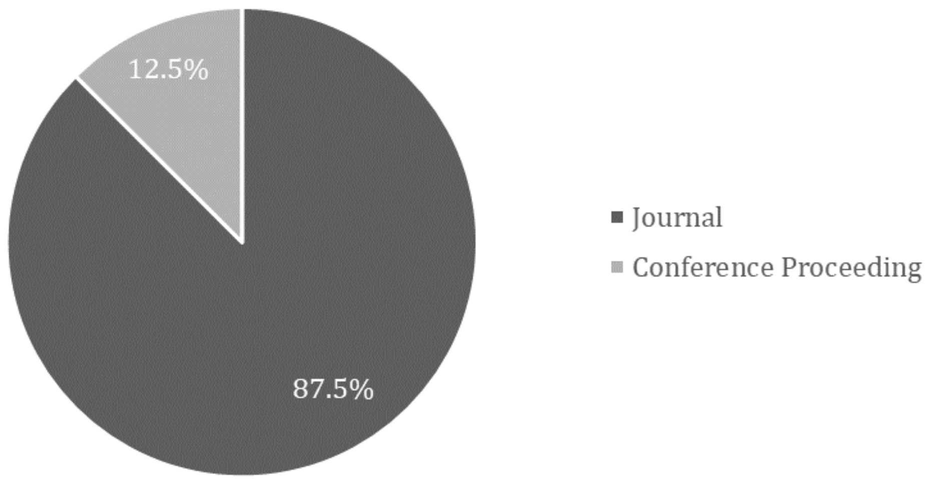


Figure 5.4: Publication type

Researcher Origins: Taking into account the geographical location of the main authors as well as the co-authors, it is possible to gather an idea of where the research could be more applicable and relevant. Figure 5.5 represents the authors' country of origin, but due to the small pool size it does not allow for any deductions to be made as to which geographical location researches this topic the most. It is seen however that the papers included are somewhat spread out across the globe.

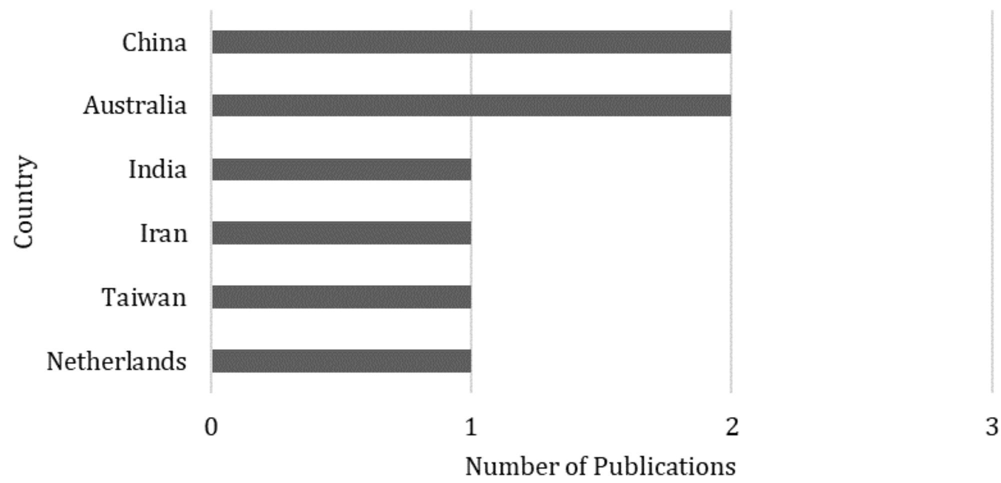


Figure 5.5: Authors' country of origin

5.3.3 Existing Frameworks

Upon completion of the review, eight papers were incorporated into the final study. Thus, this section aims to describe the frameworks each of the selected papers contains.

5.3.3.1 PIMT Framework

The integrate Process, Institutional, Market, and Technology (PIMT) framework for blockchain technology adoption was developed to analyse the adoption of blockchain technology by determining the complex relationship between institutional, market and technical factors. This framework aims to capture the challenges and issues organisations face relating to blockchain technology adoption. The PIMT framework's intended use is to be a reference point for organisations to aid them with the process of adopting blockchain technology (Janssen *et al.*, 2020).

Blockchain is an emerging technology which is creating unrest in organisations by revolutionising the way business transactions take place. This innovative technology, as with other disruptive technologies in any sector, introduces challenges. These challenges are of a technical, regulatory, social, and adoption-related nature (Janssen *et al.*, 2020).

The conceptual framework is constructed by first analysing blockchain technology and organisation-related literature to find all of the main factors surrounding blockchain technology. The factors were then grouped together based on the institutional framework of Koppenjan and Groenewegen, which takes into account these (i) institutional, (ii) market, and (iii) technical factors. The PIMT framework adds to the institutional framework by incorporating (iv) *change process*. This refers to the (1) changes required and (2) management of the changes required. The *institutional factors* refer to the changes required by: (1) norms and culture, (2) regulations and legislation, and (3) governance. The *market factors* evaluate how the market structure is evolving due to the technology and include the: (1) market structure, (2) contracts and agreements, and (3) business processes. The *technical factors* are those incorporated with the design of the technology: (1) information exchange and transactions, (2) distributed ledger, and (3) shared infrastructure (Janssen *et al.*, 2020).

To conclude, this framework can be used to understand the broader scope of adoption, as adoption is not only achieved by changing on a technological level, but also by changing processes and governance mechanisms. Thus, be cautious that a technological concept's hype does not supersede the potential benefits, opportunities, costs, and risks it poses to organisations (Janssen *et al.*, 2020).

5.3.3.2 Selection and Acquisition Framework – LED Technology

The selection and acquisition framework is developed by Ma and Hung (2015), to enable the identification of core LED technologies and effective methods of technology acquisition. The framework incorporates expertise from both industry professionals and academics, as a foundation for evaluating the LED technologies and also to decide on a best suited method for acquiring the technology. The paper describes the need for technology acquisition as it enables various industries to keep up with rapid technological developments and thus it has become a popular strategy for ensuring corporate growth. The most noticeable challenges for an organisation's strategy are related to (i) what and (ii) how to acquire the required technology (Ma and Hung, 2015).

For a company, technology selection in cases of investing can be extremely difficult in an environment where that particular company wants to gain an competitive advantage above others, based on technological, social, and economical criteria. Therefore, determining the correct criteria for each specific case is critical. This framework selected three criteria of importance; (i) property, (ii) profitability, and (iii) risk. *Property* is described as the degree to which the particular technology is relevant and competitive, *profitability* is described as the measure of how much profit can be generated from the introduction of a particular technology, and *risk* is described as the risk experienced with the introduction of a particular technology. In terms of acquisitions the literature included five different means of acquiring technologies. The acquisition methods are: (i) internal R&D, (ii) joint ventures, (iii) contract R&D, (iv) licensing, and (v) direct purchase (Ma and Hung, 2015).

This paper proposes an integrated framework which includes three phases. Phase 1 (steps 1-6), utilises the *Fuzzy Analytic Hierarchy Process (FAHP)* to evaluate the critical technologies. Phase 2 (steps 7-8), performs a *patent analysis* to determine which firms possess these critical technologies. Lastly, phase 3 (step 9) determines the best suited mode of technology acquisition regarding the identified firms in steps 7 and 8. The underlying steps of the three phases are (Ma and Hung, 2015):

1. Defining the core technology selection questions, confirmation of the chosen scope and analysed technologies.
2. Investigation of technology selection criteria (property, benefit, and risk).
3. Use FAHP and expert views to determine weights of technology selection criteria.
4. Selection of promising candidate technologies based on experts' views.

5. Derivation of a technology selection plan.
6. Prioritisation of selected technology options.
7. Patent search from industry database.
8. Critical firm identification through generated patents.
9. Analysing inter-organisational technology transfer modes.

5.3.3.3 Selection Framework – Condition Monitoring (1)

The technology selection framework as described by Davis *et al.* (2013), aims to identify and prioritise potential technologies capable of performing condition monitoring of infrastructures in water and wastewater networks, with the intended purpose to suggest technologies for in-field pilot trials (Davis *et al.*, 2013).

The following three phases are implemented to insure the technology selection framework best conforms to the needs of the water and wastewater network industry:

1. Mapping the potential technologies, based on their capabilities, to their respective network assets and failure modes.
2. Prioritising the technologies based on their perceived value.
3. Developing the business case for each of the technology pilot trials.

The framework made use of "failure pathway(s)" to generate a graphical representation of the link between the asset deterioration events, failure events, and the particular asset in question. Furthermore, from the "failure pathway" certain monitoring parameters are revealed that potentially allow for early detection and prevention actions to be implemented. These monitoring parameters are used to select the candidate technologies for evaluation. After the technologies are mapped to their respective failure modes they are evaluated through a Multi Criteria Assessment (MCA). The subset criteria was identified through workshop discussions with industry professionals and from these discussions they concluded that the criteria be based on (i) financial, (ii) environmental, and (iii) social factors, whilst aligning with (iv) regulatory requirements of expenditure. Lastly, the business case is developed for each of the prioritised technologies by assessing the costs versus the benefits of each case (Davis *et al.*, 2013).

5.3.3.4 Selection Framework – Condition Monitoring (2)

Davis and Brockhurst (2015) developed a technology selection and review framework to assist asset owners with the selection of potential condition monitoring technologies capable of performing non-invasive infrastructure condition monitoring on subsea pipelines. The framework follows a similar methodology as the one described in Section 5.3.3.3 which was also developed by Davis. The only difference is that the focus is shifted slightly from creating a business case for each potential technology to identifying the asset deterioration process.

The following three phases are implemented to ensure the technology selection framework best conforms to the needs of the subsea oil and gas pipeline industry (Davis and Brockhurst, 2015):

1. Identifying the deterioration process and "failure pathways" for the subsea infrastructure assets in the scope.
2. Mapping potential current and emerging inspection technologies to the previously identified infrastructure types.
3. Prioritising the inspection technologies based on their perceived value for further investigation and field trials.

5.3.3.5 Technology Portfolio Evaluation (TPE) Framework

The Technology Portfolio Evaluation (TPE) framework is developed to assist companies with the decision-making process for new renewable energy technology investment projects. This is to ensure that the projects decided upon provide the greatest possible value for an organisation. Incorporated into the framework are benefit measurement models, mathematical programming and heuristic modelling (Davoudpour *et al.*, 2012).

The TPE framework made use of a *Analytic Hierarchy Process (AHP)* theoretical approach to help with the selection of the renewable technology projects. The evaluation criteria were based on an analysis of the relevant literature and a set of primary and subcriteria was constructed. The primary factors (criteria) that influence the selection are (i) market, (ii) competitiveness, (iii) technical factors, (iv) capabilities, and (v) environmental factors. From these factors the hierarchy model is constructed. Furthermore, the hierarchy model was reviewed by industry experts and adjusted accordingly to ensure it met industry requirements. The weights of all the criteria were also determined through industry experts' inputs. After obtaining all the relevant criteria weights, the overall importance of each primary and subcriterion was determined. From these results the top ten most important factors were included in the final mathematical model (Davoudpour *et al.*, 2012).

The TPE framework concludes with a mathematical optimisation model that integrates portfolio managers' existing tools into a linear, integer program. This model calculates total performance from both expert data and estimated financial performance data (Davoudpour *et al.*, 2012).

5.3.3.6 Framework for Green Technology Adoption

The framework developed by Xia *et al.* (2019), is aimed at identifying the barriers associated with the adoption and transformation process of green technology, with the intention of providing a better understanding of the obstacles and the supporting resources required to address these obstacles, so as to facilitate decision-making (Xia *et al.*, 2019).

In the framework development it is found that the factors affecting green technology adoption are: (i) technical features, (ii) specific business characteristics, and (iii) task circumstance simultaneously (Xia *et al.*, 2019).

The development of the framework is based on related theoretical theories and literature analysed. From the research two categories of barriers were identified: (1) functional barriers and (2) phycological barriers. These primary barriers were then further split into subcategories; (1.1) individual, (1.2) process, (1.3) procurement, (2.1) individual, (2.2) group, and (2.3) social. The barrier evaluation method used in the framework is a FAHP technique, because it is argued that it would best suit the hierarchical nature of the two barrier dimensions whilst obtaining valuable input from experts. Furthermore, the paper describes that the AHP alone would be able to use experts' knowledge, but would not be able to portray human thinking and cognition exactly. Lastly, to test the applicability of the framework a case study is performed (Xia *et al.*, 2019).

5.3.3.7 Housing Technology Selection Framework

The framework developed by Nanyam *et al.* (2015), aims to help guide the selection of housing technologies by being a scientific, holistic, and transparent evaluation framework governed by mandatory and preferred attributes. The framework is an multi-criteria evaluation framework for emerging systems and technologies of residential construction. This framework was tested for applicability through two case studies (Nanyam *et al.*, 2015).

The research methodology followed by Nanyam *et al.* (2015) is a multi-step process listed here:

1. Attribute identification for all emerging housing systems and technologies in the scope.
2. Attribute definitions and criteria.
3. Technical advisory group review of attributes.
4. Gathering of expert opinions.
5. Attribute finalisation.
6. Development of Evaluation Framework.

The evaluation criteria are divided into three levels, (i) primary, (ii) secondary, and (iii) tertiary, where the primary level includes two subsets of attributes: (1) mandatory attributes and (2) preferred attributes. On a primary level, technologies are rejected if they do not meet the mandatory requirements. The technologies not rejected are evaluated against the preferred attributes, with the ones not meeting the requirements also being rejected. This leaves only the accepted technologies. The secondary level includes attributes such as: (1.1) strength and stability requirements, (1.2) performance and statutory compliance, (2.1) functional requirements, (2.2) constructability, (2.3) economic viability, (2.4) maintenance, (2.5) sustainability, and (2.6) finish quality. All of the mandatory attributes' acceptance criteria were decided by the technical advisory group. Furthermore, all of the attributes were also given relative weights based on the advisory group's opinions through a AHP decision matrix. The output of the matrix assigns a TPI (Technology preference index) for each of the attributes. The TPIs are evaluated against a predefined scale and this is able to give feedback in terms of if a technology would be recommended or rejected (Nanyam *et al.*, 2015).

In conclusion this framework serves as decision support system for selecting emerging housing technologies for affordable housing construction (Nanyam *et al.*, 2015).

5.3.3.8 Sustainable Hydrogen Production Technology Selection Framework

The framework described in the paper by Xu *et al.* (2019), aims to guide the selection of sustainable hydrogen production technologies through a multi-criteria assessment framework. The framework combines interval best-worst method (IBWM), interval enthropy technique (IET), and interval best-worst projection (IBWP) prioritisation methods to minimise data uncertainties (Xu *et al.*, 2019).

The MCDA based mathematical model incorporated into this framework consists of three stages; (i) system definition, (ii) weights determination, and (iii) alternative prioritisation. The *system definition* needs to be implemented case-by-case by first by: (1) establishing a list of alternative technologies, (2) creating the assessment criteria, and (3) collecting performances regarding the criteria. The *weight determination* is handled next, by: (1) calculating the interval-valued subjective weights using the IBWM, (2) calculating the interval-valued objective weights by using the IET, and then (3) calculate the combined weights. The last step of the framework development is the *alternatives prioritisation* which uses the IBWP method to prioritise the alternative technologies through ranking (Xu *et al.*, 2019).

5.3.4 Framework Design Requirement Evaluation

As mentioned in Section 5.3.3, eight frameworks are selected from the structured review to obtain further knowledge of existing methods and processes that guide the selection and adoption of new and emerging technologies. In this section the existing frameworks are evaluated against the set of *design requirements* developed in Section 5.2. This evaluation aims to justify the development of a conceptual framework in this research. See Table 5.2, which displays the design requirements that each of the existing frameworks addresses.

Table 5.2: Existing Framework Evaluation

		Design Requirements									
FR	**Section**	**DR1**	**DR2**	**DR3**	**DR4**	**DR5**	**DR6**	**DR7**	**DR8**	**DR9**	**DR10**
1	5.3.3.1						X				
2	5.3.3.2						X	X	X	X	X
3	5.3.3.3	X	X	X		X	X	X	X		
4	5.3.3.4						X	X			
5	5.3.3.5						X	X			
6	5.3.3.6						X	X			
7	5.3.3.7	X	X	X		X	X	X	X		
8	5.3.3.8						X	X	X		

From Table 5.2, it is seen that none of the evaluated frameworks conforms to all of the design requirements. This can be attributed to the fact that not all of the frameworks have the same end goal aligned with this research thesis. However, each of the evaluated frameworks describes a particular area of expertise and from that the underlying methods utilised can be useful for the development of a new technology selection framework. This evaluation's results show that all of the frameworks incorporate some means of defining an evaluation criterion. These frameworks' criteria have different categories and subcategories, but can be summarised as they aim to measure the benefits, challenges, and risks associated with the acquisition of each technology. It is also seen that all but one framework use multi-criteria analysis techniques to evaluate the technologies against the predefined criteria. As part of defining the criteria or determining the weight of each criterion it is seen that experts' opinions are valued and incorporated through workshops and surveys.

Only two frameworks, numbers 3 and 7, included technologies that are used by the organisations as equipment to monitor the condition of their assets and therefore they meet design requirements 1, 2, 3, and 5. Design requirements 1-5 are aimed at contextualising the technologies by understanding their capabilities and matching them to the specific assets in need that they can supplement. According to the design requirements, for a framework to align with the goals of this thesis it must aid organisation not only with the selection and adoption of emerging technologies, but also assist with the acquisition of the technology. Thus, design criteria 9 and 10 aim to support organisations with the acquisition. Against the evaluation in Table 5.2, it is seen that only framework 2 addresses the process after technology selection which is acquisition.

In conclusion, regarding the evaluation of the existing technology selection frameworks, it is deduced that none of the frameworks investigated meet all of the design requirements as described in Section 5.2. Thus, it states the case for justifying the development of a conceptual framework that addresses all of the design requirements.

5.4 Multi-Criteria Decision Analysis Techniques

From the existing framework analysis, Section 5.3, it is found that seven out of the final eight technology selection frameworks included some sort of MCDA technique. In the frameworks these techniques are responsible for providing technology selection decision support, by evaluating candidate technologies against a set of predefined criteria to provide the best solution.

There are currently various types of MCDA techniques being used throughout different industries and across the world. Despite the differences between techniques, they all follow a similar *process* to help identify the preferred or most ideal alternatives (Salo *et al.*, 2003). Salo *et al.* (2003), mentions that the general process consists of six phases as follows:

1. **Identification of stakeholders:** All the stakeholders affected by the decision must be identified and can include policymakers, R&D managers, subject matter experts, government representatives, and even members of the public.
2. **Development of goals, criteria, and alternatives:** With the help of the relevant stakeholders the goals, criteria, and alternatives are defined. (i) The *goal(s)* is seen as the objectives or problem that requires attention (that

which must be achieved), (ii) the *criteria* is used to measure the attainment of the goal, and (iii) the *alternatives* is seen as the different choices.

3. **Model development:** Structures the goal, criteria, and alternatives in a hierarchical manner with the goal at the top and the subcriteria at the lowest level. Generally each of the lowest level criteria have a *measurement* or *rating* scale which is used to determine an alternatives performance against each of the subcriteria.
4. **Score elicitation:** The alternatives are rated with respect to the lowest level criteria.
5. **Weight elicitation:** The criteria weights are determined to define the relative importance of each criterion with respect to the others. The weights can be determined through the opinions of (i) an individual, (ii) a group whose individuals work independently, and (iii) a group whose individuals work in tandem.
6. **Computation of overall performance measures:** An *aggregated performance value* is derived for each alternative by combining the results of both score and weight elicitation. This value serves as an indication of how desirable an alternative is in relation to the others.

The technology selection frameworks that were reviewed in this chapter incorporated the following MCDA techniques; AHP (Davoudpour *et al.*, 2012; Nanyam *et al.*, 2015), FAHP (Ma and Hung, 2015; Xia *et al.*, 2019), and a simple scoring scheme that uses the criterion-weighted sum to rank alternatives (Davis *et al.*, 2013; Davis and Brockhurst, 2015). The selection of an appropriate technique is not limited to only one, based on the fact that different techniques can be used in combination. This is supported by the review conducted by Russo and Camanho (2015), where 33 MCDA cases implementing AHP or FAHP are evaluated and it is found that the literature is mainly used to develop the criteria, AHP or FAHP are used to determine the criteria weight, and other techniques are used to evaluate the alternatives.

Based on the research design followed it is decided that the evaluation criteria will be developed with the help of both literature and industry experts, (see Section 5.5). When it comes to determine the relative weights of the criteria, AHP is the chosen method. This is attributed to the fact that AHP is able to break down and simplify a complex problem whilst being extremely effective to achieve results. It has the capability to take into account both quantitative and qualitative aspects during the decision-making process (Özcan *et al.*, 2017). In terms of alternative evaluation AHP is not as effective when it has a large number of alternatives to choose from due to the effort required to make the pairwise comparisons. Thus, a better solution is required. A simple scoring scheme that rates the performance of each individual technology against each evaluation criteria is seen as a simple yet powerful method (Davis *et al.*, 2013; Davis and Brockhurst, 2015). Especially when the number of technologies and categories (different asset groups and monitoring parameters) are relatively high. Therefore, a simple scoring scheme is chosen in conjunction with the criterion-weighted sum method to rank the alternatives.

The Analytic Hierarchy Process (AHP) is frequently used by decision-makers and researchers alike. It is a method that utilises pairwise comparisons for measurement purposes and relies on the judgement of subject matter experts to derive priority scales (Russo and Camanho, 2015). The AHP method is developed by Thomas L. Saaty in the 1970s, as a means to systematically define priorities and support complex decision-making (Saaty, 1987). It structures the problem in the form of a hierarchy, whereas the primary goal is divided and subdivided into its constituent criteria. The hierarchy that is constructed, encompasses a detailed representation of all the relevant concerns and alternatives. With the alternatives positioned at the lowest-level criteria (Salo *et al.*, 2003). Figure 5.6 represents a generic AHP hierarchy that incorporates two-levels of criteria and two different alternatives.

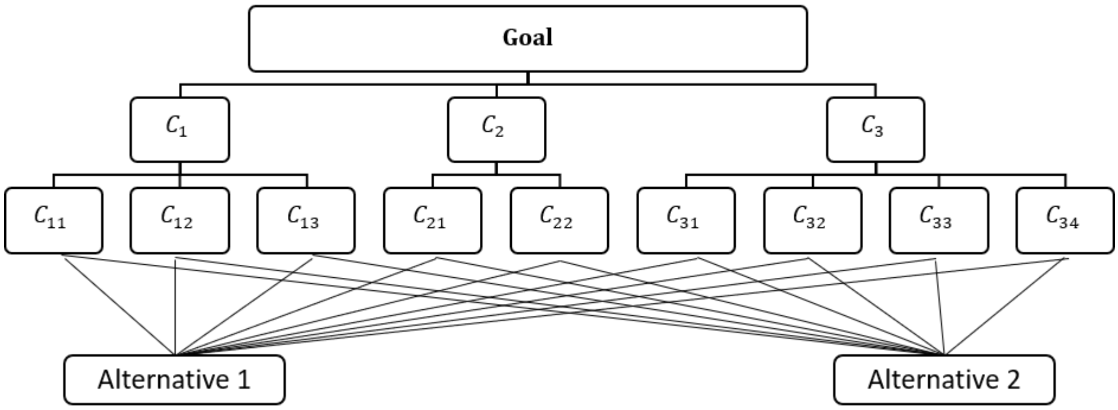


Figure 5.6: AHP hierarchy

When using AHP for complex decision-making, the process looks as follows: (i) first of all the decision-making problem must be broken down into a hierarchy, (ii) after which pairwise comparisons are implemented to establish the relative priorities amongst the elements in the hierarchy, (iii) synthesise the judgements to obtain the overall weights for achieving the goal, and (iv) finally the consistency of the judgements is evaluated and checked.

The pairwise comparisons are implemented by asking industry experts or decision-makers which criterion is most important regarding the end goal. These comparisons are judged on a scale of 1-9, which was created by Saaty, and is shown in Table 5.3 (Saaty, 1987; Özcan *et al.*, 2017).

Table 5.3: Saaty rating scale (Saaty, 1987)

Importance	Description	Explanation
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance	Experience and judgement favour one element over another.
5	Strong importance	An element is strongly favoured.
7	Very strong importance	An element is very strongly dominant.
9	Extreme importance	An element is unparalleled in importance.
2,4,6,8	Intermediate values	Compromise between two.

The pairwise comparison matrix C_{ij} is presented below. This matrix must be normalised first to obtain the relative weights of the criteria.

$$C_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

To normalise the pairwise matrix, the sum of the values in each column is calculated:

$$C_{ij} = \sum_{i=1}^{n} C_{ij} \tag{5.4.1}$$

Now each element in the matrix is divided by the sum of each column and this generates a normalised pairwise matrix, X_{ij},

$$X_{ij} = \frac{C_{ij}}{\sum_{i=1}^{n} C_{ij}} \tag{5.4.2}$$

$$X_{ij} = \begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix}$$

The last step to obtain the relative criteria weights is to divide the sum of the normalised column matrix by the number of criteria (n),

$$W_{ij} = \frac{\sum_{j=1}^{n} X_{ij}}{n} \tag{5.4.3}$$

From the division the weighted matrix is generated, W_{ij},

$$W_{ij} = \begin{bmatrix} W_{11} \\ W_{12} \\ W_{13} \end{bmatrix}$$

The second part of the AHP process is to check the consistency of the judgements. This is achieved by multiplying the pairwise matrix by the weighted matrix and then dividing the weighted sum vector by the criterion weights:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} * \begin{bmatrix} W_{11} \\ W_{12} \\ W_{13} \end{bmatrix} = \begin{bmatrix} Cv_{11} \\ Cv_{12} \\ Cv_{13} \end{bmatrix}$$

λ_{max} is calculated by the following equation,

$$\lambda_{max} = \sum_{i=1}^{n} Cv_{ij} \tag{5.4.4}$$

In AHP the judgements are only considered consistent if the Consistency Ratio (CR) is less than 10%, where the CR is only calculated after the Consistency Index (CI). The CI is calculated as follows:

$$CI = \frac{\lambda - n}{n - 1} \tag{5.4.5}$$

Next step is to divide the CI by the Random Index (RI), created by Saaty. This provides the calculated value of the CR. The equation used is as follows:

$$CR = \frac{CI}{RI} \tag{5.4.6}$$

The consistency check is completed if the CR $<$ 10%. If the CR $>$ 10%, the judgements of the experts are inconstant and must be revised.

The alternatives are ranked according to the criterion-weighted sum methods, which takes into account the weight of each criteria (W) and the technology performance score (S). The priority score (A) for each candidate technology is calculated through the summation of the product of the criteria weight and performance scores. The calculation for the priority score is as follows:

$$A = \sum_{i=1} W.S \tag{5.4.7}$$

After the priority score is calculated for each candidate technology, they are then ranked in order of best (highest) to worst (lowest).

5.5 Evaluation Criteria Development

The evaluation criteria are the most important aspect of any MCDA techniques used, this is seen from both the existing technology selection frameworks analysed (Section 5.3) and the different MCDA techniques considered (Section 5.4). Thus, careful consideration is given during the development of the evaluation criteria. The first question is what information source would best serve as the foundation upon which the criteria are developed? When implementing AHP, the evaluation criteria are predominately constructed from literature sources, but in the MCDA review conducted by Russo and Camanho (2015), it is also highlighted that the use of subject matter experts to obtain a set of criteria is another viable option. For the intended purpose of this research it is decided to integrate the views from literature and the subject matter experts. This is done to eliminate potential gaps created by only utilising one or the other. The literature provides a solid understanding of all the influencing factors that play a role in the successful selection and adoption of new technologies, but can tend to be generic. Therefore, by incorporating the views from subject matter experts the criteria are more orientated towards a specific topic or the goal at hand (Davis *et al.*, 2013; Davis and Brockhurst, 2015). In the case of this thesis, the criteria must reflect the consideration taken into account for ensuring a favourable selection of data acquisition technologies for condition monitoring of railway infrastructure.

The second important question to answer is, what must the criteria reflect? Ma and Hung (2015) developed a technology selection framework to select LED technologies (Section 5.3.3.2), whereas the selection criteria that were used are property, profitability, and risk. A technology selection model study conducted by Shen *et al.* (2010), looked at the criteria from a perspective of technological merit, business effect and technology development potential, and risk. This model especially highlighted the importance of qualitative benefits and risks. The framework presented in Chapter 6 incorporates a set of evaluation criteria that addresses the costs, benefits, challenges, and risks associated with data acquisition technology selection and adoption in the railway maintenance field.

The technology evaluation criteria presented in this thesis tends to be more qualitative in nature, as the criteria tries to emphasise the qualitative benefits and risks associated with each technology rather than focusing on all the associated costs. This is a result of the most expensive technologies not always being the best option for each case or the cost is not that much of an issue because the technology is critical to operations (need overshadows cost). However, the evaluation criteria include the costs associated with each technology. The framework is constructed in such a manner that it first identifies the top candidate technologies capable of presenting the organisation with the most benefits and least amount of risks, with cost playing a minor role.

The criteria are derived from the feedback of the railway subject matter experts who are presented in Chapter 4 and their input is further supported and supplemented by literature findings from both Chapter 2 and this Chapter 5. This has led to the development of 19 different criteria to assist with the selection of data acquisition technologies. Due to the use of the AHP technique it is decided to lower the number of criteria to 13 by combining certain criteria that are similar in nature. This choice lessens the work required by the subject matter experts when performing the pairwise comparisons to ensure higher participation rates whilst maintaining the decision-making impact of the criteria itself. Furthermore, the 13 criteria are grouped together under four different categories or primary criteria; namely, (i) *technical*, (ii) *institutional*, (iii) *social*, and (iv) *other*. See Table 5.4 for the description of the four primary criteria and Table 5.5 for the description of the 13 subcriteria. The evaluation criteria are presented again in Section 6.2.2.1 as part of the framework.

Table 5.4: Description of primary criteria

Criteria	**Description**
Technical	Criteria that are directly related to the capabilities and potential of the candidate technologies.
Institutional	Criteria that influence the organisation in question through the addition of emerging technologies (Strategic and Operational level).
Social	Criteria that take into account the social impact on stakeholders such as employees, passengers, public etc.
Other	Criteria that are important to evaluate the benefits, challenges, and risks of adopting emerging technologies that do not fall under one of the other criteria.

Table 5.5: Description of subcriteria

Criteria	**Subcriteria**	**Description**
Technical	Accuracy	The accuracy at which the technology is able to acquire condition monitoring data.
	Cost	The life cycle cost associated with a particular technology includes acquisition, maintenance, and operations.
	Influence of external factors	The degree to which a technology's performance is not altered by external factors such as operator error, environmental effects, etc.
	Continuous monitoring capabilities	The degree to which a technology is capable of providing continuous condition monitoring data.

Continued on next page...

Table 5.5 – *continued from previous page*

Criteria	**Subcriteria**	**Description**
	Maturity of technology	A measure of the technological readiness level to address mistrustfulness and feasibility of implementing new technology.
Institutional	Traffic interference	Measures the effect of monitoring with respect to halted operations or normal operating schedule of the trains.
	Early failure prediction	The degree to which the technology performs in terms of preventative capabilities (How early can potential failures be detected?).
	Operator skills	The skill level required by the operators to operate technology safely and effectively.
	Security	Degree to which technology is susceptible to theft and other damages as well as cyber security threats to protect privacy, confidentiality, and intellectual property.
Social	Safety	Ability of technology to ensure the safety of both the operator and the environment.
	Job uncertainty	The effect of acquiring new technology on job uncertainty. Measure of job creation or elimination due to implementation of new technology.
Other	Environmental	The effect the technology has on noise and other pollution.
	Support	The degree of local and international technical and service support that a technology possesses.

The evaluation criteria is insignificant if there are no means of measuring the performance of the candidate technologies when they are assessed with respects to each criteria. Again, the feedback from the railway subject matter experts are utilised to create a criteria rating scale which assigns a value from 1-5 to the technology for each criteria, depending on the technology assessment of the criteria. The criteria being more qualitative in nature makes the rating scale more difficult to construct as there are not always concrete numerical values to assess each criteria. Therefore, the rating scale which is presented in Table D.1, Appendix D, is constructed by analysing numerous literature sources as well as the finding from the survey in Chapter 4.

The accuracy of the sensors utilised in the data acquisition technology is very important, because the correct data is required to analyse and make judgements. If inaccurate data were to be presented it would potentially affect the predictions and then the wrong actions could be taken. Cost generally plays an important role during any form of transaction/agreement and that is exactly what technology acquisition is. It is found from the research that the life-cycle cost associate with an technology must be considered in order to determine any cost saving benefits a specific technology might bring to the organisation. Thus, a lower cost would be seen as more beneficial. The influence of external factors are assessed based on the robustness of a technology. Therefore, it aims to score the reliability and repeatability of a technology when external factors are acting on it, such as weather, environment (rocks, trees, plants, etc.), and people in the case of theft and vandalism or unskilled operator. Thus, it measure how the condition monitoring performance is affected by external factors. Continuous monitoring capabilities are assessed based on the continuity of the data being collected, when the data can be observed and interpreted with respect to the time of acquiring the data. This ranges from data being collected and observed in real-time without any interruptions, real-time data being collected while travelling along the railway track (periodically through the help of a carrier), data interpretation after travelling along the railway track is completed (with carrier), data is collected and observed while scheduled manual inspection takes place, and finally data interpretation commences once manual inspections are completed. In short the measuring intervals are very important. The maturity of the technology affects both the organisations capabilities to utilise it effectively and the distrustfulness experienced by people. Thus, the maturity is assessed based on the technology readiness level (TRL) each candidate technology possesses.

A technology is assessed as to how much it interferes with the regular train schedule. Interference is determined through if the technology is able to monitor whilst the trains travel along the track either attached to a train or not in its path. The speed at which the technology can obtain condition data also plays a role as some carriers can operate at similar speeds as those of the in-service trains meaning that the measuring can take place between two trains (slightly or even not affecting regular operations). Technologies requiring halted operations for periods of time affect the train schedules the worst. The time required for monitoring is also an important aspect. The idea behind failure prediction is that earlier is better. Thus, the failure pathways are investigated to determine how early failures can be predicted by certain technologies. The monitoring parameter of each technology indicates its relative position with respects to a major failure. Employee 'up-skilling' is an important part of all organisations and as such having employees that are highly skilled or have special training is favoured, because more competent employees tend to lead to less mistakes and more efficient work. On the other hand having highly skilled workers perform tasks below their capabilities can be seen as wastage if a less competent worker can perform the tasks for a smaller cost to company. The security of the technology is measured by both how well the physical technology is protected from theft or damages and the data protection capabilities.

Safety is rated according to the degree of risk experienced by both the operator and people in close proximity to the location of where the technology is being operated. Job uncertainty is judged based on if the implementation of the new technology creates more jobs or requires less people to perform the task and this can lead to certain job becoming obsolete or at risk. Environmental impact is assessed through the amount of noise pollution created by the technology during operation. No other type of pollution is included as it is not possible to compare the data acquisition technologies identified in this thesis with each other through a uniform performance metric. According to the World Health Organisation, (Berglund *et al.*, 1999), and Goines and Hagler (2007), noise pollution under 70 dB should not pose any hearing risks for people while noise levels over 85 dB can cause problems. The after sales technical support is assessed by evaluating the type of support given for each technology (Ma and Hung, 2015). Technology suppliers are investigated to determine if training of the operators is included as well as continuous technical aid even after the sale to help with day to day difficulties.

5.6 Technology Acquisition Modes

The adoption of new technologies by any organisation consists of two parts, first the selection of the best technologies from a list of viable candidates and second the selection of an appropriate technology *acquisition mode*. The identified technologies carry no weight if an organisation does not know to acquire the required technology. This problem can be attributed to the fact that there are various modes of acquiring technology, but no clear guideline as to which one is better suited for a particular case. These different modes are broadly classified as either acquisition through internal development, cooperation between different organisations, or buying the technology itself (Lee *et al.*, 2009). To ensure the outcome favours an organisation strategic goal(s), the selection of an acquisition mode should follow a systematic approach that considers the conditions of each mode influencing the strategic goal(s) of an organisation. A term used by Paton and Van Der Lingen (2016), to describe this systematic approach is *technology acquisition strategy* which is seen as,

> *"...the process of selecting acquisition modes by using technical and non-technical capabilities, and an integration of the selected technology into the value chain." – Paton and Van Der Lingen (2016)*

Technology acquisition is a function of internal and external factors such as research and development (R&D) experience, technology life-cycle, and competitive intensity according to Ashwin (2014).

From the research conducted, (Ashwin, 2014; Ma and Hung, 2015; Paton and Van Der Lingen, 2016; Lee *et al.*, 2009), numerous modes of acquiring technology has been identified and are: mergers and acquisitions (M&A), licensing, joint ventures, joint R&D, R&D contracts, strategic alliances, consortium, outsourcing, and in-house R&D. These acquisition modes can be grouped together according to the broad classification as described in the introductory paragraph of this section, Lee utilised this approach to develop the analytic network process (ANP) model. Lee *et al.* (2009), developed a ANP model for the selection of a technology acquisition mode that assesses quantitatively whether it is better to *make*, *cooperate*, or *buy* to acquire the technology. Paton and Van Der Lingen (2016), investigated a framework developed by Cho and Yu (2000), and in this framework three acquisition mode categories are identified namely *in-house development*, *technology purchasing*, and *collaborative development*. In-house development is described as when the organisations existing structures are utilised to perform the developments, R&D departments. Technology purchasing is seen as the process of acquiring technologies through contracts, licensing, or basic purchasing from a supplier. Lastly, collaborative development is described as the joint effort of two or more organisations through which internal resources are combined innovatively to complement each other (Paton and Van Der Lingen, 2016).

Ashwin (2014) classifies five different modes of acquisition used in their integrated framework. The five acquisition modes are: internal R&D, unilateral contract-based acquisition, bilateral cooperative alliance, M&A for technology and embodied technology acquisition. Ashwin (2014) argued that internal and external modes of technology acquisition is complementary towards each other and should not be substitutes. This is shown in the theoretical framework developed by Ashwin (2014), where the transaction cost theory is combined with technology familiarity. Organisation implementing transaction cost theory chooses acquisition modes that minimise the transaction cost – transaction cost increases when uncertainty and transaction frequency increases. Furthermore, technology familiarity is a measure of the technical capabilities an organisation possesses to acquire a certain technology. See Figure 5.7 for the framework as described by Ashwin (2014). The framework indicates the general likelihood of organisations to select particular acquisition modes based on the transaction cost and technological familiarity.

The framework identified that organisations are more likely to choose, (...) when (...);

1. **Internal R&D:** higher transaction cost and higher technological familiarity.
2. **M&A:** higher transaction cost and lower technological familiarity.
3. **Bilateral alliance:** moderate transaction cost and moderate technological familiarity.
4. **Unilateral alliance:** Lower transaction cost and higher technological familiarity.
5. **Embodied mode:** lower transaction cost and lower technological familiarity.

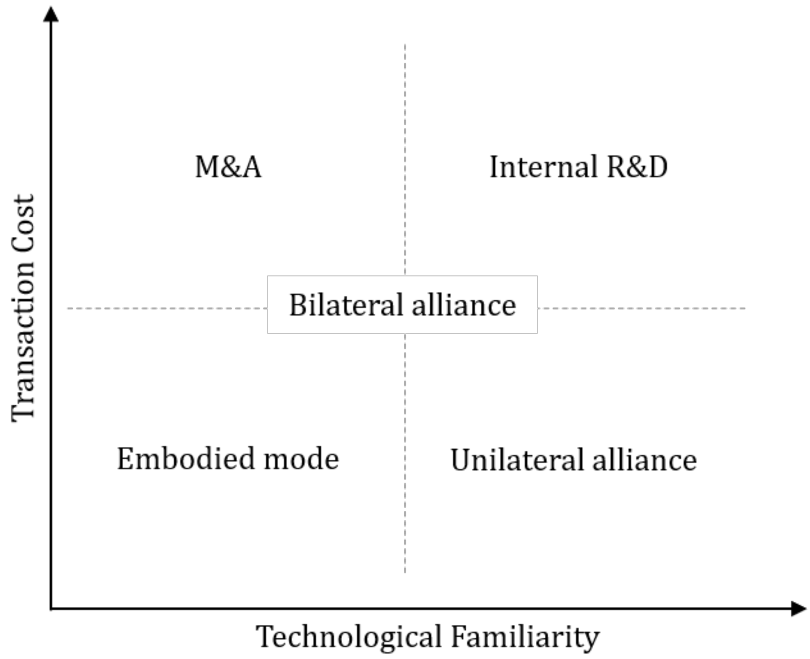


Figure 5.7: Combined model, adapted from Ashwin (2014)

Simatupang (2006) investigated the choice between *making* and *buying* for technology acquisition modes. As such a theoretical framework was developed for addressing technology acquisitions in the Indonesian electronics industry. The framework consists of various subsystems of which selecting the sourcing (acquisition) mode is one. The sourcing subsystem is responsible for aiding an organisation to make a decision on whether to *make* or *buy* the technology. The two main aspects for selecting an acquisition mode as described by Ashwin (2014), have similar traits as the criteria incorporated in Simatupang's framework. The criteria as defined by Simatupang (2006) are (i) *technology importance*, (ii) *time pressure*, (iii) *resource availability*, and (iv) *dependency analysis*. Through the assessment of the technology against the criteria a technology acquisition mode can be determined. The acquisition mode selection criteria can be described as follow:

- **Technology importance:** is assessed with respect to its strategic importance, based on the influence it has on a organisation's competitive advantage and core competency.
- **Time pressure:** is a measure of the urgency for when a technology is required by an organisation.
- **Resource availability:** is measured through the availability of the internal R&D capabilities and the availability of capital.
- **Dependency analysis:** measures the organisation's dependency on external sources through the type of acquisition mode.

Technology importance and time pressure are closely related, this is seen from Figure 5.8 as they are considered simultaneously during the selection of a acquisition mode. Technologies that are responsible for the core competency of an organisation should be developed in-house, whereas, the technologies that do not fall under core technologies could be externally sourced. The same can be said for technologies that are critical for competitive advantage, as they should also be developed in-house. In terms of time pressure, if the required technologies are needed urgently external acquisition modes deem to be the favoured choice, seeing as internal developments usually require more time.

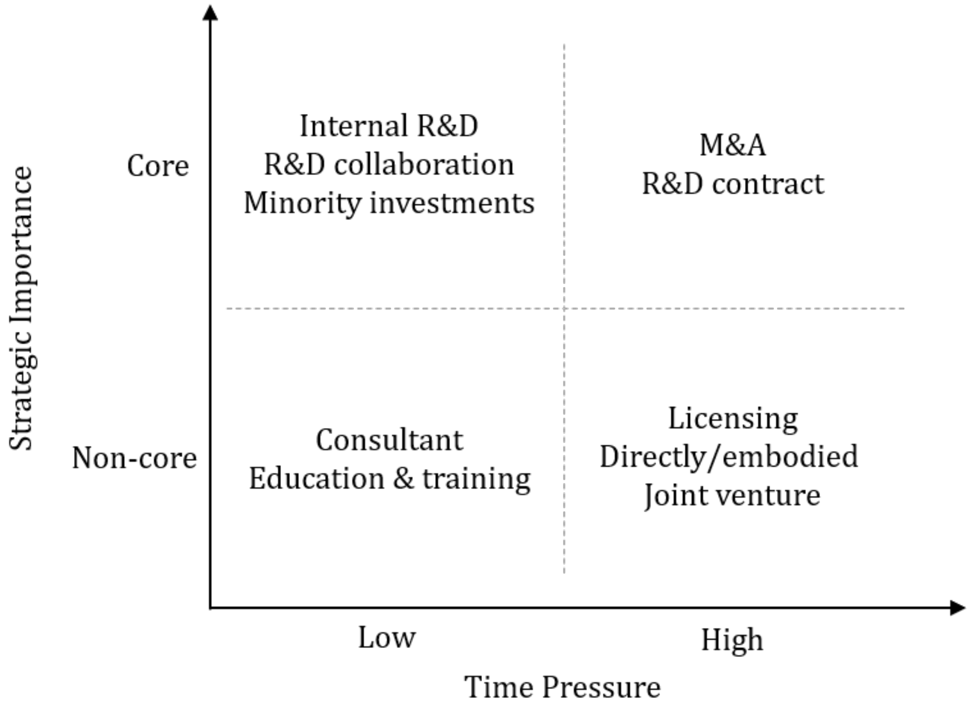


Figure 5.8: Acquisition mode selection based on time pressure and strategic importance, adapted from Simatupang (2006)

Resource availability is an important factor that one must always consider when deciding on a technology acquisition mode. The resources are what makes the acquisition possible in the first place. Figure 5.9 presents the effect the availability of capital and R&D capabilities have on the number of acquisition mode options. For internal developments, the internal R&D capabilities of an organisation must be high and at the same time the organisation must have sufficient capital available. High amounts of capital creates the opportunity for numerous acquisition modes, while low amounts of capital on the other hand limits the number of options.

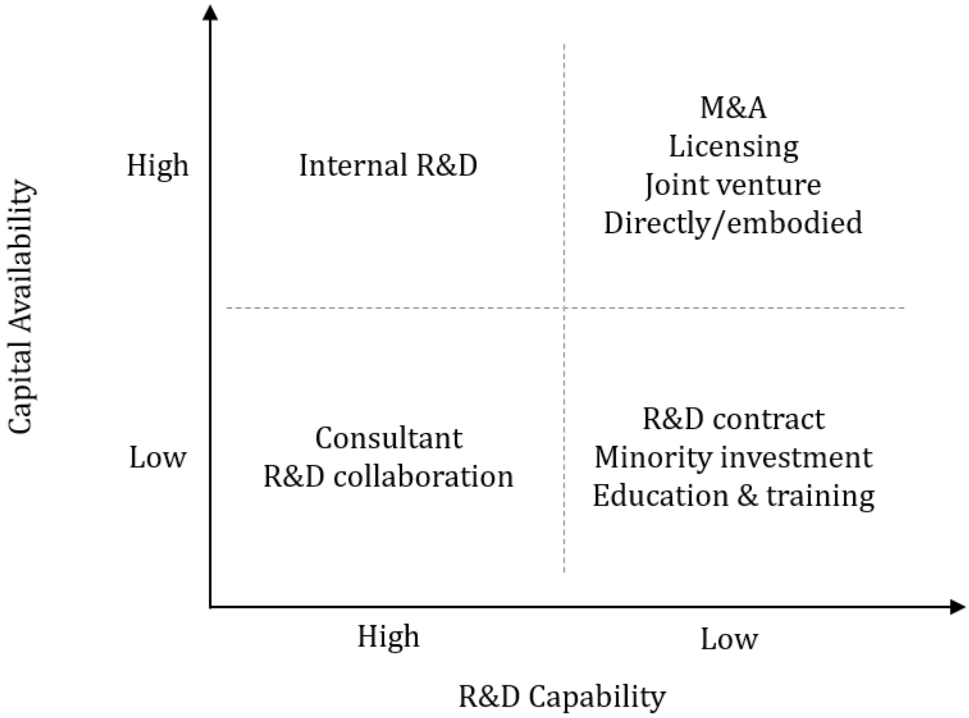


Figure 5.9: Acquisition mode selection based on resource availability, adapted from Simatupang (2006)

The dependency analysis becomes important when a organisation wants to minimise its dependence on external sources. The dependencies of the various acquisition modes are seen in Table 5.6. Important to note from the table is that to ensure low dependency with respect to other organisations, external methods should be avoided.

Table 5.6: Dependency analysis, adapted from Simatupang (2006)

High	**Low**
• Licencing • Joint venture • R&D collaboration	• Internal R&D • Eduction & training • M&A • Directly/embodied • R&D contract • Consultant • Minority investment

This section highlights various technology acquisition modes that can be utilised to source new technology. However, it is found that the researcher all use different terminology when describing the acquisition mode. Therefore the following 10 acquisition modes are identified and presented in Table 5.7 along with a description of each. The knowledge obtained form this section is used to develop Stage 3 of the framework in Section 6.2.3, Chapter 6, which serves as a guide for selecting a technology acquisition mode.

Table 5.7: Description of the acquisition modes

Mode	**Description**
Internal R&D	Is the in-house development, 'making', of technology by an organisation's research and development and/or engineering departments. Internal technology sourcing method. (Simatupang, 2006; Lee *et al.*, 2009; Wen and Liu, 2011; Ashwin, 2014; Paton and Van Der Lingen, 2016)
Eduction and training	Is the recruitment of people or smaller companies that poses the technological or managerial expertise required for a certain technology. (Simatupang, 2006)
Mergers and acquisition	Is the process where two or more separate organisations integrate. This form of integration can either involve one organisation buying a small portion of another (acquisition), or the complete absorption by one (merger). The intended purpose of M&A can be attributed to one organisation wanting to acquiring technology know-how, increase capabilities, reduce risk, or increase competitiveness. (Simatupang, 2006; Ashwin, 2014)
Direct/embodied acquisition	When an organisation buys the technology directly from a supplier or obtains the required technology by it being embodied in another component, system, equipment, or service. (Simatupang, 2006; Wen and Liu, 2011; Ashwin, 2014; Paton and Van Der Lingen, 2016)
R&D contract	The research and development are outsourced by hiring or funding an external organisation to undertake the endeavour. (Simatupang, 2006; Lee *et al.*, 2009)
Consultant	It is a variation on the education and training acquisition method. A consultant is hired to perform a specific task in a given period of time. (Simatupang, 2006)
Minority investment	Is the external sourcing method that acquires a technology where one organisation buying a small equity in another. That equity has the technology embedded in it and therefore the acquiring organisation may utilise the technology. However, this agreement does not transfer managerial control. (Simatupang, 2006)

Continued on next page...

Table 5.7 – *continued from previous page*

Mode	**Description**
Licensing	It is an external technology sourcing method bonded by a contract. The contract aids with the acquisition of a product or process technology, designs, or marketing expertise. In the exchange a fee can be involved, whereas the fee could be royalties or knowledge exchange or take the form of commitments to the involved parties. (Simatupang, 2006; Lee *et al.*, 2009; Paton and Van Der Lingen, 2016)
Joint venture	A form of cooperation between two or more organisations, where a new entity is created for the purpose of achieving a productive economic activity. (Simatupang, 2006; Lee *et al.*, 2009)
R&D collaboration	It is the collaboration of two or more organisations' R&D departments to conduct R&D projects together based on agreements. (Simatupang, 2006; Lee *et al.*, 2009; Wen and Liu, 2011; Paton and Van Der Lingen, 2016)

5.7 Chapter 5 Summary

This chapter started by presenting the framework design requirements, describing the fundamental outcomes the framework must achieve. These requirements are derived from multiple parts in this research such as Chapters 2, 4, 5, and 6 through an iterative process, after which an structured review is conducted to identify existing technology selection frameworks. These frameworks were then evaluated against the design requirements and it was found that none of them achieved all the requirements, thus motivating the development of a new framework. The existing framework analysis highlighted the need for an MCDA stage in the framework and therefore different techniques were analysed. The evaluation criteria is an important aspect of any MCDA technique and as such the criteria is developed to be used in the selection framework presented in Chapter 6. This chapter concludes with the exploration of various technology acquisition modes and which modes are preferred for organisations under different conditions.

Chapter 6

RITSS Framework

6.1 Introduction

This chapter describes the refined framework which is a product of integrating all the research findings in this thesis. Against the knowledge obtained from the literature (Chapter 2), subject matter experts (Chapter 4), and existing technology selection frameworks (Chapter 5) a set of framework *design requirements* are created, see Section 5.2. The requirements generated serve as a guide for a technology selection framework to align with the end goal of this thesis. However, none of the existing frameworks analysed met all of the requirements and therefore this chapter aims to describe the framework to address them all, the **Railway Infrastructure Technology Selection Support (RITSS)** framework. Figure 6.1 represents the position of this chapter regarding the entire research process.

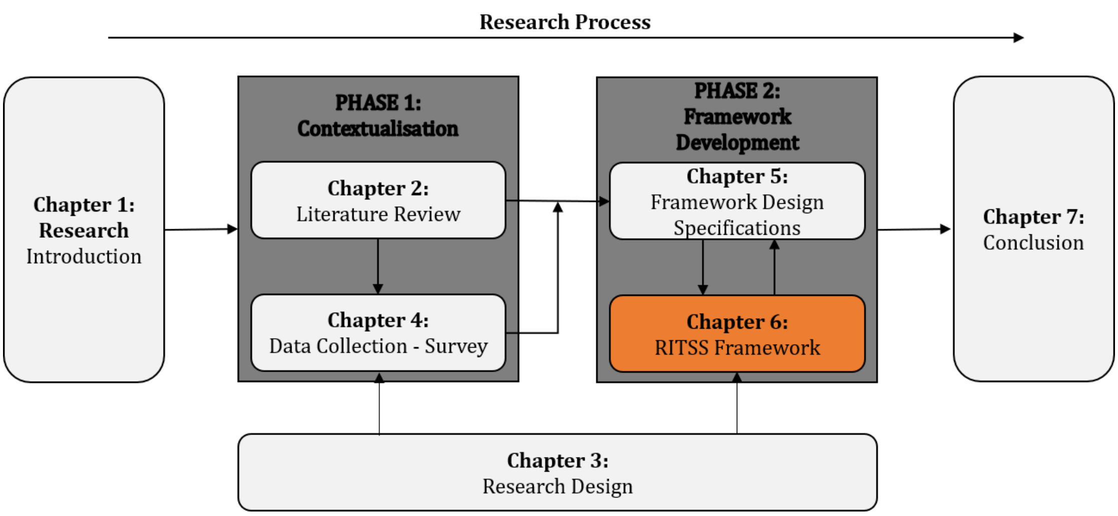


Figure 6.1: Research design: Chapter 6

6.2 RITSS Framework

The acquisition of emerging technology is seen as a key strategic method for enabling organisations to grow and stay competitive in an industry. However, determining how to acquire the needed technology can pose problems for some organisations (Ma and Hung, 2015). Therefore, an organisation can benefit from a guide to aid with the selection and acquisition of suitable technologies. Technology selection is best described to:

> *"...involve the gathering of information from various sources about alternatives and the evaluation of alternatives against each other or some set of criteria." – (Lamb and Gregory, 1997)*

The idea behind the RITSS framework is to serve as decision support for railway operators when identifying, selecting, and acquiring new technologies. Also, the framework can serve as decision support in other industries by making small adjustments to the framework. However, a governing factor is the type of candidate technologies under consideration. The framework is geared towards selecting technologies that will be used by organisations to monitor the condition of their physical assets, in most cases for maintenance purposes. In terms of applicability of the framework to an industry, it can be used by an organisation to guide them systematically from the identification of emerging technologies to the evaluation of the candidate technologies and finally to present them with suggestions for acquiring the selected technologies. Furthermore, this framework consists of multiple stages that are linear in nature except for some information and process flow between the respective stages and their concepts.

The framework is developed according to the methodology as described by Jabareen (2009). This approach consists of 8 phases that illustrate the process of developing a conceptual framework of which phases 3–6 are incorporated in this section. Furthermore, the approach of Jabareen (2009) is supplemented by the research of Rautenbach *et al.* (2019), where he applied the methodology of Jabareen, to develop a *Digital Initiative Initiation Decision-Support Framework*. Phase 3 is responsible for identifying and naming the concepts; phase 4 deconstructs and categorises the concepts; phase 5 integrates the concepts; and phase 6 synthesises and resynthesises the concepts. Thus, from the research, the following concepts are identified:

- **Mapping:** Process of integrating two or more concepts by linking corresponding aspects.
- **Technology selection:** Act of choosing a suitable technology from a list of alternatives.
- **Technology evaluation:** Process of assessing technology against a set of criteria.

- **Technology acquisition:** Act of sourcing and implementing technology in an organisation.

Based on the approach by Jabareen, the framework is developed to address the four different concepts identified. Therefore, it is decided to split the framework into different stages, each addressing the identified concepts. The stages of the framework are:

Stage 1: *Mapping assets and technology* – Establish a link between the candidate technologies and the particular assets in question by mapping the technological capabilities to the monitoring parameters of the failure modes.

Stage 1.1: *Defining asset scope* – Establish what assets are included in the inquiry process and determine the assets' failure modes and the particular monitoring parameters associated with each of the failure modes.
Stage 1.2: *Technology identification* – Identify suitable candidate technologies capable of monitoring the parameters mentioned in Stage 1.1.
Stage 1.3: *Mapping* – Develop 'failure pathways' for each asset and incorporate the candidate technologies.

Stage 2: *Technology evaluation* – Evaluate the candidate technologies against a set of criteria and each other to determine which are more favourable.

Stage 2.1: *Define evaluation criteria* – Define the evaluation criteria to be used in the analysis of the candidate technologies and structure them in a hierarchy.
Stage 2.2: *Determine criteria weight* – Determine the respective weights of the evaluation criteria.
Stage 2.3: *Prioritise technology* – Prioritise the candidate technology from the results of a multi-criteria decision analysis process.

Stage 3: *Acquisition mode guide* – Based on the technologies identified and the organisational structure provide suggestions with regards to the acquisition modes.

Stage 3.1: *Acquisition choice evaluation* – Evaluate whether it is better to develop in-house or source technology from an external source.
Stage 3.2: *Acquisition mode selection* – Select the technology acquisition mode that aligns with an organisations goals.

Figure 6.2 illustrates the different stages and concepts graphically as well as the process flow and information flow between the concepts. The sections to follow elaborate on the each of the stages represented in the RITSS framework.

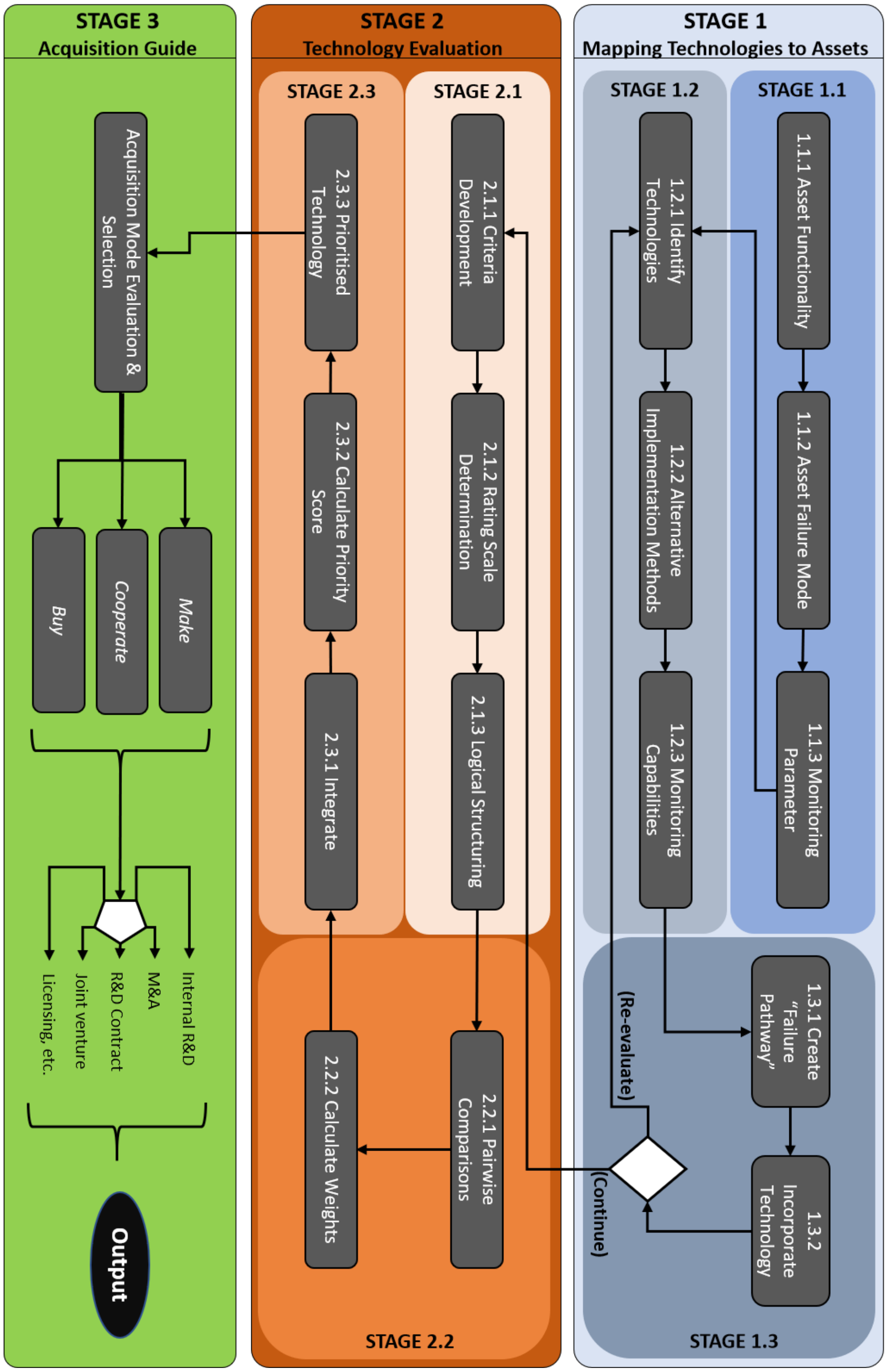


Figure 6.2: RITSS framework

6.2.1 Stage 1 – Mapping Technologies to Assets

Technology selection frameworks, in general, include an evaluation stage where the candidate technologies are measured against each other to determine the best-suited technology for a particular case. However, to ensure that the evaluation provides the best possible outcome, it is important to understand the intended purpose of the technology in question, if it were to be selected. As mentioned in Section 6.2, this framework aims to guide the selection of technologies to be used for condition monitoring purposes. Therefore, it is decided to incorporate the matching of candidate technologies to the respective assets they are capable of monitoring in this stage of this framework. This stage follows a similar pattern as described in the frameworks by Davis *et al.* (2013) and Davis and Brockhurst (2015) in Section 5.3.3.

Davis *et al.* (2013) explain that "for any monitoring technology to be effective and provide benefit, it must be able to report on specific indicators relevant to the performance of an asset". Therefore, the framework must guide the creation of asset *failure pathways* with the addition of the candidate technologies assigned to their respective monitoring parameters. *Failure pathways* are graphical representations linking the failure modes of assets to the monitoring parameters capable of identifying and predicting asset deterioration and failures.

Figure 6.2 illustrates the RITSS framework as a whole but can be used as a reference for Stage 1 in terms of the overall design. Stage 1 is divided into sub-stages; (1.1) *defining asset scope*, (1.2) *technology identification*, and (1.3) *mapping*. Stage 1.1, defining asset scope, guides organisations to select a specific set of assets and define (i) the functionality of each of the assets, (ii) their respective failure modes, and (iii) the monitoring parameters associated with each of the failure modes. Stage 1.2, technology identification, guides the identification of candidate technologies based on the asset's failure modes and monitoring parameters described in Stage 1.1. As part of the technology identification, it is important to determine the (i) technological monitoring capabilities and (ii) alternative methods for the technology to be administered. Stage 1.3, mapping, guides organisations with the linking of the technologies and their monitoring capabilities to the monitoring parameters of the assets. This is achieved by first (i) creating failure pathways for each of the assets and then (ii) adding the candidate technologies to the failure pathways.

6.2.1.1 Stage 1.1 – Defining Asset Scope

For an organisation to ensure that the correct candidate technology is identified they first need to determine the exact scope of assets they want to monitor. Thus, as an initiating step for the technology selection framework, a list of assets of importance needs to be defined. As for defining the scope, it can be described to include the (1.1.1) *asset functionality*, (1.1.2) *asset failure modes*, and (1.1.3) the failure modes *monitoring parameters*, (see Figure 6.2). Figure 6.3 represents a more detailed depiction of the process followed to define the asset scope.

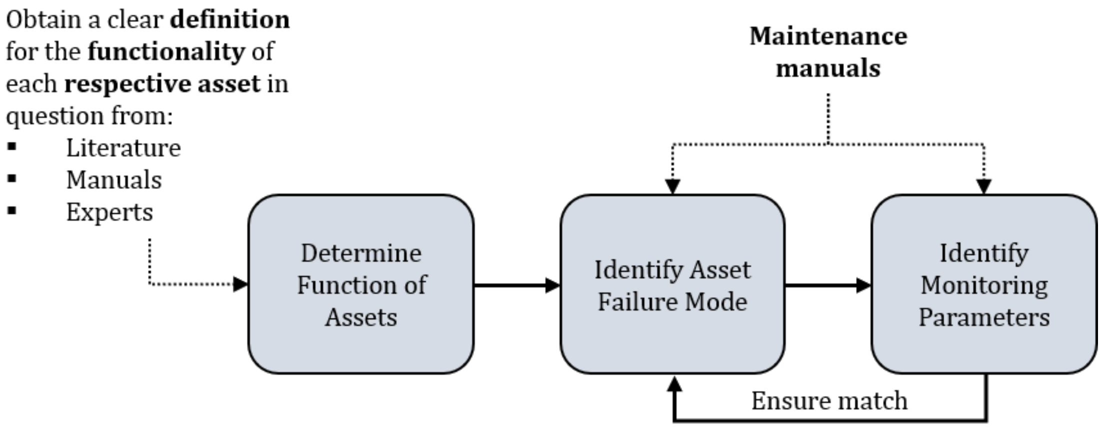


Figure 6.3: Asset scope defining process

The asset functionality aims to highlight the purpose and importance of a particular asset. Thus, it is important to obtain a clear definition of the function each asset possesses. This information can be used later in Stage 2.1 for aiding the construction of the evaluation criteria. The definition can be obtained either through various sources of literature, organisations' manuals, industry experts, or a combination of the aforementioned. After the functionality of an asset is addressed, organisations need to identify all of the failures that can occur with respect to a particular asset and group similar failures as different failure modes. The last step of defining the asset scope is to determine the monitoring parameters applicable to each failure mode. These monitoring parameters are seen as distress indicators that signal the deterioration of assets and potential failures. Therefore, if the parameters are monitored, they can provide useful information for maintenance and prolonging the life of the asset (Davis *et al.*, 2013). It is important to match each of the identified monitoring parameters to either a failure mode or another parameter. These failure modes and monitoring parameters can be obtained from industry maintenance manuals. The failure modes and monitoring parameters of the infrastructure components included in the scope of this study are summarised in Appendix A, Table A.1.

6.2.1.2 Stage 1.2 – Technology Identification

According to the existing technology selection frameworks analysed in Section 5.3.3, in most cases, the organisation that is in the process of selecting emerging technologies already has an idea of the technology they want to evaluate. However, if that is not the case, they need to identify appropriate candidate technologies for evaluation. Candidate technologies can be identified through various methods which include literature reviews, advising industry professionals, and scanning for providers (Davis and Brockhurst, 2015; Ma and Hung, 2015). For this framework, the asset scope determined in Stage 1.1 narrows the field of technologies, meaning that organisation only need to search for technologies capable of monitoring the parameters as defined in the asset scope. Furthermore, as part of this Stage three areas need to be addressed when selecting candidate technologies; (1.2.1) *identify technologies*, (1.2.2) *technology monitoring capabilities*, and (1.2.3) *alternative implementation methods* (see Figure 6.2). Figure 6.4 represents a more detailed depiction of the process followed to identify suitable candidate technologies.

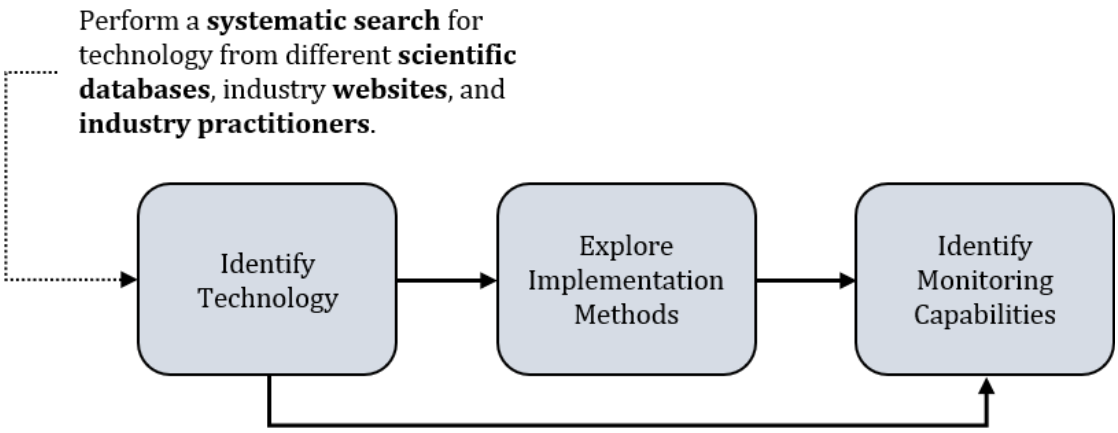


Figure 6.4: Technology identification process

The candidate technologies are firstly identified though the methods mentioned previously. When identifying the candidate technologies, it is also critical to determine the extent of its capabilities, because it is used to map the respective technologies to the different asset failure modes in the next step, Stage 1.3. The capabilities are also used in Stage 2.1 for developing the evaluation criteria. Lastly, alternative means of implementing the technologies to monitor the condition of assets must be highlighted. In some instances where there is more than one alternative implementation method, it is able to change and supplement the capabilities of the candidate technology (e.g. a video recording device attached to a 'drone' can reach places which it would not be able to when attached to an in-service train). The various data acquisition technologies identified, their monitoring parameters, and carriers are presented in Tables B.5-B.7.

One aspect of this framework to note is that the technology identification (Stage 1.2) occurs after the asset scope is defined (Stage 1.1). These two stages are capable of switching their order around or be implemented simultaneously. The main reason for first defining the asset scope before the candidate technologies are identified is to ensure that the organisational issues or desired upgrades are addressed (with regard to the assets). The technology is more geared towards the organisation's goals. If the order was switched, an organisation stands the chance of being overwhelmed by the vast amount of technologies identified capable of monitoring some of the asset parameters in question, potentially missing relevant monitoring parameters organisations would like addressed.

6.2.1.3 Stage 1.3 – Mapping

For an organisation to obtain a clear picture of the candidate technologies under consideration, it is important to understand where the technology is applicable. This is achieved by linking candidate technologies (Stage 1.2) to the monitor parameters of each of the assets (Stage 1.1). Davis *et al.* (2013) developed *failure pathways* to establish the link in the technology selection framework described in Section 5.3.3.3. Developing the complete failure pathways for the RITSS framework consists of two steps; (1.3.1) *pathway creation* and (1.3.2) *incorporating technologies* (see Figure 6.2). The pathway is constructed first to include only the monitoring parameters capable of measuring the asset's deterioration up to the point of a failure, after which, each of the identified technologies is assigned to the monitoring parameters they are capable of monitoring. Figure 6.5 best describes the mapping process graphically.

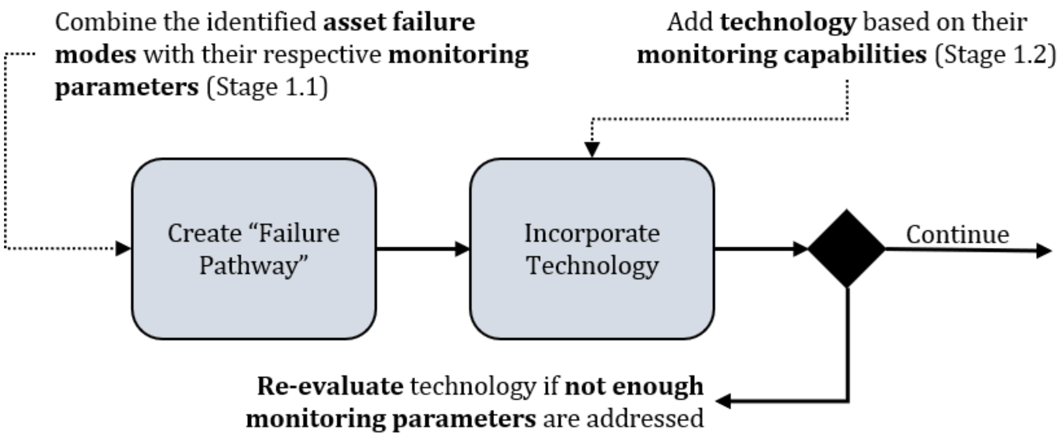


Figure 6.5: Mapping the asset and technology process

The starting point for creating a failure pathway is to choose an asset. Then for that particular asset write down each of the possible failure modes and the monitoring parameter associated with each of the respective failure modes. It is best to first take one failure mode and then systematically create links between it and the monitoring parameters until you have a network of interlinked objects. The technology is incorporated by pairing each technology to the monitoring parameters based on their respective capabilities. Once all the technologies are assigned to the failure pathways an evaluation is required. This is to ensure that a sufficient number of technologies are identified. If too many monitoring parameters are unpaired with the candidate technologies, based on the preferences of the organisation, the technologies can be re-evaluated, which can then lead to going back to the previous stage to search for more technologies that possess the required capabilities. Otherwise, if the organisation is satisfied, the process can continue to Stage 2. Figure 6.6, depicts an example of a failure pathway. The failure pathways of each railway infrastructure component included in this study is represented in Appendix A.2.

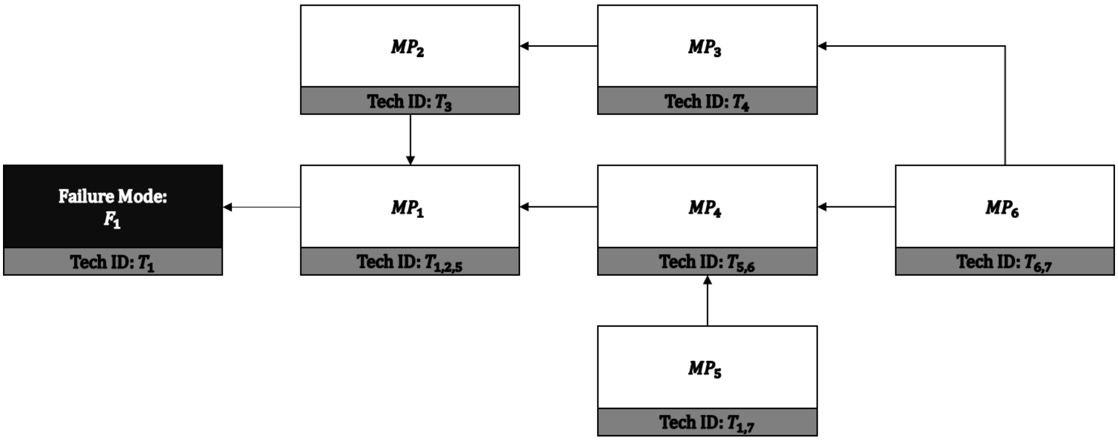


Figure 6.6: Example of a failure pathway

6.2.2 Stage 2 – Technology Evaluation

As mentioned in Stage 1, the process of technology selection generally includes some form of evaluation step that incorporates all the influencing factors that contribute to the final outcome. The evaluation stage is critical to the selection of the most favourable candidate technologies, as it creates the platform for integrating various sources of information in a manner that is structured and logical, ensuring that the complex problem is fully addressed.

Figure 6.2 illustrates the RITSS framework as a whole but can be used as a reference for Stage 2 in terms of overall design. Stage 2 is divided into sub-stages; (2.1) *define evaluation criteria*, (2.2) *determine criteria weight*, and (2.3) *prioritise technology*. Stage 2.1, define evaluation criteria, guides organisations with the (i) development of the evaluation criteria by incorporating the judgements of multiple sources (both literature and industry experts), (ii) choosing an appropriate rating scale to measure each candidate technology with respect to its capability of addressing each of the defined criteria, and (iii) structuring the criteria in a logical sense. Stage 2.2, determine criteria weight, guides organisations to determine the relative importance of the evaluation criteria based on (i) subject matter experts' judgements, and (ii) combining the judgements with a known multi-criteria decision analysis technique to transform the subjective judgements into a numerical priority value. Stage 2.3, prioritise technology, guides organisations with the (i) integration of the defined evaluation criteria, their respective weights, and the candidate technologies to eventually (ii) present them with a prioritised list of the most favourable technologies based on the outcome of mathematical calculations.

6.2.2.1 Stage 2.1 – Define Evaluation Criteria

The first step with regard to the technology evaluation stage is to define a set of criteria. This step is critical for ensuring an acceptable outcome, therefore organisations must be diligent with the process. As for defining the evaluation criteria, it can be described as including the (2.1.1) *criteria development*, (2.1.2) *rating scale determination*, and (2.1.3) the *logical structuring* of the criteria. Figure 6.7 presents a detailed depiction of the process followed to define the evaluation criteria.

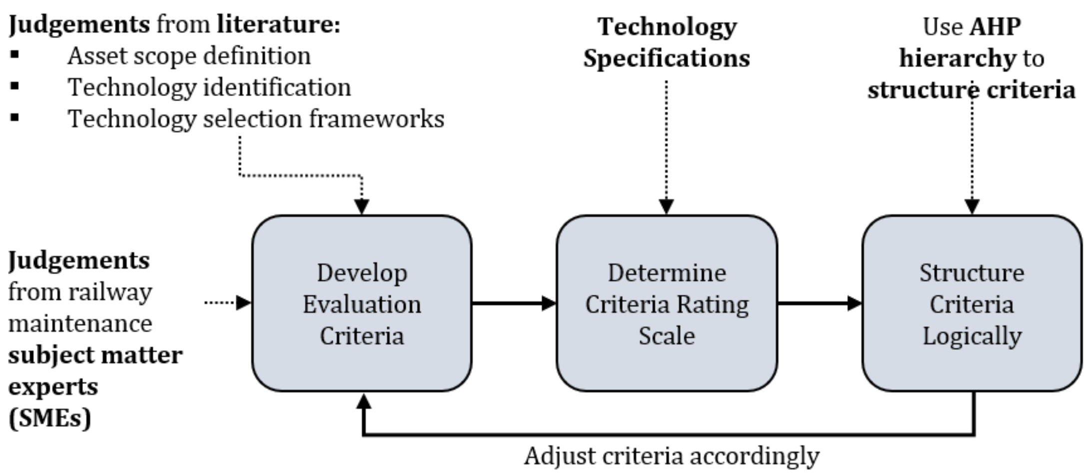


Figure 6.7: Evaluation criteria defining process

In Section 5.5, two important aspects to consider are highlighted as part of the criteria development. The aspects are (i) the sources of knowledge being utilised as the foundation for the criteria and (ii) what the criteria reflect with respect to achieving the goal. The goal of the evaluation is to select favourable data acquisition technologies to be used for condition monitoring of railway infrastructures with the potential of progressing the shift towards predictive maintenance for an railway organisation. As for the RITSS framework, it is chosen to include both judgements from various literature and railway maintenance subject matter experts. The combination of literature and subject matter experts gave the possibility to mitigate potential shortcomings of using only one or the other. In terms of how the criteria aid in achieving the goal, it is decided that the criteria must address the costs, benefits, challenges, and risks associated with the selection and adoption of the data acquisition technology in the railway maintenance field.

The evaluation criteria can be either qualitative or quantitative in nature, as the AHP technique allows for the incorporation of both during decision-making. The descriptions of the criteria used in this framework are seen in Section 5.5, Table 5.4 and 5.5. However, for reference purposes in this chapter the primary and subcriteria names and their respective numbers are given in Table 6.1. Initially 19 criteria were developed after which it was decided to decrease the number based on the use of pairwise comparisons to determine criteria weights. Similar criteria were grouped leaving only 13 criteria left. These criteria can be categorised to address the effect of selection from an technical, institutional, social and external (other) point of view.

Table 6.1: Evaluation criteria numbering

#	**Criteria**	#	**Subcriteria**
CR1	Technical	CR11	Accuracy
		CR12	Cost
		CR13	Influence of external factors
		CR14	Continuous monitoring capabilities
		CR15	Maturity of technology
CR2	Institutional	CR21	Traffic interference
		CR22	Early failure prediction
		CR23	Operator skills
		CR24	Security
CR3	Social	CR31	Safety
		CR32	Job uncertainty
CR4	Other	CR41	Environmental
		CR42	Support

Part of obtaining a set of evaluation criteria is to determine how each one will be assessed. Thus, a rating scale for each criterion is assigned as a means of measuring how well the candidate technologies perform with respects to each criterion. This rating scale is unique for each criterion and aims to provide a numerical basis, common ground, for evaluation purposes. Even qualitative criteria are judged and transformed into a numerical ranking. To determine the rating scale for each criterion, the technical specifications of the candidate technologies are used in combination with a five-point Likert scale. Refer to Appendix D, Table D.1, for a representation of the rating scales.

Progressing onwards to Stage 2.2 the defined evaluation criteria along with the goal, candidate technologies, and outcome must be structured in a logical sense, So as to make it easier to understand the criteria placement in the evaluation process. See Figure 6.8 for the AHP hierarchy used to structure the criteria in the RITSS framework. Creating a hierarchy with different levels allows for a 'birds-eye view' of the selection process. This presents the opportunity to adjust criteria if required and keep track of all the changes as part of the adjustments.

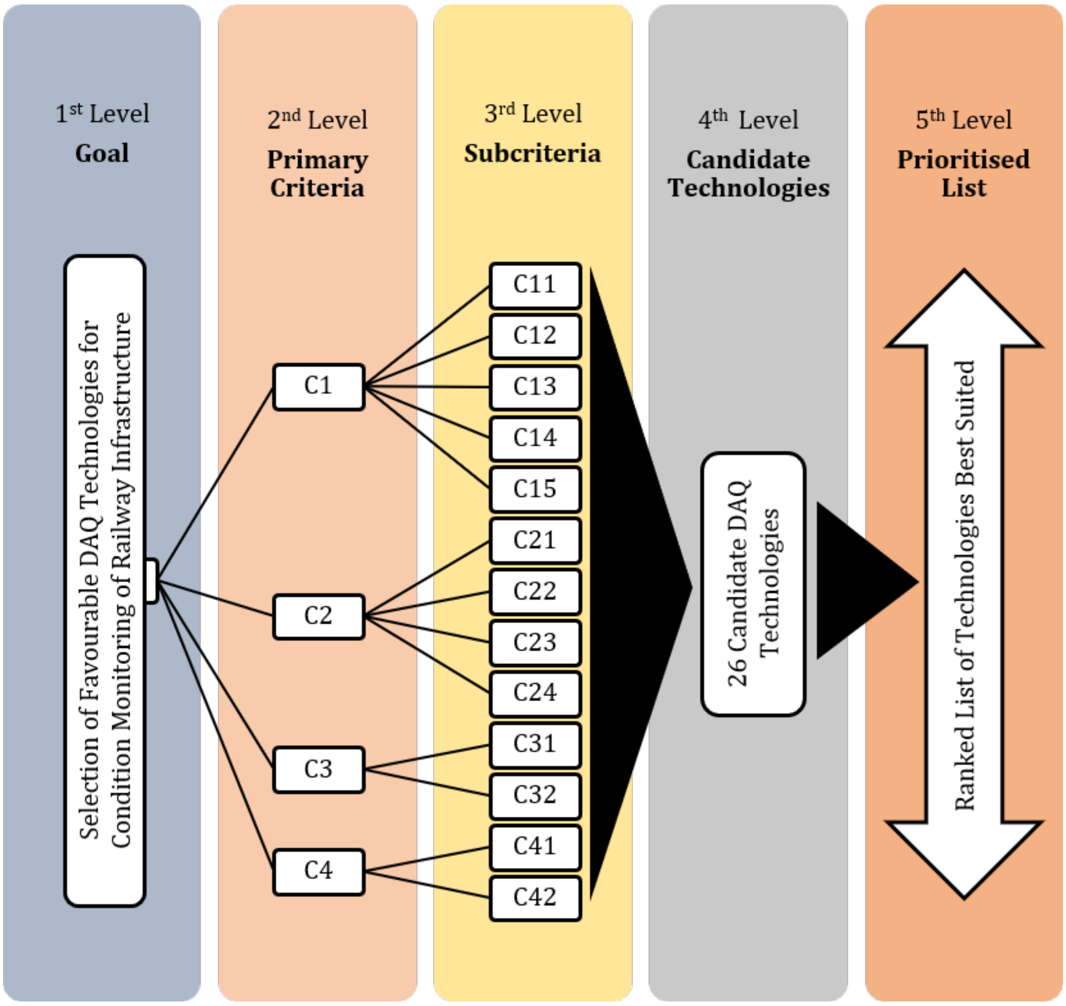


Figure 6.8: RITSS AHP hierarchy

6.2.2.2 Stage 2.2 – Determine Criteria Weight

Now that the criteria are defined and the AHP hierarchy is constructed, it is time to determine the weights of the criteria. The weighted values represent the relative importance of the criterion. It is decided to give each criterion a unique weighted value due to them all not being equally important. Assuming equal importance will therefore provide inaccurate results. The weighting of the criteria is achieved through first (2.2.1) performing *pairwise comparisons* and then (2.2.2) *calculate the weights* through the AHP method described in Section 5.4. Figure 6.9 portrays the detailed method to acquire the criteria weights.

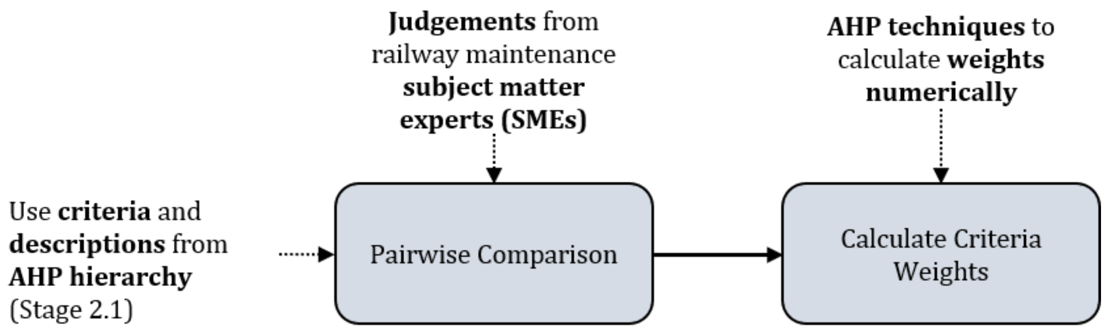


Figure 6.9: Criteria weight determination process

Carrying out pairwise comparisons is a form of group decision-making that takes the judgements from experts and turns it into a quantifiable value. It constitutes that each criterion must be compared to every other one to determine which is the more important of the pair. This is achieved by assigning a priority value to each comparison. The value is based on the rating scale of Saaty (see Table 5.3). As part of this framework's development, a group of subject matter experts that worked independently was used to perform the pairwise comparisons, but this can also be performed by an organisation's decision-makers. Seven out of the eight subject matter experts that participated in the first questionnaire, Chapter 4, were used to perform the pairwise comparisons. The amount of comparisons can be calculated based on the number of criteria (n) using the following equation, $n(n-1)/2$. The number of comparisons can be reduced by grouping subcriteria under a set of primary criteria. Taking advantage of subcriteria the comparisons required by the experts decreased from 78 to 24. The experts were asked to perform the pairwise comparisons by completing a *SurveyMonkey* questionnaire.

The responses from the pairwise comparisons are then used in a series of AHP calculations to determine the weights. The calculation steps are described in Section 5.4 which consists of two parts, first (i) normalising the pairwise matrix and calculating the criteria weights and secondly (ii) calculate the consistency of the experts judgements. Due to the experts answering the questionnaires individually, their judgements must be combined. Dong *et al.* (2010) describes two well-known methods of aggregating individual responses during AHP group decision-making. The first is aggregation of individual judgements and the second is the aggregation of individual priorities, whereas the aggregation is achieved through the geometric mean method (Dong *et al.*, 2010; Chatterjee and Stević, 2019). Both methods were implemented and tested. The implementation revealed that aggregating the individual priorities required far more calculations than aggregating the judgements. Furthermore, the aggregation of individual priorities eliminated five out of the seven responses when the consistency checks were performed. Thus, based on this it is decided to aggregate the individual judgements before calculating the priorities.

Upon aggregating the individual pairwise responses the pairwise comparison matrices is constructed (Tables D.4 and D.6). The next step is to normalise each pairwise matrix and this is done by dividing each element in the pairwise matrix by the sum of each column. Tables D.5 and D.7 represent each of the normalised matrices. Taking the normalised matrices and dividing them by the number of criteria generates a weighted matrix representing the criteria weights. From the weights the relative priority or rank is obtained. Tables 6.2 and 6.3 displays the weight of each criteria as well as their respective rank. The global weights and rank of each subcriteria are also displayed. The AHP calculations ranked the *technical* criteria the most important amongst the primary criteria followed by *social* then *institutional* and the least important is the *other* criteria. Looking at the subcriteria it is seen that *safety* is the most important criterion to consider whilst *traffic interference* is the least important. Furthermore, from the ranking of the subcriteria it is seen that criteria directly related to the performance of the technology during operations are very important and the criteria such as *cost*, *environmental*, and *operator skills* not as much.

Table 6.2: Normalised weighted values of the primary criteria

Criterion	**Weight Value**	**Rank**
Technical	0.490	1
Institutional	0.177	3
Social	0.268	2
Other	0.065	4

Table 6.3: Normalised and global weighted values of the subcriteria

Criterion	Sub-Criterion	Weight Value	
		Normalised (Rank)	Global (Rank)
Technical	Accuracy	0.275 (2)	0.135 (3)
	Cost	0.053 (5)	0.026 (11)
	Influence of external factors	0.179 (3)	0.088 (4)
	Continuous monitoring	0.121 (4)	0.059 (6)
	Maturity of technology	0.373 (1)	0.183 (2)
Institutional	Traffic interference	0.099 (4)	0.018 (13)
	Early failure prediction	0.421 (1)	0.075 (5)
	Operator skills	0.168 (3)	0.030 (10)
	Security	0.311 (2)	0.055 (7)
Social	Safety	0.844 (1)	0.226 (1)
	Job uncertainty	0.156 (2)	0.042 (9)
Other	Environmental	0.304 (2)	0.020 (12)
	Support	0.696 (1)	0.045 (8)

The final step when applying AHP to calculate criteria weight is to check the consistency of the judgements made by the subject matter experts, whereas the consistency is measured by the consistency ratio (CR). The judgements are only acceptable if CR $<$ 10%. To calculate CR the consistency index (CI) and random index (RI) values are required (refer to Section 5.4). From Table 6.4, it is deduced that the judgements for all the matrices were smaller than 10% and therefore consistent.

Table 6.4: Judgements consistency check

	Primary	Technical	Institutional	Social	Other
CI	0.089	0.037	0.079	0	0
RI	0.900	1.120	0.900	-	-
CR	0.099	0.033	0.088	0	0

The criteria weights obtained during this stage of the RITSS framework can be used in Stage 2.3 as part of the technology prioritisation.

6.2.2.3 Stage 2.3 – Prioritise Technology

The outcome of the technology prioritisation stage serves as a guide for organisations on which technology would best suit their requirements. The prioritisation of the technologies is derived from cumulative calculations that integrate key findings from various stages in the framework. The prioritisation is described to include the (2.3.1) *integration* of different Stages, (2.3.2) *calculation* of the priority score, and the (2.3.3) *prioritised technology* list. Figure 6.10 presents a detailed overview of the technology prioritisation process.

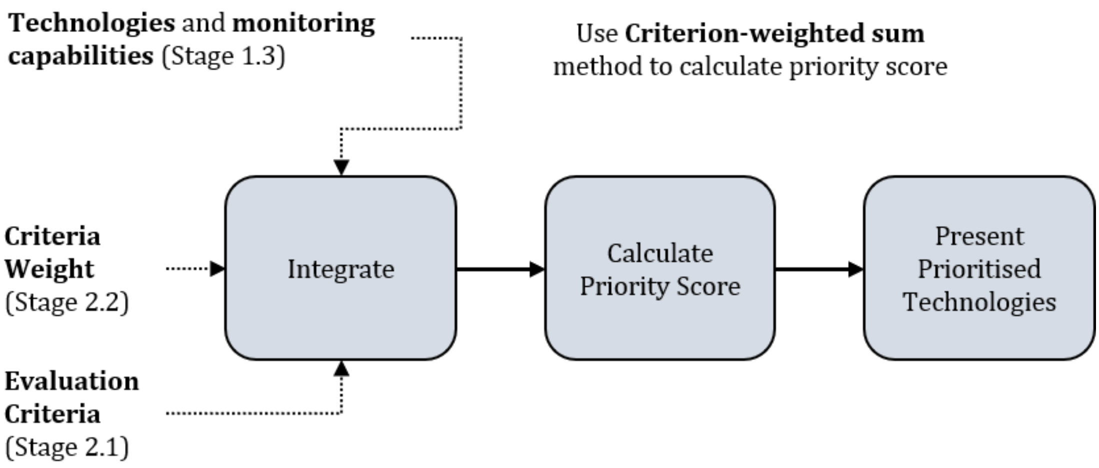


Figure 6.10: Technology prioritisation process

The main aspect of the technology prioritisation is the calculation of the prioritisation score (A_{ij}). This calculation would not be possible if the *data acquisition technologies* and their respective *monitoring capabilities* were not known as well as the *evaluation criteria* and its *weights*. Therefore, it requires the integration of the Stages 1.3, 2.1, and 2.2. In the RITSS framework integration is achieved by constructing the data acquisition (DAQ) technology evaluation and prioritisation table, Table 6.5.

Table 6.5: DAQ Technology evaluation & prioritisation

		Evaluation Criteria Weight (W_{ij})						
Infrastructure	**Tech**	**CR11**	**CR12**	**CR13**	. . .		**CR42**	**Sum**
Rails	**T1**	$S_{t,n}$	$S_{t,n+1}$	.	. .			A_{ij}
	T2	$S_{t+1,n}$	$S_{t+1,n+1}$	.	. .			.
	T3	.	.					.
Sleepers	**T4**	.	.					
	T5	.	.					
	T6							
	T7							
Formation	**T8**							
	T9							

The left-hand side of Table 6.5, consists of the railway infrastructure components being monitored and their respective technologies capable of monitoring the failure mode parameters at each asset. The DAQ technologies are each given a unique technology identifier as presented in the table. The top of the table is reserved for the evaluation criteria and their weights (W_{ij}). The middle section represents the scores ($S_{t,n}$) from 1–5 as to how well each technology performs with regard to each criteria whereas the scores are obtained from the rating scales described in Appendix D, Section D.1.1. Lastly, the right-hand side of the table contains the prioritisation score, which is the cumulative sum of the performance scores multiplied by the respective criteria weights. Thus, the prioritisation score is calculated by the following equation:

$$A_{ij} = \sum_{i=1} W_{ij}.S_{t,n} \tag{6.2.1}$$

The last step of the technology prioritisation stage is to present a prioritised list of technologies (Table D.9). The list is created by ranking the priority scores of each technology from the highest to the lowest. Higher scores are more favourable and lower scores less so. Organisations are able to choose from the list the top-ranking technologies that they wish to explore further. Refer to Appendix D.3, for the technology prioritisation calculations.

6.2.3 Stage 3 – Acquisition Mode Guide

The last stage of the RITSS framework aims to provide organisations with advise on which technology acquisition mode(s) to select for acquiring a new technology. This stage completes the framework and presents the organisation (user) with an output. The output is generated as a final step in the process, see Figure 6.2, by incorporating all of the knowledge obtained from the previous stages into the selection of an appropriate technology acquisition mode. The selection of a technology acquisition mode comes down to whether it is in the organisations best interest to either *make* or *buy* a particular technology that will benefit the organisation in some manner. As for making a technology, it refers to internal development and sourcing, while the buying option implies external sourcing of the technology. A third option is also available which is *cooperation* and as the word implies it is a combination of both internal and external sourcing. Stage 3 is predominately based on the research conducted in Section 5.6, Chapter 5.

The technology acquisition mode selection as depicted in this stages employs an adaptation on one of the subssystem incorporated in the technology acquisition framework developed by Simatupang (2006). At this point in the process the candidate technologies are already ranked in accordance to their priority scores, as calculated in Stage 2. Thus, the prioritised list of technologies showcases which technologies are worth acquiring upon further investigation. As for identifying a acquisition mode suitable for selection, the process can be described as to include (3.1) the *choice evaluation* and (3.2) the *selection* of a acquisition mode based on the outcome of the evaluation. Figure 6.11 portrays the process followed to select an technology acquisition mode.

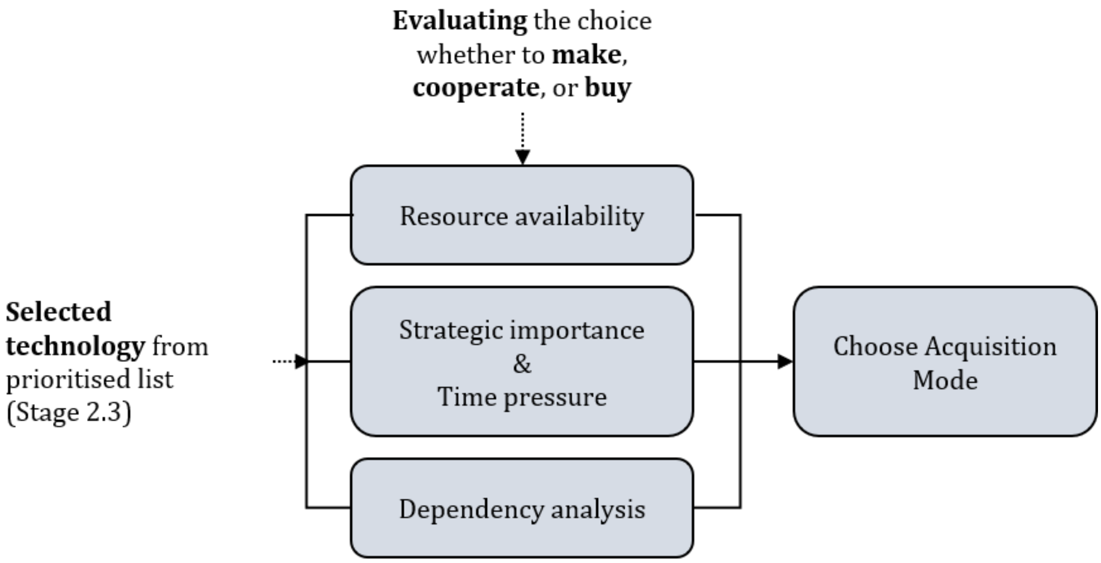


Figure 6.11: Technology acquisition mode selection process

The first step is to evaluate the available choices such as make, cooperate, and buy from a perspective of the short listed technology and the organisation's needs, goals, and limitations. To evaluate the choices four criteria are identified. The criteria are (i) *resource availability*, (ii) *strategic/technology importance*, (iii) *time pressure*, and (iv) *dependency* (described in Section 5.6). The method of approaching this evaluation is to consider the technology and organisation together as one, after which the pairing must be judged in accordance with each criteria. The judgments determine how the pair place with respect to the criteria. For example, in terms of resource availability the pair can be classified as to have high or low capital available for the acquisition and the internal R&D capabilities are also measured as either high or low. The strategic importance is classified as core and non-core technologies. Core technology implying that the organisation is dependent on that specific technology or the technology is a key part of achieving a competitive advantage, the opposite for non-core technologies. Time pressure is an indication of the time frame (urgency) as to when the technology must be acquired. Lastly, is the dependency which is an indication of how dependent an organisation wants to be on external sources. These, four criteria can be assessed systematically in any order as preferred by the organisational itself, except for strategic importance and time pressure must be grouped together. However, it is suggested to assess the criteria in order of priority, starting with the most important based on the organisation's judgment.

The make, cooperate, and buy options for technology acquisitions can further be broken down into 10 different technology acquisition modes. The acquisition modes included in this framework are in-house research and development (R&D), education and training, merger and acquisition (M&A), direct or embodied acquisition, R&D contract, consultant, minority investment, licencing, joint venture, and R&D collaboration. The last step of Stage 3 is the selection of the acquisition mode from one of the 10 highlighted. The selection can be simplified through process of elimination in collaboration with Figures 5.8, 5.9, Table 5.6, and the four criteria. Assume that an acquisition mode must be selected for a shortlisted technology with the following conditions, after evaluation, as shown in Table 6.6. A basic example of the elimination process for the shortlisted technology can be observed in Figure 6.12.

Table 6.6: Example shortlisted technology's criteria evaluation conditions

Criteria	**Conditions**	
Strategic importance	Non-core	Core (X)
Time pressure	Low	High (X)
R&D capability	Low (X)	High
Available capital	Low (X)	High
Dependency	Low (X)	High

Note that from the example in Figure 6.12 there are five decisions made although there are only four criteria. This is attributed to the fact that resource availability can be split in two, R&D capabilities and available funds. The process of elimination starts with the 10 acquisition modes identified. From there the next step is to analyse the technology's strategic importance which is classified as a core technology, as such five modes are eliminated (see Figure 5.8). The next step evaluates the time pressure, due to it being grouped with strategic importance. The time pressure is high which eliminates three more modes. Now the resource availability is incorporated in the process (see Figure 5.9), first the R&D capabilities are judged and from the capability figure it is seen that M&A and R&D contract's only require low levels of R&D capabilities, even if the organisation possess high R&D capabilities these two modes would not be eliminated. The same figure applies to the availability of funds and in the conditions decided the funds

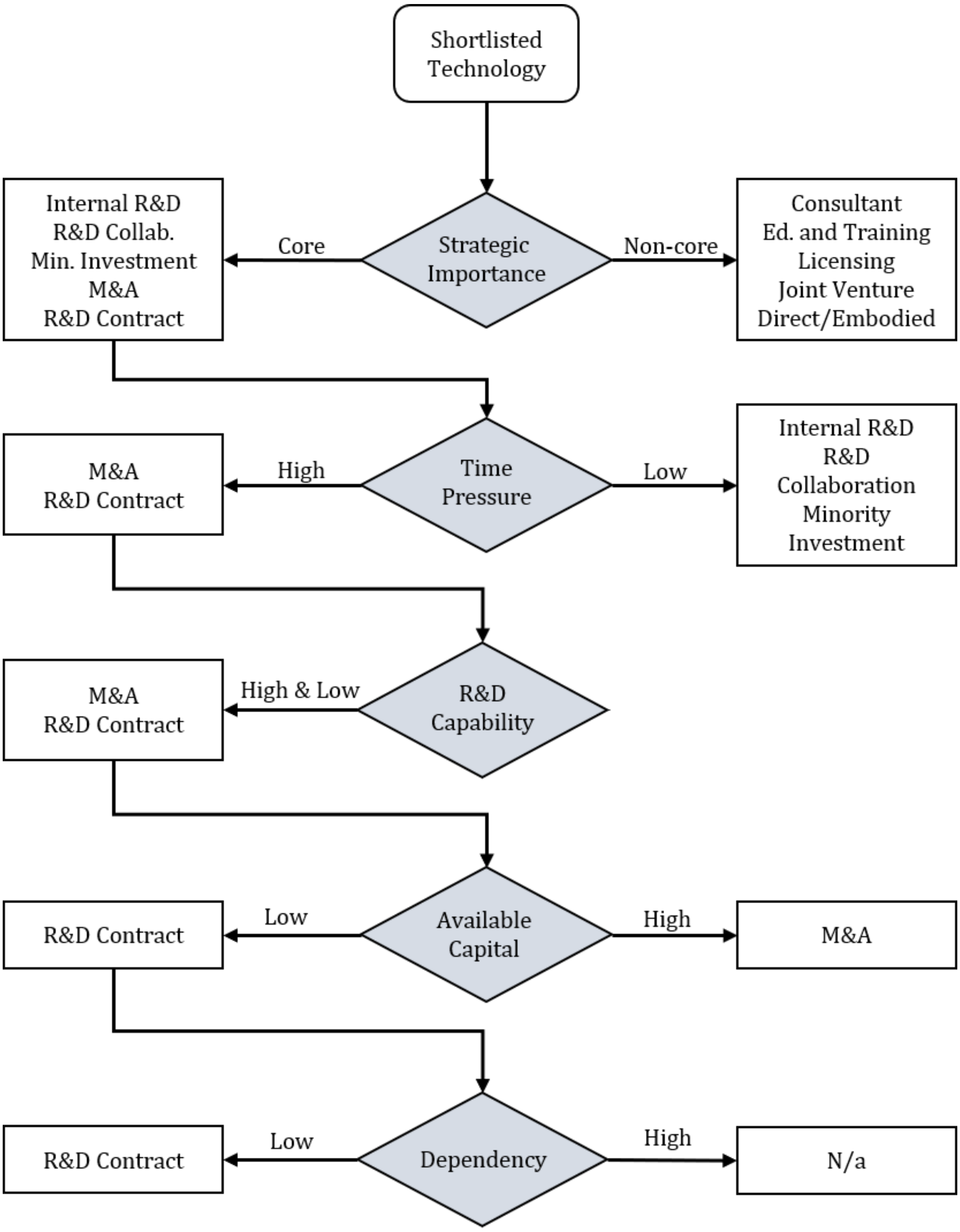


Figure 6.12: Acquisition mode guide example

are low therefore M&A is eliminated. The final step is not so much a elimination step, but rather an analysis of the dependency on external sources if this particular mode were to be selected. Thus, the selected technology acquisition mode is R&D contract and it has a low dependency (see Table 5.6).

6.3 RITSS Real-World Applicability

The goal of the RITSS framework is, to serve as decision support for railway operators when identifying, selecting, and acquiring new technologies. This decision support nature of the framework is achieved by the linear, systematic guidance as depicted in Figure 6.2. The framework is developed through an iterative process which incorporates various sources of literature and inputs from industry experts. The input from industry experts allowed for the validation of certain aspects of the framework, but not the RITSS framework as a whole and as such, requires further assessment. From the framework methodology developed by Jabareen (2009), it is known that some form of validation, Phase 7, is required to ensure that the proposed framework is clear and relatable not only to the 'creator', but also for other researchers and industry practitioners. Therefore, this section aims to test the real-world applicability of the framework to assesses if its primary goal is achieved. After testing and validating the real-world applicability of the RITSS framework, it is possible to refine the framework and turn it into a useful tool which organisations can utilise. It is decided to assess the success of the RITSS framework according to the following three criteria, as argued by Platts (1993), *feasibility*, *usability*, and *utility*. The feasibility is determined by testing if it can be applied in the railway industry. The usability is determined through whether or not it is easy to apply. Furthermore, the utility is assessed based on if the output provided is useful.

The validation methodology of the RITSS framework is adapted from Borenstein (1998), where he developed a methodology to validate the development of a decision support system. In Borenstein's research, it is stated that the purpose of validating something like a decision support system is not to test if it is an exact representation of the real-world, but rather to determine whether or not cooperative relationships exist as to permit an acceptable representation. Two aspects of validation, as described by Borenstein (1998), are combined and applied in this research. They are *face validation* and user *user assessment*.

- **Face validation:** ensures that there is uniformity between the developer's/creator's view of the problem and the potential user's view. Also, it creates an opportunity for refinement, reformulation, and revision.

- **User assessment:** process of determining whether or not the model's output can be used for decision-making, through the assessment of interested parties that were not involved with the origins, development, and implementation.

The validation is achieved through questionnaire feedback from research participants, mentioned in the following paragraph. The participants are asked to attend a *Microsoft Teams* meeting, where the researcher presented the RITSS framework. The presentation covered the research topic and scope, the research problem, framework development methodology, and the RITSS framework itself and how to use it. At the end of the presentation, participants are given two options, either to answer and discuss the questions immediately verbally or to complete the same questionnaire online using *SurveyMonkey* once the researcher has explained each question. Appendix C.2 presents the questionnaire used during the validation process.

Multiple subject matters experts are used throughout this research to create the RITSS framework. Each of the experts provided valuable feedback and inputs during the research based on their different backgrounds, creating an all-encompassing perspective. The experts, as mentioned in previous chapters, included researcher, independent consultants, and employees at different railway operators all hailing from different geographical locations internationally. However, it is decided to limit the sample of experts used during the face validation of the RITSS framework to only industry practitioners, seeing as the aim is to test the framework's real-world applicability. The industry practitioners included as part of the validation procedures: one participant is a management consultant and professional engineer who is the head of the "Center of Technology" department at a South African railway operator; one participant is the infrastructure maintenance operations manager at a South African railway operator. The sections to follow summarises the feedback received from the respective participants.

6.3.1 Participant One Feedback

The feedback from participant one, in general, is very much positive. This participant stated that in principle, the theory behind the framework is sound, but highlighted that the theory is only one side of determining such a framework's practicality. When practicality is investigated, it is crucial to know the environment and the organisation in which the organisation operates. As for the RITSS framework, this participant said that it follows an excellent holistic approach and that there is lots of potential for exploiting it in the Railway maintenance sector. Furthermore, the framework is not only limited to the railway industry, but the participant can see the potential for it being utilised by other industries by making minor adjustments to some stages. This participant showed a personal interest in utilising the RITSS framework as an input for future complex decision-making problems that he might encounter.

In terms of the framework's strengths, the participant was very interested in the evaluation criteria that were identified, how the criteria did not only focus on the technical aspects of the candidate technologies but also incorporate the organisational and social aspects. Furthermore, the expansion of the 13 subcriteria is also seen as a plus. The participant appreciated the methodology followed for developing the criteria and how it can be applied again to other organisations because they have different expertise and needs for different projects. In short, the customisation ability of the evaluation criteria and how it can be applied to different sample spaces is favoured, "Once the concept is there, you can use it again.".

One weakness identified by this participant is how the relative importance of the criteria is obtained, not directed at the AHP calculations, but rather the judgements obtained from a set of international railway experts. The judgments from an international perspective might not apply to a specific organisation in a specific country. The same goes for like-minded people, for instance, most engineers might think the same, but they might not necessarily agree with someone from the financial department as to what criteria is more important. To address this, the participant stated that the group responsible for judging the importance of the criteria must be part of the organisation or part of the project in question and that the group must be multi-disciplinary to eliminate biased opinions.

The participant highlighted two essential functions that would benefit from the output delivered by the RITSS framework. The first, which is that the framework can promote communication between all the relevant decision-makers. Promoted communication is achieved by the opportunity to create a dialogue between technical and non-technical people, finds common ground as decision-makers can refer to a particular stage in the RITSS framework which is familiar to every one part of the process. The second is that the framework has the potential to mitigate or minimise corruption during 'high-tech' acquisitions by presenting a consistent process to make decisions. This creates less room for mistakes (intentional or not) to occur from the beginning user to the end-user. Thus, the RITSS framework is useful for strategic purposes and communication creation in projects.

6.3.2 Participant Two Feedback

The feedback from participant two is positive. The general feedback obtained is similar to that of participant one. Participant two believes that a program which follows the procedures (stages) as described by the RITSS framework has been long overdue and the potential of it being applied to the real-world would assist maintenance and engineering managers immensely. The participant stated that the key factors would be ease of availability and ease of usage.

The strengths of the framework as mentioned by participant two are that it is very detailed and can be customised to suit the needs of different countries and can also be used in various disciplines inside the railway environment itself. When asked on its applicability in other industries, this participant indicated that he thought the framework has the capabilities of being applied in other industries. The participant justified this response by stating that *"the RITSS framework is based on maintenance philosophy and maintenance philosophies are the same irrespective of the industry, especially predictive maintenance which is really about detecting and preventing". In terms of weakness, none were identified.*

This participant indicated that if the RITSS framework were to be applied in the global perspective, there are no adjustments required. However, adjustments/improvements would be required if the framework is applied to a country-specific and railway specific. This participant indicated that he would personally use customised versions of the RITSS framework, which would differ for the respective fields within the railway such as rails will be different to signalling and overhead traction equipment. Participant two finished by saying that the output presented by the framework would be beneficial, how much the benefit will be is only affected by how it will be sold to the operators and how it differs from current models.

6.3.3 Deductions based on the Combined Feedback

As part of the validation process, it is essential to determine what aspects of the RITSS framework the participants think are good and what aspects they still think requires attention. This feedback is helpful in the sense that the framework can be refined in the future by addressing the shortcomings. The different stages of the framework are rated in accordance to a scale ranging from *poor* to *very good*, were as the participant responses are seen in Figure 6.13. The consensus from the participants is that the approaches followed during the various stages were favourable and that they are happy with how each stage is addressed. However, the figure shows that Stages 1.2, 1.3, and 3 received an *average* score each, which makes these stages the lowest scored. Participant one gave the technology identification stage (Stage 1.2) an average rating, based on the fact that the participant would have liked to see a bit more detail for the identification process. Participant one gave the acquisition mode guide (Stage 3) a *good* score, although preferring that it incorporated a bit more detail because he identified it as not a core part of the research and it was able to capture the acquisition decision on a high level.

Participant two gave a *average* score to both the mapping (Stage 1.3) and acquisition mode guide (Stage 3), as this participant felt that these stages would be more beneficial to the framework were they more specific to a particular country or railway field (e.g. rails, signalling). Of the three main stages (Stage 1, 2, and 3), the participants were the most satisfied with Stage 2, which is responsible for the evaluation of the candidate technology.

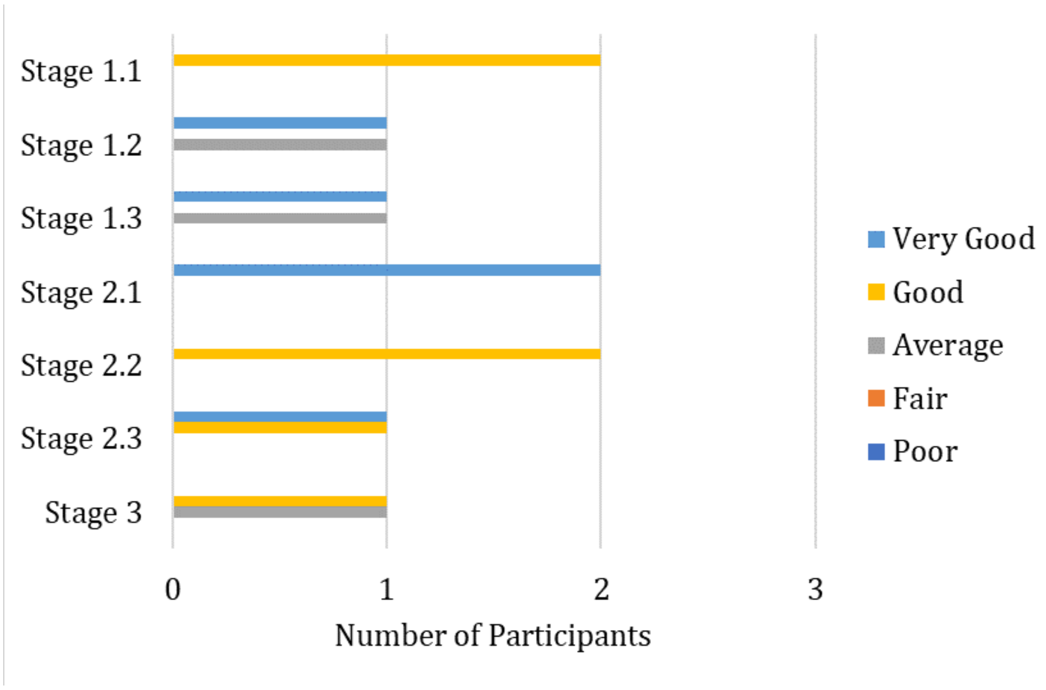


Figure 6.13: Validation questionnaire: Q5

User assessment questions, adapted from Borenstein (1998), are also incorporated into the validation questionnaire as to determine how the potential user(s) would experience implementing the RITSS framework as part of the decision-making process–testing the *usability* of the framework. All the participants were on the same page and were satisfied with the potential user's experience. The scored the logical structure, simplicity of use, and terminology used in the framework all as *very good*, see Figure 6.14.

6.4 Chapter 6 Summary

This chapter is justified by conclusion that none of the existing technology selection frameworks evaluated in Chapter 5 were able to meet the design requirements

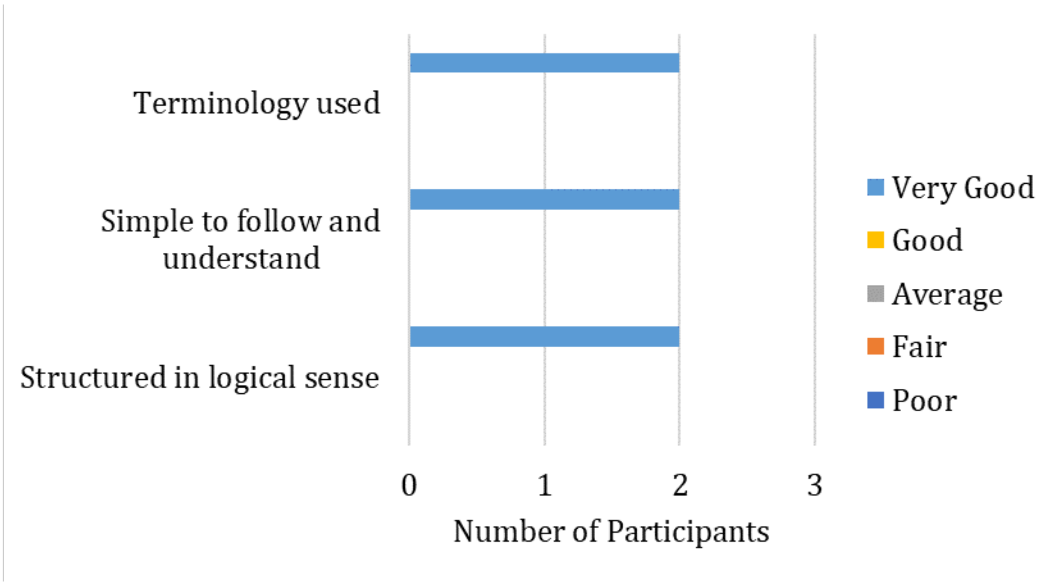


Figure 6.14: Validation questionnaire: Q7

created in this research. Therefore, the Railway Infrastructure Technology Selection Support (RITSS) framework was created. The framework integrates various concepts identified throughout the research. These concepts were grouped and described during the different stages of the RITSS framework starting with the asset scope definition, creating a shortlist of candidate technologies that an organisation should acquire to evolve their current condition monitoring practices and shift towards a predictive maintenance approach and finishing with a guide aimed at providing support for organisations as to what acquisition mode would best work for each of the shortlisted technologies. Final section of this chapter tests the real-world applicability of the framework through face validation incorporating industry practitioners.

Chapter 7

Conclusion and Recommendations

7.1 Introduction

This chapter summarises the research finding from both the conceptualisation phase and the framework development phase. The summary of the research findings is presented and discussed in relation to the research objective, as described in Section 1.3. After which, the expected research contributions are discussed, followed by the limitation identified from the research. This chapter concludes with recommendations for future research opportunities, and this then serves as the concluding chapter for this thesis. Figure 7.1 represents the position of this chapter regarding the entire research process.

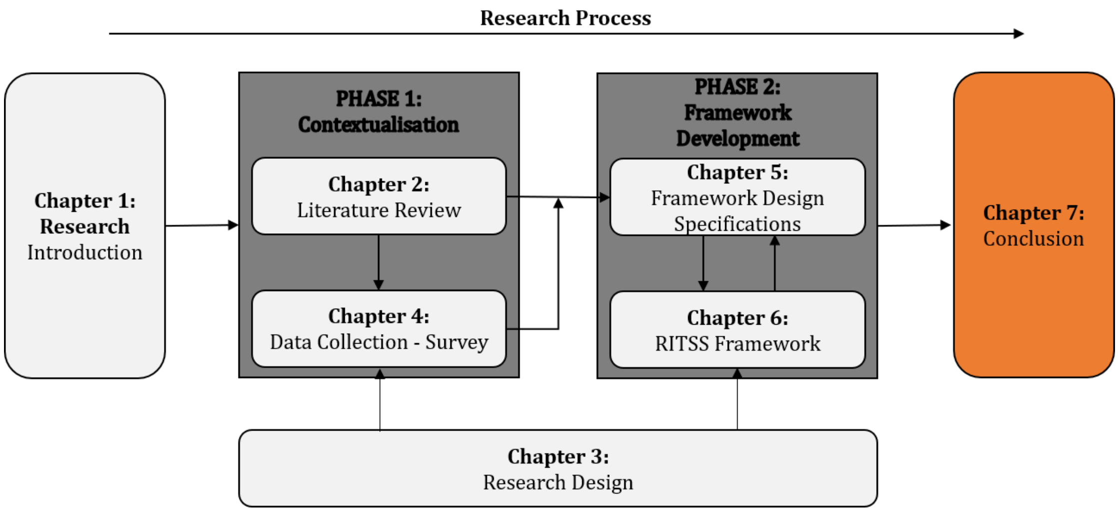


Figure 7.1: Research design: Chapter 7

7.2 Research Overview

This section is responsible for giving an overview of the research conducted in this thesis. It aims to assess if the original research problem, described in Section 1.2, is addressed and the primary research question, Section 1.3, is answered. To measure whether or not the primary research question is answered sufficiently, the research findings is discussed in relation to the research objectives.

Pertaining to the problem statement which arose as part of the early research findings, it is determined that the full potential of emerging data acquisition (DAQ) technologies have not been leverages by maintenance managers to support a predictive maintenance approach, with regards to railway infrastructure maintenance. This problem statement led to the creation of the primary research question, which is the driving factor behind the research conducted in this thesis. This research question wants to determine, *How can a framework be constructed to assist railway operators with the selection and implementation of emerging data acquisition (DAQ) technologies for predictive maintenance of railway infrastructure assets?*

7.2.1 Research Summary

Chapter 1 served as the introduction and foundation upon which the research in this thesis is conducted. This chapter emphasised the background of the study, problem statement, research questions, research objectives, and methodology followed to complete this study. Furthermore, a list of research delimitations and limitations are presented, followed by the ethical considerations and a chapter outline of the thesis.

Chapter 3 covers the methodology employed in each step of the research process to deliver a solution to the research problem. It explores different possible methodologies as to how the research can be conducted. This chapter determined that for this particular study, a mixed method exploratory sequential design would best serve as the strategy of inquiry and that it should incorporate a pragmatic world-view philosophy. Furthermore, this chapter supported the choice of developing a framework to address the primary research question rather than utilise a model, roadmap, or a tool.

These two chapters above described the researcher's plan as to how the process would play out in terms of addressing the research problem and its relevant questions, that were derived from the problem statement. The research conducted incorporated two separate phases, the first phase is responsible for contextualising the research problem, and the second phase is responsible for developing the framework. A continuous validation 'phase' is also incorporated into the design.

See the following subsections for a summary of the two phases and how the continuous validation occurred.

7.2.1.1 Phase 1: Conceptualisation

Research Objective 1 (RO1), see Section 1.3, is addressed as part of the contextualisation phase (Phase 1) of the research design. This contextualisation is achieved through an intensive literature review (Chapter 2) which explored various aspects of railway infrastructure maintenance, starting with the different maintenance philosophies and its developments over the years due to technological advancements. Furthermore, it is found that emerging digital technologies favour a predictive maintenance approach by providing the means to monitoring assets' condition and predict failures. The first part of Chapter 2 concluded with the exploration of various railway infrastructures to determine their respective failures and the causes of the failures. In the second part of this chapter, a structured review is conducted to identify various emerging Data Acquisition (DAQ) technologies capable of monitoring the infrastructure assets' and their respective failures or monitoring parameters, from the literature review. The final review identified 26 different DAQ technologies utilised in the railway industry for condition monitoring as well as various carriers that can supplement the DAQ technologies' capabilities.

Chapter 4 was responsible for substantiating the findings from the literature in Chapter 2 and then build on it by incorporating the inputs from a panel of international railway subject matter experts through a web-based survey. Three things were achieved by the survey responses namely (i) the factors that affect the criticality of the infrastructure are identified, (ii) the DAQ technologies and their monitoring capabilities are validated, and (iii) the barriers, promoters, and strategies of technology adoption are explored. The barriers and promoters for technology adoption are used to develop the evaluation criteria in Chapter 5.

7.2.1.2 Phase 2: Framework Development

Research Objective 2 (RO2), see Section 1.3, is addressed during the framework development phase (Phase 2) of the research design. Chapter 5 was responsible for developing all of the tools required by the framework. The first step was to construct a set of design requirements (features) the framework must include, based on the findings from Chapters 2, 4, 5, and 6 through an iterative process. The design requirements were then used to evaluate eight different technology selection framework identified through a systematic review process. The existing framework analysis identified that none of the frameworks addressed all of the design requirements. Therefore, the development of a new framework is justified. It was found that the most crucial part of a technology selection framework is the evaluation part and that this is best pursued by using some multi-criteria decision analysis (MCDA) technique. This chapter then motivated and described the use of the analytical hierarchy process (AHP) in combination with a simple criterion-weighted sum method to evaluate and prioritise the candidate technologies. After which the evaluation criteria are developed primarily based on the subject matter expert responses (Chapter 4) and supplemented by the literature (Chapter 2). Chapter 5 is concluded with the exploration of various acquisition modes, the conditions under which each of the acquisition modes are favoured, and methods for choosing a suitable acquisition mode based on the technology in question.

Chapter 6 is dedicated to describing the Railway Infrastructure Technology Selection Support (RITSS) framework. The RITSS framework is described by first defining the applicable concepts identified throughout the research. Then the concepts are categorised and integrated into the framework to present a logically structured process which guides the user (organisation) systematically to reach the desired output. Each of the RITSS framework stages is explained in-depth to provide the user with the rational and the means of applying the methodology. Chapter 6 concludes by testing the real-world applicability of the framework through the process of face and user validation, utilising railway industry practitioners as the sample. The consensus amongst the participant was favourable in terms of its applicability.

7.2.1.3 Research Validation

Research Objective 3 (RO3), see Section 1.3, is addressed throughout the research proses. The RITSS framework's validity and feasibility are achieved through the triangulation of the literature, feedback received from international subject matter experts at multiple instances, and feedback received from the industry practitioners during the test for real-world applicability, as described in Section 1.4. Figure 7.2 presents when and where the three distinct sources are used to achieve triangulation. On the left-hand side of the figure the RITSS framework stages are presented and at the top of the figure represents the research inputs.

The literature is used during all three stages of the framework first to map the DAQ technologies to the respective asset failure modes they are able to monitor, secondly to develop the MCDA technique and prioritisation method, and lastly to create the acquisition mode guide. Inputs from international subject matter experts were included in this study twice. The first round of questionnaires (Chapter 4) helped to validate the DAQ technological capabilities and was also used to develop the evaluation criteria. The second round of questionnaires (Chapter 6) validated the evaluation criteria and was used to determine the relative importance

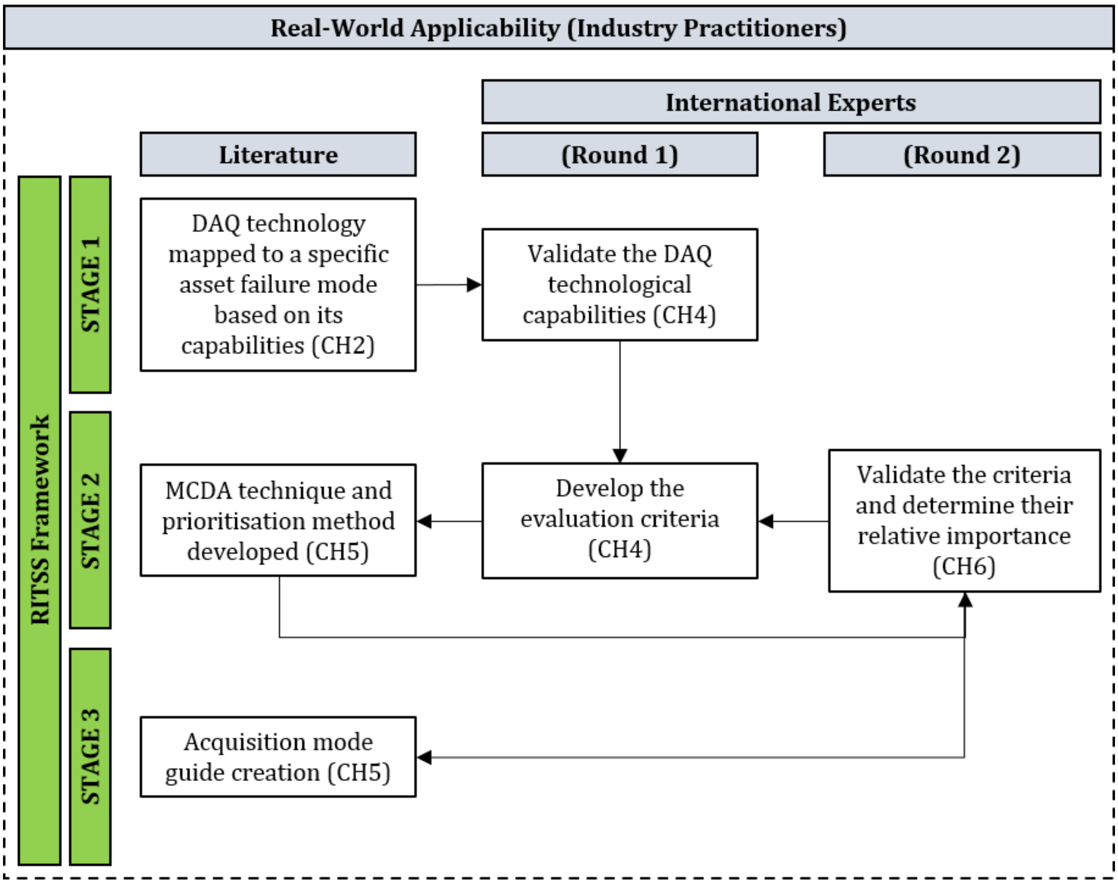


Figure 7.2: RITSS framework validation

(weight) of the criteria. The literature and international subject matter experts were responsible for ensuring the validity at critical points during the development of the RITSS framework giving the research, scientific credibility. However, the completed RITSS framework needed to be validated to test its real-world applicability. Thus, the final step was to perform face and user validations with railway industry practitioners. The final validation resulted in the framework being tested for feasibility, usability, and utility (see Section 6.3). The response from the industry practitioners was positive with them, believing that this framework would support decision-makers in the railway industry.

7.2.2 Research Objectives

This section provides a summary of the research objectives and makes reference to the chapter(s) that addresses each of the objectives, see Table 7.1.

Table 7.1: Research objectives summary

Research Objective	Reference
RO1(i) To identify the critical railway infrastructure components that require maintenance for ensuring reliable and safe transportation.	Chapter 2
RO1(ii) To identify the failure modes at each of the infrastructure components identified in RO1(i), as well as the possible signs to detect imminent failures for prevention.	Chapter 2
RO1(iii) To identify suitable emerging data acquisition technologies for monitoring the condition of railway infrastructure.	Chapter 2
RO1(iv) To establish what the factors are that promote and slow the adoption of new data acquisition technology in the railway environment.	Chapter 4
RO1(v) To determine potential strategies for ensuring the successful adoption of new technology by a railway company.	Chapter 4
RO2(i) To establish a set of design requirements, to which the technology selection framework must adhere.	Chapter 5
RO2(ii) To evaluate existing technology selection frameworks against the set of design requirements established in RO2(i).	Chapter 5
RO2(iii) To develop a framework for the selection of data acquisition technologies incorporating the design requirements.	Chapter 5 & 6
RO2(iv) To refine the framework and transform it into a practical selection framework railway operators can use.	Chapter 6
RO3(i) To validate the DAQ technology monitoring capabilities mapped to their respective failure modes by means of subject matter experts.	Chapter 4
RO3(ii) To validate the technology selection criteria and their relative importance through judgements from subject matter experts.	Chapter 5 & 6
RO3(iii) To validate the refined framework through real-world application.	Chapter 6

7.3 Contribution of the Research

The research presented in this thesis contributes to both the academic literature and practical side of railway maintenance decision-making, with regards to emerging technologies selection, evaluation, and acquisition. The contributions made are as follow:

Academic contributions:

(i) The research performed a structured review to identify emerging DAQ technologies capable of monitoring the condition of railway infrastructures – 26 different DAQ technologies were identified. The identification of the technologies, their monitoring capabilities, and potential carriers to support condition monitoring is valuable knowledge summarised for use by railway decision-decision makers.

(ii) As part of shifting towards a predictive maintenance approach through the use of emerging technologies, this research explored various barriers or challenges that slow the adoption of new technologies, promoters that support the adoption of new technology, and strategies of how the challenges can be addressed to ensure successful adoption. All being relevant to the railway sector.

(iii) The methodology used to develop the framework in this research can be used by future researchers to create their own technology selection or similar frameworks.

(iv) A framework is developed that guides decision-makers:

- with identifying emerging technologies for condition monitoring of railway infrastructures.
- with the evaluation of the candidate technologies against a set of criteria and each other.
- with the acquisition mode selection for sourcing the shortlisted technologies.

Practical contributions: selective feedback from the framework face validations is presented in *italics.*

(v) A framework that has the potential of being applied in the railway maintenance sector. The potential of the framework is not limited to only the railway infrastructure maintenance industry, other industries can also benefit from a refined version of the framework.
"Yes, there is lots of potential for the framework."
"I believe that it is long overdue."
"Alway possible of tweaking it again."
"...maintenance philosophies are the same irrespective of industry."
"Can be used in various disciplines in the railway environment."
"The framework can be customised."

(vi) A framework that follows an clear holistic approach for addressing the decision-making process accompanied by emerging technology selection, evaluation, and acquisition.
"The framework is very detailed."

(vii) A framework that promotes communication between all the relevant decision-makers by presenting the opportunity to create dialogue between both technical and non-technical people.
"Assists various role players within the industry."
"Good for strategic purposes and communication creation in projects."

(viii) A framework that presents a consistent approach to make decision during 'high-tech' acquisition, that has the potential of minimising or mitigating corruption.
"With all the corruption going around you require a consistent approach for decision-making, such as the framework."

7.4 Limitation of the Research

Limitations in the research are identified during the development and validation of the RITSS framework. These limitations can be categorised according to (i) literature, (ii) experts used, and (ii) the framework.

Literature:
Railway infrastructure maintenance has a broad scope, and by incorporating the various infrastructure components (e.g. rails, sleepers, signalling. etc.), the research is forced to consider them at a high level, because each component is seen as a different field within the infrastructure maintenance environment and are unique. This decision has also affected the amount of detail incorporated in the research for each of the DAQ technologies. The last limitation identified from the literature is the use of only two scientific databases (SCOPUS and ScienceDirect) to conduct the structured reviews in Chapters 2 and 5, this limits the scope of literature assessed to identify the DAQ technologies and the existing technology selection frameworks.

Experts used:
A panel of international subject matter experts are used twice during the research, see Figure 7.2, whereas they were included in the study by responding to web-based surveys. The limitation presents itself in the form of each expert working independently when answering the questions, and this can create uncertainty if the experts do not correctly understand the questions. The responses from the expert are also very diverse, and it would have been better to incorporate some discussion either between the researcher and the experts or the experts themselves before the surveys are completed. The industry practitioners work for the same railway operator in South Africa that was used for testing the real-world applicability of the RITSS framework. Therefore, it cannot be assumed that the framework is applicable on a global scale as it could be biased and based purely on what is experienced in South Africa.

RITSS framework:
The feedback received during the final validation highlighted that the use of international subject matter experts might pose problems when it comes to determining the relative importance of the evaluation criteria. As 'like-minded' people

have different opinions as to what is more important to them, this is seen from the experts' judgments. The expert from the same countries seemed to provide similar judgments, whereas the judgments from different countries sometimes contradicted each other. The use of an international panel limits the applicability of the RITSS framework to a global scale, meaning that the framework would need refinement when looking at a specific country. One participant suggested that the framework should be separated into the different infrastructure fields as they are unique and that the current RITSS framework can only address each infrastructure component on a high level. Lastly, the feedback received with regards to the methodology used in the framework is reasonably positive; however, stages in the framework that require work is the technology identification, failure pathways, and the acquisition mode guide stages.

7.5 Recommendation for Future Research

The general idea behind the research is that it was successful in developing a framework to assist railway operators with the selection of emerging DAQ technologies in support of railway infrastructure predictive maintenance. It is described that the adoption of the emerging DAQ technologies is seen as an initiating step towards creating new or transform current predictive maintenance strategies to an autonomous process enabled through digital technologies. However, no research is ever complete and can always be improved. Thus, based on the limitations identified in Section 7.4, certain avenues of future research is recommended for the RITSS framework:

(i) Divide the scope of RITSS framework into the separate infrastructure fields and implement the methodology for each. This sepertion presents the opportunity to explore each field separately and in more depth, by adjusting the framework requirements accordingly. The same is relevant for directing the framework towards a specific organisation and not keep it generic or on a high level.

(ii) A framework such as the RITSS framework can be applied to various industries according to the feedback received. Thus, it creates the opportunity to investigate what customisations/adjustments are required by other industries and new methods of testing the relevancy of the output.

(iii) The industry practitioners identify improvement opportunities for future research during the RITSS framework validation:

- A more detailed process of identifying new and emerging technologies.

- A better method of linking the respective candidate technologies to the assets that are relevant.
- A more detailed acquisition mode that addresses the capital available versus the operating expenses.

(iv) Develop a physical tool/software that incorporates the RITSS framework's methodology. This tool can then be used by railway operators by providing them with an easy way of applying the framework. Note that this tool should allow railway operators to customise certain aspects by choosing different inputs at various stages to suit their respective needs.

(v) As mentioned, the RITSS framework is aimed at selecting DAQ technologies as an initiating step towards a more autonomous and digital predictive maintenance strategy. Upon refinement of the framework, methods can be explored to incorporate the information and communication technologies (ICTs) side as well. This will allow users to select and devise strategies based on the entire data acquisition system (DAS) and not only the DAQ technology.

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Appendices

Appendix A

Railway Infrastructure Defects

This appendix contains the summarised findings from the railway infrastructure failures and causes identified in Chapter 2.

A.1 Infrastructure Failure Modes

Table A.1: Infrastructure failures and causes

Component	**Category**	**Failure**	**Cause of Failure**
Rail	Rail Wear	Crown Wear	Interaction between rail and wheel
		Side Wear	Centrifugal force push wheel flange against the side of the rail when entering a corner. Guage widening has not been implemented, check rails not installed, and rail/wheel contact band not well defined.
		Rail Corrugation	High contact stresses between wheel and rail, poor wheel and rail profiles, differential wheel diameters. Common to find corrugation where the sleepers are severely fouled which decreases the elasticity.
	Cracked Rail	Surface cracks	Excessive shear stresses between wheels and rails caused by rolling contact fatigue.
		Internal cracks	
	Rail Damage	Long Groove and line defects	Defects during the manufacturing.
		Battered rail ends and dipped joints	Develops when rail continuity is comprimised and is caused by lack of joint maintenance and dynamic wheel impact loads on the joint.

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Table A.1 – *continued from previous page*

Component	Category	Failure	Cause of Failure
		Metal flow	Train wheels hunting across the rails due to contact area between the wheels and rails becoming compromised.
		Wheel burn	The continuous slipping of the wheels because adhesion limit is exceeded.
		Crushing	Traffic loading or even cracks underneath the rail running surface.
	Broken Rail	-	Rail wear, cracked rails, and rail damage.
Sleepers	Timber	Rotting	Timber is an organic material and therefore susceptible to bio-deterioration due to numerous micro-organisms. Moisture is a major cause or accelerator for degradation. Structural integrity is affected.
		Splitting	Splitting can occur from large transverse shear loading. The insertion of the screw spike when fastening the rail may cause sleeper to split over time.
		Insect attacks	Termite attacks the timber.
	Concrete	Rail-seat deterioration	Rail-seat abrasion, hydra abrasive erosion, hydraulic pressure cracking or chemical deterioration. These can all be caused by the presence of water, heavy axle loads, fastener and sleeper pad failures, steep track gradients, and track curves greater than two degrees.
		Tensile fracture	Fracture on a pre-tensioned sleeper as a result of longitudinal cracks caused by high shearing tensile stress on the edge of the bolt hole.
		Bending cracks	High impact loading for short periods by the train wheel.
	Steel	Corrosion	Forming when sleepers come into contact with salts from the soil, ground water, or aggregates from the ballast and sub-grade materials.
		Fatigue cracking	Repeated stress caused by cyclic loading and the shear stress surrounding the rail seat.

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Table A.1 – *continued from previous page*

Component	**Category**	**Failure**	**Cause of Failure**
Ballast	Composition	Fouling	Operational loads from the train causing the ballast rocks to re-arrange and form more fines due to friction. It can also occur due to infiltration of external alien fines from either wind, rain, or even dropping from freight trains.
		Internal degradation	Dynamic loading, rail surface defects, tamping and chemical wear fracturing and abraising the ballasts.
	Profile	Shortage/Excess rocks	Caused by negligent maintenance, people and animals spreading ballast around, theft of ballast, dynamic loading experience from the trains, and also the tamping process.
Formation	Water	Maintains moisture	Fouling causes the formation to holds the water longer than the period of absorption.
	Clay	Decrease in capillary space	The presence of clay reduces the amount of water absorption of the soil. Soil saturates faster creating a slurry.
	Water and Clay	Combination	The causes of the above occurring simultaneously.
OHTE	Electrical	Electrical arcing	Incorrect static contact forces, excess friction, worn components, and poor geometric adjustments.
	Physical equipment	Breaks or damage	
		Corrosion of the wires	
	External	Obstructions	Birds creating nests on the OHTE.
Surface drains	Obstruction	Blockage	Build up of soil or any other form of obstruction that hinders the flow of water. Usually as a result of poor maintenance.
Signalling	Electrical	Faulty electrical systems	Defects are caused by degradation due to extreme weather conditions, damages from operations, or vandalism.
	Physical	Damaged signalling equipment	

A.2 Failure Pathways

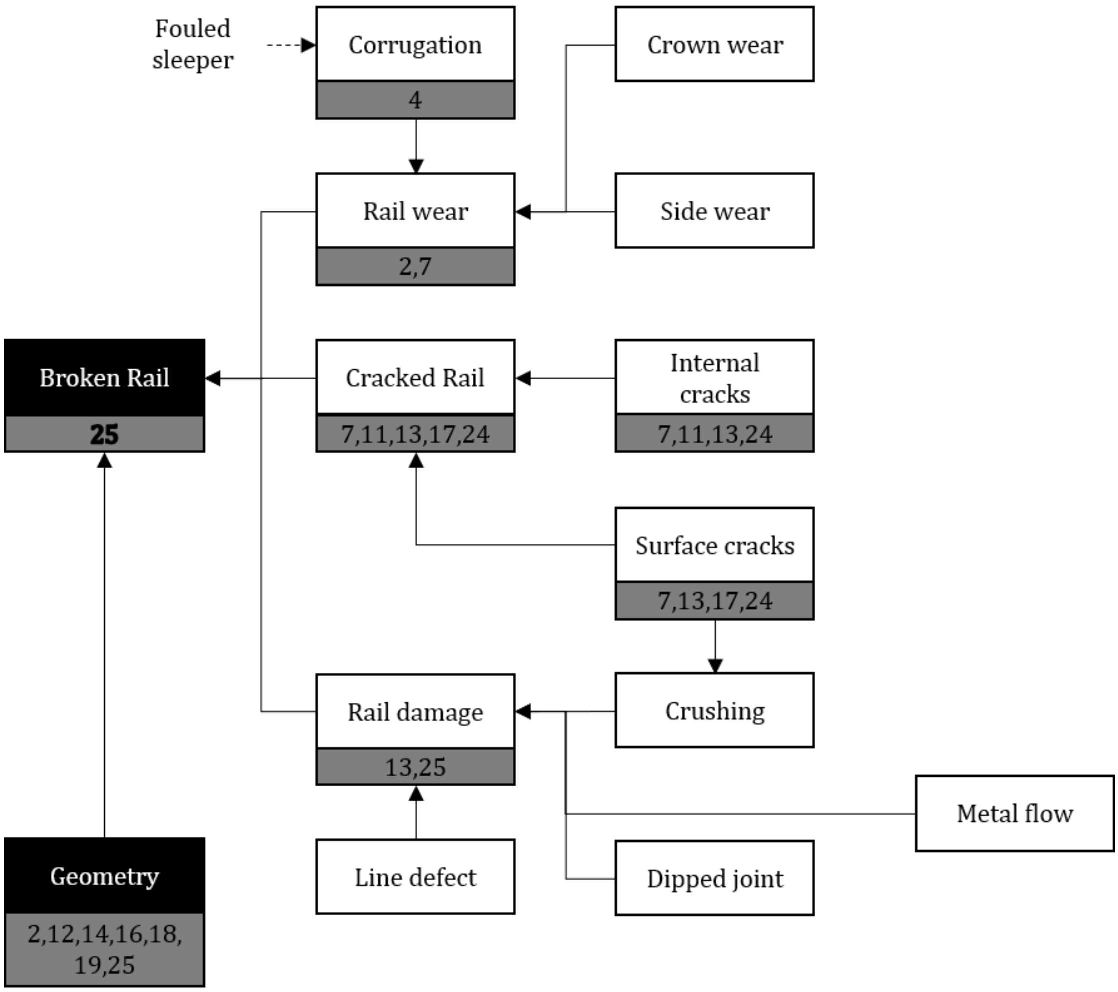

Figure A.1: Rail failure pathway

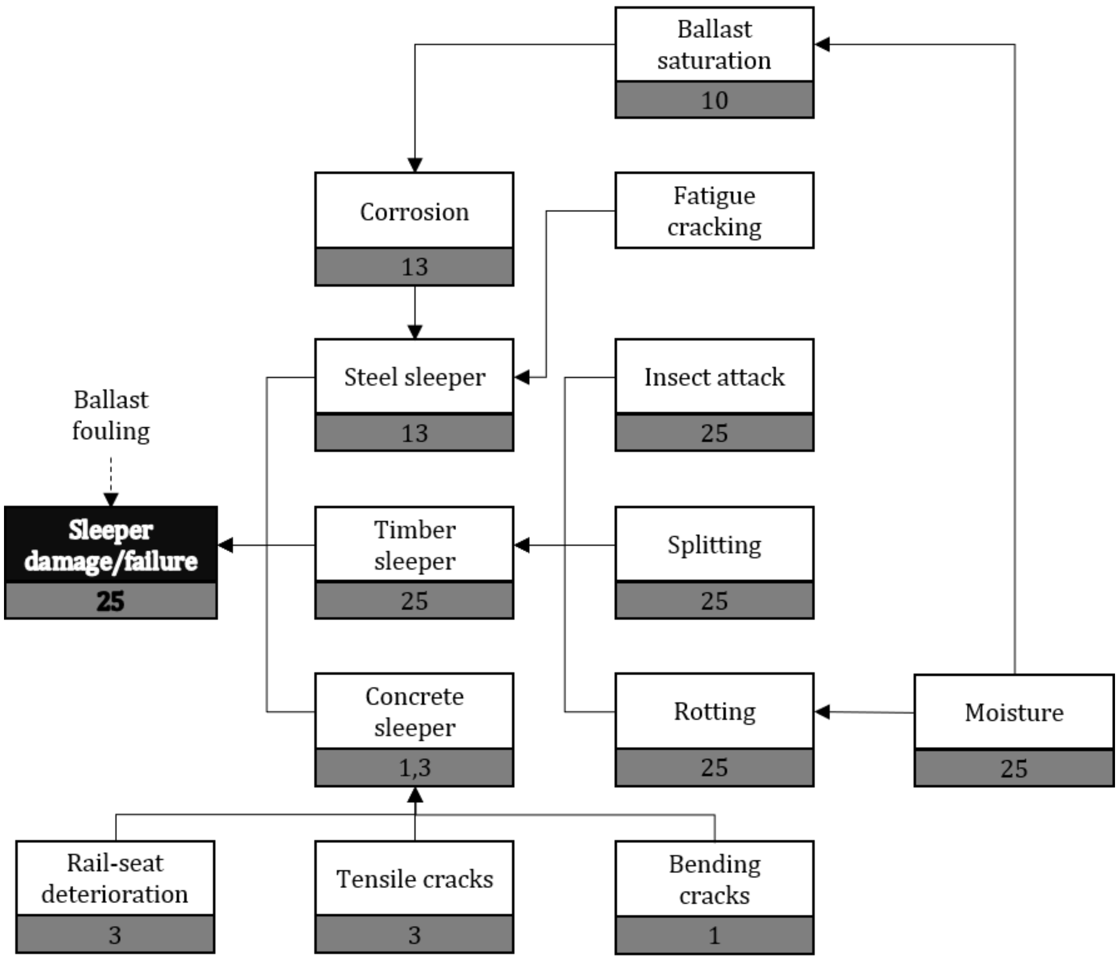

Figure A.2: Sleeper failure pathway

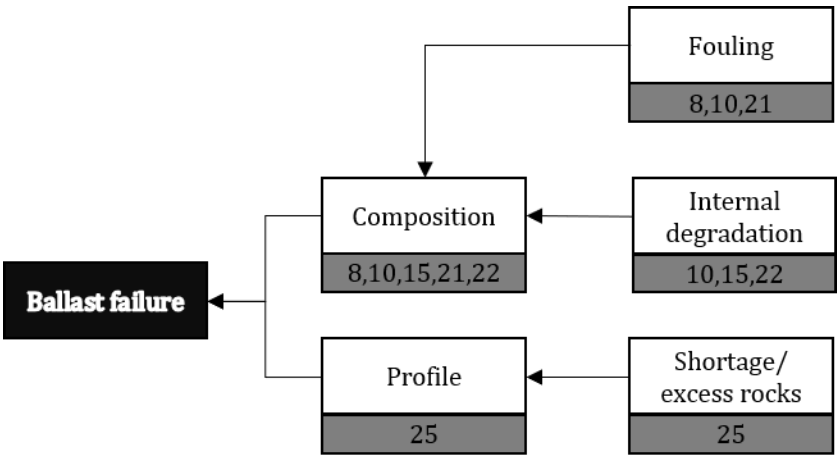

Figure A.3: Ballast failure pathway

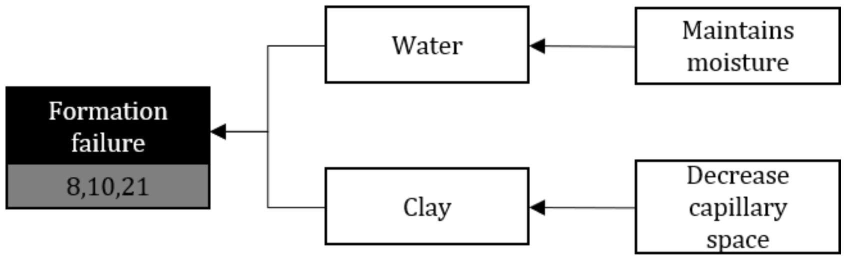

Figure A.4: Formation failure pathway

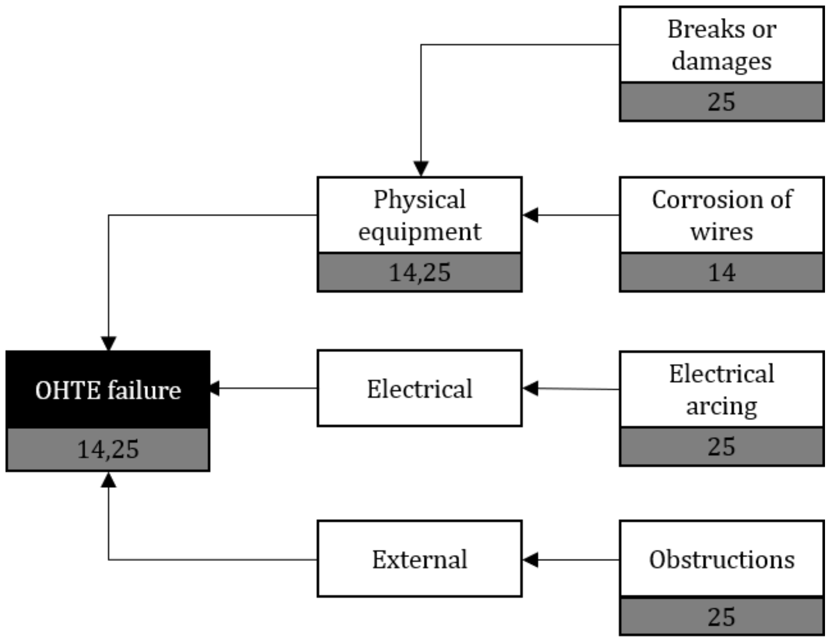

Figure A.5: OHTE failure pathway

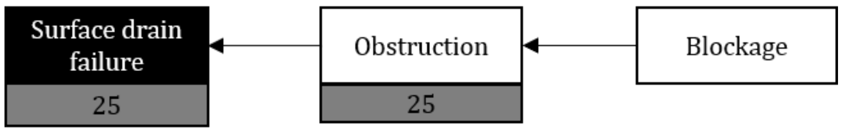

Figure A.6: Surface Drains failure pathway

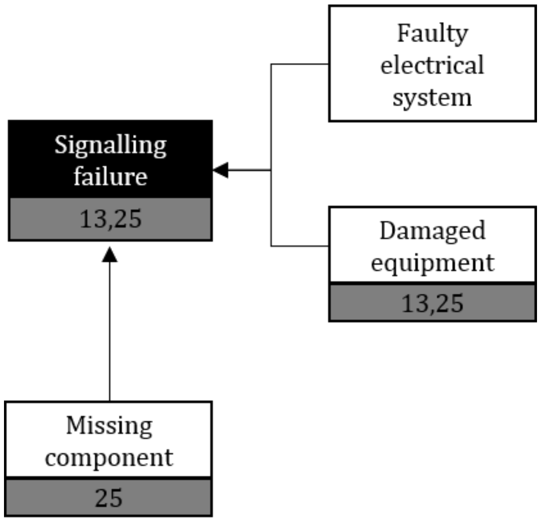

Figure A.7: Signalling failure pathway

Appendix B

Data Acquisition Technology Landscape

This appendix contains additional findings from the structured review deemed valuable to the research that is portrayed and discussed in Chapter 2, Section 2.3.

B.1 Structured Review - Context

This section aims to highlight the reasons for each papers inclusion or exclusion from the research as well as give the detailed information of all the selected papers that is used for the bibliometric analysis in Section 2.3.2.2.

B.1.1 Inclusion/Exclusion Criteria of Papers

Table B.1: Inclusion and exclusion of reviewed papers

Paper Number	**Paper Title**	**Reference**	**Included**	**Excluded**	**Reason for Selection**
1	An ensemble-based change-point detection method for identifying unexpected behaviour of railway tunnel infrastructures	Vagnoli and Remenyte-Prescott (2018)	x		Railway tunnel, structural health monitoring (SHM)
2	A new methodology for assessment of railway infrastructure condition	Kovacevic *et al.* (2016)	x		Rail infrastructure maintenance, Croatia
3	Assessment of cracks in pre-stressed concrete railway sleepers by ultrasonic testing	Tatarinov *et al.* (2019)	x		Monitoring of cracks in concrete railway sleeper by ultrasound
4	Comparison of Results of Geometrical Position of the Track Diagnostics – Spot and Continuous Measurement	Šestáková and Gocálová (2014)	x		Rail track geometry measuring
5	Deterioration model and condition monitoring of aged railway embankment using non-invasive geophysics	Gunn *et al.* (2018)	x		Geophysical imaging, condition monitoring, opportunities for predict and prevent tactics
6	Estimation of lateral and cross alignment in a railway track based on vehicle dynamics measurements	De Rosa *et al.* (2019)	x		Geometric track irregularities, in-service vehicles, three different methods
7	European integration and national models for railway networks (1840–2010)	Martí-Henneberg (2013)		x	No condition monitoring of infrastructures, models of rail networks
8	Geomechanical studies on slow slope movements in Parma Apennine	Segalini *et al.* (2009)		x	Assesses the causes of slow slope movements, links it to causes of infrastructure failure, no mention of monitoring or processing of data

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Table B.1 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Included**	**Excluded**	**Reason for Selection**
9	Health condition monitoring of insulated joints based on axle box acceleration measurements	Molodova *et al.* (2016)	x		Monitoring of insulated rail joints, detection algorithm
10	Hydro-thermal boundary conditions at different underlying surfaces in a permafrost region of the Qinghai-Tibet Plateau	Zhang *et al.* (2019)		x	No mention of monitoring technologies
11	Improving rail network velocity: A machine learning approach to predictive maintenance	Li *et al.* (2014)		x	Full text exclusion - due to rolling stock not part of the scope
12	Innovative approach in the use of geotextiles for failures prevention in railway embankments	Fuggini *et al.* (2016)		x	Full text exclusion - focus on railway embankments only not including rail track substructure, outside scope
13	Integration of cost-risk assessment of denial of service within an intelligent maintenance system	Carlander *et al.* (2016)		x	Cost modelling of maintenance
14	Mapping interactions between geology, subsurface resource exploitation and urban development in transforming cities using InSAR Persistent Scatterers: Two decades of change in Florence, Italy	Pratesi *et al.* (2016)		x	Geography mapping through satellite radar images. Not part of infrastructure monitoring - outside scope
15	Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction	Kaewunruen (2014)	x		Railway turnout system monitoring, track inspection vehicle "AK Car"
16	Novel efficient technologies in Europe for axle bearing condition monitoring – the MAXBE project	Vale *et al.* (2016)		x	Rolling stock monitoring not scope of infrastructure
17	Predictive maintenance using tree-based classification techniques: A case of railway switches	Allah Bukhsh *et al.* (2019)		x	Does not focus on condition monitoring technology, focus is technique for using data already in practice

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Table B.1 – *continued from previous page*

Paper Number	Paper Title	Reference	Included	Excluded	Reason for Selection
18	Proving MEMS Technologies for Smarter Railway Infrastructure	Milne *et al.* (2016)	x		Criteria selection micro electrical mechanical systems (MEMS)
19	Railroad infrastructure 4.0: Development and application of an automatic ballast support condition assessment system	Qian *et al.* (2019)	x		In track sensors between ballasts
20	Railways Track Characterization Using Ground Penetrating Radar	Fontul *et al.* (2016)	x		Ground penetrating radar for monitoring layers rail.
21	Statistical Model of Railway's Turnout based on Train Induced Vibrations	Barkhordari and Galeazzi (2018)		x	Statistical model for monitoring railway turnouts.
22	The issue of uncertainty of visual measurement techniques for long distance measurements based on the example of applying electric traction elements in diagnostics and monitoring	Skibicki (2018)	x		Visual Monitoring of OHTE
23	The Mala Rijeka Bridge - Specificity of maintenance	Vujović (2018)		x	No mention of monitoring technologies
24	Time series modelingmodelling by a regression approach based on a latent process	Chamroukhi *et al.* (2009)		x	ModelingModelling approaches
25	Towards a new perspective in railway vehicles and infrastructure	Zangani and Fuggini (2012)		x	Focus not on maintenance and monitoring of infrastructure
26	Tunnelling undercrossing existing live MRT tunnels	Esen Sze *et al.* (2016)		x	Focus on railway tunnelling and not the maintenance of infrastructure in scope
27	Vibration measurement-based simple technique for damage detection of truss bridges: A case study	Siriwardane (2015)		x	Bridges are not in the scope of infrastructure of this research

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Table B.1 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Included**	**Excluded**	**Reason for Selection**
28	A smart sewer asset information model to enable an 'Internet of Things' for operational wastewater management	Edmondson *et al.* (2018)		x	Does not form part of the scope of this study
29	Health and emergency-care platform for the elderly and disabled people in the Smart City	Hussain *et al.* (2015)		x	Human health monitoring
30	Improving a production site from a social point of view: an IoT infrastructure to monitor workers' condition	Gregori *et al.* (2018)		x	Monitors the workers' performance and not the infrastructure
31	Rules engine and complex event processor in the context of internet of things for precision agriculture	Mazon-Olivo *et al.* (2018)		x	Full text excluded - no focus on maintenacemaintenance, infrastructure or condition monitoring;
32	Towards Sustainable Water Supply: Schematic Development of Big Data Collection Using Internet of Things (IoT)	Koo *et al.* (2015)		x	Includes communication methods but focusses on service provision rather than infrastructure condition
33	A cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance	Mourtzis and Vlachou (2018)		x	A high level look at Cyber physical systems including acquisition, storage, and processing of data. No Detail about sensors
34	A cost estimation approach for IoT modular architectures implementation in legacy systems	Tedeschi *et al.* (2018)		x	Estimate the cost of implementing IoT systems
35	A new vibration analysis approach for transformer fault prognosis over cloud environment	Bagheri *et al.* (2018)		x	Full text exclude - Vibration analysis approach transformer monitoring, not applicable to the scope;
36	A stochastic optimization framework for planning of waste collection and value recovery operations in smart and sustainable cities	Jatinkumar Shah *et al.* (2018)		x	No mention of monitoring technologies

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Table B.1 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Included**	**Excluded**	**Reason for Selection**
37	An indoor power line based magnetic field energy harvester for self-powered wireless sensors in smart home applications	Maharjan *et al.* (2018)		x	Smart home sensor technology with smart phone networking
38	An intelligent framework for workouts in gymnasium: M-Health perspective	Bhatia and Sood (2018)		x	Focus on IoT for human health
39	An intelligent model for assuring food quality in managing a multi-temperature food distribution centre	Tsang *et al.* (2018)		x	Overview of enabling technologies more emphasis on temperature regulating and location monitoring
40	Closed-loop design evolution of engineering system using condition monitoring through internet of things and cloud computing	Xia *et al.* (2016)		x	Focusses on the optimising of process rather than infrastructure monitoring
41	Design guidelines of laser reduced graphene oxide conformal thermistor for IoT applications	Romero *et al.* (2018)		x	Thermistor not applicable to scope of structure review
42	Design, modelling, simulation and integration of cyber physical systems: Methods and applications	Hehenberger *et al.* (2016)		x	Looks into the cyber physical system with no look at the enabling technologies.
43	Development of a novel telecare system, integrated with plantar pressure measurement system	De Silva *et al.* (2016)		x	Human health systems
44	Energy efficient wearable sensor node for IoT-based fall detection systems	Nguyen Gia *et al.* (2018)		x	Human health systems
45	Fuzzy adaptive cognitive stimulation therapy generation for Alzheimer's sufferers: Towards a pervasive dementia care monitoring platform	Navarro *et al.* (2018)		x	Human health systems
46	Green data centre with IoT sensing and cloud-assisted smart temperature control system	Liu *et al.* (2016)		x	IoT sensing temperature control system

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Table B.1 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Included**	**Excluded**	**Reason for Selection**
47	Health and emergency-care platform for the elderly and disabled people in the Smart City	Hussain *et al.* (2015)		x	Human health systems
48	Hybrid data-driven vigilance model in traffic control centre using eye tracking data and context data	Li *et al.* (2019*a*)		x	Traffic control systems and data tracking
49	Improving a production site from a social point of view: an IoT infrastructure to monitor workers condition	Gregori *et al.* (2018)		x	Integration between workers and digitized factories
50	Improving the safety of atrial fibrillation monitoring systems through human verification	Faust *et al.* (2019)		x	Human Health Care monitoring systems
51	Integrating wearables with cloud-based communication for health monitoring and emergency assistance	Sinnapolu and Alawneh (2018)		x	Human health system, wearable devices cloud communication
52	Investigating the performance of internet of things based anaerobic digestion of food waste	Logan *et al.* (2019)	x		Use of real time condition monitoring, anaerobic digestion plants. Possible correlation between railway infrastructure monitoring.
53	IoT embedded systems network and sensors signal conditioning applied to decentralized photovoltaic plants	Pereira *et al.* (2019)	x		Decentralised photovoltaic (PV) plants monitoring
54	IoT-based human action prediction and support	Lunardi *et al.* (2018)		x	Human health system
55	Narrowband-IoT Performance Analysis for Healthcare Applications	Malik *et al.* (2018)		x	Human health system
56	Probing operational conditions of mixing and oxygen deficiency using HSVcolor space	Li *et al.* (2019*c*)		x	Not related to equipment or infrastructure monitoring

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Table B.1 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Included**	**Excluded**	**Reason for Selection**
57	Research and application of risk and condition based maintenance task optimization technology in an oil transfer station	Wang and Gao (2012)	x		Real-time infrastructure management
58	System design for wearable blood oxygen saturation and pulse measurement device	Fu and Liu (2015)		x	Human health system
59	The evolution of the internet of things industry and market in China: An interplay of institutions, demands and supply	Kshetri (2017)		x	Scope of paper is supply and demand industry
60	The internet of things (IOT) and cloud computing (CC) based tailings dam monitoring and pre-alarm system in mines	Sun *et al.* (2012)		x	Dam monitoring of mines
61	The Research of Safety Monitoring System Applied in School Bus Based on the Internet of Things	Xu *et al.* (2011)		x	Safety monitoring of equipment, school bus
62	Towards an Intelligent Approach for Ventilation Systems Control using IoT and Big Data Technologies	Lachhab *et al.* (2018)		x	Real-time monitoring HVAC system
63	Towards Distributed IoT/Cloud based Fault Detection and Maintenance in Industrial Automation1	Xenakis *et al.* (2019)	x		Real-time machine condition monitoring
64	Type-2 fuzzy ontology–aided recommendation systems for IoT–based healthcare	Ali *et al.* (2018)		x	Human Health
65	Experimental and numerical study for detection of rail defect	Montiel-Varela *et al.* (2017)	x		Rail defect detection through condition monitoring
66	A Railway Track Geometry Measuring Trolley System Based on Aided INS	Chen *et al.* (2018)	x		Geometry measuring of railway track

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Table B.1 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Included**	**Excluded**	**Reason for Selection**
67	Multi-information location data fusion system of railway signal based on cloud computing			x	Full text exclusion - Focus on information sharing and real-time processing; Aimed at train positioning rather than monitoring infrastructure condition;
68	Modular Fault Diagnosis in Fixed-Block Railway SignalingSignalling Systems	Durmus *et al.* (2016)	x		Fault diagnosis in fixed-block railway signalling
69	Cloud computing for maintenance of railway signalling systems	Morant *et al.* (2012)	x		Looks at the data collection and distribution through cloud computing of railway signalling systems
70	Wireless Sensor Networks for Condition Monitoring in the Railway Industry - A Survey	Hodge *et al.* (2015)	x		Condition monitoring using wireless networks
71	Inspection methods - overview and comparison	Campbell (2013)	x		Inspection methods applicable in engineering for monitoring
72	Infrared Thermography's Application to Infrastructure Inspections	Garrido *et al.* (2018)	x		Infrastructure inspection through thermography
73	The Basic Principles of Mechanised Track Maintenance	Zaayman (2017)	x		In-depth look into railway infrastructure inspection and monitoring techniques
74	Automating condition monitoring of wooden railway sleepers	Yella *et al.* (2009)	x		
75	A real time study on condition monitoring of distribution transformer using thermal imager	Mariprasath and Kirubakaran (2018)	x		

B.1.2 Bibliometric Analysis

Table B.2: Bibliometric analysis of selected papers

Paper Number	**Paper Title**	**Reference**	**Publication Year**	**Paper Source**	**Category**	**Country**
1	An ensemble-based change-point detection method for identifying unexpected behaviour of railway tunnel infrastructures	Vagnoli and Remenyte-Prescott (2018)	2018	Journal article	Tunnelling and Underground Space Technology	United Kingdom
2	A new methodology for assessment of railway infrastructure condition	Kovacevic *et al.* (2016)	2016	Conference article	Transportation Research Procedia	Croatia, Ireland, Netherlands
3	Assessment of cracks in pre-stressed concrete railway sleepers by ultrasonic testing	Tatarinov *et al.* (2019)	2018	Conference article	Procedia ComputorComputer Science	Latvia
4	Comparison of Results of Geometrical Position of the Track Diagnostics – Spot and Continuous Measurement	Šestáková and Gocálová (2014)	2014	Conference article	Procedia Engineering	Slovak Republic
5	Deterioration model and condition monitoring of aged railway embankment using non-invasive geophysics	Gunn *et al.* (2018)	2018	Journal article	Construction and Building Materials	United Kingdom
6	Estimation of lateral and cross alignment in a railway track based on vehicle dynamics measurements	De Rosa *et al.* (2019)	2019	Journal article	Mechanical Systems and Signal Processing	Italy
7	Health condition monitoring of insulated joints based on axle box acceleration measurements	Molodova *et al.* (2016)	2016	Journal article	Engineering Structures	Netherlands

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Table B.2 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Publication Year**	**Paper Source**	**Category**	**Country**
8	Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction	Kaewunruen (2014)	2014	Journal article	Case Studies and Non-destructive Testing and Evaluation	Australia, USA
9	Proving MEMS Technologies for Smarter Railway Infrastructure	Milne *et al.* (2016)	2016	Conference article	Procedia Engineering	United Kingdom
10	Railroad infrastructure 4.0: Development and application of an automatic ballast support condition assessment system	Qian *et al.* (2019)	2019	Journal article	Transportation Geotechnics	USA
11	Railways Track Characterization Using Ground Penetrating Radar	Fontul *et al.* (2016)	2016	Conference article	Procedia Engineering	Portugal, Italy
12	The issue of uncertainty of visual measurement techniques for long distance measurements based on the example of applying electric traction elements in diagnostics and monitoring	Skibicki (2018)	2018	Journal article	Measurement	Poland
13	Investigating the performance of internet of things based anaerobic digestion of food waste	Logan *et al.* (2019)	2019	Journal article	Process Safety and Environmental Protection	Thailand, Ireland
14	IoT embedded systems network and sensors signal conditioning applied to decentralized photovoltaic plants	Pereira *et al.* (2019)	2019	Journal article	Measurement	Brazil
15	Research and application of risk and condition based maintenance task optimization technology in an oil transfer station	Wang and Gao (2012)	2012	Journal article	Journal of Loss Prevention in the Process Industries	China

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Table B.2 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Publication Year**	**Paper Source**	**Category**	**Country**
16	Towards Distributed IoT/Cloud based Fault Detection and Maintenance in Industrial Automation1	Xenakis *et al.* (2019)	2019	Conference article	Procedia ComputorComputer Science	Greece, Ireland
17	Experimental and numerical study for detection of rail defect	Montiel-Varela *et al.* (2017)	2017	Journal article	Engineering Failure Analysis	Mexico, Italy
18	A Railway Track Geometry Measuring Trolley System Based on Aided INS	Chen *et al.* (2018)	2018	Journal article	Sensors	China
19	Modular Fault Diagnosis in Fixed-Block Railway SignalingSignalling Systems	Durmus *et al.* (2016)	2016	Conference article	IFAC PapersOnLine	Turkey, Russia, Germany
20	Cloud computing for maintenance of railway signalling systems	Morant *et al.* (2012)	2012	Conference article	Condition Monitoring and Machinery Failure Prevention Technologies	Sweden, Spain
21	Wireless Sensor Networks for Condition Monitoring in the Railway Industry - A Survey	Hodge *et al.* (2015)	2015	Journal article	IEEE Transaction on Intelligent Transportation Systems	United Kingdom
22	Inspection methods - overview and comparison	Campbell (2013)	2013	Book Section	Inspection of Metals	International
23	Infrared Thermography's Application to Infrastructure Inspections	Garrido *et al.* (2018)	2018	Journal article	InfrastucturesInfrastructures	Spain
24	The Basic Principles of Mechanised Track Maintenance	Zaayman (2017)	2017	Book	Mechanised Track Maintenance	South Africa

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Table B.2 – *continued from previous page*

Paper Number	**Paper Title**	**Reference**	**Publication Year**	**Paper Source**	**Category**	**Country**
25	Automating conditiond monitoring of wooden railway sleepers	Yella *et al.* (2009)	2009	Journal article	Transportation Research	Sweden, Spain
26	A real time study on condition monitoring of distribution transformer using thermal imager	Mariprasath and Kirubakaran (2018)	2018	Journal article	Infrared Physics and Technology	India

B.2 Structured Review - Findings

This section aims at providing the detailed findings as presented by the structured review. All further reference to papers in this section of this appendix will be based on the numbers given to them in the previous section B.1, Table B.2. The numbers are 1 through 26, based on the final inclusion of the structured review.

B.2.1 Structured Review Detailed Findings

Table B.3: Review findings Part 1

#	Paper Title	Overview	DAQ Technology	Sensors Utilised	Observed Physical Parameters	Reference
1	An ensemble-based change-point detection method for identifying unexpected behaviour of railway tunnel infrastructures	Structural Health Monitoring (SHM), Railway Infrastructure (Tunnel), Artificial Neural Network (ANN) to predict horizontal displacement of a tunnel for installation of OHTE.	Optical and Mechanical: (i) total stations; (ii) laser scanner system; (iii) densitometer, (iv) fiberfibre optical sensor. (v) Shape Accel Array (SAA) sensor	(i) Angle sensor, infrared sensor, camera sensor; (ii) 3D laser scanner sensor; (iii) Densitometer; (iv) fiberfibre optical sensor; (v) MEMS gravity sensor;	(i) Angel, distance, 3D coordinates; (ii) ; (iii) Density of fluids; (iv) strain, temperature, pressure; (v) tilt in two directions;	Vagnoli and Remenyte-Prescott (2018)
2	A new methodology for assessment of railway infrastructure condition	Part of decision support framework for IM's; Data acquisition used for critical infrastructure for quantitative risk assessment procedure.	(i)Electromagnetic ground penetrating radar (GPR); (ii)UAV imaging; (iii) Seismic refraction; (iv) SASW/MASW		(i) Relative dielectric permittivity, Electrical conductivity, Magnetic permeability, Electromagnetic wave velocity; (ii) Topography; (iii) Longitudinal wave velocity; (iv) Shear wave velocity	Kovacevic *et al.* (2016)

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Table B.3 – *continued from previous page*

#	**Paper Title**	**Overview**	**DAQ Technology**	**Sensors Utilised**	**Observed Physical Parameters**	**Reference**
3	Assessment of cracks in pre-stressed concrete railway sleepers by ultrasonic testing	Proposed ultrasonic testing of concrete sleeper crack instead of current visual inspections. Confirmed practicability of ultrasonic testing for crack characterisation. Proposed further study to improve accuracy, automation of measurements and elimination of human factor.	(i) Acoustic emissions; (ii) Imaging based on LED and Cameras; (iii) Ultrasonic data acquisition unit	(iii) Piezoelectric transducer,	(i) ;(ii) ;(iii) Ultrasonic pulse velocity, impact-echo response, vibration spectroscopy;	Tatarinov *et al.* (2019)
4	Comparison of Results of Geometrical Position of the Track Diagnostics – Spot and Continuous Measurement	Spot and continuous measurements at two life stages of track, installation and operation life stages, gauge and cant measuring, further study to compare results of track geometry recording vehicle.	(i) KRAB™ -Light (continuous); (ii) Gauge-checker ROBEL;	(i) potentiometric sensor, inclinometer, incremental rotary encoder; (ii) ;	Displacement	Šestáková and Gocálová (2014)

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Table B.3 – *continued from previous page*

#	**Paper Title**	**Overview**	**DAQ Technology**	**Sensors Utilised**	**Observed Physical Parameters**	**Reference**
5	Deterioration model and condition monitoring of aged railway embankment using non-invasive geophysics	Geophysical imaging creates opportunity to aid preventative and predictive practices for aged railway embankments; Framework to support risk-based asset management with geophysical methods.	(i) Electrical resistivity tomographic (ERT) imaging; (ii) Surface wave survey using continuous surface wave (CSW); (iii) Multi-channel analysis of surface wave (MASW); (iv) Light detection and Ranging (LiDAR); (v) Robotic total stations; (vi) Photogrammetry	(i) ERT electrodes; (ii) Vertical oscillator, geophones; (iii) Sledge hammer, geophones; (iv) laser, scanner, GPS; (v) Angle encoder, automated target recognition (ATR) sensor, Tilt compensator, electrical discharge machine (EDM) sensor;	(i) Lithological variations, changes in soil moisture; (ii and iii) Shear wave velocity and stiffness of shallow subsurface; (iv - vi) Ground displacement;	Gunn *et al.* (2018)
6	Estimation of lateral and cross alignment in a railway track based on vehicle dynamics measurements	Measuring track geometry from in service vehicles; Three different approaches to estimating lateral and corss-level alignments	(i) Laser-optical system (ii) Virtual measurements from axle-box mounted, bogie mounted and car-body mounted;	(ii) Accelerometers, gyroscopes,	Lateral and cross-level displacement	De Rosa *et al.* (2019)
7	Health condition monitoring of insulated joints based on axle box acceleration measurements	On-train automatic health condition monitoring system for insulated rail joints; Detection algorithm proposed; Method to eliminate the need for visual inspections;	(i)On-train automatic Axle-box acceleration measurements; (ii) Eddy current; (iii) Ultrasound measurements; (iv) Hammer test;	(i) Accelerometers, GPS; (iv) Force sensor, unidirectional accelerometer;	(i) Acceleration measurements in 3D, GPS co-ordinates, train speed; (iv) Hammer impact force, acceleration;	Molodova *et al.* (2016)

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Table B.3 – *continued from previous page*

#	**Paper Title**	**Overview**	**DAQ Technology**	**Sensors Utilised**	**Observed Physical Parameters**	**Reference**
8	Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction	Monitoring rail track deterioration through wayside and train mounted sensors, SHM	(i) AK Car - axle box accelerations and ride quality data;	(i) Accelerometers	(i) Acceleration measurements	Kaewunruen (2014)
9	Proving MEMS Technologies for Smarter Railway Infrastructure	Provides evidence of adopting low cost technologies in self-monitoring smart infrastructure	(i) Micro electrical mechanical systems (MEMS); (ii) Piezo-electric;	(i) Accelerometers, gyroscope, magnetometer, geophones, high speed video for digital image correlation (DIC), multi-depth deflectometers (MDD); (ii) Piezo-electric accelerometers;	(i) Tri-axial acceleration, angular velocity, reference orientation, velocity, digital image ; (ii) Accelerations;	Milne *et al.* (2016)
10	Railroad infrastructure 4.0: Development and application of an automatic ballast support condition assessment system	Development of an automatic ballast condition monitoring system, industry 4.0	(i) Ground penetrating radar (GPR); (ii) Matrix based tactile surface sensors (MBTSS); (iii) Wheel impact load detector (WILD); (iv) Concrete surface straingstrain gauge; (v) "SmartRock";	(ii) Pressure sensor; (iii) Pressure sensor; (iv) strain gauge;	(ii) Load (iii) Static and dynamic load; (iv) Material strain ;	Qian *et al.* (2019)

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Table B.3 – *continued from previous page*

#	**Paper Title**	**Overview**	**DAQ Technology**	**Sensors Utilised**	**Observed Physical Parameters**	**Reference**
11	Railways Track Characterization Using Ground Penetrating Radar	Characterising substructure layers through GPR; Plasser and theurer EM 120 equipment	(i) GPR via EM 120, TIV;	(i) "Ingegneria de Sistemi" (IDS) antennas;	(i) Longitudinal profile and cross section, geometric profile;	Fontul *et al.* (2016)
12	The issue of uncertainty of visual measurement techniques for long distance measurements based on the example of applying electric traction elements in diagnostics and monitoring	Investigation of visual inspection method for measuring displacements of OHTE.	(i) 2D camera; (ii) 3D laser scanning system;	(i) Image sensor; (ii) ;	(i) Geometric displacement; (ii) Geometric displacement, wear;	Skibicki (2018)
13	Investigating the performance of internet of things based anaerobic digestion of food waste	Focus is on a decentralised performance monitoring of anearobicanaerobic digestion plants, real-time DAQ and analysing	Remote monitoring of DAQ sensor technology;	(i) pH sensor; (ii) Temperature sensor; (iii) Oxidation reduction potential (ORP) sensor;	(i) pH; (ii) Temperature; (iii) Gas levels;	Logan *et al.* (2019)
14	IoT embedded systems network and sensors signal conditioning applied to decentralized photovoltaic plants	Real time performance and condition monitoring of PV plants; Communication through cloud wireless WiFi;	IoT monitoring module;	Temperature sensor; air humidity sensor; wind sensor; irradiance sensor, voltage and current sensor;	Ambient temperature; Humidity; Wind speed; irradiance; voltage; current;	Pereira *et al.* (2019)

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Table B.3 – *continued from previous page*

#	**Paper Title**	**Overview**	**DAQ Technology**	**Sensors Utilised**	**Observed Physical Parameters**	**Reference**
15	Research and application of risk and condition based maintenance task optimization technology in an oil transfer station	Optimising risk and condition based maintenance through remote condition monitoring systems;		(i) displacement sensor; (ii) velocity sensor; (iii) accelerometer; (iv) temperature sensor; (v) pressure sensor; (vi) flow sensor;	Sensor names indicate physical parameters;	Wang and Gao (2012)
16	Towards Distributed IoT/Cloud based Fault Detection and Maintenance in Industrial Automation1	Proposed framework for real-time machine condition monitoring;		Vibration sensors, etc.	Vibration signals;	Xenakis *et al.* (2019)
17	Experimental and numerical study for detection of rail defect	Natural frequency analysis (NFA) to detect rail defects; Finite Element Analysis	(i) National Instruments DAQ module, PCB impact hammer, Triaxial accellerometer-accelerometer, LabView software;	(i) Triaxial accelerometer;	(i) Frequency signals;	Montiel-Varela *et al.* (2017)
18	A Railway Track Geometry Measuring Trolley System Based on Aided INS	Track geometry measuring trolley with integrated inertial navigation system (INS); Modular;	Track geometry measuring trolley's using - (i) Inertial sensors - IMU; (ii) Total stations; (iii) Laser scanner; (iv) cameras; (v) Global navigation satellite system (GNSS) recieversreceivers;	Inertial measuring unit (IMU) gauge sensor, odometer, absolute positioning sensor - GNSS, Total station;		Chen *et al.* (2018)

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Table B.3 – *continued from previous page*

#	Paper Title	Overview	DAQ Technology	Sensors Utilised	Observed Physical Parameters	Reference
19	Modular Fault Diagnosis in Fixed-Block Railway SignalingSignalling Systems	Fault detection in fixed-block signalling systems by inpectinginspecting whole system - railway field components				Durmus *et al.* (2016)
20	Cloud computing for maintenance of railway signalling systems	Takes a look at the data collection and distribution of railway signalling; Shows a maintenance point of view;	DAQ by means of automatic inspection vehicle, manual visual inspections, records of in-service vehicles;	(i) track circuits; (ii) Axel counters;	(i and ii) Track availability; (iii) Track condition;	Morant *et al.* (2012)
21	Wireless Sensor Networks for Condition Monitoring in the Railway Industry - A Survey	Survey's sensor network technology for condition monitoring of railway infrastructure;				Hodge *et al.* (2015)
22	Inspection methods - overview and comparison	NondestructiveNon-destructive methods of monitoring; analyse materials to detect flaws or damage from use; Advantages and disadvantages;	(i) Visual inspections; (ii) Machine vision; (iii) Ultrasonics; (iv) Radiography; (v) Visual optical; (vi) Eddy current; (vii) Liquid penetrant; (viii) Magnetic particles;	(i) none; (ii) Camera; (iii) accelerometers;	(i) Visual observed; (ii) Image acquisition; (iii) Changes in acoustic impedance; (iv) Changes in density; (v) Surface characteristics; (vi) Changes in electrical conductivity; (vii) Surface openings; (viii) Leakage magnetic flux;	Campbell (2013)

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Table B.3 – *continued from previous page*

#	**Paper Title**	**Overview**	**DAQ Technology**	**Sensors Utilised**	**Observed Physical Parameters**	**Reference**
23	Infrared Thermography's Application to Infrastructure Inspections	Review of infrared thermography (IRT) applications to infrastructure inspections;	(i) Infrared thermography;	(i) Thermal sensors;	(i) Thermal infrared radiation;	Garrido *et al.* (2018)
24	The Basic Principles of Mechanised Track Maintenance	Basics of railway infrastructure maintenance and inspection technologies;				Zaayman (2017)
25	Automating condition monitoring of wooden railway sleepers					Yella *et al.* (2009)
26	A real time study on condition monitoring of distribution transformer using thermal imager					Mariprasath and Kirubakaran (2018)

Table B.4: Review findings Part 2

#	**DAQ Technology**	**Implementation Method**	**Operating Speed**	**Monitoring Capabilities**	**Area of Inspection**	**Reference**
1	Optical and Mechanical: (i) total stations; (ii) laser scanner system; (iii) densitometer, (iv) fiberfibre optical sensor. (v) Shape Accel Array (SAA) sensor	Fixed to specific location		Measures the displacement of a railway tunnel during works; (iii) Measures the density of a fluid; (iv) Adaptable to measure strain, temperature and pressure; (v) measures the position in 3D.	Railway tunnels and OHTE.	Vagnoli and Remenyte-Prescott (2018)

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Table B.4 – *continued from previous page*

#	**DAQ Technology**	**Implementation Method**	**Operating Speed**	**Monitoring Capabilities**	**Area of Inspection**	**Reference**
2	(i)Electromagnetic ground penetrating radar (GPR); (ii)UAV imaging; (iii) Seismic refraction; (iv) SASW/MASW	Custom-made cart; UAV	(i) Up to 70 km/h; (ii) Up to 20 km/h, (iii) 1 km per day; (iv) 1 km per day;	(i)Trackbed structure determination, Ballast depth variation, Trackbed condition, Identifying fouling, Intermixing between the ballast and subgrade material, Subgrade material condition, Relative degree of moisture within the ballast; (ii) 3D coordinates, geometry and detection of settlements, soil movement...; (iii) Trackbed structure and subgrade material determination, Modulus of elasticity profile of trackbed and subgrade; (iv) Trackbed structure and subgrade material determination, Shear modulus profile of track bed and subgrade;	Railway embankments; Trackbed structure - formation and ballast	Kovacevic *et al.* (2016)
3	(i) Acoustic emissions; (ii) Imaging based on LED and Cameras; (iii) Ultrasonic data acquisition unit	Physical testing setup (case with computorcomputer)		(iii) Identifies and measures the intensity of concrete sleeper cracks;	Pre-stressed concrete sleepers	Tatarinov *et al.* (2019)

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Table B.4 – *continued from previous page*

#	**DAQ Technology**	**Implementation Method**	**Operating Speed**	**Monitoring Capabilities**	**Area of Inspection**	**Reference**
4	(i) KRAB™ -Light (continuous); (ii) Gauge-checker ROBEL;	Measuring trolley: KRAB™ -Light; measures no-load continuous contact (@250 mm)		(i) Alignment of track, gauge deviation, change of gauge, rail top level, cant, quasi-twist on a short base, longitudinal gradient of the track, track distance; (ii) Deviations of cant and gauge;	Rail track	Šestáková and Gocálová (2014)
5	(i) Electrical resistivity tomographic (ERT) imaging; (ii) Surface wave survey using continuous surface wave (CSW); (iii) Multi-channel analysis of surface wave (MASW); (iv) Light detection and Ranging (LiDAR); (v) Robotic total stations; (vi) Photogrammetry	(i) Permanent installation of sensors; (ii) Rail skate or truck mounted; (iii) Manual (Human) (iv) Ground or SateliteSatellite based vehicle; (v) Portable ground location		(i) Vertical delineation estimates volume of contamination at a site, ground water location and contamination identifyeridentifier, geological mapping; (ii and iii) Measures the formation stiffness; (iv) 3D mapping of natural and manmade environments;	Railway embankments; Trackbed structure - formation and ballast	Gunn *et al.* (2018)
6	(i) Laser-optical system (ii) Virtual measurements from axle-box mounted, bogie mounted and car-body mounted;	(i) Track recording vehicle (TRV); (ii) In service vehicle		Measures the irregularities in of the track geometry in the lateral and cross-level directions	Rail track	De Rosa *et al.* (2019)

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Table B.4 – *continued from previous page*

#	**DAQ Technology**	**Implementation Method**	**Operating Speed**	**Monitoring Capabilities**	**Area of Inspection**	**Reference**
7	(i)On-train automatic Axle-box acceleration measurements; (ii) Eddy current; (iii) Ultrasound measurements; (iv) Hammer test;	(i) Measuring train; (ii and iii) Measuring trolley;	(i) Normal operating speed of measuring train (100 km/h);	(i) Rail defects in proximity to insulated rail joints - surface degradation, cracks in fasteners, damaged insulation layer;	Rail track; Insulated rail joints;	Molodova *et al.* (2016)
8	(i) AK Car - axle box accelerations and ride quality data;	(i) Track inspection vehicle; (ii)Wayside detection system;	(i) 60 km/h	(i) Measures the vibration and force of the wheel/rail interaction, defects in geometry, worn parts, ballast breakage;	Railway turnouts; rail track;	Kaewunruen (2014)
9	(i) Micro electrical mechanical systems (MEMS); (ii) Piezo-electric;	(i) Trackside measurements;		(i) Accelerations and velocity of train, displacement of rail track from acceleration measurements; (ii) Acceleration; (*) measurements of acceleration, velocity or displacement of sleepers, rails, trackbed	Rail track; Trackbed; sleepers;	Milne *et al.* (2016)

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Table B.4 – *continued from previous page*

#	**DAQ Technology**	**Implementation Method**	**Operating Speed**	**Monitoring Capabilities**	**Area of Inspection**	**Reference**
10	(i) Ground penetrating radar (GPR); (ii) Matrix based tactile surface sensors (MBTSS); (iii) Wheel impact load detector (WILD); (iv) Concrete surface straingstrain gauge; (v) "SmartRock";	(i) Hi-rail-based or geometry-car-mounted; (ii) Fixed under sleepers; (iii) ; (iv) Trackside measurements; (v) Fixed in ballast;		(i) Measures the subsurface profile and ballast particle distribution; (ii) Measures ballast pressure distribution beneath sleepers; (iii) Static and dynamic wheel loads from wheel/rail interaction; (iv) Measures in-service flexural demand of concrete sleepers; (v) Measures ballast movement;	Rail track; sleepers; ballast;	Qian *et al.* (2019)
11	(i) GPR via EM 120, TIV;	(i) Track inspection vehicle (TIV) - Plasser and Theurer;	Up to 120 km/h;	(i) Measures the geometric parameters of substructure to identify the length and depth at which intervention is required;	Ballast; formation;	Fontul *et al.* (2016)
12	(i) 2D camera; (ii) 3D laser scanning system;			(i) Measures the displacement of the overhead contact line in a 2D plane; (ii) Measures the displacement of OHTE, measures wear of contact wire;	OHTE;	Skibicki (2018)

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Table B.4 – *continued from previous page*

#	**DAQ Technology**	**Implementation Method**	**Operating Speed**	**Monitoring Capabilities**	**Area of Inspection**	**Reference**
13	Remote monitoring of DAQ sensor technology;	Fixed to equipment		Measures the performance of the Continuously stirred tank reactor (CSTR)	Waste management tank; Not rail related	Logan *et al.* (2019)
14	IoT monitoring module;	Fixed to equipment		Ambient temperature; Humidity; Wind speed; irradiance; voltage; current;	Photovoltaic plants; Not rail related;	Pereira *et al.* (2019)
15				The sensors measure the physical parameters of the oil transfer station;	Oil transfer station; Not rail related;	Wang and Gao (2012)
16		Sensors distributed across the machine;			Machine; Not rail related;	Xenakis *et al.* (2019)
17	(i) National Instruments DAQ module, PCB impact hammer, Triaxial accellerometer-accelerometer, LabView software;			(i) Measures the natural frequencies in the x and y directions;	Rail;	Montiel-Varela *et al.* (2017)
18	Track geometry measuring trolley's using - (i) Inertial sensors - IMU; (ii) Total stations; (iii) Laser scanner; (iv) cameras; (v) Global navigation satellite system (GNSS) recieversreceivers;	(i) Measuring trolley;	Stop-and-go surveying mode - 0.15 km/h; real mobile surveying mode - 2.5 km/h;	3D position coordinates, gauges, an event signals; used to derive all track geometry - gauge, cross level, alignment, longitudinal level, twist, track irregularities in both the horizontal and vertical directions;	Rail;	Chen *et al.* (2018)
19					Railway Signalling;	Durmus *et al.* (2016)

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Table B.4 – *continued from previous page*

#	**DAQ Technology**	**Implementation Method**	**Operating Speed**	**Monitoring Capabilities**	**Area of Inspection**	**Reference**
20	DAQ by means of automatic inspection vehicle, manual visual inspections, records of in-service vehicles;			(i and ii) Track availability; (iii) Track condition;	Railway Signalling;	Morant *et al.* (2012)
21					Rail Infrastructure	Hodge *et al.* (2015)

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Table B.4 – *continued from previous page*

#	DAQ Technology	Implementation Method	Operating Speed	Monitoring Capabilities	Area of Inspection	Reference
22	(i) Visual inspections; (ii) Machine vision; (iii) Ultrasonics; (iv) Radiography; (v) Visual optical; (vi) Eddy current; (vii) Liquid penetrant; (viii) Magnetic particles;			(i) Surface decectsdefects of equipment and infrastructure, or abnormalities, Sometimes used to varifyverify or supplement other inspection techniques; (ii) identify shapes, measurements of distance and ranges, determining orientation of parts, quantifying motion, and detecting surface shading; (iii) Cracks, nonbonds, inclusions or interfaces; (iv) Voids, inclusions, material variations, placement of internal parts; (v) Material variations, cracks, voids, or inclusions; (vi) Cracks, porosity, seams, or folds; (viii) near-surface cracks, voids, inclusions, material or geometry changes;	General materials of structures and equipment	Campbell (2013)
23	(i) Infrared thermography;			(i) Surface and subsurface defects;	General infrastructure inspections	Garrido *et al.* (2018)

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Table B.4 – *continued from previous page*

#	**DAQ Technology**	**Implementation Method**	**Operating Speed**	**Monitoring Capabilities**	**Area of Inspection**	**Reference**
24		Plasser and Theurer - Infrastructure measuring vehicle;			Rail, Ballast, OHTE,	Zaayman (2017)
25						Yella *et al.* (2009)
26						Mariprasath and Kirubakaran (2018)

B.2.2 Identified DAQ Technologies - Description

Table B.5: DAQ Technology description

#	Data Acquisition Technology	Technology Description
1	Acoustic emission	Utilises an array of acoustic sensors installed in locations that are prone to damage. The sensors measure acoustic waves generated by defects or failures. It can measure railway sleeper cracks and the evolution of damage.
2	Axle box measurements	Utilises accelerometers mounted to a trains axle box to measure the displacement of the train due to the track. The capabilities include measuring the absolute displacement of the train wheels to determine vertical and lateral track irregularities, from which the track geometry can be obtained. Track defects such as corrugation, inadequate welds, and squats can be detected. Operations: mounted to the axle box of either an in-service train or a track inspection vehicle.
3	Concrete surface strain gauge	Consist of strain gauges mounted on concrete to measure deformation experienced by the railway sleepers. Operations: sensors are fixed to specific locations on the rails.
4	Corrugation measuring system	Track inspection vehicle-mounted measuring system, utilising optical measuring with cameras and lasers. It measures the existence, severity, and location of rail corrugations.
5	Differential Global Positioning System (DGPS)	An enhanced version of a GPS. It utilises a network of fixed ground-based stations to determine the difference between positions indicated by the GPS satellite.
6	Distance measuring indicator (DMI)	An external sensor which determines distance from the rotation of the train wheels. This measurement can be used to determine the position and distances along the rails. Operations: mounted on an in-service train or a measuring train.
7	Eddy current	Non-destructive testing (NDT) method utilising electromagnetic induction to detect and characterise surface and sub-surface flaws in conductive materials. It detects surface or near-surface rail defects. Operations: technology attached to rail track measuring trolley.
8	Electrical resistivity tomographic (ERT) imaging	This technology creates a sub-surface structural image. The image is obtained from electrical resistivity measurements that are made at the surface, or by electrodes in one or more borehole. This is done by mapping lithological variations and changes in soil moisture content. Operations: permanent installation of sensors in the ground around train tracks.
9	Global navigation satellite system (GNSS)	Any satellite constellation that provides positioning, navigation, and timing services on a global basis. In the rail environment, it supplements other measurements by providing accurate localisation information for each measurement, longitude and latitude. Operations: versatile and incorporated with various devices.

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Table B.5 – *continued from previous page*

#	Data Acquisition Technology	Technology Description
10	Ground penetrating radar (GPR)	Electromagnetic radar used to detect and define the physical boundaries of shallow structures. GPR utilises the transmission of radio energy into subsurfaces and then reads the reflected pulses created by the different materials. It can determine the trackbed structure and condition, ballast depth variation, fouling, intermixing between the ballast and subgrade material, and the relative amount of moisture within the ballast. In short, it records the subsurface profile and ballast particle distribution. Operations: antennas can be attached to rail inspection trains or any other form of trolley/vehicle which can operate along the railway track.
11	Hammer test	Utilises accelerometers which record frequencies generated by an impact hammer. This is used to detect internal rail defects and can also detect ballast defects by utilising the vibrations measurements of exited concrete sleepers. Operations: manual inspection from a skilled worker.
12	Inertial measuring unit (IMU)	The device measures acceleration and rotations through a combination of accelerometers, gyroscopes, and magnetometers. Utilising these sensors, it senses the three-dimensional acceleration and rotations to determine the track position in space. Track profile and alignment deviations can be determined from the positional space map. Operations: the device is mounted to the bogie of a track recording vehicle.
13	Infrared thermography	Detects infrared energy emitted from an object, converts it to apparent temperature, and displays the results as an infrared image. These infrared images are used to detect internal flaws, measures thermo-elastic stress for fatigue crack detection from welded joints. Detects hidden cracks on corroded metal surfaces without removing corrosion layer, voids in concrete blocks, subsurface cracks in welding, and barely visible impact damage. Operations: infrared cameras can be hand-held, mounted to a fixed position or attached to a carrier vehicle (in-service train, measuring train, track trolley, drone, etc.)

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Table B.5 – *continued from previous page*

#	Data Acquisition Technology	Technology Description
14	Laser scanning systems	1D and 2D laser scanning – this technology makes use of the controlled deflection of laser beams, visible or invisible, combined with a laser rangefinder to survey objects. It can measure the irregularities of the track geometry in the lateral and cross-level directions. For OHTE, it measures the geometry by determining the vertical and horizontal displacement. The wear of the overhead contact wire can also be detected. Operations: fitted onto rail inspection vehicles or in-service trains. Similar to 1D and 2D laser scanning systems, LiDAR is a laser scanning system that senses the 3D space. It is for mapping natural and manmade environments. Operations: either ground-based or aerial acquisition; (i) the technology can be stationary and moved manually by the labour force, (ii) attached to ground vehicles (in-service trains, rail inspection vehicles, or other), (iii) and it can be attached to aerial vehicles such as UAVs.
15	Matrix based tactile surface sensors (MBTSS)	In general, it can be described as an "electronic skin" consisting of several sensors which record and interprets pressure distribution and magnitude between any contacting or mating surfaces. Operations: the sensors are placed in fixed locations between the ballasts just under the sleepers to capture data at real-time.
16	Micro electrical mechanical systems (MEMS)	Utilises a microprocessor to process data and microsensors to interact with surroundings and acquire data. Common MEMS sensors include accelormetersaccelerometers, gyroscopes, pressure sensors, and mangneticmagnetic field sensors.
17	Monochromatic line scan cameras	Consist of high-resolution cameras, mounted to the bogie frame of a track inspection vehicle, that record images. Images are geo-tagged by a DGPS. This technology can be used to detect external defects the rails might have.
18	Optical gauge measuring system (OGMS)	Utilises a set of lasers, mirrors, and cameras mounted to a measuring frame of a rail inspection vehicle. The system measures the horizontal displacement to the left and right rails from the bogie.
19	Piezo electrical systems	Utilise piezoelectric sensors to measure changes in pressure, temperature, acceleration, strain or force by converting them to an electrical charge.
20	Radiography	Utilises x-rays and digital radiography equipment. This technology is used to monitor voids, inclusions, material variations, placement of internal parts. It can also detect rail surface, sub-surface, and internal defects in either the rail track welds, switchblades, or fish bolts.
21	Seismic refraction tomography and surface wave analysis	Utilises seismographs and geophones, in an array and an energy source to characterise the subsurface geologic condition and structure. Capabilities include trackbed structure and subgrade material determination as well as the modulus of elasticity profile of trackbed and subgrade. Operations: permanent sensor installations in the ground surrounding the rail track.

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Table B.5 – *continued from previous page*

#	**Data Acquisition Technology**	**Technology Description**
22	"SmartRock"	A wireless sensor device covered in a shell of similar shape and size to that of a ballast particle. The device consists of a tri-axial gyroscope, accelerometer, and a magnetometer. It can measure the ballast particles movements as well as the contact forces between them in real-time. Operations: ballast particles are replaced with multiple devices.
23	Total station / Robotic Total Station	An electronic/optical instrument used for surveying. It consists of an electronic transit theodolite integrated with electronic distance measuring. It can measure vertical as well as horizontal angles, and also the slope distance from the instrument to a particular point. The device has an onboardon-board computer which can perform triangulation calculations based on the data collected. Operations: regular total stations require at least two people to operate whereas the robotic total station only requires one person; can either be manually transported or fitted to a rail-trolley measuring cart.
24	Ultrasound	Utilises high-frequency sound energy to perform examinations and make measurements. It can detect rail defects in proximity to insulated rail joints - surface degradation, cracks in fasteners, damaged insulation layer. Identifies and measures the severity of internal rail defects such as cracks, defective welds, rail surface defects, etc. Operations: versatile means of implementation, which include hand-held devices, attached to rail track trolleys, in-service trains, and rail inspection vehicles.
25	Visual camera imaging	Using visual images obtained by a high-resolution camera in conjunction with video analysis software to measure and inspect objects. Capabilities include measuring track geometric parameters. Combined with a UAV measures the 3D coordinates, geometry, and soil movement of the trackbed structure. Measures OHTE displacement in two-dimensions. Views measured contact wire defects to eliminate or establish the cause of the error. It is also used to detects defects or abnormalities of infrastructure and equipment. Operations: manual inspection crews can use image recording devices or device can be attached to rail inspection vehicles (trains and trolley's), drones, and stationary infrastructures.
26	Wheel impact load detector (WILD)	A hardened electronic device which collects data from track mounted strain gauges exited by train wheel impact loads. The device measures the dynamic loads between the train wheels and rails. The measurements can be used to detect irregularities of rails, sleepers, and ballast. Operations: sensors are fixed to specific locations on the tracks.

B.2.3 Identified DAQ Technologies - Monitoring Capabilities

Table B.6: DAQ Technologies monitoring capabilities

Infrastructure Component	**Monitoring Aspect**	**Capable Technology**	**Reference**
Rails and joints	Wear	Axle box measurements	Kaewunruen (2014); Molodova *et al.* (2016); Zaayman (2017); De Rosa *et al.* (2019)
		Eddy current	Campbell (2013); Zaayman (2017); Molodova *et al.* (2016)
		Corrugation measuring system	Zaayman (2017)
	Surface cracks	Ultrasound	Campbell (2013); Molodova *et al.* (2016); Zaayman (2017)
		Eddy current	Campbell (2013); Molodova *et al.* (2016); Zaayman (2017)
		Infrared thermography	Garrido *et al.* (2018)
		Monochromatic line scan cameras	Zaayman (2017)
	Internal cracks	Ultrasound	Campbell (2013); Molodova *et al.* (2016); Zaayman (2017)
		Eddy current	Campbell (2013); Molodova *et al.* (2016); Zaayman (2017)
		Hammer test	Molodova *et al.* (2016); Montiel-Varela *et al.* (2017)
		Infrared thermography	Garrido *et al.* (2018)
	Damage	Infrared thermography	Garrido *et al.* (2018)
		Visual camera imaging	Campbell (2013); Zaayman (2017)
	Breakage	Visual camera imaging	Campbell (2013); Zaayman (2017)

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Table B.6 – *continued from previous page*

Infrastructure Component	**Monitoring Aspect**	**Capable Technology**	**Reference**
	Geometry	1D and 2D Laser scanning systems	De Rosa *et al.* (2019)
		Visual camera imaging	Chen *et al.* (2018)
		Axle box measurements	Kaewunruen (2014); Molodova *et al.* (2016); Zaayman (2017); De Rosa *et al.* (2019)
		Inertial measuring unit (IMU)	Zaayman (2017); Chen *et al.* (2018)
		Optical gauge measuring system (OGMS)	Zaayman (2017)
		Micro electrical mechanical systems (MEMS)	Milne *et al.* (2016); Vagnoli and Remenyte-Prescott (2018)
		Piezo electrical systems	Milne *et al.* (2016)
Rail fasteners	Damaged components	Visual camera imaging	Campbell (2013)
	Missing components	Visual camera imaging	Campbell (2013)
Sleepers	Flexural demand	Concrete surface strain gauges	Qian *et al.* (2019)
	Internal defects	Acoustic emissions	Tatarinov *et al.* (2019)
		Infrared thermography	Garrido *et al.* (2018)
		Hammer test	Molodova *et al.* (2016); Montiel-Varela *et al.* (2017)
Trackbed	Geometry	Visual camera imaging	Kovacevic *et al.* (2016)
		Ground penetrating radar (GPR)	Kovacevic *et al.* (2016); Fontul *et al.* (2016); Qian *et al.* (2019)
		Seismic refraction	Kovacevic *et al.* (2016)
		Surface wave analysis	Kovacevic *et al.* (2016)
		Electrical resistivity tomographic (ERT) imaging	Gunn *et al.* (2018)
		Matrix based tactile surface sensors (MBTSS)	Qian *et al.* (2019)

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Table B.6 – *continued from previous page*

Infrastructure Component	**Monitoring Aspect**	**Capable Technology**	**Reference**
		SmartRock	Qian *et al.* (2019)
Surface Drains	Obstructions	Visual camera imaging	Campbell (2013)
OHTE	Geometry	1D and 2D Laser scanning systems	Zaayman (2017); Chen *et al.* (2018)
		Visual camera imaging	Skibicki (2018)
	Wear	Visual camera imaging	Zaayman (2017); Skibicki (2018)
	Missing components	Visual camera imaging	Zaayman (2017)
Signalling	Damaged components	Infrared thermography	Garrido *et al.* (2018)
		Visual camera imaging	Campbell (2013)
	Missing components	Visual camera imaging	Campbell (2013)
General	Ground and structural displacement	Robotic total stations	Chen *et al.* (2018); Gunn *et al.* (2018); Vagnoli and Remenyte-Prescott (2018)
	Irregularities of rails, sleepers, and ballast	Wheel impact load detector (WILD)	Qian *et al.* (2019)
	Positioning coordinates	Global navigation satelitesatellite system (GNSS)	Chen *et al.* (2018)
		Differential global positioning system (DGPS)	Zaayman (2017)
	Track distance	Distance measuring indicator (DMI)	Zaayman (2017)

B.2.4 Carriers and DAQ Attachments

Table B.7: DAQ Technology attachments for designated carries

Carriers	**DAQ Technology Attachments**	**Reference**
In-service train	Axle box measurements	Molodova *et al.* (2016); De Rosa *et al.* (2019)
	Visual camera imaging	Zaayman (2017)
Rail inspection vehicle	Axle box measurements	Kaewunruen (2014); Molodova *et al.* (2016); Zaayman (2017); De Rosa *et al.* (2019)
	Laser scanning systems	Zaayman (2017); De Rosa *et al.* (2019)
	Ground penetrating radar (GPR)	Fontul *et al.* (2016); Zaayman (2017); Qian *et al.* (2019)
	Visual camera imaging	Zaayman (2017)
	Corrugation measuring system	Zaayman (2017)
	Inertial measuring unit (IMU)	Zaayman (2017)
	Thermal imaging	Zaayman (2017)
	Ultrasound	Zaayman (2017)
	Optical measuring system	Zaayman (2017)
	Monochromatic line scan camera	Zaayman (2017)
	Distance measuring indicator (DMI)	Zaayman (2017)
Measuring Trolleys	Ground penetrating radar (GPR)	Kovacevic *et al.* (2016); Qian *et al.* (2019)
	Ultrasound	Molodova *et al.* (2016); Zaayman (2017)
	Robotic total station	Chen *et al.* (2018)
	Laser scanning systems	Chen *et al.* (2018)
	Inertial measuring unit (IMU)	Chen *et al.* (2018)
	Eddy current	Molodova *et al.* (2016); Zaayman (2017)
UAVs	Visual camera imaging	Kovacevic *et al.* (2016)
	Laser scanning systems	Tatarinov *et al.* (2019)
	Thermal imaging	Garrido *et al.* (2018)

Appendix C

Survey Transcripts

This appendix provides the detailed responses of the survey conducted in Chapter 4.

C.1 Detailed First Survey Responses

Section 4.3 is summarised from the information portrayed in this section. This questionnaire included two initial sets of questions. The first being the letter of consent that a participant could either accept or reject, the latter which would then automatically trigger the participant to exit the *SurveyMonkey* questionnaire. The second set of questions is to determine the background of the participants (i.e. job title, expertise, and geographical region).

Q1 – As the participant I hereby select the following option...

From the 14 experts invited to participate in the survey, a total of 8 (57%) participants responded positive.

Q2 – Please provide a short description of your background in the railway industry under the following headings (Do not include any information that can identify you the participant as an individual, e.g. name, numbers, contact details, name of your company/employer, etc.)

Table C.1 represents the results of the participants background information and expertise.

Table C.1: Participants background

#	Job Title	Experience and Expertise	Country Based In
1	Maintenance manager	Maintenance management	South Africa
2	Researcher	5 Years	Austria
3	Train systems engineer	Testing and validation of rolling stock, analysing and proposing ways of improving the reliability of the rolling stock including wear of parts due to the poor condition of wayside equipment. Advising the railway operator on improvements necessary on their wayside infrastructure in order to improve train throughput and reduce risk of harm to the rolling stock.	South Africa
4	Consultant	EU-financed and nationally financed projects, mainly concerning railway restructuring according to EU law	Austria
5	Associate professor	Research in asset management and asset maintenance	The Netherlands
6	Associate professor	Railway vehicles maintenance and operation	Slovakia
7	University lecturer	Railway engineering and track management	Slovakia
8	University lecturer	Railway transport, 1x 7.FP, 3x H2020 projects, 12 years on university	Slovakia

The rest of this appendix addresses the main three parts of the questionnaire (i) infrastructure maintenance, (ii) DAQ technology validation, and the (iii) adoption of new technology.

C.1.1 Part 1: Infrastructure Maintenance

This section is aimed at determining the criticality rankings of the infrastructure components included in this study and what factors influence their criticality. As an introduction into the data acquisition technology for part 2 of the questionnaire, the SMEs are asked how they would rate the effectiveness of current technologies.

Q1.1 – How critical do you think railway infrastructure inspection and condition monitoring is in terms of preventing failures?

Table C.2 presents the response distribution for Q1.1.

Table C.2: Q1.1

Not	**Slightly**	**Moderately**	**Very**	**Extremely**
-	-	-	25%	75%

Q1.2 – A failure of the following infrastructure components is detrimental to the successful operations of a railway. Rate the severity of the effect that specific component failures will have on operations.

Table C.3 presents the response distribution for Q1.2.

Table C.3: Q1.2

Component	**Not**	**Slightly**	**Moderately**	**Very**	**Extremely**
Rails	-	-	-	-	100%
OHTE	-	-	-	28.6%	71.4%
Signalling	-	-	-	28.6%	71.4%
Formation	-	-	28.6%	42.8%	28.6%
Sleepers	-	-	42.8%	28.6%	28.6%
Ballast	-	-	42.8%	42.8%	14.3%
Surface drains	-	-	57%	28.6%	14.3%

Q1.3.1 – Based on the following reasons how have they impacted your severity decision in the previous question?

Table C.4 presents the response distribution for Q1.3.1.

Table C.4: Q1.3

Component	**Not**	**Slightly**	**Moderately**	**Very**	**Extremely**
Safety	-	-	-	14.3%	85.7%
Downtime	-	14.3%	14.3%	42.8%	28.6%
Cost	-	14.3%	14.3%	57%	14.3%
Frequency	-	14.3%	28.6%	42.8%	14.3%
Complexity	-	14.3%	14.3%	71.4%	-
Labor force	-	28.6%	28.6%	42.8%	-

Q1.3.2 – What other considerations, not mentioned, need to be accounted for when determining the severity of failures?

The SMEs highlighted a few other factors which could affect the criticality of a specific infrastructure component failure. These include:

- Halted operations leads to a loss of customers which leads to a loss of revenue. Therefore, halted operations ties indirectly in with the cost associated with a failure.
- Impact the failure has on the service. For example, failure of the OHTE and rails cause trains to stop operating completely, often with rolling stock stuck in the section. Failure of the formation, surface drains and signalling normally means that trains can continue to operate, but at a significantly reduced speed. In the short term this leads to suboptimal utilisation of rolling stock and on-board staff, since journeys take significantly longer and more resources are required to move the same number of people/goods. Strict adherence to operational rules are necessary to prevent major safety incidents during the abnormal working. Failure/degradation of sleepers and ballast have a negative effect on the lifetime of both rolling stock and other infrastructure.
- Liability issues under costs as well as the legal matters on the subject.
- Locality of failures can also determine the severity depending on the traffic associated or affected by that particular location, the soil conditions of a particular part of track can increase the downtime.
- "Consequential damage", from congested schedules can be affected in a snowball effect originating from any small failure. Thus, the location of a failure can affect the severity.

Q1.4 – What are some of the most significant condition monitoring obstacles you have experienced or know of, regarding the following infrastructure components? (Briefly describe where applicable or write N/a)

The SMEs have experience the following obstacle in their careers for each respective infrastructure component:

- **Rails:** wear and tear prohibiting the ability to measure correctly, broken rails and internal crack gradually lead to sudden breaks, difficult to monitor remotely – requires physically travelling over the track (usually with a rail bound vehicle), temperature differences, and insufficient time due to occupancy rate (traffic).

- **Sleepers:** damaged sleepers, internal damages, failure modes not visible to the eye – such as degraded condition of concrete reinforcements, insufficient time due to occupancy rate (traffic), only visual methods used i operational diagnostics.
- **Ballast:** degradation, accumulation of fines and dirt, uncertain if modern equipment can measure the size and wear of all the ballast stones such as in the old manual methods of doing so, insufficient time due to occupancy rate (traffic), it does not form part of the regular diagnostic system – only inspected before or after work.
- **Formation:** changes in the geometry, multiple layers and being buried below the ballast poses problems, insufficient time due to occupancy rates, it does not form part of the regular diagnostic system – only inspected before or after work.
- **OHTE:** accurate measuring equipment, damage to the catenary wire, loss of contact, trap of wire beneath pantograph, in South Africa the theft is to such an extent that priority lies with getting the OHTE back in service rather that ensuring it's in good condition and that it conforms to the original design, safety, and complexity of track changes (e.g. 50 hectares, 43 distribution tracks, 14 arrival tracks and 12 preparatory lines on one location).
- **Surface drains:** overgrown vegetation not allowing for access to the drains, non-drained water accumulation on the superstructure and substructure, often connected with municipal storm water drains or clogged by the encroachment of settlements into the railway reserve, extent fo blockage is usually realised only after major storm and by then has caused signifiant damage to the rest of the per-way too, and only visual methods are used in operation diagnostics.
- **Signalling:** no proper defined technology to measure, signalling damage, poor maintenance of existing equipment, high prevalence of vandalism/sabotage, as a safety system there is usually a lot of redundancy (to improve both availability and safety) railways exploit this by waiting until it is totally failed before fixing it in stead of using the condition monitoring to ensure 100% availability, and lastly safety in overcrowded tracks.

Q1.5 – How effective do you think the current technology used for inspections and condition monitoring of an infrastructure is?

Table C.5 presents the response distribution for Q1.5. The responses are wide spread. From these responses it is seen that the SMEs still feel that the current technology and equipment used for the monitoring of infrastructure still requires improvements.

Table C.5: Q1.5

Not	Slightly	Moderately	Very	Extremely
-	12.5%	37.5%	37.5%	12.5%

C.1.2 Part 2: DAQ Technologies Validation

This section is aimed at validating the data acquisition technologies and their monitoring capabilities identified from Chapter 2.

Q2.1 – The data acquisition technologies identified through a structured review have a variety of measuring/monitoring capabilities which include internal and external defects, geometric defects, positioning data, etc. Indicate if you agree or disagree with the identified technologies/methods and their capabilities of measuring specific railway infrastructure components.

The detailed responses from this question is not provided here as the is similar to Table 4.2. The SMEs were asked to validate each of the identified data acquisition technologies mapped to the failure methods or defect it is capable of monitoring (combinations are based on the findings from the literature in Chapter 2). Specific combination are omitted if the majority of the responses disagree with that particular mapping. Thus, Table 4.2 represents the final mapping of the technologies and their capabilities included in this study.

Q2.2 – Based on your expertise, do you think that their are specific data acquisition technologies, used to inspect and monitor railway infrastructures, that are not included in this study? (Mention addition data acquisition technologies that require exploration in your opinion)

The general consensus from the participants were that the data acquisition technologies included in this study are satisfactory. One expert suggested closer investigation into infrared imaging technology to monitor overhead traction equipment and another suggested the non-destructive testing method of Barkhausen noise for inspecting rails.

C.1.3 Part 3: Adoption of New Technologies

This section is aimed at exploring the factors that influence the successful adoption of new and emerging technologies in the railway industry.

Q3.1 – A method of automating or reducing the amount of labour required to acquire condition data is by combining the data acquisition technology with specific carriers. What type of carriers are used in your railway environment? (In-service train, rail inspection vehicle, rail track trolley, drones or other.)

Table C.6: Q3.1

	Inspection Vehicle	Measuring Trolley	In-service Train	UAV
Carrier	100%	62.5%	50%	12.5%

Q3.2 – What is your opinion of the following statement,"A labour force is still critical for inspecting and analysing the condition of infrastructures and can not be completely replaced, even with the current advancements in technologies"?

The experts have acknowledged that due to safety, downtime, effectivity and costs reasons the labour forces have been seeing reductions. However, the general idea amongst the railway experts are that a labour force is still an important aspect in the rail environment. Furthermore, they highlighted that there is actually a growing need for highly skilled workers not to perform the physical monitoring but rather down the line for interpreting the collected condition data and turning it into usable information, including the prioritizing of defects and developing a preventative and corrective maintenance regime (including the funds to do the work).

Q3.2 – Does your railway company or countries rail operator(s) make use of predictive maintenance?

Only one of the expert panel indicated that he/she has no knowledge of predictive maintenance being implemented by their railway company or countries rail operators. Whereas, the others have stated that some form of predictive maintenance is being implemented.

Q3.4 – Based on your opinion, what are the key characteristics and components required for implementing a predictive maintenance strategy in the railway industry?

The SMEs have identified the following as components of importance when implementing a predictive maintenance strategy:

- Availability of methods (labour or programs) to analyse and quantify the data received and translate that into actions.
- Regular inspection and data analysis.
- Systematic inspection and data management.
- Application of the performance data along with the life cycle costing for maintenance planning (predictive maintenance)
- Willingness to buy into the 21st century solutions and promptly act on deficiencies highlighted by monitoring equipment.
- Comprehensive automated condition data collection combined with cost data in a structure database system.
- Ability to purposefully model expected behaviour and degradation.
- Proper instrumentation and skilled workers.
- Compatible format of diagnosis data of track and connection to diagnostic data of vehicles.
- Optimization of measurement intervals or replace measurements by continuous monitoring.
- (Semi) automated diagnostic data evaluation system. Algorithmising and automation of the design of maintenance activities as a supportive decision-making tool.
- Adequate financing of maintenance.
- Investing, standardization, data collection, application of A.I.

Q3.5 – Based on the research conducted, the following factors are identified, which *promotes* the adoption of new and emerging technologies for maintenance activities, more specifically, predictive maintenance; (i) reduced downtime, (ii) reduce repair cost by eliminating unneeded replacements, (iii) extend asset life, and (iv) improve customer satisfaction. **What other factors do you think *promotes* the adoption of technologies?**

- High unemployment rates in a country. Leads some to believe that adopting technologies will lead to more jobs being lost.
- Safety and LCC.

- Ability for salesperson to reach out to the right people in a railway company who believes in modern solutions.
- Ability to source funds to buy, operate, and maintain monitoring equipment.
- Improve investment decisions by basing them of life-cycle costing. (know what the item costs at purchase, when maintained, and when disposed of.
- The possibility of reductions of out-of-service-time by clustering maintenance and even overhaul. Better understanding of assets and their models.
- Labour force shortage.
- Improving safety of operations.
- Reduction in mistakes in maintenance.

Q3.6 – Based on the research conducted, the following factors are identified which *prohibits or slows* the adoption of new and emerging technologies for maintenance-related activities, more specifically predictive maintenance; (i) technology, (ii) privacy and confidentiality, (iii) security, (iv) intellectual property, (v) different skills required by the labour force, and (vi) public policy. **What other *barriers* do you think prohibits or slows the adoption of technologies?**

- Politics and the adoption of new technologies. (Most rail operators funded by government.)
- Lack of knowledge – lack of training
- Lack of awareness about the benefits of predictive maintenance on the long-term cost reduction (lower LCC).
- Decision makers, institutional and management obstacles, lack willingness to perform long-term planning for next generations.
- Being stuck in the 20th century way of doing things by hand, mostly due to a workforce (managerial and labour) that lacks engineering skills and basic know-how (basically because people are being taken off the street and expected to know how to maintain a railway).
- Money (or rather the inability to realise the savings that can be realised by following a more efficient maintenance regime).
- Quality of data management and sense of ownership of labour force.
- Government.

- Inability to select technology because too many new technologies arise (too) fast.
- Inability to convert data into information for informed decision making.
- Lack of money
- Lack of money for new technologies.
- Apprehension and distrustfulness about changing of long term used "conventional" technologies.
- Investments.

Q3.7 – What strategy(ies) would you use to ensure the successful adoption of emerging data acquisition technologies?

- Need to highlight benefits of technology in terms of time and cost.
- Before all, work on awareness, training, and knowledge on the long-term advantage of predictive maintenance. Showing the experiences from different countries that are already applying predictive maintenance and the benefits of it. Selecting cost effective data acquisition technologies that suit best to the country – especially technologies that enable systematic data acquisition.
- Approaching all aspects of monitoring as a service. Private companies should install the monitoring equipment on the wayside or rail vehicles and sell the information (not data, information) to the railway infrastructure manager.
- Lobby up to the highest level in government that the focus should shift from building new things to rehabilitating and maintaining the infrastructure that already exists.
- Infrastructure maintenance is seen as operational expenditure (OPEX, for which there is no budget) instead of capital expenditure (CAPEX, for which there is a huge budget, but where periodical activities, like maintenance of track and OHTE is excluded).
- Involving all stakeholders; trying to identify main obstacles during implementation; finding consensus solutions for overcoming the obstacles.
- (i) Start with the possibilities to actually perform maintenance; (ii) outline the underlying decisions and decision making mechanisms; (iii) identify the information content required for that; (iv) determine the best option to gather data for that with the appropriate accuracy (e.g. modelling, simulation, historical data, or measurements) and (v) then effectively and efficiently

obtain that data (and not the data where one doesn't know what to do with it)

- To quantify the impact of using the new diagnostics and maintenance system - in the cost savings of track structure and vehicle maintenance and downtimes. Evaluate the impact on simplification of work and communication processes of managers and executives.
- International (EU) standardization, interoperability of railway systems in EU.

C.2 Framework Validation Questionnaire

The questionnaire is based on that of Borenstein (1998), and it includes questions that incorporate aspects from both face validation and user assessments.

Face validation questions:

Question 1: Considering the RITSS framework developed, what is your opinion on the potential of it being utilised by railway operators for the selection of data acquisition (DAQ) technologies in support of railway infrastructure predictive maintenance?

Question 2: In your opinion which are the strong points of the RITSS framework?

Question 3: The weak points?

Question 4: Even though the RITSS framework is focussed on railway infrastructure maintenance and railway operators, do you think it is possible (with minor adjustments) to apply the framework methodology to other industries? Please justify your answer.

Question 5: Please comment on how you perceived the approach followed for the different stages of the RITSS framework (tick the appropriate response category):

Aspect	Poor	Fair	Average	Good	Very Good
Asset scope definition (Stage 1.1)					
Technology identification (Stage 1.2)					
Mapping of the technologies and monitoring parameters (failure pathways) (Stage 1.3)					
Criteria development (Stage 2.1)					
Criteria weighting (Stage 2.2)					
Technology prioritisation (Stage 2.3)					
Acquisition mode guide (Stage 3)					

Question 6: Based on your previous comments, how do you think it is possible to improve the RITSS framework?

User assessment questions:

Question 7: Please comment on how you perceived the potential user's experience if you were to apply the RITSS framework? (tick the appropriate response category):

Aspect	Poor	Fair	Average	Good	Very Good
Structured in logical sense					
Simple to follow and understand					
Terminology used					

Question 8: Would you apply the methodology/RITSS framework to address any future complex decision-making problems incorporating the selection of new and/or emerging technologies in the railway sector? Please justify your response:

Question 9: Do you feel that the output of the RITSS framework would be useful for decision-makers? Provide a reason(s) for your answer:

Appendix D

Technology Evaluation

This appendix presents the detailed calculations as part of the technology evaluation stage of the RITSS framework (Chapter 6).

D.1 Evaluation Criteria

The criteria rating scale and scores achieved by each technology is presented in this appendix.

D.1.1 Criteria Rating Scale

Table D.1: Criteria rating scale

Criteria	**Measure**	**Reasoning**	**Rate**
Accuracy	Qualitative	Extremely high	5
		High	4
		Moderate	3
		Low	2
		Extremely low	1
Cost	Qualitative	Extremely low	5
		Low	4
		Moderate	3
		High	2
		Extremely high	1
External factors	Robustness (reliability and repeatability)	Not affected	5
		Affected by one factor	4
		Affected by two factors	3
		Affected by three factors	2
		Affected by four or more	1
Continuous monitoring	Continuity of data collection	Real-time	5
		Real-time (travelling)	4
		On demand (after travelling)	3
		Inspection (during)	2

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Table D.1 – *continued from previous page*

Criteria	**Measure**	**Reasoning**	**Rate**
		Inspection (after)	1
Maturity of technology	Technology readiness level	TRL 9 <	5
		TRL 7-8	4
		TRL 5-6	3
		TRL 3-4	2
		TRL 1-2	1
Traffic interference	Speed of measuring or obstructing traffic	No interference	5
		> 100 km/h	4
		100 km/h – 70 km/h	3
		70 km/h >	2
		Stationary	1
Early failure prediction	Failure pathways	Future failure predictable	5
		-	4
		Immanent failure predictable	3
		-	2
		Identifies failure	1
Operator skills	Special training or knowledge	Up-skilling required	5
		-	4
		Same skill level required	3
		-	2
		Lower skill level required	1
Security	Physical and data protection	Data and technology protected	5
		-	4
		Either one protected	3
		-	2
		Data and technology unprotected	1
Safety	Potential risk to people/operator	People and operator no risk	5
		One no risk, other little risk	4
		People and operator little risk	3
		One high risk, other little risk	2
		People and operator high risk	1
Job uncertainty	Loss/Creation	Job requires less people	5
		-	4
		Unchanged	3
		-	2
		Job requires more people	1
Environmental	Noise (dB)	< 70 dB	5
		-	4
		70 dB – 85 dB	3
		-	2
		> 85 dB	1
Support	After sales technical support	Training and continued support	5
		-	4
		Operator training or support	3
		-	2
		No after sales support	1

D.1.2 DAQ Technology Criteria Ratings

Table D.2: DAQ Technology rating scores

ID	Technology	Carrier	Evaluation Criteria (CR)												
			11	**12**	**13**	**14**	**15**	**21**	**22**	**23**	**24**	**31**	**32**	**41**	**42**
1	Acoustic emissions	Fixed	3	4	3	2	4	1	5	3	1	4	3	5	3
2a	Axle box measurements	In-service train	3	3	4	4	5	5	5	3	3	5	5	1	3
2b		Rail inspection vehicle	4	1	4	4	5	4	5	5	3	4	5	1	5
3	Concrete surface strain gauge	Fixed	5	5	2	1	5	5	3	1	1	5	3	5	1
4	Corrugation measuring system	Rail inspection vehicle	4	1	4	4	5	5	5	5	3	4	5	1	5
5	Differential global positioning system (DGPS)	(Supplement)	-	-	-	-	-	-	-	-	-	-	-	5	-
6	Distance measuring indicator (DMI)	Rail inspection vehicle (Supplement)	-	-	-	-	-	-	-	-	-	-	-	-	
7a	Eddy current	Operator	5	4	2	1	5	1	3	3	1	4	3	5	3
7b		Measuring trolley	5	3	2	2	5	2	3	5	1	4	3	5	3
8	Electrical resistivity tomographic (ERT) imaging	Fixed	4	2	4	1	5	1	1	5	1	3	3	5	3
9	Global navigation satellite system (GNSS)	(Supplement)	-	-	-	-	-	-	-	-	-	-	-	-	-
10a	Ground penetrating radar (GPR)	Rail inspection vehicle	4	1	4	1	5	4	5	5	3	5	5	1	5
10b		Measuring trolley	5	2	3	2	5	2	5	3	1	4	3	5	3
11	Hammer test	Operator	4	5	2	1	5	1	1	3	1	4	3	5	1
12a	Inertial measuring unit (IMU)	Rail inspection vehicle	4	1	4	4	5	4	1	5	3	5	5	1	5
12b		Measuring trolley	5	3	2	1	4	2	1	3	1	4	3	5	3
13a	Infrared imaging	Operator	3	3	2	2	5	1	5	3	1	5	3	5	3
13b		Rail inspection vehicle	5	1	3	4	5	4	5	5	3	5	5	1	5
13c		UAV	4	2	3	4	5	5	5	5	3	4	5	3	5

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Table D.2 – *continued from previous page*

ID	Technology	Carrier	Evaluation Criteria (CR)												
			11	**12**	**13**	**14**	**15**	**21**	**22**	**23**	**24**	**31**	**32**	**41**	**42**
14a	Laser scanning systems	Rail inspection vehicle	4	1	4	4	5	4	1	5	3	5	5	1	5
14b		UAV	4	2	3	4	5	5	1	5	3	4	5	3	5
15	Matrix based tactile surface sensors (MBTSS)	Fixed	3	3	2	5	4	5	3	3	5	5	5	5	3
16	Micro electrical mechanical systems (MEMS)	Fixed	4	5	4	5	5	5	3	3	1	5	3	5	1
17	Monochromatic line scan camera	Rail inspection vehicle	4	1	4	4	5	4	1	5	3	5	5	1	5
18	Optical gauge measuring system (OGMS)	Rail inspection vehicle	4	1	4	4	5	4	1	5	3	5	5	1	5
19	Piezo electrical systems	Fixed	4	4	2	5	5	5	3	3	1	5	3	5	1
20	Radiography	-		-	-	-	-	-	-	-	-	-	-	-	-
21	Seismic refraction tomography and surface wave	Fixed	4	2	4	1	5	1	1	5	1	5	3	5	5
22	"SmartRock"	Fixed	4	3	4	5	3	5	5	3	5	5	5	5	3
23a	Total station	Operator	5	2	4	2	5	5	1	3	1	4	3	5	3
23b		Measuring trolley	5	2	3	2	5	2	1	3	1	4	3	5	3
24a	Ultrasound	Rail inspection vehicle	4	1	4	4	5	4	3	5	3	5	5	1	5
24b		Measuring trolley	5	2	3	2	5	2	3	3	1	4	3	5	3
25a	Visual camera imaging	In-service train	4	3	4	4	5	5	1	3	3	5	5	1	3
25b		Rail inspection vehicle	4	1	4	4	5	4	1	5	3	5	5	1	5
25c		UAV	4	2	3	4	5	5	1	5	3	4	5	3	5
26	Wheel impact load detector (WILD)	Fixed	3	3	4	5	5	5	3	3	1	5	3	5	3

D.2 Criteria Weight Calculations

This appendix contains the tables that form part of the criteria weigh calculations that is presented in Chapter 6, Stage 2.2 of the RITSS Framework.

D.2.1 Pairwise Responses

Table D.3: Pairwise expert judgments

	Importance Scale																	
Crit 1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Crit 2
CR1			1			1	2		1		1		1					CR2
CR1					2	1	1	1				1		1				CR3
CR1			3		1	1	1									1		CR4
CR2			1					1		2	3							CR3
CR2			1		2		2	1			1							CR4
CR3			1	1	1		1	2							1			CR4
CR11		1	1	1	1		2		1									CR12
CR11		1					2	1					2			1		CR13
CR11							3	2		1					1			CR14
CR11			1				1	1	1	1			1		1			CR15
CR12	1				1						2		1		1	1		CR13
CR12					1		1			2	1			2				CR14
CR12					1					1	1		1		2		1	CR15
CR13			1				1	1	1		3							CR14
CR13					1		1	1		2	1	1						CR15
CR14							2		1	1	2				1			CR15
CR21			1	1						2	2				1			CR22
CR21							1	2		1	1	1		1				CR23
CR21				2			1			1						1	2	CR24
CR22					1		1	2	1			1	1					CR23
CR22			1			2			2						1	1		CR24
CR23					2					2	1				2			CR24
CR31		2	1	1	1			1	1									CR32
CR41					2			1	1		1			1			1	CR42

D.2.2 Primary Criteria Matrices

Table D.4: Primary criteria pairwise matrix

Criteria	**CR1**	**CR2**	**CR3**	**CR4**
CR1	1	2.825	3.190	5.016
CR2	0.354	1	0.364	4.333
CR3	0.313	2.746	1	4.270
CR4	0.199	0.231	0.234	1

Table D.5: Primary criteria normalised matrix

Criteria	**CR1**	**CR2**	**CR3**	**CR4**
CR1	0.536	0.415	0.666	0.343
CR2	0.190	0.147	0.076	0.296
CR3	0.168	0.404	0.209	0.292
CR4	0.107	0.034	0.049	0.068

D.2.3 Subcriteria Matrices

Table D.6: Subcriteria pairwise super matrix

Criteria	**CR11**	**CR12**	**CR13**	**CR14**	**CR15**	**CR21**	**CR22**	**CR23**	**CR24**	**CR31**	**CR32**	**CR41**	**CR42**
CR11	1	5.048	2.159	2.746	0.477								
CR12	0.198	1	0.276	0.307	0.197								
CR13	0.463	3.619	1	2.143	0.450								
CR14	0.364	3.254	0.467	1	0.362								
CR15	2.095	5.063	2.222	2.762	1								
CR21						1	0.341	0.382	0.326				
CR22						2.937	1	2.476	2.238				
CR23						2.619	0.404	1	0.299				
CR24						3.063	0.447	3.349	1				
CR31										1	5.429		
CR32										0.184	1		
CR41												1	0.437
CR42												2.286	1

Table D.7: Subcriteria normalised super matrix

Criteria	**CR11**	**CR12**	**CR13**	**CR14**	**CR15**	**CR21**	**CR22**	**CR23**	**CR24**	**CR31**	**CR32**	**CR41**	**CR42**
CR11	0.243	0.281	0.353	0.307	0.192								
CR12	0.048	0.056	0.045	0.034	0.079								
CR13	0.112	0.201	0.163	0.239	0.181								
CR14	0.088	0.181	0.076	0.112	0.146								
CR15	0.508	0.282	0.363	0.308	0.402								
CR21						0.104	0.155	0.053	0.084				
CR22						0.305	0.456	0.344	0.579				
CR23						0.272	0.184	0.139	0.077				
CR24						0.318	0.204	0.465	0.259				
CR31										0.844	0.844		
CR32										0.156	0.156		
CR41												0.304	0.304
CR42												0.696	0.696

D.3 Technology Prioritisation

This appendix contains the tables responsible for prioritising the data acquisition technologies as described in Chapter 6, Stage 2.3 of the RITSS framework.

Table D.8: DAQ Technology prioritisation table

		Evaluation Criteria (CR) Weight														
Infra	**ID**	**11**	**12**	**CR13**	**14**	**15**	**21**	**22**	**23**	**CR24**	**31**	**32**	**41**	**42**	**Sum**	**Rank**
Rails	2a	3	3	4	4	5	5	5	3	3	5	5	1	3	4.194	4
	2b	4	1	4	4	5	4	5	5	3	4	5	1	5	4.182	5
	4	4	1	4	4	5	5	5	5	3	4	5	1	5	4.200	3
	7a	5	4	2	1	5	1	3	3	1	4	3	5	3	3.574	20
	7b	5	3	2	2	5	2	3	5	1	4	3	5	3	3.685	19
	11	4	5	2	1	5	1	1	3	1	4	3	5	1	3.226	22
	12a	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	7
	12b	5	3	2	1	4	2	1	3	1	4	3	5	3	3.234	21
	13a	3	3	2	2	5	1	5	3	1	5	3	5	3	3.714	17
	13b	5	1	3	4	5	4	5	5	3	5	5	1	5	4.456	1
	13c	4	2	3	4	5	5	5	5	3	4	5	3	5	4.177	6
	14a	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	7
	14b	4	2	3	4	5	5	1	5	3	4	5	3	5	3.878	15
	16	4	5	4	5	5	5	3	3	1	5	3	5	1	4.085	12
	17	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	7
	18	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	7
	19	4	4	2	5	5	5	3	3	1	5	3	5	1	3.883	14
	24a	4	1	4	4	5	4	3	5	3	5	5	1	5	4.259	2
	24b	5	2	3	2	5	2	3	3	1	4	3	5	3	3.688	18
	25a	4	3	4	4	5	5	1	3	3	5	5	1	3	4.030	13
	25b	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	7
	25c	4	2	3	4	5	5	1	5	3	4	5	3	5	3.878	15
Sleepers	1	3	4	3	2	4	1	5	3	1	4	3	5	3	3.419	5
	3	5	5	2	1	5	5	3	1	1	5	3	5	1	3.748	3

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Table D.8 – *continued from previous page*

Infra	ID	Evaluation Criteria (CR) Weight													Sum	Rank
		11	**12**	**CR13**	**14**	**15**	**21**	**22**	**23**	**CR24**	**31**	**32**	**41**	**42**		
	11	4	5	2	1	5	1	1	3	1	4	3	5	1	3.226	6
	13a	3	3	2	2	5	1	5	3	1	5	3	5	3	3.714	4
	13b	5	1	3	4	5	4	5	5	3	5	5	1	5	4.456	1
	13c	4	2	3	4	5	5	5	5	3	4	5	3	5	4.177	2
Trackbed	8	4	2	4	1	5	1	1	5	1	3	3	5	3	3.248	9
	10a	4	1	4	1	5	4	5	5	3	5	5	1	5	4.232	1
	10b	5	2	3	2	5	2	5	3	1	4	3	5	3	3.837	7
	15	3	3	2	5	4	5	3	3	5	5	5	5	3	3.934	5
	21	4	2	4	1	5	1	1	5	1	5	3	5	5	3.791	8
	22	4	3	4	5	3	5	5	3	5	5	5	5	3	4.211	2
	25a	4	3	4	4	5	5	1	3	3	5	5	1	3	4.030	4
	25b	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	3
	25c	4	2	3	4	5	5	1	5	3	4	5	3	5	3.878	6
Surface drains	25a	4	3	4	4	5	5	1	3	3	5	5	1	3	4.030	2
	25b	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	1
	25c	4	2	3	4	5	5	1	5	3	4	5	3	5	3.878	3
OHTE	14a	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	1
	14b	4	2	3	4	5	5	1	5	3	4	5	3	5	3.878	4
	25a	4	3	4	4	5	5	1	3	3	5	5	1	3	4.030	3
	25b	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	1
	25c	4	2	3	4	5	5	1	5	3	4	5	3	5	3.878	4
Signalling	13a	3	3	2	2	5	1	5	3	1	5	3	5	3	3.714	6
	13b	5	1	3	4	5	4	5	5	3	5	5	1	5	4.456	1
	13c	4	2	3	4	5	5	5	5	3	4	5	3	5	4.177	2
	25a	4	3	4	4	5	5	1	3	3	5	5	1	3	4.030	4
	25b	4	1	4	4	5	4	1	5	3	5	5	1	5	4.110	3
	25c	4	2	3	4	5	5	1	5	3	4	5	3	5	3.878	5

Table D.9: Priority list of technologies

Infrastructure	**Rank**	**ID**	**Technology**	**Carrier**
Rails	1	13b	Infrared imaging	Rail inspection vehicle
	2	24a	Ultrasound	Rail inspection vehicle
	3	4	Corrugation measuring system	Rail inspection vehicle
	4	2a	Axle box measurements	In-service train
	5	2b	Axle box measurements	Rail inspection vehicle
Sleepers	1	13b	Infrared imaging	Rail inspection vehicle
	2	13c	Infrared imaging	UAV
	3	3	Concrete surface strain gauge	Fixed
	4	13a	Infrared imaging	Operator
	5	1	Acoustic emissions	Fixed
Trackbed	1	10a	Ground penetrating radar (GPR)	Rail inspection vehicle
	2	22	"SmartRock"	Fixed
	3	25b	Visual camera imaging	Rail inspection vehicle
	4	25a	Visual camera imaging	In-service train
	5	15	MBTSS	Fixed
Drains	1	25b	Visual camera imaging	Rail inspection vehicle
	2	25a	Visual camera imaging	In-service train
	3	25c	Visual camera imaging	UAV
OHTE	1	14a	Laser scanning systems	Rail inspection vehicle
	2	25b	Visual camera imaging	Rail inspection vehicle
	3	25a	Visual camera imaging	In-service train
	4	14b	Laser scanning systems	UAV
	5	25c	Visual camera imaging	UAV
Signalling	1	13b	Infrared imaging	Rail inspection vehicle
	2	13c	Infrared imaging	UAV
	3	25b	Visual camera imaging	Rail inspection vehicle
	4	25a	Visual camera imaging	In-service train
	5	25c	Visual camera imaging	UAV