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Application of Reliability Centered Maintenance in Railway Tracks

Sarita Rattanakunuprakarn
University of Central Florida

APPLICATION OF RELIABILITY CENTERED MAINTENANCE IN RAILWAY TRACKS

by

SARITA RATTANAKUNUPRAKARN
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ABSTRACT

Rail transport has played a significant role for a long time in the U.S. history. As other alternative transport modes have been developed, rail transport has increasingly faced more challenges to stay competitive. While heavy use of the rail, shortened service life and the need to meet consumer expectations have placed challenges, maintenance has become an integral part of the railway industry to assure efficacy and reliability of rail transportation. For this reason, there is a constant need to improve maintenance for a number of purposes, such as safety, quality, capacity, reliability, availability, punctuality, etc. In addition, optimizing maintenance strategy is also contributing to a reduction in management costs and track maintenance and renewal costs, which are extremely expensive cost elements. It also contributes significantly to increasing the life of track components.

This research starts with a thorough review of how reliability-centered maintenance (RCM) approaches are applied to rail transportation, their results, analysis, and summary of benefits and limitations of the applied method in railway transport. The objective of this research is to propose recommendations for best practices to improve maintenance and RCM plan with respect to maintenance and operational costs, technology and supporting systems, component life cycle and other related aspects to be considered when designing a maintenance strategy. This research outlines all of the planning processes involved in RCM so that it can be applied comprehensively to match the objectives of different organizations.

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LIST OF ACRONYMS (or) ABBREVIATIONS

CMMS	Computerized Maintenance Management System
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FSI	Functionally Significant Items
IRCMS	Integrated Reliability-Centered Maintenance System
LCC	Life Cycle Costs
PM	Preventive Maintenance
PdM	Predictive Maintenance
RCF	Rolling Contact Fatigue
RCFA	Root Cause Failure Analysis
RCM	Reliability Centered Maintenance
RTF	Run-to-Failure
RTM	Real-Time Monitoring
M&R	Maintenance and Renewal

CHAPTER ONE: INTRODUCTION

Problem Background

In 2015, U.S. freight railroads spent $30.3 billion, more than ever before, to build and maintain locomotives, freight cars, tracks, bridges, tunnels and other infrastructure and equipment. America’s freight railroads operate almost exclusively on infrastructure that they own, build, maintain, and pay for themselves. The disadvantages that railway experiences are not only the restriction of regulation but also issues related to the decline in the rail market, run-down conditions, the need of substantial maintenance, and related costs.

Maintenance management has become an integral part of the railway industry in order to increase reliability and service life of railway system, and to reduce their maintenance and renewal costs, which are the extremely expensive, especially the construction of rail infrastructure such as tracks. There is a lot of research on this subject. There are various factors to consider when choosing a maintenance scheduling optimization such as track deterioration, types of railways and vehicle, speed and traffic congestion, available resources, etc. Each of them has different conditions and requires different management and regulations.

Problem Statement

In a changing world, in today’s market the competition is increasing with options for transportation and available customers for travel. Railway management, therefore, focuses on improving the efficiency and reliability of rail transportation which results in the need to improve maintenance because of safety, capacity, reliability, availability and punctuality. In addition, maximizing maintenance planning also contributes to a reduction in track maintenance costs and management costs and to an increase in the life of track components. This allows the money to be used to develop other parts of the railway section and improve ability to provide better service at lower cost for customers, and therefore, increases competitiveness.

RCM has been applied in maintenance planning in numerous studies which are aimed at finding the best maintenance strategies for various conditions and infrastructures in different railroads. This research outlines all of the planning processes involved in RCM in the hope that it can be applied comprehensively and matches the state or objectives of each organization.

Research Objectives

This qualitative research provides knowledge covered on the subject of RCM in railway tracks to those interested in learning about how to apply RCM to a railroad system. The goal is to study the optimal rail maintenance strategy and to provide insights into the RCM method with the ability to deal with rail issues. Furthermore, it can be used as a decision-making tool for maintenance operators and management of railway systems in order to operate their work more efficiently and economically, and to determine inspection and maintenance strategy that suits the state of system and the organization, extend service life of components and system, improve safety of railway industry, and so on.

Based on existing literature about various railway sections around the world, especially in the U.S.A., the analysis of different types of defects and irregularity, defect development factors, preventive maintenance, renewal strategy, regulation, issues related to rail maintenance, and various other aspects of rail maintenance and RCM were considered and properly addressed in this research. This study used data derived from peer review articles, books, websites, and reports to answer questions in the research question section and to propose the framework of RCM in railroad under a variety of circumstances.

Research Questions

The following five research questions guided the framework and direction of the study.

- Research Question 1: What were the processes involved in the RCM application process?
- Research Question 2: What information and resources were required in the process?
- Research Question 3: What were the major challenges and obstacles encountered while implementing the RCM method?
- Research Question 4: How could the issues encountered eliminated or mitigated?
- Research Question 5: What were the results obtained from the implementation of the RCM method on railway tracks with regard to, e.g., reliability, safety, availability, finance?

Thesis Outline

This paper is divided into five separate chapters. Chapter 1 introduces an overview of this research including problem background problem statement and goals. Chapter 2 is Literature Review section which focuses on the RCM theory; about its procedure and how to adopt in railway system and others industries. Chapter 3 provides brief information about track structure, potential defects, the insights into the RCM methodology, and related issues. Chapter 4 is the results of this study that consists of syntheses of the RCM process, e.g., process diagram, other methods used in combination with the RCM, and challenges in implication. Finally, this research is summarized in Chapter 5 that consists of the conclusion, recommendations, and direction of future work.

CHAPTER TWO: LITERATURE REVIEW

Introducing the Topic

The United States has a long railroad history dating back to the 1800's. According to Association of American Railroads (AAR, 2018), the first railroad in North America, the Baltimore and Ohio, was chartered by Baltimore merchants in 1827. This was followed by the first regularly-scheduled steam-powered rail passenger service in the U.S. which began operation in South Carolina, 1830. The continuous development of the railway system continued and flourished until the Golden Age (1865 to the early 20th century). The rail network grew to its peak of 254,000 miles in 1916. However, in the early 20th century other modes of transportation grew from small beginnings to challenge rail dominance for freight and passenger transportation. By the eve of World War II, automobiles, large buses, trucks, etc. - supported by government subsidies and less burdened by regulation than railroads - had become full-fledged competitors to railroads. Eventually in 1929 to 1940, the Great Depression forced substantial segments of the rail industry into bankruptcy because of the economic crisis and competition from the automobile.

The disadvantages that railway systems experience are not only the restriction of regulation but also issues related to the decline in rail market, run-down conditions, the need of substantial maintenance, and related costs. In 2015, U.S. freight railroads spent $30.3 billion, more than ever before, to build and maintain locomotives, freight cars, tracks, bridges, tunnels, and other infrastructure and equipment. America's freight railroads operate almost exclusively on infrastructure that they own, build, maintain, and pay for by private funds.

After severe financial difficulties in the 1960s and 1970s, regulatory reforms helped railroads become more competitive. In the 1980s railroads were freed from the requirement of providing service where it did not pay, by discarding miles of unprofitable track, railroads operate 140,000 miles of track, less than half as much as in the mid-1960s. Railroads also consolidated, reducing the total number of companies operating Class I railroads, from 106 Class I companies in 1960 to 7 in 2014. Five of those seven companies generate almost 90% of total railroad revenue (Berridge, 2015).

Nowadays, railways are experiencing higher demands for the transportation of passengers and goods. This will in turn impose higher demands on the railway capacity and service quality. As a result, infrastructure managers are being compelled to develop strategies and plans to meet new requirements that include a higher level of resilience against failure, more robust and available infrastructure, and cost reduction. To achieve these goals, one of the key elements is the employment of an effective and efficient maintenance program. A large part of the railway maintenance burden concerns track geometry maintenance. Maintenance actions are used to control the degradation of the track and restore the track geometry condition to an acceptable state (Soleimanmeigouni, Ahmadi, Nissen, & Xiao, 2019).

Important and Impact of Railway on Other Aspects

By 1876, railroads have already spanned the continent and united the country in an unprecedented transportation network. The results were soon profoundly changed both economically, culturally, and politically. Personal mobility radically expanded because now one could travel across the country in a week in the 1870s instead of taking several months as in the past. The economy began a huge expansion by growing almost ten-fold in the last quarter of the 19th Century. According to the Smithsonian National Museum of American History (2018), physical mobility became essential for social mobility.

In the early 20th century, annual revenues of railroads constituted the largest industry in America. This is no longer the case. However, according the Association of American Railroads (AAR), in 2013 because of economic growth and population growth railroad revenue exceeded $70 billion and railroad employment rose to approximately 180,000 (Berridge, 2015).

Railroads haul the most freight of any form of transport in terms of ton-miles, a measure of cargo volume that considers weight and distance carried. The double-container stacked freight trains carry coal, gas, and every commodity imaginable. According to U.S. Bureau of Transportation data, in 2014, railroads hauled 40 % of total U.S. freight which was up from 27 % in 1980 (Berridge, 2015).

In Figure 1, the following graph shows how tonnage was carried by the different forms of freight transportation.

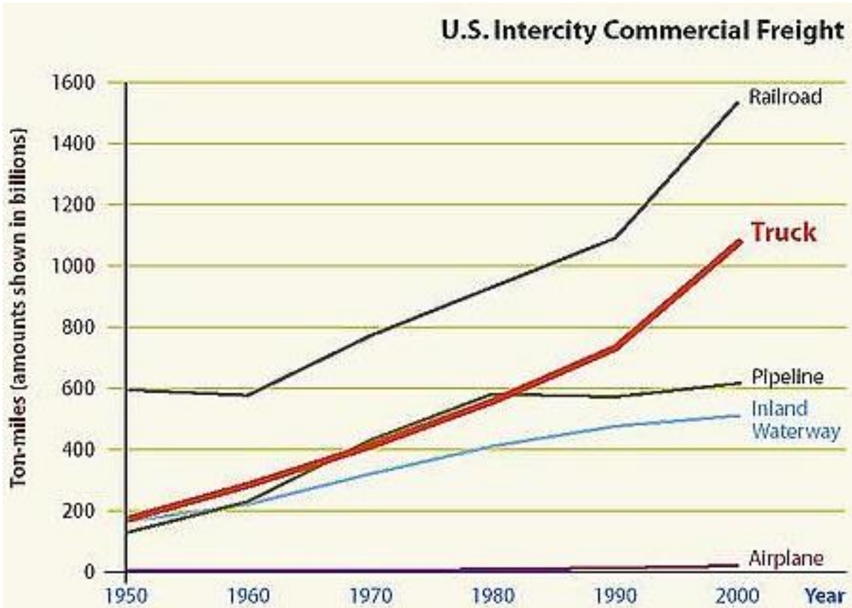


Figure 1: Railroads' role among other modes since 1950 to 2000

Source: Smithsonian National Museum of American History
https://americanhistory.si.edu/america-on-the-move/essays/american-railroads

Freight railroads in the U.S. are the best in the world and are a crucial national economic resource. According to Association of American Railroads (2019), every year, railroads save consumers billions of dollars while reducing energy consumption and pollution, lowering greenhouse gas emissions, cutting highway gridlock, and reducing the high costs to taxpayers for highway construction and maintenance. They also have a broader economic impact. In 2017 alone, America's major freight railroads supported 1.1 million jobs, nearly $219 billion in output, and $71 billion in wages across the U.S. economy. In addition, millions of Americans work for firms that are much more competitive in a tough global economy thanks to the affordability and productivity of America's freight railroads (AAR, 2019).

Deterrents and Problems Involved

Detection and rectification of rail defects are major issues for all rail players around the world. Some of the notable defects include worn out rails, weld joint problems, internal defects, corrugations and rolling contact fatigue (RCF). The RCF initiates problems such as surface cracks, head checks, squats, spalling and shelling. If undetected and/or untreated these can lead to rail breaks and derailments (Kumar, Chattopadhyay, Reddy, & Kumar, 2006).

There are challenges to the infrastructure maintenance people with logistics for effective inspection, competitiveness in rail system, and cost effective rectification decisions. If these issues are addressed properly then inspection and rectification decisions can reduce potential risk of rail breaks and derailments. Many of the defects are not visible or occur beneath surface. Thus, the effectiveness of rail inspection depends on the efficiency and accuracy of the inspecting and maintenance equipment. Selection of rail material and lubricant are the other aspects of concern for maintenance people. Of upmost importance is the skill level and experience of inspectors. Another factor in the inspection process is governed by weather conditions. In cold areas of countries, inspection of rail becomes difficult and costly affair in winter. Another important issue is management of rail traffic during inspection; such as availability of rail track and traffic delay. Some of the rail routes are so busy that it becomes very difficult to stop train traffic and do rail inspection and maintenance. For these routes rail inspection and maintenance is done during night time. The workers and inspectors have to be paid more for working during night hours, but it is a necessary cost. Still it is a challenge to effectively carry out inspection and maintenance procedures due to the effort to keep optimal rail inspection and maintenance cost and minimal traffic disruption (Kumar, Chattopadhyay, Reddy, & Kumar, 2006). The following figure represents issues related to rail maintenance.

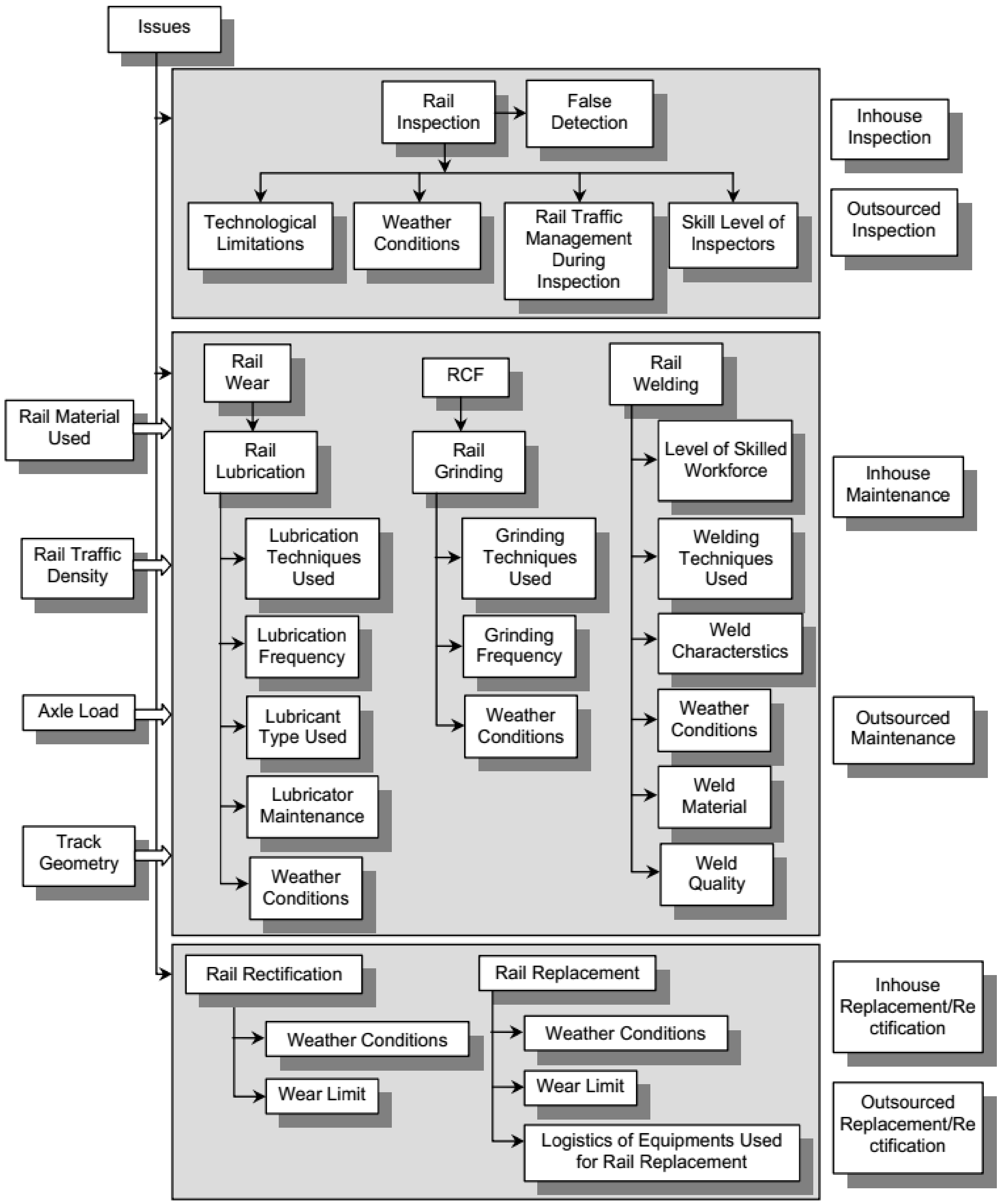


Figure 2: Issues related to rail maintenance

Source: Kumar et al., 2006

Introducing Maintenance Approach

In the past, railway maintenance procedures have been traditionally planned based on the knowledge and experience of each company that has been accumulated over many decades of operation but without any kind of reliability- or risk-based approaches. With the major goal of providing a high level of safety to the infrastructures, there was not much concern over the economic issues. However, nowadays, limitations in budget force the railway infrastructure managers to reduce operational expenditures. Therefore, efforts are being made for the application of reliability-based and risk-informed approaches to maintenance optimization of railway infrastructures. The underlying idea is to reduce the operation and maintenance expenditures while still assuring high safety standards (Carretero et al., 2003).

Maintenance optimization of railway infrastructure includes several aspects, such as safety, economic, operational, organization and regulatory issues (Đorić, Cadi, Hanafi, Mladenović, & Artiba, 2017). It also includes an estimation of the degradation of an object or a system and the consequence of this degradation, often in form of cost. Having knowledge about the degradation, makes it easier to estimate when measures are necessary, when life span reaches its technical and/or economic end, etc. As the result, accurate life cycles including all maintenance work to be carried out throughout useful life can be drawn. Furthermore, the possibility of predicting residual lifetime of any asset is of extreme importance. The consequence of degradation relates to safety and operational expenditures as well as speed limitations and corrective maintenance actions (Lyngby, Hokstad, & Vatn, 2008). In addition, other aspects that can be the subject of optimization include decisions regarding maintenance intervals, balance of corrective and preventive maintenance, grouping of maintenance activities, and the timing of maintenance and renewal, spare part optimization, etc. (Økland, Seim, Vatn, Bruaset, Gabriel, Halvorsen, & Ekambaram, 2013).

Preventive maintenance (PM) is the maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item. There exist several approaches to determine a preventive maintenance program. A concept that is becoming more and more popular is the concept of Reliability Centered Maintenance (RCM). RCM is a systematic consideration of system functions, the way functions can fail, and a priority–based consideration of safety and economics that identifies applicable and effective PM tasks. It is usually conducted as a pure qualitative analysis with focus on identifying appropriate maintenance tasks. However, the RCM methodology does not usually give support for quantitative assessment in terms of e.g. interval optimization. The strength of RCM is its systematic approach to consider all system functions and set up maintenance task for these functions (Økland et al., 2013).

Formalized maintenance optimization models rely on system reliability models. These are models that express the system (reliability) performance as a function of component performance. Further, the component performance is expressed in terms of component reliability models. Some basic models are: 1) Reliability block diagram (RBD) and structure functions; 2) Fault tree analysis (FTA); 3) Event tree analysis (ETA); 4) Markov analysis; 5) Failure Mode and Effect Analysis (FMEA/FMECA). In addition, within maintenance optimization literature it is common to present some basic maintenance models such as the Age Replacement Policy (ARP) Model, the Block Replacement Model (BRP,) and the Minimal Repair Policy (MRP) (Økland et al., 2013).

Overview of Reliability-Centered Maintenance Approach

Reliability played an important role for the 747 Aircraft in the 1960s with the U.S. on the threshold of the jumbo jet aircraft era. At that time the licensing of an aircraft of that type by the Federal Aviation Administration (FAA) required that the FAA approve preventive maintenance program to be specified for initial use by all owners/operators of the aircraft. No aircraft can be sold without this certification. The recognized size of the 747 (three times as many passengers as the 707 or DC-8), its new engines (the large, high bypass ratio fan jet), and its many technology advances in structures, avionics, and the like, all led the FAA to initially take the position that preventive maintenance on the 747 would be very extensive. This development led the commercial aircraft industry to essentially undertake a complete reevaluation of preventive maintenance strategy. This effort was led by United Airlines who, throughout the 1960s, had spearheaded a complete review of why maintenance was done and how it should best be accomplished. In 1975, United States Department of Defense directed that the MSG concept be labeled "Reliability Centered Maintenance," and that it be applied to all major military systems (Smith & Hinchcliffe, 2004). The application of RCM followed for nuclear power plants by the Electric Power Research Institute (EPRI) that initiated RCM pilot studies in 1983, and then continued to be used by large segments of U.S. industry until today

RCM philosophy employs preventive maintenance, predictive maintenance (PdM), real-time monitoring (RTM), run-to-failure (RTF), and proactive maintenance techniques and is an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with a minimum of maintenance. RCM operates by balancing the high corrective maintenance costs with the cost of programmed (preventive or predictive) polices (Afefy, 2010).

Basically, the RCM methodology addresses key issues not dealt with by other maintenance programs. This approach recognizes that all equipment in a facility is not of equal importance to either the process or to facility needs and safety. Focusing on the reliability of equipment means recognizing that the equipment design and operations differ and that each piece of equipment has a different probability of failure from degradation than another. A reliability-focused approach will mean structuring a maintenance program based upon the understanding of equipment needs and priorities, as well as limited financial and personnel resources, to plan activities such that equipment maintenance is prioritized while operations are optimized (RFD Reliability and PdM Technology, 2010).

Because RCM is so heavily weighted on utilization of predictive maintenance strategies, its program advantages and disadvantages mirror those of predictive maintenance. The advantage of it includes: 1) providing the most efficient maintenance program; 2) lowering costs by eliminating unnecessary equipment maintenance; 3) minimizing the frequency of overhauls; 4) reducing probability of sudden equipment failures; 5) focusing maintenance activities on critical system components; 6) increasing component reliability; and 7) incorporating root cause analysis. In addition to these advantages, RCM will allow a facility to more closely match its resources to operational needs and at the same time improve both reliability in order to decrease the spare parts consumption of system components and also reduce associated maintenance costs, minimize the downtime, and improve the availability of the plant components (Afefy, 2010; RFD Reliability and PdM Technology, 2010).

However, RCM approach can have significant startup costs associated with staff training and equipment needs. However, the applied RCM savings potential is not readily seen by management. The other limitation to this approach is that it is difficult to select a suitable maintenance strategy for each piece of equipment and each failure mode because of the great quantity of equipment and uncertain factors of maintenance strategy decision (RFD Reliability and PdM Technology, 2010).

Reliability-Centered Maintenance in Railway field

Ruijters, Guck, Noort, and Stoelinga (2016) modeled and analyzed several maintenance policies for the EI-joint via fault maintenance trees. EI-joint is a critical asset in railroad tracks for train detection and is a relative frequent cause for train disruptions. They also analyzed several key performance indicators, such as the system reliability, number of failures, and costs to figure out the best maintenances policies regarding those indicators. Their analysis shows that the current maintenance policy is close to cost-optimal. It is possible to increase joint reliability, e.g. by performing more inspections, but the additional maintenance costs outweigh the reduced cost of failures.

Macchi, Garetti, Centrone, Fumagalli, and Pavirani (2012) studied the models used for assessing the current maintenance plans and taking decisions for new maintenance standards over the different varieties of railway items as well as for different railway tracks, i.e. for high or low traffic tracks. A fundamental aspect of the proposed modeling approach is based on the relationship that is established between the railway system reliability and the transportation service level offered by the system itself. The result shows that the traditional technology, less complex from a functional view point, is more reliable in comparison to the new more complex technology, coded track circuit. In addition, the most effective preventive maintenance interval of track circuit traditional which analyzed by the sensitivity analysis shows that to-be policy of 3 month intervals could give more reliability index than the current policy of 6 month intervals.

In 2000, the European Union founded a project named ‘Reliability centered maintenance approach for infrastructure and logistics of railway operations’. It is a structured technique to obtain maintenance strategies based on the awareness of the nature and causes of malfunctions of various types of track circuitry, axle counters, point machines, signals, and interlocking devices which are Safety Critical Railway Infrastructure components (SCRICs). They established three models estimating the cost of maintenance operations; i.e., Corrective maintenance costs, Preventive maintenance costs, and LCC (Life Cycle Costs). Further, the preventive maintenance task supported by a database was developed.

Marten (2010) conducted qualitative case study to identify the types of obstacles and patterns experienced by a single heavy rail transit agency located in North America that embedded a RCM Process. The specific problem that the study addressed is the lack of sufficient knowledge about the obstacles and patterns when implementing an RCM process and the outcome of RCM with regard to rolling stock about its availability, reliability, and safety. The results of Marten’s questionnaire in his case study are as following; 1) the most challenging aspects of implementing RCM is culture change (80% of the participants), 2) the two biggest obstacles of implementing RCM are lack of computer skills (75 % of the participants) and unions (60% of the participants), 3) the two most significant impacts of RCM application are the availability of rolling stock increased (85% of the participants) and the reliability of rolling stock increased (65% of the participants).

Garciamarquez, Schmid, and Collado (2003) applied RCM to remote condition monitoring for complex mechanisms and railway points that have various performance parameters such as speed of movement, vibration, supply voltage, power, throwing time, temperature, current, force, etc. The researchers used RCM and remote condition monitoring systems with the overall aim of using advanced electronics, control, computing and communication technologies to address the multiple objectives of cost effectiveness, and improved reliability and services. The most important results are as follows. With a Kalman Filter, the authors could detect 100% of faults in the reverse to normal direction, and without the Kalman Filter this drops to 97.33%. When using the Kalman Filter, they can currently detect only 97.1% of faults and without it only 94.2%. In general, employing Kalman Filter has improved the margins of criteria in both directions.

Conclusion

The processes of applying RCM methodology are varied in terms of the number of steps involved, related methods, calculation formulas, considerations in data analysis, and decision support tools. In addition, railway system is a highly complex system; it consists of many subsystems, sections, parts, and components that are distinguished by different criteria as well as different management allocations. The complexity and variety have been challenging for many studies and research undertakings. Therefore, this research focuses on the application of reliability-centered maintenance in railway systems and other issues in railway maintenance, as an implementation framework under a variety of circumstances, including the decision support systems, challenges, and stakeholders and their actions to overcome those challenges.

CHAPTER THREE: RCM IMPLEMENTATION IN RAILWAY TRACKS

This chapter begins with an overview of the track components, defect, key maintenance, and information that needs to be understood, before beginning the analysis process in RCM which are system breakdown, function analysis, FSI selection, FMECA, task selection, and maintenance optimization, respectively. The last part of the chapter covers RCM implementation including the decision support systems, challenges in implementation, and stakeholders and their actions to remedy those challenges.

Component of Tracks

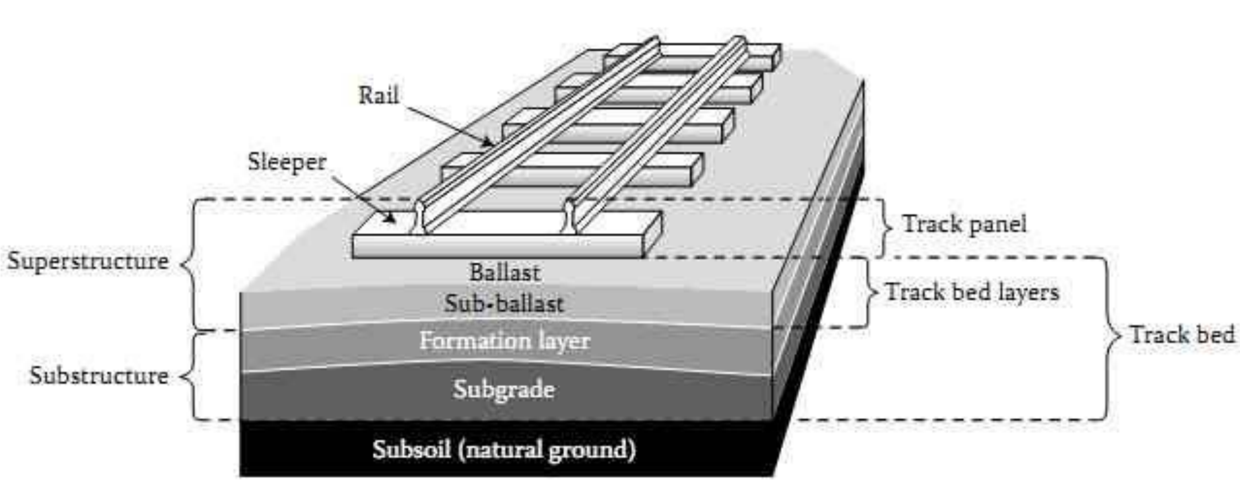


Figure 3: Cross-section of a typical railway track

Source: Pyrgidis, 2016

The railway track consists of a series of components of varying stiffness that transfer the static and dynamic traffic loads to the foundation, Figure 3. It comprises from top to bottom the rails, the sleepers, the ballast, the sub-ballast, the formation layer, and the subgrade, sequentially.

The rails are mounted on the sleepers on top of elastic rail pads to which they are attached by means of a rail hold-down assembly called the rail fastening (Pyrgidis, 2016).

Rails, sleepers, fastenings, elastic pads, ballast and sub-ballast constitute the ‘track superstructure’, and the subgrade and the formation layer constitute the ‘track substructure’. The upper section of the track superstructure that comprises the rails, the sleepers, the fastenings and the rail pads forms what could be commonly called the ‘track panel’. Switches and crossings by means of which the convergence, cross section, separation and joining of tracks at specific points of the network is accomplished are also considered to be part of tracks (Pyrgidis, 2016).

The lower part of the track superstructure that comprises the ballast and its sublayers is called ‘trackbed layers’. The trackbed layers and the track subgrade, considered as a whole, are called ‘trackbed’ (Pyrgidis, 2016).

Apart from the ballasted trackbed (conventional or flexible trackbed), a concrete track bed (slab track or rigid trackbed) is used rather than the more tradition ballasted. Using the concrete track has proven to be very efficient in the case of underground track sections where maintenance requirements are greatly restricted (Pyrgidis, 2016).

Types of Defects and Irregularity

This subsection introduces examples of the typical defects and irregularities found in railroad tracks as well as their characteristic, effects, and how to alleviate those irregularities.

Irregularity of ballast is one of the main sources of track geometry deterioration and observed derailments. The main function of ballast is to retain track position by resisting vertical, lateral and longitudinal forces applied to the sleepers. The vertical force of the moving train and the squeezing force of maintenance tamping are the two main forces that act on the ballast. The deterioration of the track geometry is mainly caused by the settlement of the substructure and ballast, being its main component because by its function, is important for providing the fastest and most economical method of restoring track geometry, especially at a subgrade failure situation **(**Minsili, Jérémie, Simo, & Simo, 2012).

Another instance of defect is abrasive wear. Abrasive wear occurs when there is contact between the side of the flange of a wheel and the gauge face of the rail. This contact usually takes place between the leading outer wheel of a vehicle bogey and the outer rail of a curve. On curves, careful periodic check must be carried out of the outer rail to ensure that side wear is kept within prescribed limits. Failure to do this could result in a derailment. Where curves are tighter than 200 m radius, continuous check rails should be provided inside the inner rail. This defect can be reduced by the use of rail lubricators placed at strategic positions. However, great care needs to be exercised in the use of lubricators to ensure that only flanges are lubricated. Lubricant deposited on the top of rail heads can cause problems with braking, acceleration and wheel-spin (Bonnett, 2005).

In addition to abrasive wear, even when wheels run along a fairly straight track with flanges just clear of the rails, various wear patterns were frequently found because of the contact area between wheel and rail which is extremely small. In theory, the contact would only be a point which would make contact pressures infinitely high. In practice both surfaces deform slightly to give a contact 'patch'. Even so, typically such a patch has only an area of about 100 mm2 under the heaviest wheel load. This gives pressures as high as 1200 N/mm2 that is higher than the yield point of the steel. This has the effect of causing the contact patch to become plastic and to flow causing various wear patterns and irregularities over time (Bonnett, 2005).

A dipped rail joint is a short-wavelength defect. A 'dipped angle' is a term used to define the sum of an angle of dipped trajectory between each rail and the horizontal (in milliradians) at rail joints or welds. The two components of this angle consist of permanent deformation of the rail ends and the deflection of the joint under load. When trains travelling at high speed approach a rail joint, the wheel will lose contact with the railhead of rail and land on the connected rail which generates the high dynamic impact force. The shape of the irregularity and characteristics of the vehicle create impact loading when the force at the dipped joint increases almost linearly with the speed and angle of the dip (Jenkins, Stephenson, & Clayton, 1974).

Track settlement is a long-wavelength defect that can cause a bumpy ride of the train passing. The train passing such the track settlement will induce higher dynamic load and increase high-frequency variations to the sleepers, ballast, and subgrade. Increased dynamic loads will then cause non-elastic or plastic deformations with permanent setting of track foundation. In normal situations, the track will generally not return to the same position but to a very close point (accumulated deformation). As time passes, all non-elastic deformations will make change on track position, track alignment and surface level, and therefore, this phenomenon becomes new differential track settlement. The irregularity of the track will increase low frequency oscillation of vehicles. However, the track settlement often takes place at the transition area to a bridge. In addition, the quality of ballast, sub-ballast and the subgrade are also factors inducing permanent deformation (Kaewunruen & Chiengson, 2018). Track settlements typically consist of two phases. The first phase is after tamping when the gap between ballast particles is reduced quickly and so this layer is consolidated. The second phase is slower since the densification and inelastic behavior of the ballast and subgrade materials are the main concern. The major parameters influencing the ballast settlement are the deviatoric stress, vibrations, degradation, and subgrade stiffness (Kaewunruen & Chiengson, 2018).

Transverse fissure defects are inherent from the manufacturing process and are found predominantly in non-control cooled rail prior to the mid-1930s. However, these defects can develop in more modern high-chrome rail from a hydrogen imperfection (Office of Railroad Safety, 2015).

Rail break is the last phase of crack development process and might lead to catastrophic derailment. The consequences can include death, injury, costs, and loss of public confidence. In addition, these events may have devastating and long-lasting effects on the reputation and public perception of the industry (Popović, Radović, Lazarević, Vukadinović, & Tepić, 2013).

Apart from the defects mentioned above, a typical defect classification nomenclature (FRA and Industry) used by U.S. Railroads (Office of Railroad Safety, 2015) are stated as follows:

Rail Defect Abbreviation and Definition

BBJ = Broken Base Joint Area

BBO = Broken Base Outside Joint Area

BHB = Bolt Hole Break

BHJ = Bolt Hole Break Joint Area

BHO = Bolt Hole Break Outside Joint Area

BRJ = Broken Rail Joint Area

BRO = Broken Rail Outside Joint Area

CF = Compound Fissure

CH = Crushed Head

DF = Detail Fracture

DWE = Defective Weld – Electric

DWG = Defective Weld – Gas Pressure

DWP = Defective Weld Plant

DWF = Defective Weld Field

EBF = Engine Burn Fracture

HSJ = Horizontal Split Head Joint Area

HSH = Horizontal Split Head Outside Joint Area

HWJ = Head and Web Separation Joint Area

HWO = Head and Web Separation Outside Joint Area

PRJ = Piped Rail Joint Area

PRO = Piped Rail Outside Joint Area

REWF = Rail End Weld Fracture

SWJ = Split Web Joint Area

SWO = Split Web Outside Joint Area

TDC = Compound Fissure

TDD = Detail Fracture

TDE = Transverse Defect Electrode Burn

TDT = Transverse Fissure

TDW = Transverse Defect Welded Burn

TF = Transverse Fissure

TWB = Thermite Weld Boutet

TWBW = Thermite Weld Boutet Wide Gap

TWO = Thermite Weld Orgotherm

TWOW = Thermite Weld Orgotherm Wide Gap2

VSJ = Vertical Split Head Joint Area

VSH = Vertical Split Head Outside Joint Area

WEBF = Welded Engine Burn Fracture

Objective of Railroad Maintenance

Railroad maintenance consists of inspecting, repairing, maintaining, and sometimes renewal, of railway tracks to allow the trains to operate safely at full capacity as well as to prolong the service life of tracks components. However, if maintenance has not been executed properly, the service life of tracks will be shortened as well as increase the probability of fatal accidents due to collisions and derailments.

There are also some challenges related to ability to maintain track performance due to their exposure to the natural environment. Therefore, infrastructure manager (IM) is obligated to define the maintenance plan for railway infrastructure, which contains corresponding values for intervention limits and alert limits, for each railway line before putting it into service (Popović, Lazarević, Brajović, Mićić, & Mirković, 2020). Then, maintenance plan should be updated throughout the tracks lifetime in order to ensure the quality and the integrity of the components and system.

The maintenance on track includes the varying types of detailed work to keep the track in safe and proper condition for traffic. It varies with the climatic conditions, the character of the track, and the amount of traffic; becoming especially burdensome under conditions of a light track carrying a heavy traffic (Tratman, 2010). Below are the main types of maintenance accomplished by a variety of specialized machines.

1. Rail grinding

    This consists of grinding machines travelling along the track with grinding stones, which are rotating stones or stones oscillating longitudinally, to remove metal from the surface in longitudinal facets or ridges. Rail grinding is conducted to reduce and control RCF development and to re-profile the rail. The purpose of rail grinding is to achieve the longest life of the rail through preventive rail maintenance. It also benefits the improvement of rail inspection system capabilities. This practice is designed to result in rail removal once the parent rail head loss has reached its maximum effective use and not because of fatigue (FRA, 1015).

    Preventive grinding removes a minimal amount of rail steel during the grind process; whereas, corrective grinding removes larger quantities of rail steel by multiple low-speed grind passes. The best rail grinding strategy is to make sure that the cycles are adequate to maintain balance of wear and fatigue (FRA, 1015)

    The grinding frequencies are not normally driven by accumulated tonnage. Instead, they are normally driven by other factors like significant shelling development, corrugation, or the presence of other severe surface anomalies. Preventive rail grinding strategy, along with a properly developed rail lubrication, and friction management programs, are essential in a successful rail management program. In order to reduce track occupancy time for the process, it is normal to use more grinding stones and have the ability to remove metal and shape the rail head with one pass. Figure 4 displays the surface of rail after grounding and Figure 5 shows a rail grinding machine.

Figure 4: Freshly ground rail

Source: Track Inspector Rail Defect Reference Manual, Office of Railroad Safety, 2015

Figure 5: Rail grinding machine works on the rails of Tianjin-Bazhou railway in North China's Tianjin, June 9, 2020

Source: Alamy Live News, Photo by Feng Kai/Xinhua

The machine used for surfacing is the Patterson surfacing machine. A blower driven by hand is mounted on a frame which runs on one rail and is clamped to it.

The machine consists of two vertical pipes, one connected with the blower by a hose and the other with a hopper on the top for the ballast. The pipes unite in a shoe at the bottom and to this is fitted a thin flat horizontal nozzle with variable width of opening. The material used is screened stone or gravel not exceeding ¾ in. in size. The ballast is cleared away from the ends of the ties and the track is raised to surface by bars or jacks. The nozzle is then inserted under the end of a tie and the blower put in operation, driving the fine material into all the cavities and packing it solid. This method can be used for a raise of ¼ in. to l½ ins. (Tratman, 2010).

Research and experience have shown that rail grinding has an important role in the reduction of rail degradation. The modern strategy of rail grinding includes preventive, corrective, and cyclical activities. Rail grinding can reduce rail brakes and early rail replacements (Popović et al., 2013).

2. Tamping

This is conducted to correct longitudinal profile, cross level, and alignment of the track. A number of sleepers at a time are lifted to the correct level with vibrating tamping tines inserted into the ballast (Tratman, 2010). Figure 6 displays how tamping is performed and Figure 7 presents a tamping machine.

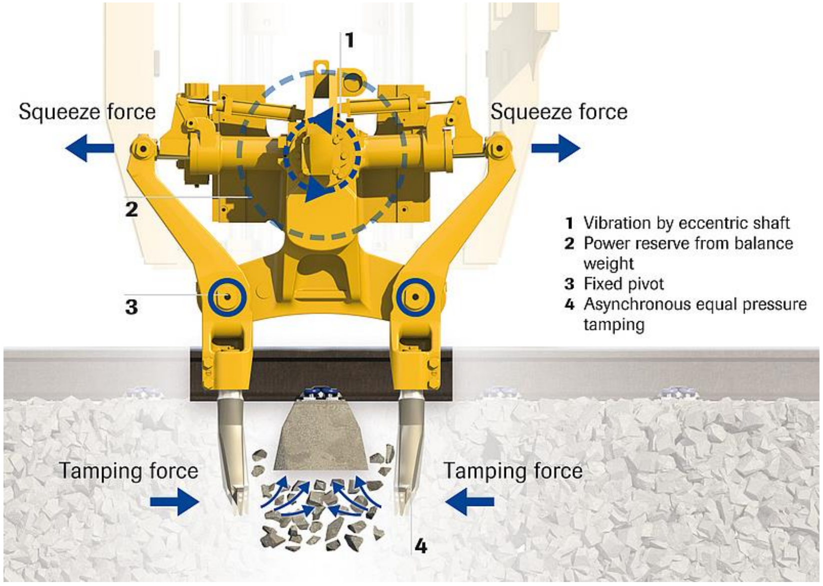


Figure 6: Tamping operation

Source: https://www.plassertheurer.com/en/machines-systems/tamping.html

Figure 7: Tamping machine

Source: https://en.wikipedia.org/wiki/Tamping_machine

3. Raising track

About once in three to five years the entire track will be required to be raised out of face or brought up to a new surface. At such a time grade stakes are set to give the elevation of the top of the rail. Ballast is distributed for raising the track. In raising, jacks are used under each rail and both sides of the track brought up and tamped simultaneously. The raise does not exceed 6 ins. at any one lift. Then are the 6 ins. of ballast are well tamped, another raise made (Tratman, 2010).

4. Renewing rail

In laying new rails on a section there are two principal methods of practice. One method is to lay the new rails along the ends of the ties, to fully bolt up the joints, and then to take up the old rails and throw in the string of new rails. The other method is to lay in one rail at a time. There is also a compromise method, by which the rails are bolted together in lengths of five or six, the intermediate joints being left open, to be bolted up when the rails are in the track. In either method, the details of the work and the distribution of the men depend largely upon the traffic, and vary considerably on different roads (Tratman, 2010).

5. Sub-ballast layer treatment

A sub-ballast layer is required to reduce the stresses on the subgrade. In case of degradation or in order to improve its mechanical performances, a treatment of this layer is required. It can consist on compacting, reinforcing or substituting the materials of this layer (Rhayma et al., 2013).

6. Renewing ties

The old ties to be renewed are previously marked conspicuously by the roadmaster, and the only ties so marked must be removed. With most types of tie flaws, the work is to replace and not remedial action. The work should be done before or immediately after new rails are laid, so as to give a good substantial bearing to the newly laid rails. Then, all new ties are thoroughly tamped. When the work is once commenced it should be pushed steadily along and completed as soon as possible. For continual maintenance, renewals of a few ties at a time all through the season are done to prevent the track from being well settled and consolidated. This continual disturbance results in an increase in maintenance expenses and train expenses (Tratman, 2010). Defective ties can result in the rail losing the correct gauge and derailments.

7. Clearing right of way

   All grass, weeds, and brush on the right of way is cut at least once a year and preferably twice a year to prevent seeding. This should be done in the months which are most suitable according to the latitude. If the brush on the right of way is allowed to grow too long, it is liable to cause accidents by concealing cattle and to catch fire in dry weather. Moreover, the spark arresters of locomotives should be examined frequently in hot, dry weather to prevent a needless fire. The idea is to keep the areas near the tracks well maintained. This work could be done, such as, by hand, long handled sharp hoe, shovel, jets from burners, or ditching machine, depends on the amount of work to be finished. At the time of general clean up old ties, splice bars, tools, etc. are removed to prevent future disasters and fires (Tratman, 2010).

8. Day-to-day maintenance of track

   Track condition visual inspection and track geometry measurement systems are necessary to establish a quality standard and to ensure the standard is being maintained.

Service Life Influencing Factors

From the study of the two previous sections (types of defects and irregularity, and objective of railroad maintenance), the important factors which affect the service life of railroad system are summarized in Table 1:

Table 1: Factors which influent the service life of tracks

Authors	Type of Components	Type of Defects	Influencing Factors				Solution
			Operational stresses	External Stresses	Design or infrastructure	Improper Maintenance	
Tratman, 2010	Rail surface	RCF	Heavy loads and traffic		Rails out of level transversely on tangents	Weak fastenings, poor ballast, faulty/ insufficient work (e.g., tamping)	Surfacing, Putting rail and track in a uniform plane.
Dao et al., 2018	Tracks					Worn-out stock decreased by PM	Worn-out stock reset to max. after a renewal
Popović et al., 2014	Rail head surface	Crack, RCF, head checks	Operational loads, axle load, speeds	Temperature , vibratory, vehicle conditions	Location (curve, straight, slope), track geometry, track stiffness, track quality	Maintenance policy	Grinding, replacement of rails and sleepers

Authors	Type of Components	Type of Defects	Influencing Factors				Solution
			Operational stresses	External Stresses	Design or infrastructure	Improper Maintenance	
Popović et al., 2020	Superstructure	Deterioration of sleeper support, ballast				The unevenness of the rail head surface	
Ferreira & Murray, 1997	Track components	Degradation (e.g., cracking, plastic flow)	Dynamic actions (e.g., centrifugal forces, braking forces), Static mass, Speeds		Vibrational forces induced from imperfections in the rail surface (corrugations, joints, welds, defects)		
Soleimanmeigouni et al., 2019	Ballast	Ballast fouling		Vibratory process	Poor drainage	Poor drainage, dirty ballast, higher permanent deformation, increased geometry deterioration	Ballast cleaning and replacement, tamping
Bonnett, 2005	Ballast	Ballast degradation	Traffic			Maintenance operations	

Authors	Type of Components	Type of Defects	Influencing Factors				Solution
			Operational stresses	External Stresses	Design or infrastructure	Improper Maintenance	
Bonnett, 2005	Rail	Wear, plastic flow	Contact between the side of the flange of a wheel and the gauge face of the rail				The use of lubricators placed at strategic positions
Santa et al., 2016	Rail surface	Cracks, head checks, RCF	Dynamically changing during operation.		Traction loads (caused by curves and slopes)	Grinding	Grinding, reprofilling
Office of Railroad Safety, 2015	Rail head	Wear, plastic flow, deformation, Transverse fissure	Speed, and tonnage, cyclical loading		Inherent to rail manufactured (chemical composition and quality of machine)	Track maintenance program	
Minsili et al., 2012	Ballast	Deterioration	The vertical force of the moving train	Squeezing force of maintenance tamping			

Authors	Type of Components	Type of Defects	Influencing Factors				Solution
			Operational stresses	External Stresses	Design or infrastructure	Improper Maintenance	
Kaewunruen & Chiengson, 2018	Superstructure	Track settlement	Dynamic loads, deviatoric stress	Vibrations	All nonelastic deformations will make change on track position, track alignment and surface level, often takes place at the transition area to a bridge, the quality of ballast, sub-ballast and the subgrade		

Track and Maintenance Segments

To utilize a decision support system, the track network must first be divided into relatively uniform "management units" (track segments). The uniformity is based on specific, common features and attributes. This refers to traffic, use, curvature, rail weight, existing condition and/or any other significant criteria that would affect performance (condition over time). Track performance should be relatively uniform throughout a track segment since this forms the basis for M&R decision making. Then a consistent strategy can then be applied throughout the segment. As condition data are very disaggregate, consistent procedures must be used for determining homogeneous segments (Uzarski & McNeil, 1994).

For each line segment the following data will be collected: physical characteristics of track structure; traffic task related variables (gross-tonne-km, axle loads, operating speeds); track condition indicators mainly in the form of track geometry index as measured by a track recording vehicle; track maintenance costs on an historical basis; track standards; environmental conditions; and past maintenance policies. (Ferreira & Murray, 1997).

Pyrgidis (2016) considered the length of the route as another criterion to determine track segment. Based on reliability and regularity of services aspect, the acceptable delay time of a freight train depends on the length of the route. For example, one could consider the acceptable delay time to be equal to 1 h per 500 km of length. Punctuality, minimization of delays, constitutes one of the parameters that determine the level of quality that a railway system provides as well as the level of maintenance work required in each segment.

Macchi et al. (2012) clustered railway infrastructure based on the two methods: clustering by component's technology and clustering by operating conditions (volume of traffic and type of track).

Special care be needed on certain track segments depending on their overall conditions. Maintenance for each segment is also different related to factors such as location, material, traffic, and season. Those factors should be considered when assigning track maintenance activities because not the same treatment of defect is applicable for that defect every time regardless of their location, traffic, etc. The examples of factors that affect the classification of track segments and maintenance activities are as the follows.

Location

The first example is in the case of surfacing. In the general, surfacing is done each year. The track should be raised only just enough for proper tamping to bring up the low parts to a uniform surface. The track is raised out of a face only every four or five years. However, no raise is made in tunnels or under structures with headway of less than 22 ft. Also, tamping the ties at frogs, switches, crossings, etc., are especially well tamped (Tratman, 2010).

Wear on point and crossings is carefully watched on a regular basis. Some repair of bad wear can be done by welding but in most cases components need to be changed (Bonnett, 2005).

Material

With earth or mud ballast, the section gang has to be continually at work surfacing because the material will not give a uniform support under traffic as some parts will go down while others remain firm. If the force is sufficient, the track should be surfaced and tamped in the usual way; but if the section is long and the number of men allowed is small (which is frequently the case on such roads), then there is not time enough to fully tamp all low ties and low spots to proper surface. In such cases the tamping must be done partly from above by the trains instead of merely from below by the tamping bar. The jacks or raising bars are put under the part to be raised, as far from the finished part of track as is possible without causing the rail to sag between the jack and the finished track. The low track is then raised above the finished or desired surface by an amount varying from ¾ in. for small lifts to 1½ or 2 ins. for lifts of 4 to 5 ins. Earth is then shoveled under the ties and packed by the shovel blades and by bars or shovel handles at the joints. The jacks are then removed, the track sighted for surface, and rectified if necessary. The track should be lined up before the first train passes. The train will drive the ties down to surface, and after it has passed the surface should be finally sighted, and the ballast then well shoveled under the ends of the ties tamped and dressed to shape for proper drainage (Tratman, 2010).

On old track, the middle of the tie should not be tamped too hard or the track will have a tendency to rock laterally and the ties may be broken. When the track has once become center-bound in this way, it is difficult to affect a remedy without disturbing the entire track. On new track, the tie can be tamped for its entire length (Tratman, 2010). If down improperly there could be considerable work and expense.

When raising track (or changing grades) where good expensive ballast is used, there would be 6 ins. greater or less depth of ballast under the ties than the standard depth, and then the roadbed should first be raised by filling (or cut down), so as to retain a practically uniform depth of ballast and so prevent the waste of ballast as filling (Tratman, 2010).

In stone, slag or coarse gravel, a thorough tamping can rarely be done withouJt raising the track about 1 in. In sand, earth, cinders or poor gravel, a raise of 2 to 1 in. may be made by tamping without disturbing the bed of the tie (Tratman, 2010).

In renewing ties, gravel ballast is cut away from the ends of the ties and loosened along their sides. The spikes are then drawn, and the rails raised by jacks just enough to allow of the old tie being knocked out and a new one slipped in on the same bed. The ballast should not be dug out under the tie, unless the new tie is of greater thickness (which it should not be) because the less the tie beds are disturbed, the better for the maintenance of the track surface. This general rule may, however, be modified where only one or two ties are to be renewed in a rail length, but in this case a loosening of the side of the tie bed will usually enable the old tie to be taken out and the new one put in without much disturbance of the bed and without the disturbance of the adjacent track. With stone, slag, or coarse gravel ballast, which is liable to fall onto the tie bed when the tie is removed, it is necessary to dig out the ballast at one side of the tie, and to knock the tie sideways into this trench. Some foremen prefer this plan with earth or common gravel, but the amount of digging required is liable to disturb and loosen the ballast (Tratman, 2010).

Traffic

In laying new rails on a section there are two principal methods of practice. One method is to lay the new rails along the ends of the ties, to fully bolt up the joints, and then to take up the old rails and throw in the string of new rails. The other method is to lay in one rail at a time. There is also a compromise method, by which the rails are bolted together in lengths of five or six. The intermediate joints are left open to be bolted up when the rails are in the track. In either method, the details of the work and the distribution of the men depend largely upon the traffic, and vary considerably on different roads (Tratman, 2010).

Laying Rails in Strings method is not extensively used and is mainly done where work is short, only small gangs available, the traffic only moderately heavy, and the work having to be done between trains (Tratman, 2010).

Laying Single Rails, is done where the traffic is very heavy. The most satisfactory method, as a rule, is to lay a rail at a time, keeping the track all finished up behind the gang. This method requires a larger gang because six or eight men are required to lift and move single rails while two or four men with bars can easily handle a string of rails. The men in the larger gang also work somewhat at a disadvantage by being more crowded, but there is the advantage that every interval between trains can be utilized (Tratman, 2010). On double track, however, a certain length of track may be closed to traffic to allow the work being done).

In renewing ties, if the traffic is heavy, each tie should be tamped and have the outside spikes driven at once. Otherwise, a number of ties may be renewed in succession with one man going ahead to cut the earth or gravel from the ends of the ties, next two men pulling spikes, and then two men raising the track with jacks. If only one jack is to be had, the rail first raised should be blocked up, and the jack then put under the other rail (Tratman, 2010).

Speed

Railway systems can be classified in many ways and ‘speed’ is one of those ways. This section defines the term 'speed' in railway engineering and attempts a classification of railway systems based on their functionality, the track gauge, and the traffic (Pyrgidis, 2016).

The term 'speed' in a railway context may be defined in various ways, depending on the technical and/or operational context being considered. The following definitions are commonly used:

- Track design speed (Vd) is defined as the speed the track alignment and corresponding railway infrastructure as a whole (superstructure, substructure, civil engineering structures, systems/premises) has been designed and constructed. Thus, it is regarded as the maximum speed a train can safely and comfortably operate at on a given track. This speed is not related to any operational or track capacity constraints. It is desirable that the track design speed (Vd) be the same on all track sections of a railway corridor.
- Permissible track speed (Vmaxtr) is defined as the maximum speed on a railway track section at the time a given rolling stock is commissioned. This speed is determined by the Infrastructure Manager of a railway network taking in consideration the track ride quality as well as other performance aspects at the moment. The permissible track speed is directly related to the maintenance level of the track and the line as a whole.
- Maximum running speed (Vmax) is defined as the maximum speed developed by a particular train type on a given line while performing a scheduled route. This speed may either refer to a small segment of the line, or it may occure at the biggest part of the route.
- Operating speed (Vop) is defined as the speed that is developed at the biggest part of the route (e.g., at 2/3 of the route length) by a particular train type while performing a scheduled route. Passage speed (Vp) is defined as the constant speed with which a

train passes from a particular, characteristic segment of the line which is of small length, e.g., passing through a tunnel, passing through stations, etc.

- Instant speed (Vt) is defined as the speed with which a train passes from a specific kilometric point at a specific time.
- Commercial speed (Vc) is defined as the ratio of the length of a railway route (usually between the two terminals or between two important intermediate stations) to the time it takes to cover it including halt times at all intermediate stations and delays. Commercial speed always refers to a particular type of train and a given route.
- Average running speed (Var) is defined as the quotient of the length of a line segment (usually between two successive stations) to the time taken to pass this segment considering normal traffic conditions, e.g., no unforeseen delays. The average running speed always refers to a particular train type and a given line segment.
- Rolling stock design speed (Vrs) is defined as the maximum speed that, according to the manufacturer, can be developed by a particular type of locomotive, or with which a trailer vehicle can move. It can refer to the maximum speed that can be developed by a multiple unit of given formation taking into consideration the traction system (diesel or electric power), the hauled weight, the track geometry alignment design, and considering the track to be of very good ride quality.

The mathematical expressions generally apply:

$$V_{ar} = V_{maxtr} = V_d \quad (1)$$

Regarding speed, the quality of the railway infrastructure is secured when

1. Vmaxtr at individual track segments coincides with the track design speed Vd which corresponds to a particular traction system.

2. The average running speed Var is nearly equal to Vmaxtr. These two speed values cannot coincide and the value of Vmaxtr is greater. In regard to the combination of track and rolling stock, the design speed of the rolling stock (Vrs) must be slightly greater than Vd or at least equal to Vd.
3. In regard to the level of service and the run times, the maximum train running speed Vmax must be achieved for the longest part of the route (Pyrgidis, 2016).

Possession Time

Dao, Basten, and Hartmann (2018) proposed the model considering that the track accessible time for maintenance is limited. Planning of a minor possession, the maintenance window is 3–5 hr. is not difficult because minor inspections and repairs can be done at night or in a period between two consecutive trains. However, planning a major possession which often is limited to 1 or 2 days is more complex because it affects train operation and involves several parties including the rail infrastructure manager, train operating company, traffic control, and maintenance contractors. Thus, multiple and long possessions may have severe impacts on regular train timetables, and major maintenance and renewal jobs are often combined or clustered to reduce the total costs.

Dao, Basten, and Hartmann (2018) considered fixed track possession cost as one of the four cost factors in the component's life cycle. The others are maintenance and renewal cost, social-economic cost related to the effects of maintenance time on the train operation, and service life shortening cost due to the shifting of activities. The major differences are in the possession and service life shortening costs. The possession cost significantly drops when considering the clustering of maintenance activities. They found that when clustering of maintenance activities without possession time condition, the lowest number of possessions can be operated. However, it ignores the limitation of available possession time and violates the limitation of possession time. Thus, it may not be applicable or there will be a huge penalty when implementing it. Additionally, when different maintenance activities are clustered in the same time period, it is often seen that a component is maintained or renewed in a period that is earlier than its recommended time. In this case, the service life of the component is shortened compared to the service life when its recommended maintenance interval is used. Therefore, the authors also consider a service life shortening cost due to early maintenance of components (Dao et al., 2018).

Season

General improvements, tile drainage, reballasting, etc. can best be carried on from late spring to late autumn. All such work should be planned beforehand so that the track-may not be disturbed for reballasting just after the section gang has completed surfacing. Work trains and floating gangs for ditching, ballasting, widening cuts, etc., and special gangs on new interlocking plants, rearrangement of yards, repairing or building structures, etc. may be worked at any time from the end of one winter to the beginning of another. For the ordinary work on the sections no set rules or program of procedure can be formulated because the requirements vary in different sections of the country.

1. Surfacing: This work should be done immediately after tie renewals in the spring and attended to again before the winter. It should also be looked to immediately after the laying' of new rails so as to prevent the rails from being surface bent by trains running over them when they are not uniformly supported because it is almost impossible to

take out such vertical kinks. When new rails are laid, the track should be raised enough to allow all ties to be tamped to give an even bearing. The freezing of water in the ballast or roadbed in winter causes "heaving", the effect of which is to raise the track irregularly. Since frozen ballast cannot be tamped, shimming or blocking has to be resorted to in order to bring the track to surface (Tratman, 2010).

2. Renewing Ties: The new ties are usually distributed by work trains at convenient times during the winter so that all may be on the ground soon after the frost is thoroughly out of the roadbed. The work should be commenced as soon as possible after the frost has left the ground because the ballast is then loose and the crews can take advantage of the nice weather before the summer. Then by the time the heavy summer traffic begins, the new ties will have become well settled and the track will have a substantial bearing and will require but little maintenance. If the ties are put in late and the season is wet, they do not get properly tamped. That means that they may have to be shimmed in the winter. The renewal of the shims and fixing up of the roadbed in the spring then delays the new work of tie renewals (Tratman, 2010).
3. Setting Tie-Plates: Considerable economy in track work may be ensured by placing the plates on new ties for renewals before the ties are put in the track. This can be done by the section men in bad weather or during the winter (Tratman, 2010).

Others

A type of defects which occur on the running surface or the rail head is called rolling contact fatigue (RCF). Figure 8 shows the cross-section of railhead. Rail inspection and early detection of RCF are important because most of RCF crack should be removed in rail grinding campaigns (preventive, cyclical and corrective activities) during the whole rail service life. Rail wear, RCF, and plastic flow are major contributors of rail deterioration depending on the operational conditions (traffic type, speed, axle load, traffic density, rail/wheel profile and material, characteristics of bogie, track design, maintenance policy, weather and environment, etc.) and lead to the surface or subsurface initiated cracks on the rail. Fortunately, some of the cracks are removed by wear process during initial stages of crack development (Popović et al., 2013)

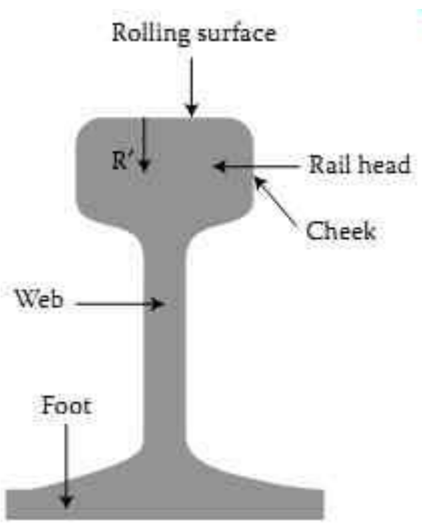


Figure 8: Railhead cross-section
Source: Pyrgidis, 2016

Through inspection process of HC defects, special attention should be drawn to the outer rail in curves: usual in curves with radius R ≤ 3000 m and most often in curves with R ≤ 1500 m. Surface fissures point out the fissures that already exist below the surface extending to certain depth and in certain direction inside the rail head. Furthermore, rail switches, rail weld zones, expansion joints, and sections with irregular track geometry should also be carefully visually investigated. (Popović et al., 2013)

Figure 9: Example 1 of RCF (shells defects)
Source: Office of Railroad Safety, 2015

Figure 10: Example 2 of RCF (flaking defects)
Source: Office of Railroad Safety, 2015

Most of the RCF defects can be addressed by surfacing. Example of RCF defects are demonstrated in Figure 9 (shells) and Figure 10 (flaking). This work is almost continually required for track maintenance. A common and troublesome cause of bad riding track is an irregular surface with sags, low joints, bent rails, and short depressions and humps in the roadbed. These defects are due to heavy loads, traffic, light rails, weak fastenings, poor ballast, insufficient tamping, rails out of level transversely on tangents, and generally faulty or insufficient work of maintenance. The remedy for this is surfacing or putting the rails and track in a uniform plane. In the general surfacing done each year, the track should be raised only just enough for proper tamping to bring up the low parts to a uniform surface with the track being raised out of a face only every four or five years. Mention may be made of the Patterson Surfacing Machine which has been tried experimentally and is intended to do away with tamping, as this necessarily disturbs the old bed of the tie to some extent (Tratman, 2010).

Standard and Regulation

RCM has been used extensively in the military aircraft (MSG-3 standard) and aerospace industries (SAE JA1011 standard). These standards provide evaluation criteria and standardized formats for analysis to design and develop maintenance programs.

. In European railway system, national safety regulations, state safety regulations, and technical specifications for interoperability (TSIs) are law and define the technical and operational standards that have to be met in order to satisfy the essential requirements and to ensure the interoperability of the European railway (Popović et al., 2020).

In order to complete the RCM standard, there are a number of quality management requirements contained within the ISO 9000 series of International standards (Cotaina et al., 2000). The example of other standards which define specific terms relating to maintenance and quality are stated as the following:

- The International Electrotechnical Commission (IEC 60-050-191) for reliability terms,
- NFX 60-010 for maintenance terms,
- ISO 9000 for quality model,
- ISO 8402 for quality terms, (Cotaina et al., 2000).

Another regulation is related to transportation of ‘dangerous goods’. The term 'dangerous goods' covers materials and objects that the transportation of which is allowed only under certain conditions. These loads are categorized according to their physical and chemical properties. Fluid and solid fuel, gas, explosives, nuclear material, polluting and corrosive materials are considered as dangerous loads. Activities related to transporting these products are legally established by international conventions and are conducted under strictly defined conditions of safety. The regulations applied to rail transport are COTIF/CIM/RID. Policies of dangerous loads railway transportation must abide by the following (Pyrgidis, 2016):

1. Creation of safe transport conditions: In case of an accident the extent of damage can be relatively higher than that caused by any other modes of transportation because of the massification of railway transport. Therefore, prevention of any incident is of the utmost importance. In this context, it is required that:
    - The condition of track superstructure used is really good to avoid derailment.
    - There is a special maintenance program and testing of the rolling stock to avoid derailment, material leakage, etc.

- The maintenance and repairing area of vehicles transporting dangerous goods is different from that of the conventional wagons. Special instructions for the repairing of vehicles are made and special areas are provided for cleaning empty tanks to avoid explosions, fainting, and fumes.
- Reception and distribution tracks specifically assigned to trains transporting dangerous goods are equipped with proper fencing, lighting, fire extinguishing, and sewage systems for protection of high-risk areas.

2. Special measures to protect the environment: The special design of the superstructure, e.g., slab track instead of ballasted track, at points of shunting tracks used by trains carrying dangerous loads regarding the protection of the groundwater in case of leakage (Pyrgidis, 2016):

Issues Related to Railroad Maintenance

Rail Degradation

The service life of rails depends especially on the operational loads and speeds on the railway lines as well as on the rail maintenance policy (Popović, Lazarević, Brajovic, & Gladović, 2014).

Track deterioration results in slower train speeds for safety reasons. This has a profound effect on operations. Reduced speeds also increase operating and capital expenses due to extra crew costs and reduced equipment availability. Additionally, slow speeds are not conducive to the shipment of time sensitive freight or passengers (Uzarski & McNeil, 1994).

Severe head wear distortion can alter the normal angle refraction of the ultrasonic beam from the transducer to such a critical level that the ultrasonic signals do not penetrate at the expected angle or to the expected location in the specimen. Therefore, it is possible that reflected sound beams normally associated with internal rail flaws may not be identified by the test system from the defective portion of the rail section. If the severity of the head wear characteristics is significant, it can impact the integrity of the test (Office of Railroad Safety, 2015).

Physical Degradation Factors

1. Dynamic Effects: A wide range of bearing and bending stresses in the track components come about not only because of the static mass of a vehicle, its wheelsets, and the cargo (freight or passenger), but also due to dynamic actions such as lateral centrifugal forces on curves, longitudinal acceleration and braking forces, rocking of the vehicle about 3 axes (roll, pitch and yaw), vertical inertial forces from the motion of the wheelset and its suspension, vibrational forces induced from imperfections in the rail surface (corrugations, joints, welds, defects) and in the wheels (flats and shells), and from the dynamic response of the track components to these actions. The consequences of the frequently large forces generated by these actions are many and varied. Fatigue cracking in rails, plastic flow or shelling out of the rail head, uneven wear of the rail head, cracking or splitting of sleepers, loosening of fasteners, grinding and redistribution of ballast, and variations in track alignments and gauge are the major deleterious effects. Such effects result in poor riding quality, reduced train speed, increased fuel consumption, potential derailment, increased maintenance, delays and reduced level of service, and loss of revenue in the longer term.
2. Train Speeds

3. Axle Loads: There are many other factors influencing the behavior of track and consequent maintenance activity required, such as ballast type and quality, ballast fouling, type and geometry of sleepers and rail pads, and the effect of defects in rails and wheels (Ferreira & Murray, 1997)

Rail Inspection and Monitoring

The effectiveness of rail inspection depends on the efficiency and accuracy of the inspection method and the necessary equipment. It also depends on the knowledge, skill, ability and experience of inspectors. Furthermore, it depends on the real conditions for implementation (temperature, visibility, contamination etc.) and on traffic management during rail inspection. False detections and undetected rail defects in inspection are an important issue and their reduction is a big challenge (Popović et al., 2013).

An optimal detection method for squats and head checkings should provide early detection of rail damage and reliable data about measured length, depth, and spatial position of fissures in rail head. However, this kind of method for non-destructive testing of rail in track does not exist so far (Popović et al., 2013).

Track inspection methods range from visual inspection to the use of sensors and sophisticated measuring systems for the identification of corrugation, measurement of track geometry, measurement of rail wear, and location of internal rail flaws (Uzarski & McNeil, 1994). Examples of the track inspection methods are including: 1) visual inspection; 2) automated rail flaw detection (ultrasonic or inductive methods) for invisible defects (Office of Railroad Safety, 2015; Popović et al., 2013; Uzarski & McNeil, 1994); 3) automated track geometry for problems such as variations in track gage, cross level, warp (twist or cross level deviation), profile, and alignment; 4) corrugation analyzers for long wave length undulations in the track that are not recorded by track geometry vehicles; and 5) rail profile analyzers to measure wear or identify areas of plastic flow by the use of intensity light of laser and cameras (Uzarski & McNeil, 1994). Figure 11 demonstrates how rail profile inspection system works and Figure 12 displays the actual inspection system under a car bogie.

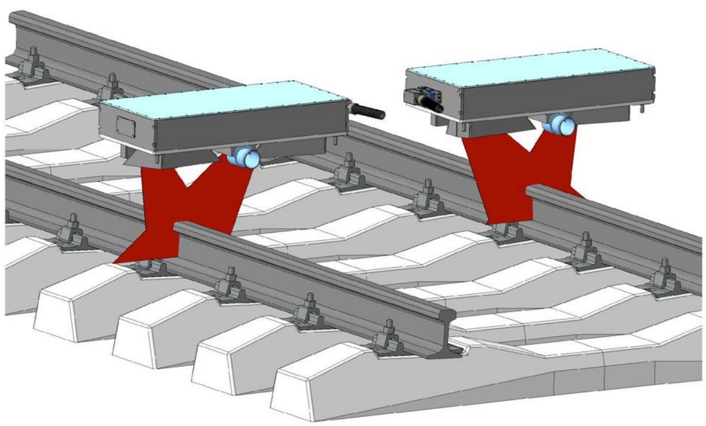


Figure 11: Rail profile inspection system

Source: https://tvema.com/639

Figure 12: Rail profile inspection system installed on the car bogie

Source: https://tvema.com/639

The primary technologies used for nondestructive testing on heavy haul lines are ultrasonic and induction test processes. The ultrasound technology is the most frequently used, and the induction is currently used as a complimentary system to ultrasound only (Office of Railroad Safety, 2015). Combination of ultrasonic and EC (one of many induction testing methods) inspection improves probability of early detection of RCF defects. This is the way to discover the most, but not all RCF defects (Popović et al., 2013). They are described as follows:

- Induction

  The basis for induction testing requires the introduction of a high-level direct current into the rail head establishing a magnetic field around the rail head. In the induction test process, the magnetic field is considered a region consisting of concentric lines of force perpendicular to the rail head. Once the magnetic field is established, it will remain constant in strength and shape as long as the rail weight, rail head contour, and current flow remain constant. As the current flows through the rail, any condition such as a defect, will distort the current path. The distortion of the current flow will also lead to a distortion of the associated magnetic field. It is this distortion of the magnetic field that is detected by the search unit. The signals received by the sensor unit are sent to the test system and evaluated to determine if they meet or exceed a set threshold. If the signals exceed the predetermined threshold level, the data is presented to the operator for interpretation as a potential defect (Popović et al., 2013).

  The example of induction testing method is Eddy Current inspection (EC). The advantages of EC rail inspection are: early detection of the initial fissures, (depth 0,2 mm), detection of fissures below the rail head surface, portability of testing device, no use of consumable materials, instant reading of measuring results, and possible integration of device in the recording cars and rail grinding trains. The vehicles are equipped with eight-channel devices for rail testing using the eddy current; four sensors on the left and four sensors on the right rail. Depth of defect can be calculated indirectly by measuring the depth of crack and angle of crack progression or by installing the EC device in the rail grinding train. It is not possible to measure the angle by using the EC method. This is a serious disadvantage of EC inspection method because depth of defect can only be measured indirectly. Besides, it is difficult to filter clearly the EC signal due to the effect of signal overlaps. It makes sense to combine the potential of a surface rail testing such as EC testing with a rail volume testing such as US testing (Popović et al., 2013)

- Ultrasonic

The range normally used during current flaw detection operations is 2.25 MHz (million cycles per second) to 5.0 MHz. If a condition is encountered of sufficient size and orientation that would offer a reflector to the ultrasound that is transferred into the rail, the ultrasound is then reflected back to the respective transducer. These conditions would include a rail head surface irregularity, rail geometry reflector (bolt hole drilling, weld upset/finish, rail end, etc.), or internal rail flaw. However, the base portion off center of the rail is currently not covered by current test systems. The information reflected back to the transducer is then processed by the test system and is recorded in the permanent test data on the coinciding display for that ultrasonic channel (Office of Railroad Safety, 2015). This method is not applicable for inspection of surface fissures at a small distance and at small angle towards the upper rail head surface. Also, the method does not provide precise measures in the narrow zone of rail gauge corner (Popović et al., 2013).

Visual inspection is governed by weather conditions and by traffic management during rail inspection. Also, this method should be improved using the detection with fluorescent penetrates, especially under poor seeing conditions in tunnels, but the rail surface needs to be clean. Unfortunately, lubrication of the outer rail in curves and soiled rails can negatively influence a visual inspection. Also, it could cause misleading results of ultrasound (US) inspection, video inspection and eddy current (EC) inspection. By combination of visual detection, ultrasonic and EC methods, the quality and reliability of the information increase significantly (Popović et al., 2013).

Maintenance

Rail maintenance such as rail lubrication, rail profile maintenance, and railroad internal track maintenance programs, greatly increases the life cycle of the rail. These practices are deterrents to the crack growth life of internal rail flaws. Without aggressive track maintenance programs, rail flaw development and failure will continue to be an issue and result in service disruption to the railroads (Office of Railroad Safety, 2015). Unfortunately, lubrication of the outer rail in curves and soiled rails can negatively influence a visual inspection. It could also cause misleading results of ultrasound (US) inspection, video inspection, and eddy current (EC) inspection (Office of Railroad Safety, 2015; Popović et al., 2013). In addition, lubricant deposited on the top of rail heads can cause problems with braking, acceleration, and wheel-spin. Hence, great care needs to be exercised in the use of lubricators to ensure that only flanges are lubricated (Bonnett, 2005).

Another case to demonstrate that sometimes maintenance lessen the performance of the component is wear due to grinding (Popović et al., 2013; Santa, Toro & Lewis, 2016). The natural and artificial wear rates were measured by evaluating the changes in the rail profiles before and after known periods of operation and rail grinding operations performed in the field. The artificial wear rates caused by rail grinding are around ten times higher than the natural wear rates caused by rolling sliding.

Maintenance tamping is the most effective way of restoring track geometry (Soleimanmeigouni et al., 2019). However, the impact from the insertion of the tamping tines into the ballast and the high squeezing force are sometimes cause particle breakage (Minsili et al., 2012).

In large and extensively used railway networks, such as those in the United States, United Kingdom, and continental Europe, maintenance planning is more challenging because a great amount of railway infrastructure is a mix of old and recently built assets that are often associated with a high demand for maintenance and under pressure to increase operation time (Dao et al., 2018).

Human Error and Systems Deficiency

Inspection and deciding on maintenance activities depend largely on operator decision. Any type of surface condition can be an influential obstacle in the detection of an underlying rail defect. Even in the best of circumstances with the most competent personnel jobs get hurried and tracks are covered in dirt and sand, mistakes are made in the inspection process (Tratman, 2010). If any doubt or uncertainty in the integrity of the test process is identified by the detector car operator concerning surface conditions, they have the option to record the rail section as an invalid test and report the location to the railroad company. It is the responsibility of the rail flaw detector car operator to properly identify the types of rail head surface conditions that can result in an improper or invalid test of the rail section in which the condition is contained.

Developing the right decision-making process, e.g., to maintain correct safety levels, is not only based on global or partial tests of the train but is also based on double control of actions carried out by the maintenance operators. For each action, a report is done by the person who performed it. Then, this report is checked verified by another person (Cotaina et al., 2000). Error prevention can also be inherent to the components since design process to assure the correction of the maintenance work. This is a well-known technique as “Poka-yoke” in quality term. To illustrate, the spike holes in the plates is designed to give the proper gage for trackman to fasten spikes through the holes into an underlying tie.

The surface irregularity can also impact the technologies currently used for flaw detection and limit their detection capabilities. Nondestructive test systems are designed to perform optimally on a perfect test specimen Therefore, it is important that emerging technology developments continue in an effort to alleviate the impact of adverse test specimen conditions (Office of Railroad Safety, 2015; Popović et al., 2013). Ultrasonic testing has been the primary nondestructive test (NDT) method used for internal rail flaw inspection. As with any NDT method, ultrasonic technology contains physical limitations that allow certain types of rail head surface conditions to be instrumental in influencing the detection of rail flaws. The predominant types of these mechanically formed conditions are referred to as shells, engine driver burns, spalling, flaking, corrugation, and head checking. Other conditions that are encountered are heavy lubrication or debris on the rail head (Office of Railroad Safety, 2015; Popović et al., 2013). It should be noted that the analyzed depth of defect is about 10 times less than the decarburization depth in the subsurface of the new rail as shown in Figure 13. This confirms the importance of preventive grinding of the new rails before putting them into service (Popović et al., 2020).

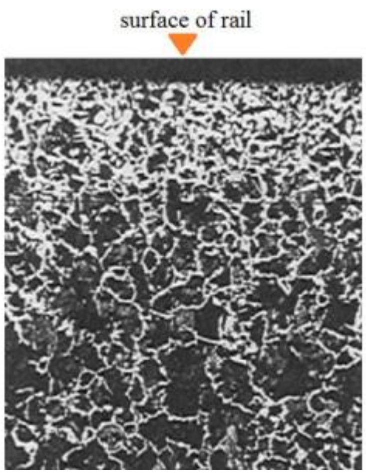


Figure 13: Decarburization depth up to 0.28 mm for the defect depth 0.03 mm

Source: Popović et al., 2020

Reliability-Centered Maintenance

Reliability and system safety analyses, drawing on techniques from engineering, statistics, risk analysis, human factors, and other fields, have been used to assess the functioning of systems in which both technology and people are involved, such as nuclear power plants and aircraft cockpit operations. In technical systems, analyses of system reliability are done for many reasons, including identifying and addressing problems during system design, understanding the likely future performance of the system under different conditions, and making cost-benefit judgments about specific alterations or repairs that might make the system's performance more predictable (Jackson, Faith & Willis, 2010).

A common feature in reliability analyses is the recognition that systems and their components do not function perfectly and that events or circumstances will inevitably arise that affect their ability to do so. The lowest level is the reliability of individual components of the system and what types of problems or events could affect the ability of individual components to function. The highest level is the reliability of the system which takes into account how the interaction of the various components might make problems with a single component more or less important with respect to the functioning of the system overall. If a single component plays many roles within a more complicated system, then even a small reduction in its performance might have a disproportionate effect on the performance of the system overall. Conversely, if multiple backups exist that make it possible to compensate for a component's failure, problems that affect the component might affect system function only a little, if at all (Jackson et al., 2010).

A number of different techniques can then be used to take estimates of the reliability of individual components and combine them to build estimates of the performance of the complex system assembled from those components. These techniques, which vary both in their difficulty and the types of approximations made, enable different types of system reliability assessments for different designs, evaluation, and analytical purposes (Jackson et al., 2010). In this research, the application of RCM methodology is being studied.

The core of an RCM analysis is a series of systematic approaches to systems functionality, failures of that functionality, failure effects, failure modes, and infrastructure affected by failures by the use of FMECA analysis, logic diagrams, maintenance optimization model, etc. This analysis aims at the maintenance task assignment of failure mode identified from the FMECA as well as maintenance implementation feedback and continuous improvement of the current maintenance program. The decision-making process is used in order to select the most appropriate task to maintain a system filtering the proposed classification of consequences through a logic decision tree (Carretero et al., 2003). One of the principles of RCM analyses is limited to the study of the main critical components. The expertise of the staff, tools like Pareto studies, critical matrix (with the FMECA principles), feedback data records, etc., are used. Finally, the preventive maintenance will be improved for the most important components and their most important failures (Carretero et al., 2003; Cotaina et al., 2000).

RCM Evolution

According to Moubray (1997), since the 1930's, the evolution of maintenance can be traced through three generations as shown in Figure 14. The first generation covers the period up to World War II. In those days industry was not very highly mechanized, so downtime did not matter much. This meant that the prevention of equipment failure was not a very high priority in the minds of most managers. At the same time, most equipment was simple and much of it was over-designed. This made it reliable and easy to repair. As a result, there was no need for systematic maintenance of any sort beyond simple cleaning, servicing, and lubrication routines. The need for specialized skills used in repair and maintenance were needed at lower level than that of today (Cotaina et al., 2000).

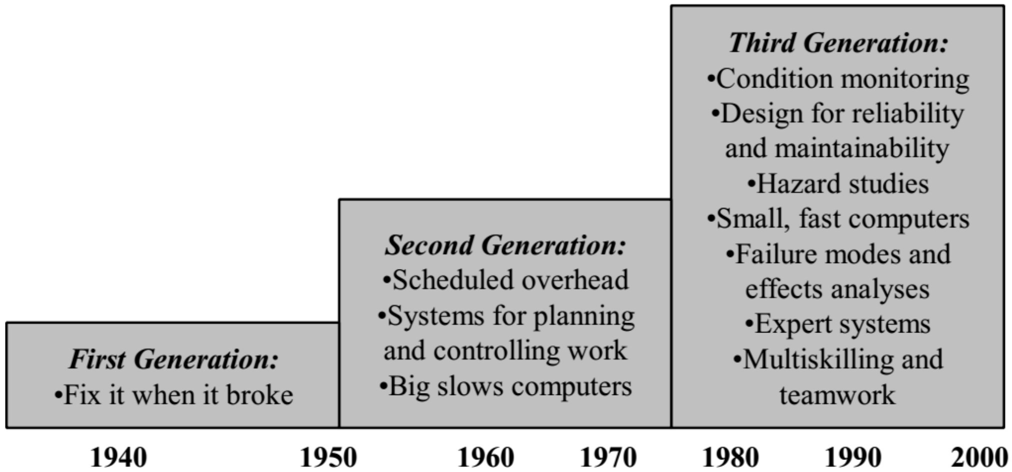


Figure 14: Evolution of RCM

Source: Cotaina et al., 2000

For the second generation, as this dependence grew, downtime came into sharper focus. This led to the idea that equipment failures could and should be prevented, which led in turn to the concept of preventive maintenance. In the 1960's, this consisted mainly of equipment overhauls done at fixed intervals. The cost of maintenance also started to rise sharply comparatively to other operating costs. This led to the growth of maintenance planning and control systems. These have helped greatly to bring maintenance under control and are now an established part of the practice of maintenance. Finally, the amount of capital tied up in fixed assets together with a sharp increase in the cost of that capital led people to start seeking ways in which they could maximize the life of their assets (Cotaina et al., 2000).

Finally, for the third generation, since the mid-seventies, the process of change in industry has gathered even greater momentum. The changes can be classified under the headings of new expectations, new research, and new techniques. Downtime has always affected the productive capability of physical assets by reducing output, increasing operating costs, and interfering with customer service. By the 1960's and 1970's, this was already a major concern in the mining, manufacturing, and transport sectors. In manufacturing, the effects of downtime are aggravated by the world wide move towards just-in-time systems where reduced stocks of work-in-progress mean that quite small breakdowns are now much more likely to stop a whole plant. In recent times, the growth of mechanization and automation has meant that reliability and availability have now also become key issues in sectors as diverse as health care, data processing, telecommunications, and building management. Greater automation also means that more and more failures affect our ability to sustain satisfactory quality standards. This applies as much to standards of service as it does to product quality. More and more failures have serious safety or environmental consequences. In some parts of the world, the point is approaching where organizations either conform to society's safety and environmental expectations or the entity ceases to exist. This adds an order of magnitude to dependence on the integrity of physical assets. It goes beyond costs and becomes a simple matter of organizational survival. At the same time as our dependence on physical assets is growing, so too is the cost to operate and compete successfully. To secure the maximum return on the investments efficiency and processes become extremely important. One component of this is the rising cost of maintenance as a proportion of total expenditure. In some industries, it is now the second highest or even the highest element of operating costs. As a result, in only thirty years it has moved from almost nowhere to the top of the league as a cost control priority (Cotaina et al., 2000).

Apart from civil and military aeronautic sectors, the application of the RCM methodology is not a statutory obligation. For this reason, a great number of methods for the development of maintenance programs based on reliability are currently available. Some of these methods are the subject of books and specialized software. The selection of the level analysis depends of the objectives fixed by the company and also availability, economic aspect, constraints, etc. (Cotaina et al, 2000).

RCM Process

In large systems with a high level of resource availability, e.g., historical data, expert, time, steps in the RCM can be more complicated. The MSG-3 method is an internationally recognized standard on which the modern usage of RCM is based. This standard was initially established for the commercial aviation industry but has now been proven and accepted as a methodology used in wide range of industries. The steps in undertaking an RCM analysis in the MSG-3 method is briefly presented as the following (Cotaina et al., 2000):

- Defining the system and/or subsystem boundaries,
- Defining the functions of each system or subsystem,
- Identifying functionally significant items (FSI),
- Identifying the pertinent FSI functional failure causes,
- Predicting the effects and probability of these failures,
- Using a decision logic tree to categorize the effects of the FSI failures,
- Identifying applicable and effective maintenance tasks which comprise the initial maintenance program,
- Redesign of the equipment or process, if no applicable tasks can be identified,
- Establishing a dynamic maintenance program which results from the routine and systematic update of the initial maintenance program and its revisions, assisted by the monitoring, collection and analysis of in-service data (Carretero et al., 2003).

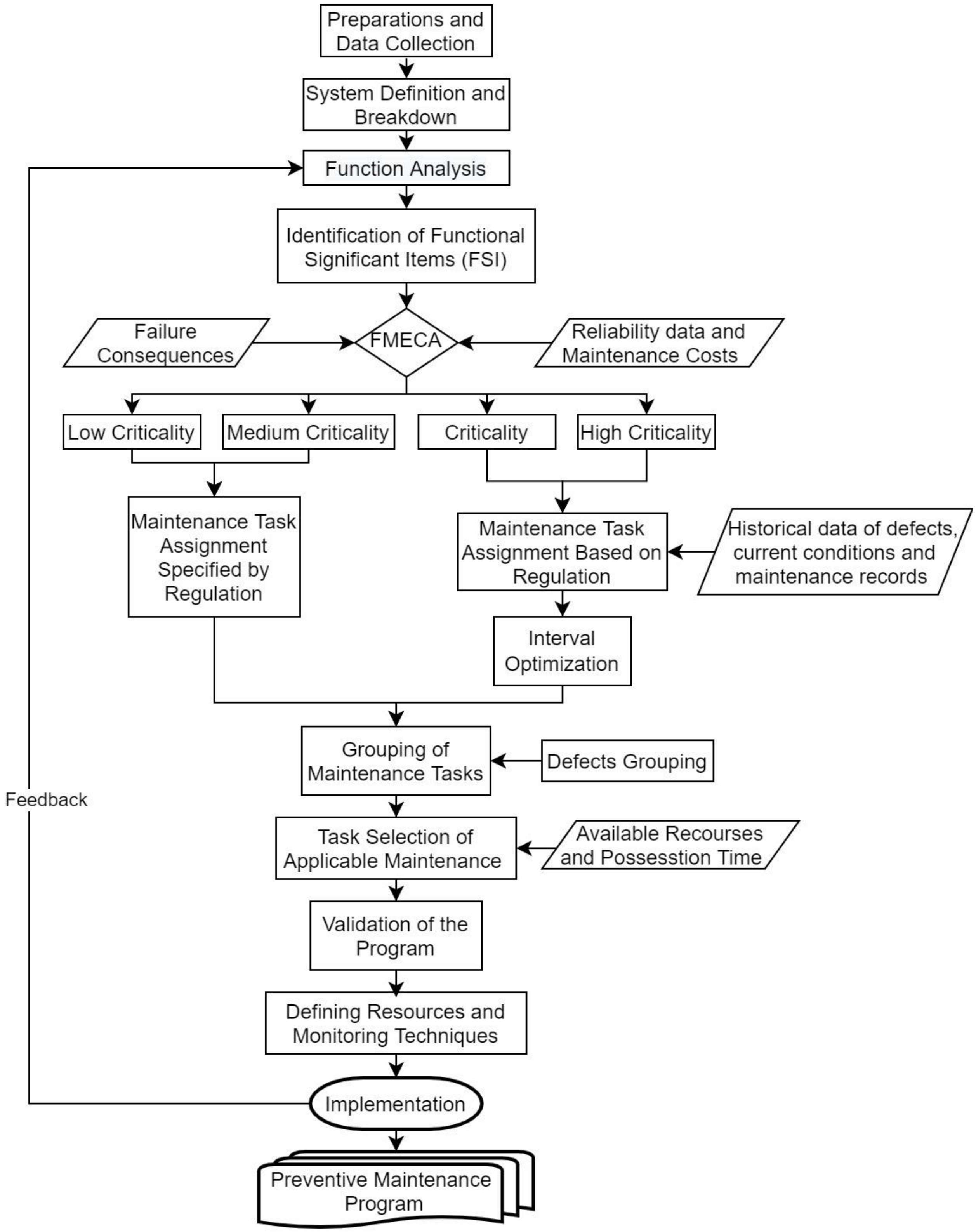


Figure 15: Steps of the RCM in railway application

As shown in Figure 15, the steps of implementing the RCM systematic approach can be identified in larger detail. The processes begin with preparation and data collection, following by system definition and breakdown, function analysis, and identification of functional significant items (FSI). Then, significant functions will be analyzed in the next step which is FMECA analysis. In FMECA process, failure modes are classified in to four classes by computing criticality number from failure consequences and reliability data. Only critical and highly critical failure mode classes will be performed in interval optimization step. The last parts of RCM are grouping of maintenance tasks, task selection, validation, defining resource and monitoring techniques, and finally implementation, respectively. RCM is an iterative process which means feedback from implementation will always be analyzed so that the processes will always be updated from function analysis to documentation. Therefore, PM program will also be continuously developed.

The RCM implementation calls on many data and supports relating to production, quality, and maintenance. All along these steps involved groups must determine objective priority and validate results of each phase in order to continue without over diversifying their work (Cotaina et al., 2000).

RCM is a very useful tool in industries with strong constraints regarding users and safety. However, in spite of being a standardized approach, applying the RCM is diverse. It can be adapted to particular constraints and requirements of the industry because each company has different maintenance policy and mandatory obligation in terms of safety, economics, and environmental effects (Cotaina et al., 2000).

System Breakdown and Data Collection

Before performing further analysis, system selection, and data collection are the preliminary process of RCM analysis. First of all, the list of the system components was determined which divided system infrastructure into lower levels. Table 2 provides the examples of system breakdown which, in this case, begins with track as the subsystem of the railway system.

Table 2: Example of system breakdown

No.	Subsystem	No.	Component	No.	Subcomponent
1.	Track	1.1	Rail	1.1.1	Rolling Surface
				1.1.2	Railhead
				1.1.3	Check
				1.1.4	Web
				1.1.5	Foot
		1.2	Sleeper (Tie)	1.2.1	Tie
				1.2.2	Tie plate
		1.3	Spike (Fastener)		
		1.4	Ballast		
		1.5	Sub Ballast and Sub Structure		

The next step is to collect data related to the above selected system. This will provide information necessary for the further analysis, i.e., FMECA, maintenance task assessment, maintenance program optimization, task selection, and other related analysis in the entire RCM program.

The FMECA requires different kind of data and documents of each component that constitute the system. To study and identify components and their failure mode, the following information is required: functional specification, failure history, manuals, functional block diagrams, conditions in which the asset was used, and so on. The factors effecting selection of a critical system are mean time between failures (MTBF), total maintenance cost, mean time to repair (MTTR), reliability, availability, etc.

In addition, in order to determine the maintenance tasks and programs to be done as well as program improvement, the various information need to be gathered; for example, requirement for equipment and system, including regulatory requirement and system functional requirement, downtime, safety level, reliability data, and existing maintenance program including its performance, feedback, and failure rate.

Function Analysis

Analysis of the system functions is the primary step in the FMECA process. The same table that will be illustrated in FMECA section is presented for the first time in this section. However, only function and functional failures are the elements considered in this stage.

Functions of component “rail “are:

- Primary function: The rails provide a continuous level surface for train movement with minimal friction against the wheels.

- Secondary function: The rails enable trains to run safely at their operational speed.

Significant Function Selection (or Critical Component Research)

Selection Logic provides a means for selecting those functionally significant items (FSI) that are worthy of analysis. FMECA is a time consuming approach because not only qualitative data are included in the analysis but also quantitative data and criticality calculation. This is the reason why only the FSI will progress to the next RCM process.

Figure 16 shows the Selection Logic diagram which is used to determine significant functions and non-significant functions. The significant functions are worth analyzing and are the functions whose failures adversely affect safety, environment, operations, economics, and so on. Selection of functions at the proper level of detail will improve not only the effectiveness of the RCM analysis in the short-term but also the effectiveness of the resulting preventive maintenance program in the long-term (Cotaina et al., 2000).

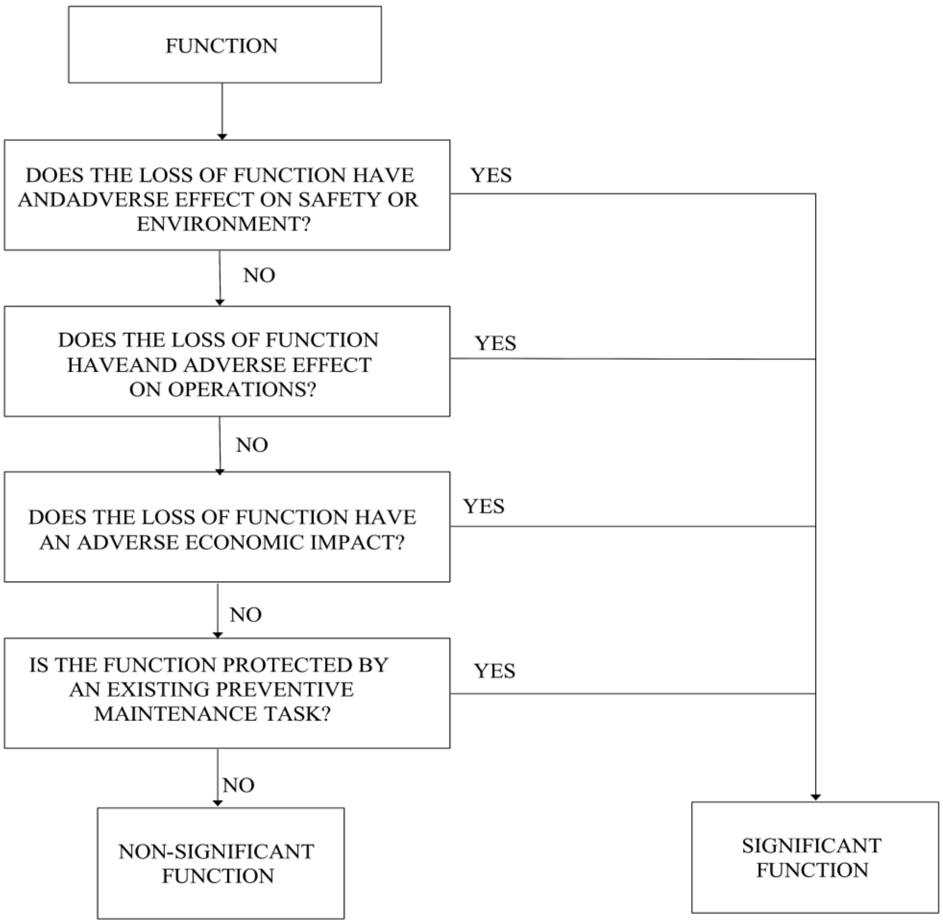


Figure 16: Selection logic diagram for significant function

Source: Cotaina et al., 2000

Qualitative and semi-quantitative criticality analysis is performed in significant function selection. Cotaina and Conan (2019) used semi-quantitative criticality analysis two times in this step: first time is to define the critical level of the section, and second time is to define the critical level of the component before choosing component to perform FMECA analysis. However, in this paper, I do recommend using the selection logic diagram instead of criticality analysis to find the right significant function because railway is a complicated system with enormous sections and components. It would take too many resources and a vast amount of wear on the rest of the RCM process. Criticality analysis can be applied in the RCM only one time in FMECA process.

Failure Mode Effects and Critically Analysis (FMECA)

FMECA is a structured approach commonly used in both maintenance and reliability analysis. The dominant failure modes of the identified FSI are identified in this process. Determining maintenance strategy is then achieved through an explicit scrutiny of failure modes and failure causes.

Requirement for equipment and system, including regulatory requirement and system functional requirement, are necessary to identify all the portions of FMECA process. Table 3 describes the most important portions of the FMECA analysis and the example of input in the analysis of "rail" component in railway tracks.

Table 3: Definition and example of FMECA analysis

FMECA of rail	Definition	Example
Function	Primary function: design operation (outcomes which contribute to goals or objectives)	The rails provide a continuous, level surface for train movement with minimal friction against the wheels.
	Secondary function: performance besides the primary functions (mostly related to, e.g., safety, environment, comfort of passenger)	The rails enable trains to run safely at their operational speed.
Functional Failure	The inability of an asset to fulfill one or more intended function(s) to a standard of performance that is acceptable to the use.	Unable to provide level surface, Friction exceeds the minimum, Restricted speed is reduced, An accident occurred.
Failure Mode (Failure Cause)	A cause of functional failure	Wear, corrosion, fatigue, cracking, loose fastener, temperature, water, improper design, improper maintenance
Failure Effect	The consequence of a functional failure	Delay, asset damage, injury, fatality, environment issue, cost

It is noteworthy that a function can have multiple functional failures, and each functional failure can have multiple failure modes. In FMEA and FMECA, failure modes can be identified to different level of detail. Different levels are appropriate in different situations. This following example demonstrates the different levels of detail identified to describe failure modes. For example, in functional failure "A. Unable to provide level surface", the failure mode can be assigned into 5 levels: A.1. Irregularity of the surface, A.1.1. Track geometry deterioration, A.1.1.1. Irregularity of ballast, A.1.1.1.1. Ballast and substructure settlement, and A.1.1.1.1.1. Improper maintenance. However, when FMECA is applied in the RCM analysis, failure modes are considered at the specific cause of failure in the lowest level of detail, which is "improper maintenance" in the example.

Combining root cause failure analysis (RCFA) to find failure mode in RCM is also recommended in some research (Afefy, 2010; Carretero et al., 2003). If an area in which RCM has been completed still experiences some failures, some failure mechanisms have been missed. This is a good technique to detect hidden failures and to achieve new stages of reliability. Solving a root cause eliminates not just one, but also eliminates the recurrence of a multiplicity of problems because the deepest root causes have been corrected (Carretero et al., 2003).

As mentioned before, FMECA requires criticality analysis, to evaluate how component failures impact several criteria, e.g., safety and environment, maintenance costs, availability of the system, in order to systematically rank component or subsystem for the purpose of maintenance tasks prioritization, spare parts management, maintenance program development, and reliability improvement initiatives. There are three different methods used to perform critical analysis: qualitative, semi-quantitative, and quantitative method (least to most complex).

First, in qualitative analysis, the criticality matrix (risk matrix) is adopted to rate the criticality of the failure mode in the case of insufficient data for quantitative analysis. Criticality matrix is a means of assigning failure mode a criticality rating based on the probability of the failure occurrences and the severity or consequence of the failure effects. There are different criteria that consist in consequence consideration, depend on each organization focus and emphasis. Thus, the matrix consists of the combination of one or more criteria on the X axle and the probability of the occurrence on the Y axle as seen in Table 4.

Table 4: The example of criticality matrix

Rank	Likelihood	Likelihood Definition					
6	Frequent	One or more failure occurred annually in the same section					
5	Probable	One or more failure occurred annually in the system					
4	Occasional	Several failures occurred during the system life circle.					
3	Remote	One failure occurred during the system life circle.					
2	Improbable	Several failures occurred a few time in the industry.					
1	Incredible	No or One failure occurred in the industry.					
Consequence Related to Safety		Consequence Definition	No injury or first-aid injury	Minor Injury (short term)	Major injury (long term)	Single Fatality	Multiple fatalities
		Consequence	Insignificant	Minor	Moderate	Major	Catastrophic
		Rank	1	2	3	4	5

The level of risk matrix commonly varies from 3x3 to 5x5 levels. In this case, 5x6 (with 5 categories of likelihood and 5 categories of severity) is selected because the sensitive data is involved in the analysis due to different impact levels which require different handling. Therefore, a detailed classification is required for the accuracy of the risk analysis.

Qualitative criticality category and their actions (Cotaina & Conan, 2019):

- Intolerable (red): Shall be eliminated
- Undesirable (orange): Shall only be accepted when risk reduction in impracticable and with the agreement of the railway authority or the safety regulatory authority, as appropriate
- Tolerable (yellow): Acceptable with adequate control and with the agreement of the Railway authority
- Negligible (green): Acceptable without the agreement of the Railway authority

For the semi-quantitative method, it does not measure the precise quantity of each criticality criteria. The difference from the qualitative method is that each criticality criteria is expressed as an estimated value from the scale from 1 to 4. The estimated values are the result of brainstorming by a team that includes operators, managers, maintenance people, etc. The example of main criticality factors and their value are expressed as Figure 17:

Factor	Description	Value 1	Value 2	Value 3	Value 4
Technology	Kind of technology of the line or section	Mechanic	Electro-mechanic	Electric	Electronic
Traffic density	Number of circulation per day	[1,20]	(20,60]	(60,200]	>200
Revenues	Revenues obtained from exploitation	Low	Medium	High	Very high
Availability	Number of hours that the line must be available per day	6	12	18	24
Exploitation	Number of passengers or dangerous freights	Low	Medium	High	Very high
Maintainability	Maintenance process complexity	Low	Medium	High	Very high
Costs	Costs associated to maintenance	Low	Medium	High	Very high
Environmental risk	Risk of environmental damage generated by an installation failure	Low	Medium	High	Very high
Safety risk	Risk of people damage generated by an installation failure	Low	Medium	High	Very high

Figure 17: Criticality factor and value for line and section

Source: Carretero et al., 2003

Some explanations of the information in the chart are explained: if value 4 is assigned to traffic density factor, this means more than there are more than 200 trains operate per day. In the same way, value 3 means between 201 and 60 trains operate per day, value 2 means between 61 and 20 trains operate per day, and finally, value 1 means not greater than 20 trains operates per day.

However, it is impossible to define all of them numerically. For example, maintenance costs are very different for each company. To easy criticality analysis, each company is allowed to tailor the methodology with their own values, grading from 1 to 4, low to very high. The meaning of each value is factor-dependent, but it can be seen as a scale from less to more critical. In most cases, the importance of each factor is not the same. Therefore, a weight for each factor is added to accommodate this issue. For this reason, criticality is mostly affected by the factors and the company policy criteria to define the weights. The criticality equation is equal to (Carretero et al., 2003):

$$C = (\sum_{i=1}^{n} \frac{W_i}{\sum_{j=1}^{n} W_j} F_i$$

where;

C is the criticality number

F is the value of factor

W is the weight of each factor

n is the number of factors involved in the computation of the criticality

After the criticality number of the failure mode is computed, the classes are introduced to classify the level of criticality in 5 categories from A to E, lowest to highest criticality categories as in Table 5. In some cases, the categories can be divided into 3 or 4 classes based on qualitative judgment. However, since the criticality came from estimated value on a scale from 1 to 4, the criticality does not reflect the exact value of failure mode criticality, and therefore, it is only approximation.

Table 5: Criticality classes

Class	Description of the class
E	Highly critical failure mode: must peruse the rest processes of the RCM analysis.
D	Critical failure mode: should peruse the rest processes of the RCM analysis.
C	Averagely critical failure mode: might continue to the rest of RCM process.
B	Not very critical failure mode: might continue to the rest of RCM process.
A	Not critical failure mode: no further analysis is required.

Another way to perform criticality analysis is the quantitative method. The failure effect factors may differ in this method because in quantitative criticality analysis, only factors that can be measured in value are used. The criticality equation from MIL-STD-1629 is equal to:

$$C_m = \beta \alpha \lambda_p t$$

where;

C_{mode} is criticality number for the failure mode

β_{mode} is conditional probability that the failure effect will result in the identified criticality classification, given that the failure mode occurs.

α_{mode} is failure mode ratio

λ_p is part failure rate

t is duration of applicable mission phase

Example of actual criticality form is shown on the next page in Figure 18 and 19.

FAILURE MODE EFFECTS & CRITICALITY ANALYSIS
SYSTEM (RADAR)

SEP 15, 1989 PAGE 1

ANALYST: R. GREENBURY REPORT FOR PART NO. AA1582

F.ID	PARTS INCLUDED	F. RATE	FUNCTION DESCRIPTION	F-MODE & CAUSE	RATIO	DET. METHOD	COMP. METHOD	SRU EFFECTS (LOCAL)	LRU EFFECTS (NEXT)	SYSTEM EFFECTS (END)	S. IND	CR
BA	U41,1/4U25,1/ 4U17,VR1,VR2, C5,C17,C30, R25,R36,2/9U26 1/9U27,2/7U	.4195	GENERATES AND CONTROLS WIDTH MODULATED PULSES TO PHASE A BRIDGE AMP.	INCORRECT PHASE A OUTPUT TO BRIDGE AMP	1.00	BIT	NONE	UNEVEN DRIVE TO AZ MOTOR	VE-UNEVEN ANTENNA DRIVE OUTPUT	DR-ANTENNA POSITIONING AND TRACKING DEGRADED	3D	.524

Figure 18: Example of actual FMECA report

Source: Luthra, 1991

CRITICALITY ANALYSIS REPORT
SYSTEM (RADAR)

DEC 4, 1989 PAGE 1

ANALYST: D. BUECHLER

REPORT FOR PART NO. AA1385

F.ID	F.RATE	FAILURE MODE RATIO	SAFETY INDEX	FEB (BETA)	OP.TIME	CRITICALITY
AA	1.2773	.50	3D	.50	2.50	.79831
AB	1.2773	.50	3D	.50	2.50	.79831
BA	.0105	.40	3D	.50	2.50	.00525
CB	.0558	.40	3D	.50	2.50	.02790
DB	.0537	.40	3D	.50	2.50	.02685
EA	1.2085	.50	3D	.50	2.50	.75531
FA	.0106	.40	3D	.50	2.50	.00530
GB	.0430	.40	3D	.50	2.50	.02150
HB	.0410	.40	3D	.50	2.50	.02050
IA	.0501	.80	3D	.50	2.50	.05010
IB	.0501	.20	3D	.50	2.50	.01253
JA	.1026	.80	3D	.50	2.50	.10260
KA	.1009	.90	3D	.50	2.50	.11351
	TOTAL FOR: 3D					2.73798
BB	.0105	.60	4D	.50	2.50	.00788
CA	.0558	.60	4D	.50	2.50	.04185

Figure 19: Example of criticality in FMECA report

Source: Luthra, 1991

The output of this FMECA is the list system functional failures which are rated by the criticality of them. Pareto analysis can be conducted and select the highest criticality in the top 20%. A caution in FMECA analysis is that each component does not necessarily have the same functionality. It varies from usage to time, and so the FMECA analysis of the same component will be different each time. Therefore, all new functional failures, effect mode, and functional effect must be specified.

RCM Decision Logic, Task Evaluation, and Maintenance Task Selection

The decision logic tree analysis used for identifying applicable and effective preventive maintenance tasks is one which provides a logic path for addressing each FSI failure. The decision logic tree uses a group of sequential YES/NO questions to classify or characterize each functional failure. Two levels are apparent in the decision logic:

- The first level requires an evaluation of each functional degradation/failure for determination of the ultimate effect category, i.e. evident safety, evident operational, evident direct cost, hidden safety, and hidden non-safety or none.
- The second level takes the failure causes for each functional degradation/failure into account in order to select the specific type of tasks (Carretero et al., 2003).

Cotaina et al., 2000, stated that Decision Logic requires that the following elements be considered for each failure mode being analyzed:

- Consequences of failure (safety, environmental, operational, economical).
- Visibility of a functional failure to the operating crews.
- Visibility of reduced resistance to failure.
- Age-reliability characteristics of each item.

- Economic trade-off decision based on a comparison of the cost of performing a preventive maintenance task to the cost of not performing the task.

The RCM Decision Logic Diagram is shown in Figure 20.

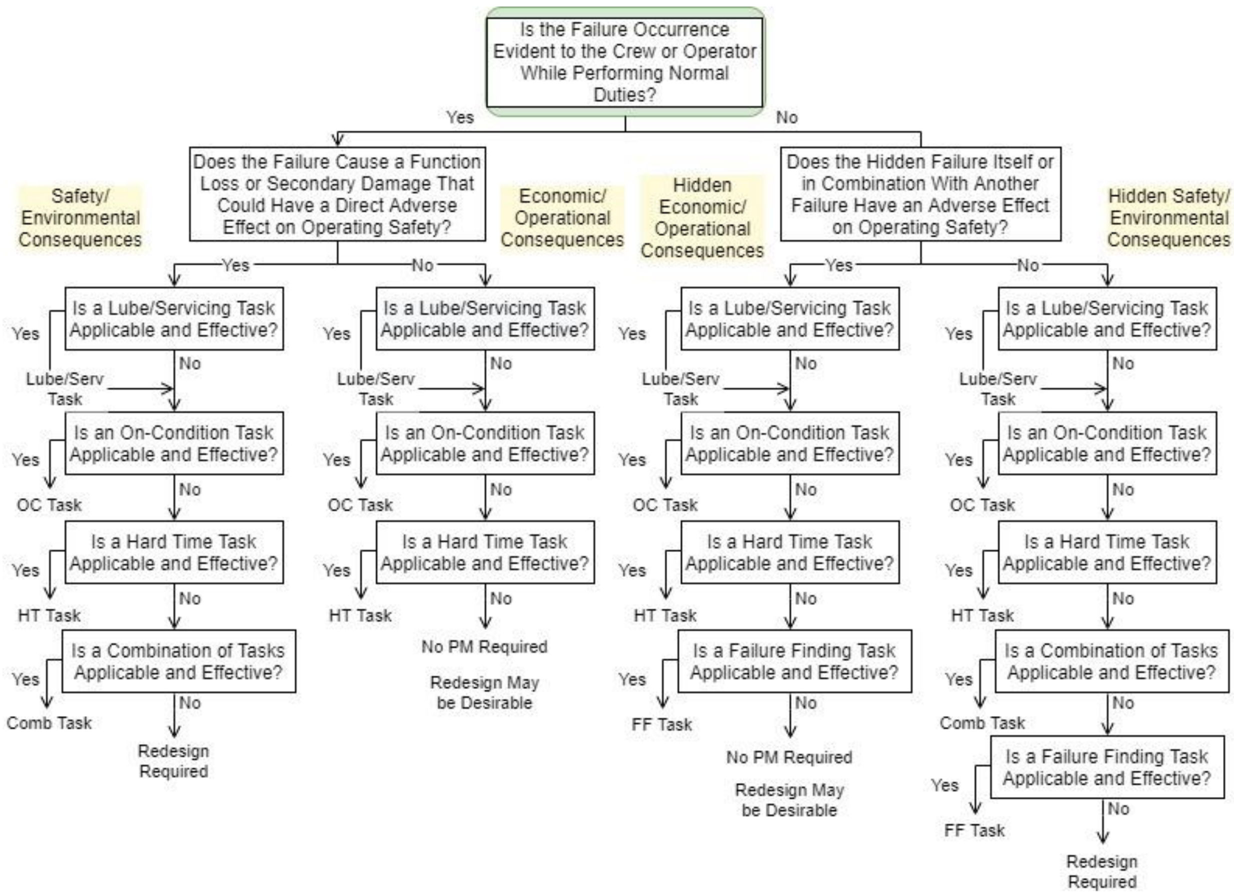


Figure 20: Decision tree for maintenance task selection

Adapted from Cotaina et al., 2000

The decision logic tree identified six types of scheduled tasks: lubrication/ service tasks, on condition tasks, hard time tasks, failure finding task combination of tasks, and redesign. Only two branches, the Hidden Safety/ Environmental Consequences and the Hidden Economic/ Operational Consequences, contain proposal for Failure Finding tasks. The output of this decision tree is the most applicable and effective maintenance task to eliminate or lessen the failure mode consequences.

Carretero et al. (2003) adapted the logical decision tree to include also the system status, and not only criticality, to choose the maintenance tasks as shown in Figure 21. A decision like this cannot be obtained from the traditional RCM methodology because only functional features, and not state of systems, are considered. The classical RCM only detects structural or design failures but not the status of systems that might cause security issues. If the failure or the status of the system might affect safety with a certain probability, the only solution recommended is 'restoration' of the whole system.

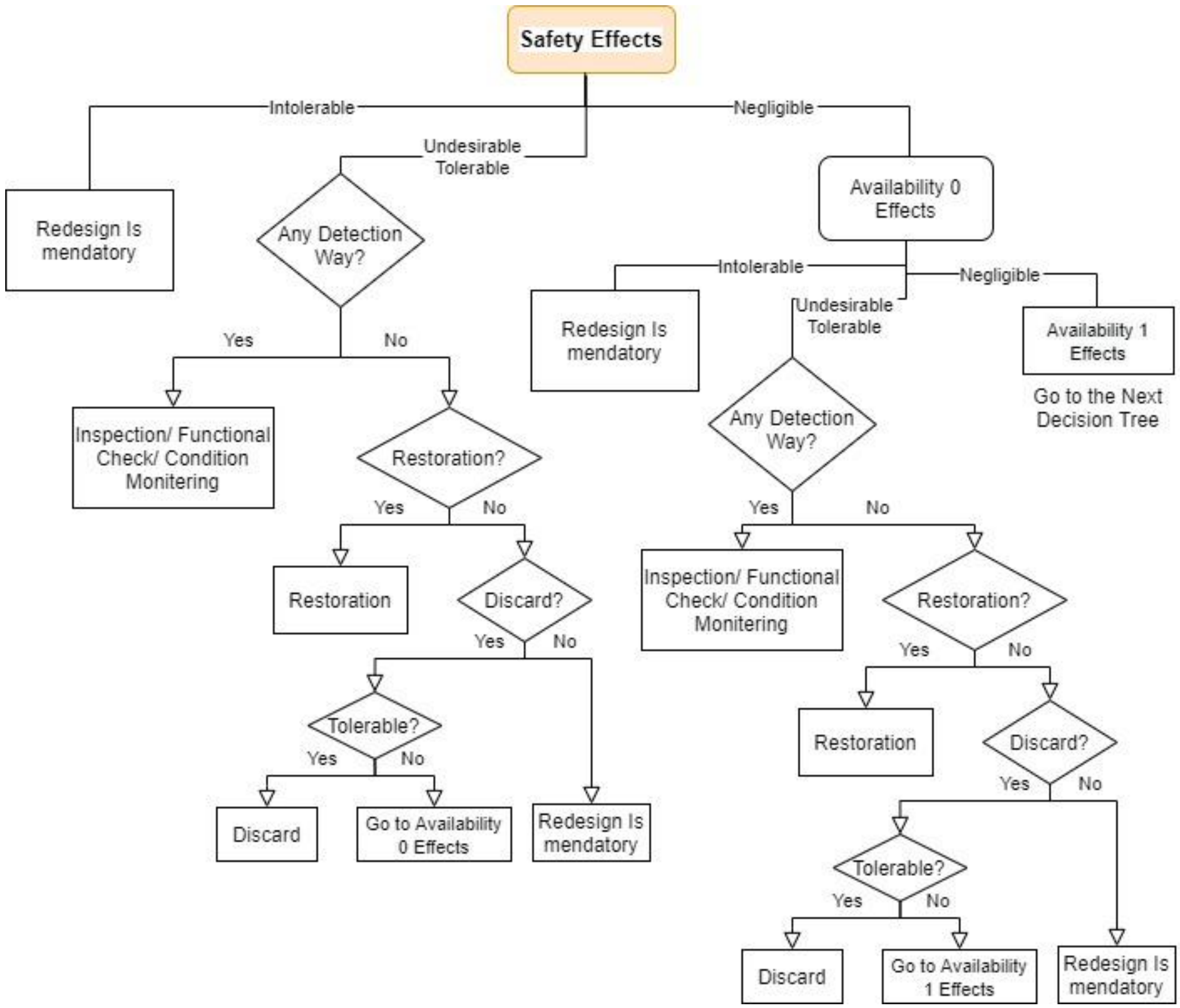


Figure 21: A decision tree considering state of the system

Adapted from Carretero et al., 2003

If failure does not concern safety, the remainder criteria are then filtered for environmental risk, availability, punctuality, and costs. If several suitable maintenance tasks are found, the cheapest maintenance task is chosen. Thus, costs is the last criteria to classify the maintenance tasks, with a branch of the logical decision tree adapted to get the most efficient maintenance task (Carretero et al., 2003). The decision tree should be modified to demonstrate the application of the methodology.

In Figure18 and Figure 19, the maintenance activities which are the result from going through decision trees are planned maintenance tasks which currently in use. Another goal of the RCM method, besides assigning the applicable tasks for critical failure modes, is to revise and optimize maintenance programs. The next process in RCM is to review and revise the existing maintenance programs by failure investigate.

Refining and Optimizing Maintenance Strategy

The best way to determine the optimal maintenance program is to anticipate the right time to perform the right tasks for certain failures. This relies on historical data with time dimension such as failure rate and service life in order to form a pattern for each failure mode. The purpose of this process is to improve existing maintenance tasks. After applying decision logic for task selection, this analysis could be performed to ensure that the current tasks are still applicable and most effective for those critical failure modes.

In this section, three subsections are described as examples of optimization strategy. This includes degradation model to optimize maintenance interval, grouping of maintenance activities, and cost model. The aim of this section is to present some basic ideas involved in analyzing the effective maintenance program.

Degradation Model

The failure rate of a component or an item can be represented in a graph model called the bathtub curve. Most methods and approaches to maintenance analysis involve the concept of hazard rate which is widely used in reliability engineering. The bathtub curve describes a particular form of the hazard function composed of three parts as shown in Figure 22. The bath tub curve indicates that the number of failures and maintenance costs will be reduced if the item is maintained before running into a certain part of the curve.

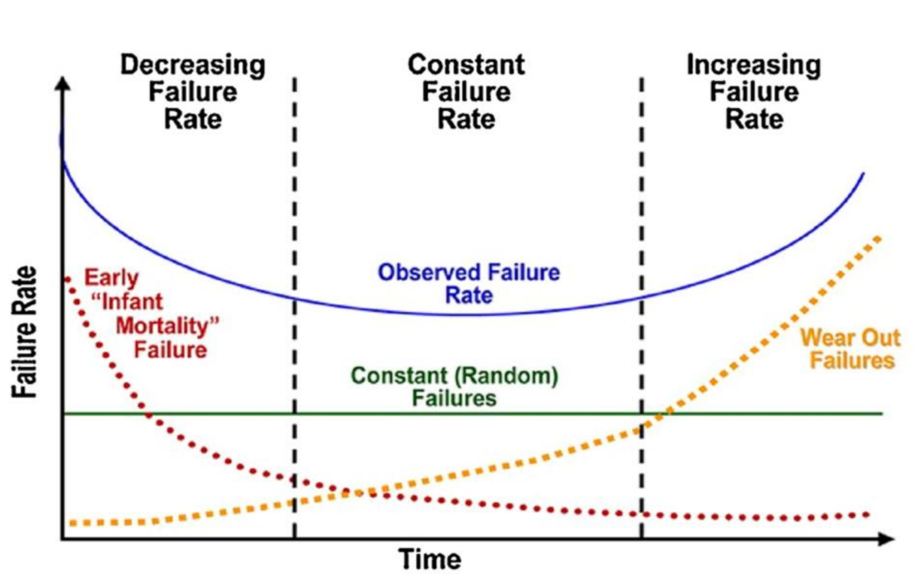


Figure 22: The bathtub curve with the three main causes of failure
Source: Maisonnier, 2018

The first part is a decreasing failure rate, known as early failures or infant mortality; the second part is a constant failure rate, known as random failures; and the third part is an increasing failure rate, known as wear-out failures.

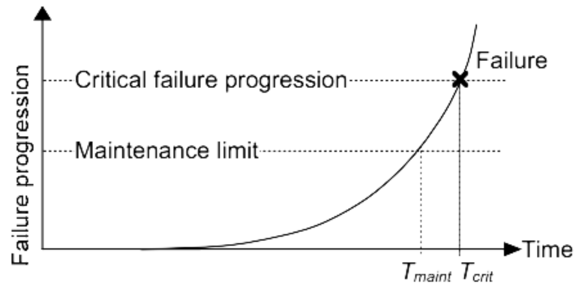
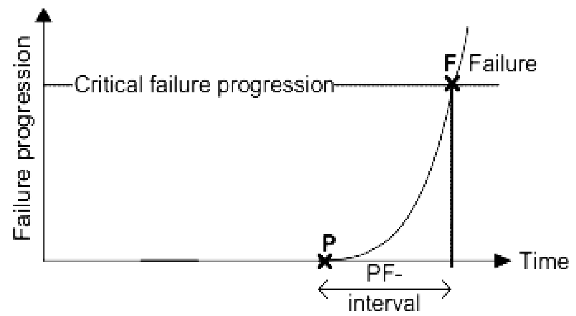
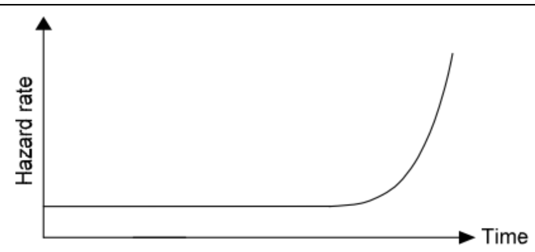
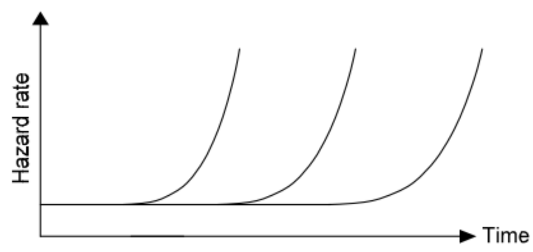
Infant mortality failures occur typically when a component is first introduced in the system or during the early operation of a new system. In this period, early failures are caused by initial weakness or defects in material, poor quality control, inadequate manufacturing methods, human error, initial settlement, etc. Early failures show up early in the life of an item and are characterized by a high failure rate in the beginning that keeps decreasing as time elapses. Other terms for this decreasing failure rate period are burn-in period, break-in period, early failure period, wear-in period and debugging period (Lyngby et al., (2008).

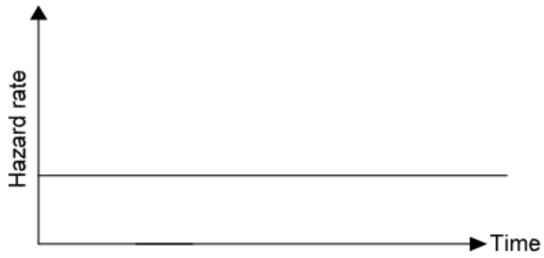
The rate of random failures corresponds to failures occurring during the useful life of the product or system. The hazard rate is fairly constant. There are various reasons for the occurrence of failures in this period: power surges, temperature fluctuations, human errors, overloading, etc. Screening techniques or maintenance practices cannot eliminate these failures. By making the design of the item more robust with respect to the environments, the effects could be reduced (Lyngby et al., (2008).

After the useful life the wear-out period starts when the failure rate increases. The causes for these 'wear-out' failures include wear due to aging, fatigue cracking, corrosion and creep, short designed-in life of the maintenance point under consideration, poor maintenance, wear due to friction ,incorrect overhaul practices (Lyngby et al., (2008), or when the product or system operates beyond its design lifetime (Maisonnier, 2018).

Not all products or systems follow the bathtub failure rate curve, but it is applicable to most prototype components or systems. In reliability engineering, the three distribution functions of a bathtub curve can be analyzed using Weibull charts that correspond to continuous probability distribution functions (Maisonnier, 2018). Table 6 shows typical failure characteristics.

Table 6: Typical failure characteristics

Failure Characteristic	Description
	Observable, gradual failure progression. It is possible to detect the failure prior to failure.
	Observable fast failure progression. The Point P is the first point in time where it is possible to reveal an emerging failure. When the failure progression exceeds a limiting value, a failure (F) occurs. This model is often referred to as the PF-model.
	Aging, defined point of time for an increasing hazard rate, z (t). In the Weibull model, assume an aging parameter (α) in the order 3 to 4.
	Aging, undefined point of time for increasing hazard rate. In the Weibull model, assume an aging parameter (α) in the order 2.

Failure Characteristic	Description
	The hazard rate is time independent (random failures, aging parameter 1). This is typical for components where a failure is caused by external shocks, e.g., for some electrical components.

Adapted from Økland et al, 2013

Figure 23 presents the global time (approximately 30-60 years) applies in the bathtub curve when the entire system is considered. On the y-axis the dimension is failure intensity, or performance loss. This reflects that the important issue now is the number of failures per unit time or general loss of performance independent of what has happened up until time t.

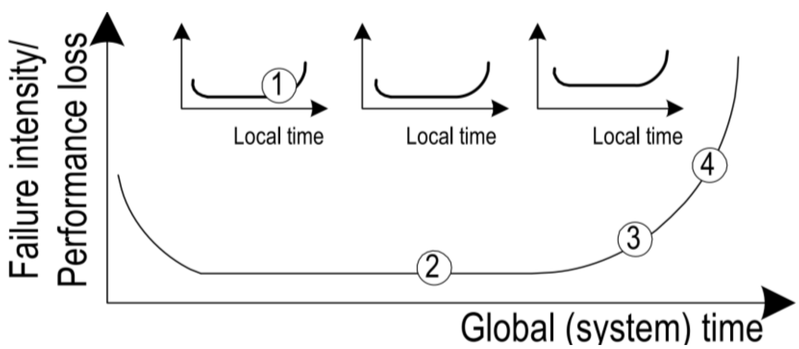


Figure 23: The bathtub curve with 4 steps of maintenance

Source: Økland et al., 2013

Lyngby et al. (2008) identified the numbers (1), (2), (3) and (4) for where the following maintenance situations apply:

(1) Point maintenance is related to the explicit failure modes of a maintenance point. The failure modes investigated in FMECA and maintenance selection in RCM analysis is relevant.

(2) Life extension maintenance is the idea of carrying out maintenance that prolongs the life length of the section such as rail grinding.

(3) Maintenance carried out in order to improve performance but not renewal such as adding ballast to improve track quality and reduce the need for track adjustment.

(4) Complete renewal of major maintenance points or sections.

Grouping

Grouping of maintenance activities is often based on an idea of executing related tasks with similar intervals at the same time to save so-called setup cost. The setup cost is the cost that could be "shared" between several activities if conducted simultaneously (Økland et al., 2013).

Dao et al. (2018) focused on planning a major possession in rail track system which is a complex operation. It affects train operation and involves several parties including the rail infrastructure manager, train operating company, traffic control, and maintenance contractors. Thus, multiple and long possessions may have severe impacts on regular train timetables, and major maintenance and renewal jobs are often combined or clustered to reduce the total costs. Figure 24 presents the maintenance interval and Figure 25 shows how the schedule changed after clustering.

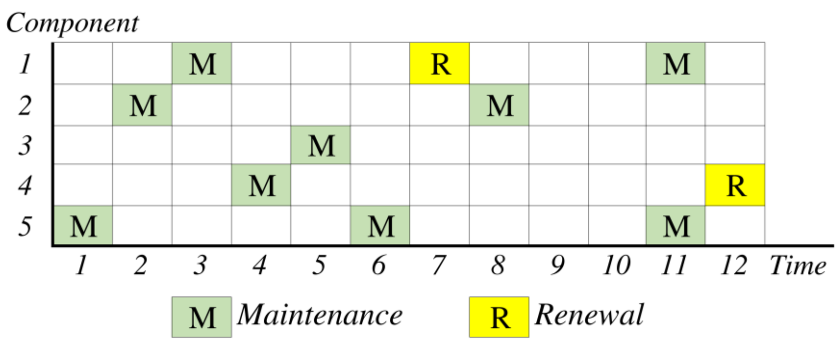


Figure 24: Original maintenance schedule

Source: Dao et al. (2018)

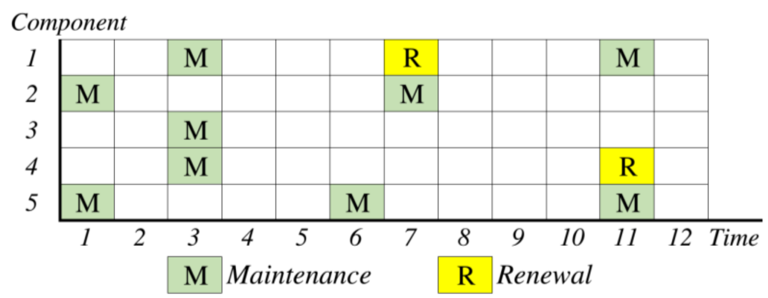


Figure 25: Maintenance schedule after clustering

Source: Dao et al. (2018)

The results display the number of possessions in 12 time periods. The original schedule has 10 possessions, and after clustering it has been reduced to only 5 possessions. In the same way, schedule A has lower possession costs of approximately 34.5%. However, in this case, the service life of the component is shortened compared to the service life when recommended maintenance interval is used. Thus, a service life shortening cost due to early maintenance of components is also considered as shown in Figure 26.

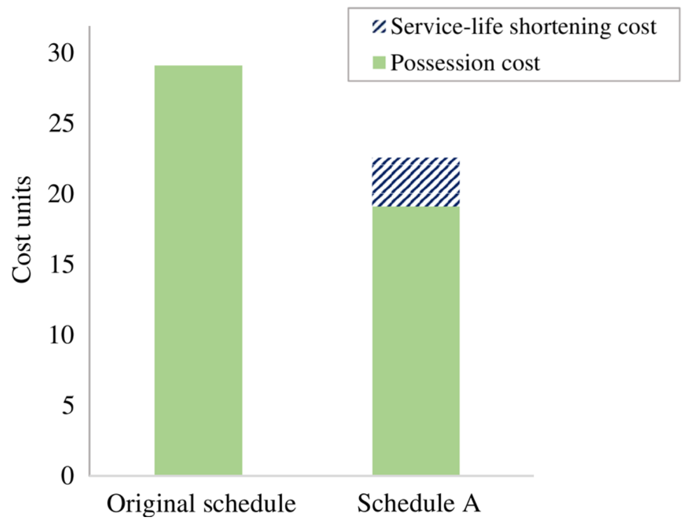


Figure 26: Possession cost and service life shortening cost

Source: Dao et al. (2018)

As you can see, despite service life shortening cost in schedule A (with clustering), the total cost of possession and service life shortening cost are still lower in schedule A. Therefore, in this paper, it can be concluded that clustering maintenance activities in the rail track system benefits with the reduction of the total cost.

Another way to use grouping to support the optimizing maintenance plan is component clustering. Đorić et al. (2017) applied clustering approach (the groups of tracks with similar attributes) to the scheduling PM problem under a given cost-structure that assumed a fixed cycle length. The authors employed variable neighborhood search metaheuristic to solve clustering.

For the real data, there are 14 elements (tracks) and a period of eight months. The schedule of the maintenance is presented in Figure 27 and it is done for each element individually.

Figure 27: Maintenance schedule before track clustering

Source: Đorić et al. (2017)

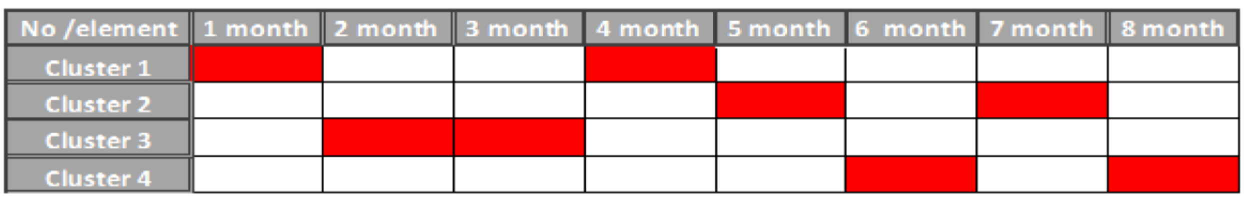


Figure 28: Maintenance schedule after track clustering

Source: Đorić et al. (2017)

After applying the cluster approach to the 14 elements, they obtained four clusters. For these four clusters, a new schedule for the maintenance activities was developed, presented in Figure 28. When comparing the two schedules, they discovered 22% savings in maintenance scheduling cost for clusters.

Life Cycle Cost

In general three different phases can be distinguished during the total life cycle of a technical system: purchase phase; user phase; and disposal phase (Cotaina & Conan, 2002). During the purchase phase, the list of requirements and the budget of costs are stated. This purchase phase will decide which system will be used (Cotaina & Conan, 2002).

The user phase is the time span in which the system is used for its intended purpose. During this phase different expedient resources are needed to keep the system operational and in good condition. Maintenance of the machine is an important factor during the user phase (Cotaina & Conan, 2002).

At the end of the economical or technical life, the system will be discarded. In this disposal phase, not only is the disposal itself is important, but also the issues regarding recycling, environment, and legislation have to be taken into consideration (Cotaina & Conan, 2002).

During the user phase two important types of costs are operating costs and maintenance costs. The operating costs consist of costs like labor, energy supply, and material costs. The maintenance costs can be divided into scheduled maintenance costs and unscheduled maintenance costs. Both types of maintenance costs can be further subdivided into costs such as material, labor, tools, production-loss, etc. Figure 29 details the three phases and in particular the operating and maintenance costs (Cotaina & Conan, 2002):

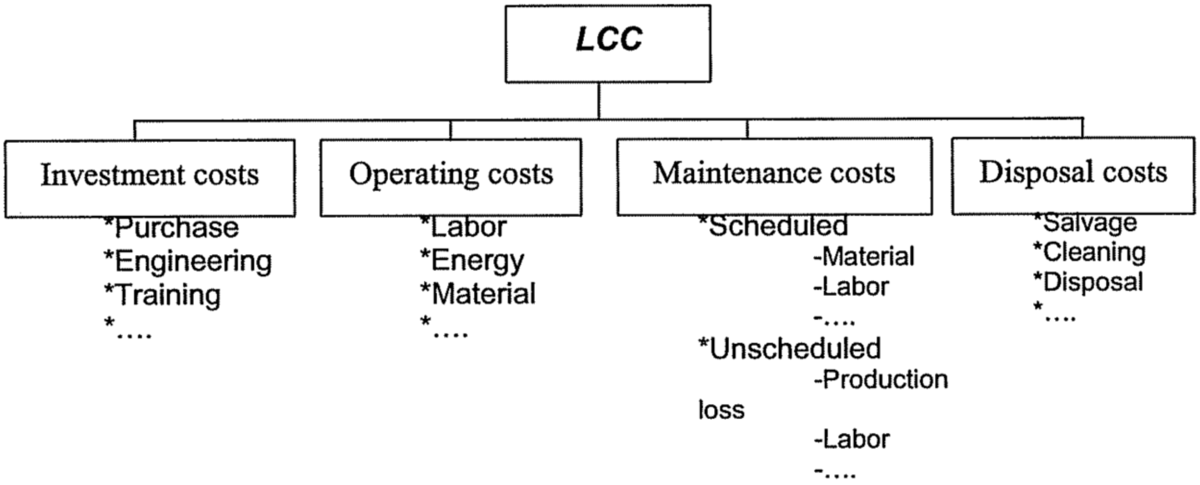


Figure 29: LCC breakdown

Source: Cotaina & Conan (2002)

Factors Considered for Maintenance Strategy Determination

This section compiles all the factors to consider and the information to gather when performing optimizations.

1. Operation
    - Track operation design, e.g., speed restriction, types of vehicle operates.
2. Time
    - Repair time (or, possession time, or MTTR), MTTF, service life, failure rate
3. Cost
    - Maintenance Cost (PM cost, CM cost, inspection cost, servicing cost, operating cost, set up cost)
    - Renewal cost
    - Costs of residual failures

- Production/punctuality loss
- Accident costs
- Cost due to degradation(extra maintenance and operation)
- Service life shortening cost due to the shifting of activities
- Fixed track possession cost
- Social-economic cost
- Salvage cost

4. Resource
    - Financial resources
    - Capacity
    - Knowledge (e.g., the number of well-trained operators)
    - Supporting System
    - Inspection and Maintenance Technology
    - Inventory
5. Regulation
    - Maintenance policy
    - Safety regulatory
    - Related standard
6. Others Aspects
    - Maintenance effectiveness
    - Environment
    - Existing maintenance plans

- Historical habits Infrastructure
- Punctuality

Other Optimization Research

Budai, Huisman, and Dekker (2004) have developed a mathematical formulation and Heuristic to schedule railway PM activities; Lyngby et al. (2008) introduced Markov failure model to optimized the maintenance/renewal program; Garciamarquez, et al. (2003) applied the Kalman Filter for detecting irregularities in railway turnout; Ruijters et al. (2016) adopted fault maintenance trees (FMTs) with Monte Carlo simulation techniques to predict failure rates.

Decision Support Systems

Ferreira & Murray (1997) focus primarily on track degradation issues and related maintenance decision support tools. Adequate databases for track data include asset condition and maintenance history. They are the building blocks for track management decision support systems. Efficient maintenance planning requires an up-to-date, locally relevant decision support tools. Their article focuses on three vital aspects which need to be considered when developing such a tool:

1. The physical factors which affect track deterioration and costs of rectification or renewal;
2. The scope and capabilities of existing track degradation and maintenance planning models; and
3. The parameters which must be included in the optimization processes to take into account engineering as well as business related factors (Ferreira & Murray, 1997).

Figure 30 represents in a hierarchical form the main categories of models which have been developed. At one end of the hierarchy are the detailed or 'microscopic' models dealing with the forces on specific track components (e.g., rail, sleeper, and ballast). Such models, which are usually based on engineering judgment or empirical evidence, can be used mainly for design purposes. At the other end of the spectrum are decision support systems for maintenance planning and overall system simulation models used mainly by rail planners to undertake cost-benefit analysis of proposed new corporate or operational strategies. Between two main levels there exists a large number of models which attempt to predict component deterioration given engineering relationships established by 'microscopic' models or by engineering 'judgment' (Ferreira & Murray, 1997).

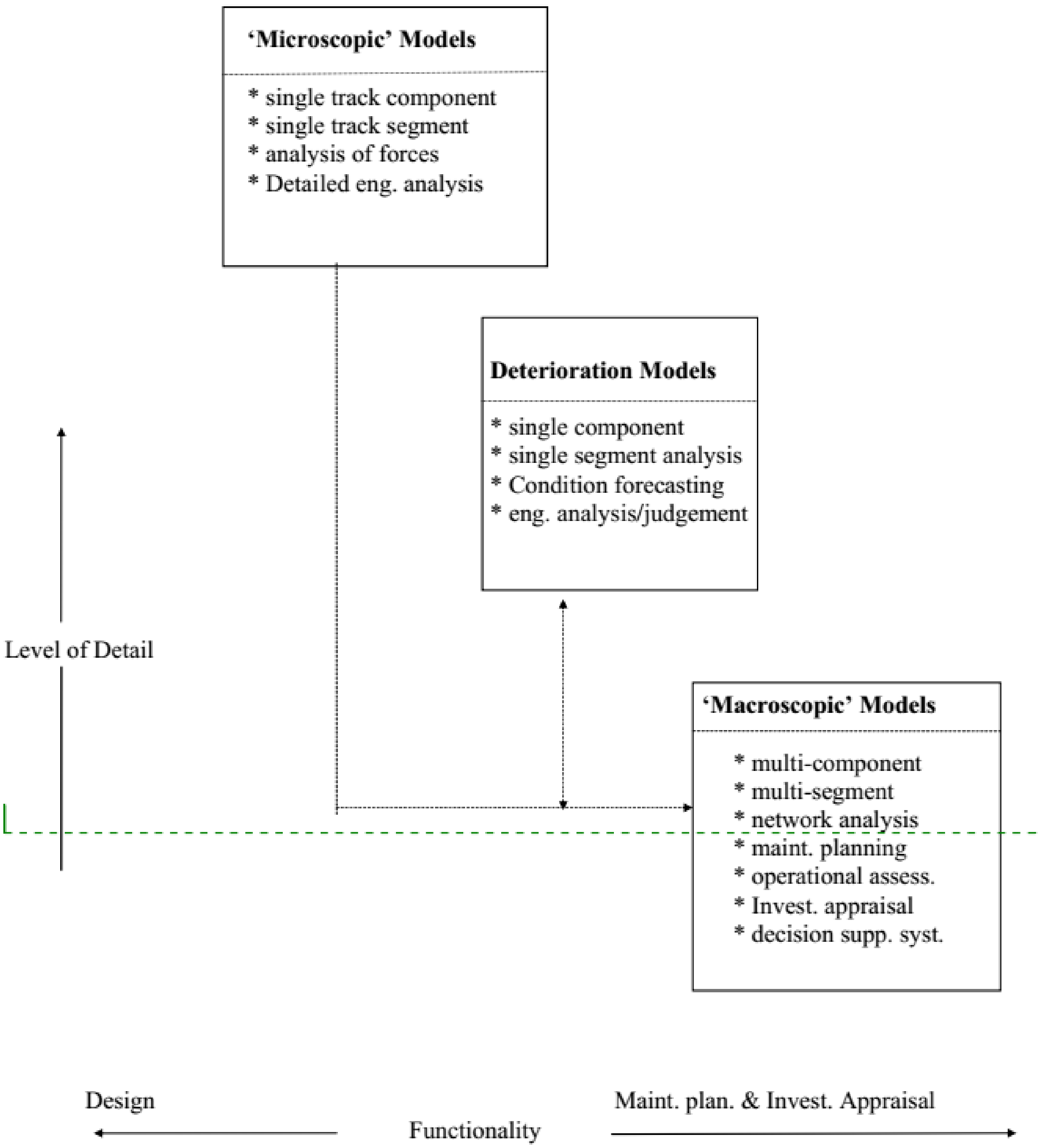


Figure 30: Track modeling hierarchy

Source: Ferreira & Murray (1997)

As shown in Figure 31, an important element of a decision support system model is the explicit inclusion of risk variables to deal with the impact of track condition on train transit times, reliability of arrivals, accident/derailment potential, rail business revenue, and effect of train delays. The optimization model needs to take into account the dynamic nature of the relationship between track condition and maintenance activity. The overall aim is to develop a tool which can be used to evaluate alternative maintenance strategies and to prioritize maintenance effort across a railway network. The model can also be used to investigate the benefits of changes in traffic characteristics (e.g., higher speeds and axle-loads); changes in track design standards; changes in track components (e.g., rail, sleeper types); and to simulate the likely effect on business activity of changes in track maintenance policies and design standards. As well as track degradation modules, the maintenance optimization model includes business risk such as delay costs, accident and derailment risk. (Ferreira & Murray, 1997).

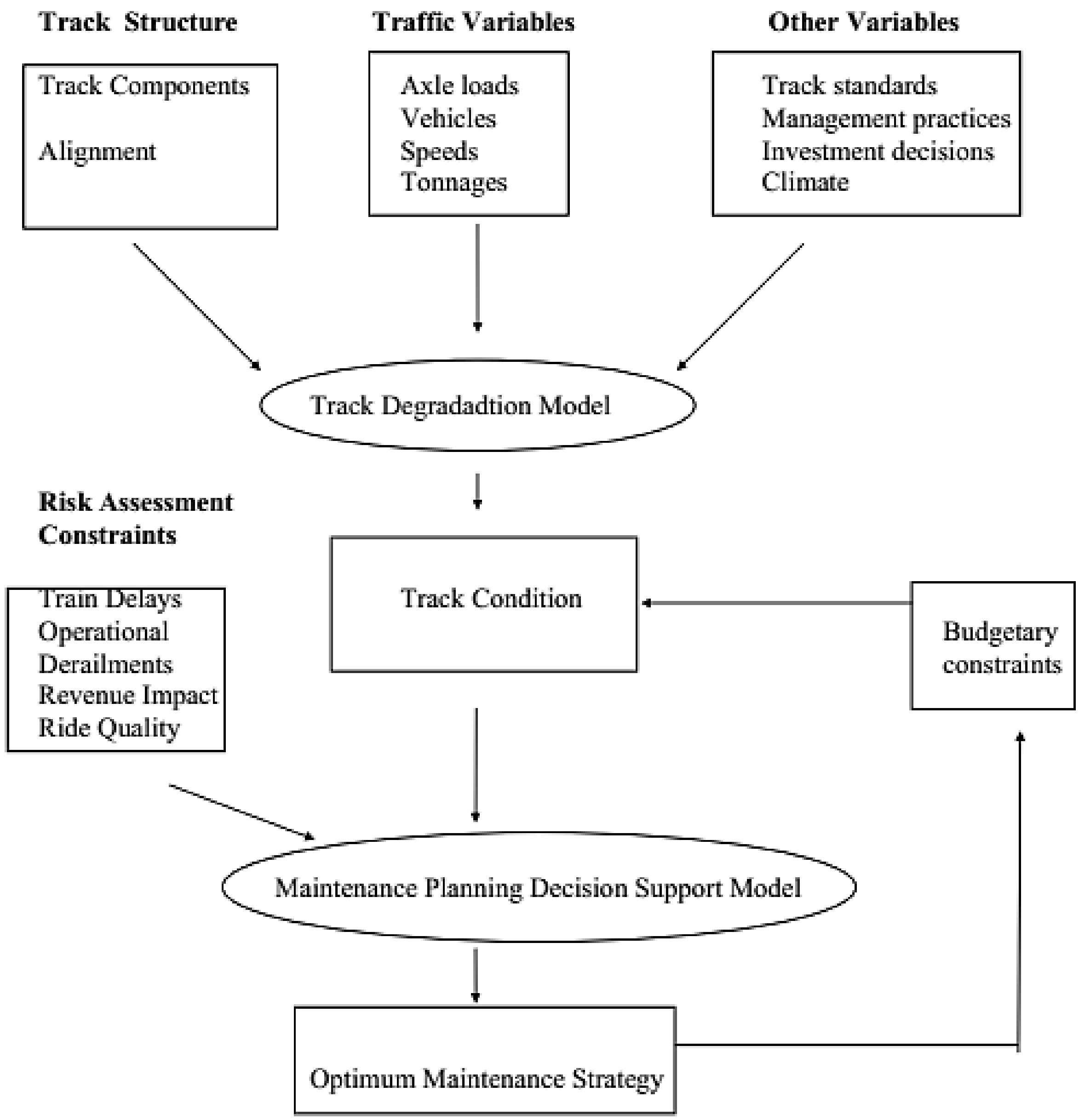


Figure 31: Track maintenance optimization parameters

Source: Ferreira & Murray (1997)

In addition to previous models, Uzarski and Mcnei (1994) defined several dissimilar components in the decision support system. The first is inventory; it is imperative that managers know "what" and "how much" to manage. Defining track segments is part of the inventory process. Pertinent information about each track segment, such as rail weight and curvature, is collected. The second component is the periodic inspection process. The analysis procedures are similar including condition prediction models, economic analyses, M&R cost estimating features, and optimization method. The final component also includes budget planning for network level management decisions.

Similarly, in the Minsili et al. (2012) article, inventory is an important component in forecasting ballast monitoring, cleaning and renewal, and in planning for availability of materials and mechanisms in order to fully optimize the track maintenance cost in each railway section.

According to Dao et al. (2018), their paper mainly focuses on the scheduling of major maintenance and renewal activities of components in a rail track system. The binary linear IP model is solved using IBM CPLEX optimizer, commercial software for solving linear optimization problems. With this, the computational time increases exponentially when the number of components and number of time periods increase. Heuristics and evolutionary computing methods are suggested for large sized problems and are recommended for future study.

The Integrated Reliability-Centered Maintenance System (IRCMS) program is a software tool used by analysts to perform and document RCM analyses to determine the applicability of and preliminary inspection intervals for potential preventive maintenance tasks. It aids the analyst in providing the justifications for and traceability of each preventive maintenance task that results from the RCM analysis. It must be emphasized that IRCMS cannot perform an RCM analysis. It requires input by an analyst who is knowledgeable in RCM theory and knows how to use the program. The current version of the IRCMS is a Windows application and is designed to run as an independent application or from a local area network. Multiple users can access an

RCMS project simultaneously but access is limited to one user at a time at or below the function level. The requirements for running the IRCMS program are Windows 95/98 or Windows NT and 486 central processing unit (minimum) (Cotaina et al., 2000).

The example of RCM decision tools are determined with the detail of their input, output, the type of analysis, and the ease of use is shown in Table 7.

Table 7: Example of the tools using in the RCM method

Source	Program	Owner	Obtained Result	Type of Input and analysis	Ease of use
Cotaina et al., 2000	IRCMS	Naval Air Systems Command	FMECA, Inspection intervals for PM, Maintenance task	Require manual input from RCM expert, decision tree analysis, cannot perform RCM analysis	*
Carretero et al., 2003	RAIL–RCM Toolkit (web-based)	The author programmed using the Java	Criticality value, data library (inventory, FF, MTBF), Maintenance task, LCC report	Uses the railway company databases, provide a complete RCM analysis	***
https://androsysinc.com/rcm-software/	RCM analyzer (web-based software application)	Andromeda Systems Incorporated	FMEA and FMECA, high risk items, prioritize issues of potential failures	Supports an RCM analysis process compliant with SAE JA1011 and NAVAIR 00-25-403, Compare cost and downtime of various failure management strategies	N/A
https://www.isograph.com/software/availability-workbench/rcm-software/	RCMcost (in Availability Workbench)	Isograph	Develop optimal maintenance strategies, FMECA, increase uptime and lower costs, optimize spares holdings	Seamlessly connect to SAP and Maximo. With optimal strategies loaded directly into company's CMMS, import and export functions are provided for Excel, SQL Server, text files and xml., supports standards such as SAE JA1011, MSG-3 and MIL-STD-2173(AS)	***

Source	Program	Owner	Obtained Result	Type of Input and analysis	Ease of use
http://www.reliability-safety-software.com/products/advanced-specialty-engineering-networked-toolkit/	FMECA Manager in ASENT	Raytheon	Perform FMECA, create Fault Trees, and document RCM Analysis.	Provide the built-in library of part types, along with failure modes and failure mode distributions, perform either top-down or bottom-up FMECAs with MIL-STD-1629A, RCM analysis with MIL-STD-2173, and UK MoD MSG-3, or NAVAIR 00-25-403.	**
https://www.bqr.com/products/care/	CARE	BQR Reliability Engineering	FMECA, FTA, MTTR, RBD, RAMS analyses, testability analysis	MTBF prediction, Maintainability Prediction (MTTR prediction), mostly used during product design or operation to improve robustness and reliability, integrates with CAD tools to automatically retrieve all design data applicable to RAMS analysis.	***
Cotaina, & Conan. (2002)	FMECA Tools in RAIL tool box	ARCOS	FMECA, Safety Critical Railway Infrastructure Component (SCRIC)	FMECA is automatically computed when 7 inputs are provided (Frequency, TTR, Availability on the line, Availability on the other line, safety, cost of maintainable items, detection way)	N/A

Source	Program	Owner	Obtained Result	Type of Input and analysis	Ease of use
https://www.reliasoft.com/products/xfmea-failure-mode-effects-analysis-fmea-software	XFMEA	ReliaSoft Corporation	FMEA, FMECA (both quantitative and qualitative criticality analysis), discover high risk items, and prioritize issues of potential failures	Input via customizable Excel® template. Transform the FMEA findings into a representative reliability model, and provide a continuous knowledge repository of the FMEA results to be reused throughout the reliability program.	**
https://www.reliasoft.com/products/rcm-reliability-centered-maintenance-software	RCM++	ReliaSoft Corporation	Risk analysis, maintenance strategy determination, asset criticality	Input via customizable Excel® templates and system configuration data from XFMEA, RBI, MPC and XFRACAS. Support all the major RCM industry standards, such as ATA MSG-3, SAE JA1011 and SAE JA1012 and provides full-featured capabilities for FMEAs and related analyses.	***

Source	Program	Owner	Obtained Result	Type of Input and analysis	Ease of use
https://support.ptc.com/products/windchill/quality/tryout/	PTC Windchill Quality Solutions (formerly Relex)	PTC Inc.	Reliabiliy prediction, RBD, FTA, FMCA, maintainability analyses, LCC, Markov analysis	Estimate component and system failure rate, MTBF and reliability early in the design process. Predict repair times, minimize downtime, and increase system availability.	N/A
https://itemsoft.com/fmeca.html	ITEM ToolKit FMECA	Item software	FMECA	Based on standards: MIL-STD-1629a, IEC-61508 FMEDA, ISO9000/QS9000, ISO 26262, BS 5760 Part 5, SAE ARP4761, SAE ARP5580, SAE J1739. Data can move to and from BOMs, Excel, Access, text and comma delimited file formats.	***

*: Require expert and time consuming
**: More flexibility, easier data input
***: User-friendly and easily input data

Other Techniques

The methods approved by OSHA include, but are not limited to: What-If Analysis, Checklist Analysis, WhatIf/Checklist Analysis, Hazard and Operability (Hazop) Analysis, Failure Modes and Effects Analysis (FMEA), FTA, and Fault Tree Analysis. All of them are included into the RCM process used in chemical industry (Cotaina et al., 2000).

Some basic models are: 1) reliability block diagram (RBD) and structure functions; 2) fault tree analysis (FTA); 3) event tree analysis (ETA); 4) Markov analysis; and 5) failure mode and effect analysis (FMEA/FMECA). In addition, within maintenance optimization literature it is common to present some basic maintenance models such as the age replacement policy (ARP) model, the block replacement model (BRP), and the minimal repair policy (MRP) (Økland et al., 2013).

There is research using a risk based maintenance approach and a qualitative assessment matrix to analyze the risk level of each failure based on probability and consequence of the failure and to design optimized inspection interval. The consequence of the failure can be classified to different aspects for each matrix; for instance, safety, economic, environment, downtime, system performance, asset damage, operational (delays), non-operational, and hidden failure consequences. (Carretero et al., 2003; Khan & Haddara, 2003; Økland et al., 2013; Ratnayake, 2014; Shuai, Han, & Xu, 2012). The varied assessment matrix is presented in Figure 32.

PoF Ranking	PoF Description	A	B	C	D	E
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	YELLOW	RED	RED	RED	RED
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	YELLOW	YELLOW	RED	RED	RED
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	GREEN	YELLOW	YELLOW	RED	RED
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	YELLOW	YELLOW	RED
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	GREEN	YELLOW	YELLOW
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirnoment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	Business	No downtime or asset damage	< € 10.000 damage or downtime < one shift	< € 100.000 damage or downtime < 4 shifts	< € 1.000.000 damage or downtime < one month	< € 10.000.000 damage or downtime one year
CoF Ranking		A	B	C	D	E

Figure 32: A risk matrix regards to safety, environment and business consequences

Source: Økland et al., 2013

The risk level is classified as:

- Low (green, action only necessary to ensure that the risk level remains low)
- Medium (yellow, functional tests or condition monitoring should be taken to ensure the risk remains at the current level)
- High (red, unacceptable risk level and action must be taken to reduce the risk).

Risk assessment can be quantitative or qualitative. The output of a quantitative risk assessment will typically be a number, such as cost impact per unit time. The number could be used to prioritize a series of items that have been risk assessed. Quantitative risk assessment requires a great deal of data both for the assessment of probabilities and assessment of consequences. Fault tree or decision trees are often used to determine the probability that a certain sequence of events will result in a certain consequence. Qualitative risk assessment is less rigorous and the results are often shown in the form of a simple risk matrix where one axis of the matrix represents the probability and the other represents the consequences. If a value is given to each of the probability and a consequence, a relative value for risk can be calculated. It is important to recognize that the qualitative risk value is a relative number that has little meaning outside the framework of the matrix. Within the framework of the matrix, it provides a natural prioritization of items assessed using the matrix. However, as these risk values are subjective, prioritizations based on these values are always debatable (Khan & Haddara, 2003).

Another international standard commonly used in railway system is the RAMS standard. RAMS constitutes the key elements of the assessment in the rail industry representing a high-quality system and product. Carretero et al. (2003) defined classification for each criteria based on RAMS standard, e.g., risk category, frequency of failures, hazard security levels, and decision criteria. The failure classification defined in the standard is presented in Figure 33. RAMS also provides guidance to guarantee the achievement of organization goals in terms of reliability, availability, maintainability, and safety.

Frequency	Safety			
	Insignificant	Marginal	Critical	Catastrophic
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Undesirable	Intolerable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Remote	Negligible	Tolerable	Undesirable	Intolerable
Improbable	Negligible	Tolerable	Undesirable	Undesirable
Incredible	Negligible	Negligible	Tolerable	Undesirable

Figure 33: Failure classification in RAMS
Carretero et al. (2003)

Table 8 summarizes the common technique applied with RCM from the reviewed articles in chapter two and three.

Table 8: The common technique applied with RCM

Authors	Criticality analysis	LCC	Prediction Model	Segmentation	RAMS	others
Soleimanmeigouni et al., 2019			degradation model (with occurrence of shock events) and binary logistic regression	Track segmentation		
Dao et al., 2018				Maintenance Activities Clustered		
Popović et al., 2020			the track geometry degradation model			
Cotaina et al., 2000		Recommended			Y	Pareto, MSG-3
Carretero et al., 2003		Y			Y	Risk of accident probability, RCFA, MSG-3

Authors	Criticality analysis	LCC	Prediction Model	Segmentation	RAMS	others
Garciamarquez et al., 2003			Kalman filtering			
Ruijters et al., 2016			the number of failures prediction			fault tree analysis
Macchi et al., 2012			sensitivity analysis			
Afefy, I. H., 2010	Semi-quantitative					RCFA
Økland et al, 2013		Y	Degradation pattern		Y	Maintenance grouping

Challenges in Implementation

RCM initiatives involve a tremendous amount of resources, time, and energy. It requires insights of the equipment and structure, i.e., systems, subsystems, components, with the possible failures and their consequences (Jasiulewicz-Kaczmarek, 2014). It is usually a long-term goal with a short-term expectation. Large projects may require 2 or 3 years to implement the process, which means expenditures but no proven benefits (Carretero et al., 2003). It can be seen that with the amount of time and costs in resources involved that is difficult to make organizations see the long term benefits of the method.

In addition to obscurity of the benefits, RCM initiations bring about change in the way people. Workplace culture is one of the barriers in implementing new approach. Any attempt needs the support of the organization at all levels.

Unavailability of documentation and information are another barrier of the analysis. The lack of historical reliability data obstructs the accuracy of analysis such as probability assessment and failure prediction (Backlund & Akersten, 2003).

The other limitation to this approach is the difficulty of selecting suitable maintenance strategy for each equipment and failure mode and for the great quantity of equipment and uncertain factors of maintenance strategy decision (RFD Reliability and PdM Technology, 2010).

In initiation phase, the organization has to experience with a lack of CMMS and RCM computer system. This makes it difficult to gather and handle data to support many analyses made in RCM process. Development of such a system is difficult and time consuming, involving issues such as design, user friendliness, and finding a suitable developer for the software

(Backlund & Akersten, 2003). Even when using the existing management system, each organization has different system functions, policies, objectives, available data, and so on. This means that one management system is applicable for some organization and not applicable or requires modification for other organizations.

Marten (2010) used a questionnaire to collect participant opinion when RCM method is utilized in their companies. The results of questionnaire are as following; 1) the most challenging aspects of implementing RCM is culture change which is 80% of participants, 2) the two biggest obstacles of implementing RCM are lack of computer skills (75 % of participants), and 3) lack of unions (60% of the participants)

Actors and Stakeholders and Their Roles in the Challenges

Owner (Infrastructure companies, i.e., track)

User /operators (transport companies)

Railway managers

Maintenance people (operator, planner, engineering, managers, trained inspector)

Maintenance contractors (outsource)

RCM experts' team (analyst, manager, working committee)

Engineering

Government organizations

Regulatory agencies, authorities

Railway safety authorities

Manufacturer

Supplier

Table 9 summarizes challenges in RCM implementation from the reviewed articles in chapter two and three. Then, the actions of the stakeholders to address those challenges have been proposed.

Table 9: Challenges in RCM implementation, stakeholders, and actions for remedy

Challenges	Stakeholders	Actions for remedy
Tremendous amount of resources	Operators, railway managers, maintenance people, RCM experts' team	Planning and preparation, data collection, adopt CMMS, database or decision support tools, evaluate and define investment cost, Clearly divided roles and responsibilities.
Lack of obvious benefit	Maintenance people, railway managers, RCM experts' team	Cleary state goals and benefit, continuous monitoring and measuring, need tools to measure whether the proposed maintenance program is effective and efficiently.
Change in work culture and Lack of cooperation	All the stakeholders within railway organization.	Cleary state steps of process. assign supervisor to ensure work performance at the beginning, clearly assign responsibility to individual, provide guidance for project work, training and education, continuously develop and

Challenges	Stakeholders	Actions for remedy
		assess proposed maintenance program, illustrate the benefit of apply RCM in successful organizations
Unavailability of data	All the stakeholders within railway organization.	Need the initial investment of CMMS and database.
Uncertain factors in maintenance strategy decision and great quantity of components	Railway managers and administrators.	Cleary state objectives, goals and focus of the organization. Using CMMS and database instead of document.
Lack of CMMS and RCM computer system	Maintenance people, RCM experts' team Transport company	Their requirement guide system direction and funds for the system development.
Lack of skills (computer and maintenance skill)	Maintenance people RCM experts' team	Provide training for their members.

CHAPTER FOUR: FINDINGS

Railway system is a highly complex system. It consists of many subsystems, sections, parts, and components that are distinguished by different criteria as well as different management allocations. In one sector of the rail, the maintenance and management team and their responsibilities is assigned. They are responsible for the decision made in the maintenance program including inspection, measurement, M&R, generate new plan, plan revision, validation, inventory, etc. Sectors are classified by either a group of stations, the length of the line, geographic location, or operator.

Likewise, care and maintenance of the rail system in each sector is different, unique, and largely depends on rules and regulations of organization. In assigning maintenance tasks, each sector is sorted into smaller groups for a particular track segment. Doing so allows assignment of access rights and areas of responsibility and makes the work more efficient and reduces duplication of work. Track segment also helps in categorizing and grouping tasks including combining similar maintenance tasks or similar track segments which require similar maintenance methods.

When failures occur, organizations have different means and criteria for prioritizing the list of problems to be resolved and selecting which methods are to be performed. It depends on regulation, how much the organization focuses on the importance of each factor such as safety, environmental issues, economy, availability, impact on reputation, and the threshold for those factors on each track segment. Realization of regulatory changes for each factor benefits maintenance task grouping and task assignments. Each repair is not exactly the same, even if it is for the same defect mode from the same functional failure because it still depends on other factors.

Track segments and their maintenance assignment are also governed by operation requirements (e.g., traffic, type of vehicle, repair time, availability of track, speed, material, passenger train or freight train, dangerous goods) and operational context (e.g., environment, season, and slope). This makes the FMECA analysis very difficult due to the uncertainty of above factors. When failure occurs, not only is the component, its function, and its failure required for the analysis, but also a more in depth look is taken at the circumstances of the failure and context. It involves considering dozens of different stresses, specific failure rate, traction loads, dynamic actions, etc. This is the reason why I consider FMECA in railway tracks as a top-down approach instead of a bottom-up approach guide by its traditional definition. Even though lots of efforts are made until specific failure modes of certain operation requirement and operational context are identified, there are still challenges when it comes to maintenance task selection.

In maintenance task selection of RCM approach, the decision logic tree consists of six types of scheduled tasks: lubrication/ service tasks, on condition tasks, hard time tasks, failure finding task combination of tasks, and redesign. The disadvantage is that the logic tree analyzes only the scheduled maintenance tasks. It does not allowance for the handling of unplanned or emergencies, e.g., corrective maintenance. Besides, the individual task selection of each failure mode assumes the failure will take place just one at a time. However, in fact, defect and its effect can also affect the occurrence of another defect, and the combination of the failure can also generate failure effect(s) that is different from the effect when one failure just arises.

In addition to task selection, maintenance program optimization is also a goal of RCM approach. This includes optimizing intervals of inspection, testing, maintenance, and renewal for changing existing maintenance performance. Prediction models and decision support tools play an important role in forecasting when failure will occur and when to address these. The most commonly used models in railroad application are degradation model, sensitivity analysis and Markov analysis. However, revising the maintenance plan in RCM only makes the maintenance program deal with defects more accurately and eliminate problems with improper maintenance (e.g., inadequate maintenance, duplication of work, too high or too low frequency, cost ineffective). It does not cover all reliability such as inherent reliability which requires new system designs without existing maintenance performance and its historical data. It also helps little with maintenance expenditure problems and it needs other techniques applied together to improve an ability to find cost effective program such as LCC, and benchmarking with the same railway industries or different industries with similar characteristics.

Implementing RCM, especially in such a complex system, is a burden and a time consuming if the organization is not currently using any CMMS or databases. All of the information can be found in documentation or it may not be available at all. To illustrate, RCM implementation requires 1) reliability data (e.g., MTTF, MTTR, failure rate, service life), 2) system description (e.g., system requirement, function requirement, operational process, regulation, available resources), 3) maintenance data (e.g., possession time, safety regulation, existing maintenance plan, maintenance interval, downtime), and 4) financial data (e.g., maintenance cost, salvage value, life cycle cost). Thus, having tools to organize and stored in one place is necessary. However, the initial investment can be expensive and time consuming in the search for a supporting system that fits the needs of that particular organization. Initialization can take time, but after completed it can significantly reduce the workflow, reduce paperwork and manual recording. Besides, the analysis of the failure mode, maintenance plans, and optimization plan can be completed within the program. Moreover, the maintenance program should be a living document which means the feedback from implementation will always be analyzed and iterative process of the RCM (from function analysis to documentation) will be performed to update and optimize maintenance strategy.

Apart from implementation challenges of tremendous amount of resources, unavailability of documentation and supporting system, difficulty of selecting suitable maintenance strategy, and complexity of the system, there are another two reasons why the implementation is hindered. Since implementing RCM requires organization culture change and long-term goal, the challenges may seem insurmountable. It would be a challenge to motivate and keep employees to continue adopting it for a long time until they can see results. If the performance of the RCM is inhibited due to the factors mentioned above, the results of the RCM application will be considered inappropriate for that organization, which in fact may not hold true. In fact, it is imperative that organization effectively communicate at all levels and plan successful collaboration for the successful implementation of the RCM.

Although this method was developed more than 60 years, the results of the method remain controversial by many studies. The results of increasing the reliability, availability, and performance of the system are quite certain to be increased. However, some research claims that the safety of the system has been improved as well, while some studies indicate that safety level were only maintained and in some cases, were decreased within acceptable levels.

CHAPTER FIVE: CONCLUSIONS

Due to heavy use of the rail, shortened service life and the need to meet and exceed consumer expectations, rail transport has increasingly faced more challenges to stay competitive with other transportation systems. Maintenance has become an integral part of the railway industry to assure efficacy and reliability of the system and its components. Since providing safety, reducing costs, and increasing efficiency are vital goals in the industry, it is important to improve maintenance and find a program that provides the systems to help in all these areas.

This qualitative research proposes recommendations for the framework to improve maintenance plan and RCM methodology with respect to information required during processes, factors influencing maintenance planning, benefits and challenges of the applied RCM in railway track, supporting systems, and other related aspects to be considered when conducting RCM process. This research guides all of the planning processes involved in RCM implementation so that it can be applied comprehensively to match the objectives of various, unique organizations. The process of the RCM is briefly described as follows:

Data collection is the initial stage before any analyzes are performed. The information collected is classified into the following main groups: 1) reliability data (e.g., MTTF, MTTR, failure rate, service life), 2) system description (e.g., system requirement, function requirement, operational process, regulation, available resources), 3) maintenance data (e.g., possession time, safety regulation, existing maintenance plan, maintenance interval, downtime), and 4) financial data (e.g., maintenance cost, salvage value, life cycle cost).

Once the prerequisites of the further analysis are gathered, the next step is system definition and breakdown. The output of this process is the list of system, subsystems, and components.

To reduce the time spent on FMECA analysis, only function and functional failure are identified at this stage. A tree diagram is used to determine significant functions and non-significant functions. The significant functions are worth analyzing and are the functions whose failures adversely affect safety, environment, operations, economics, and so on.

After identifying significant functions and functional failures, the rest of the components in this FMECA process are analyzed, i.e., failure mode, failure effect, and criticality analysis. Since one function can have more than one functional failure and multiple failure modes, one failure mode can also have one or more specific adverse effects on safety, availability, revenues, environment issues, traffic density, or even cultural or political aspects. In qualitative method, criticality matrix is applied to rate criticality of each failure mode. In semi-quantitative FMECA, those criticalities of effect are selected and weighted differently by each organization depending on their focus. For quantitative method, criticality is the product of unreliability of the component, failure mode ratio, and conditional probability of function failure. The output of this FMECA process is the list of potential failure modes with the most rated criticality.

The next sequential process is the maintenance task selection. In this step, two decision logic trees are applied. The first one identifies six types of scheduled tasks for each functional failure. Those tasks are lubrication/ service tasks, on condition tasks, hard time tasks, failure finding task combination of tasks, and redesign. The second one identifies types of maintenance in regards to the system status, not functional failure. The output of this step is the most applicable and effective maintenance task to eliminate or lessen the failure mode consequences.

Track segments and their maintenance assignment are also governed by operation requirements (e.g., traffic, type of vehicle, repair time, availability of track, speed, material, passenger train or freight train, and dangerous goods) and operational context (e.g., environment, season, slope, and location). This makes the FMECA analysis very difficult due to the uncertainty of above factors. When failure occurs, not only is the component, its function, and its failure are required for the analysis, but further work is needed to find how the component operated and what operational context was when the selected functional failure happened.

Prediction models and decision support tools play an important role in forecasting when failure will occur and when to address them. The examples of models used in railroad application are degradation model, sensitivity analysis, Markov analysis, and the combination of track degradation with operations research techniques. The supporting system can significantly reduce the workflow and automatically optimize maintenance plan.

The RCM implementation is hindered by a number of reasons such as the amount of resources needed, unavailability of documentation and supporting system, difficulty of selecting suitable maintenance strategy, complexity of the system, culture change, long-term goals with doubtful benefits, and lack of cooperation for the implementation.

Future Work

In maintenance task selection of RCM approach, decision logic trees are adopted for individual task selection of each failure mode assuming the failure will take place just one at a time. A defect and its effect can also affect the occurrence of another defect and the combination of the failures can also generate failure effect(s) that are different from the effect when only a single failure arises. These successive failures, failure effects and their relationships should be predicted and analyzed to more accurately identify the likelihood of failure modes and their consequences.

Supporting systems in RCM are various and do not have an exact pattern and configuration. None of the existing commercial RCM tools, to the best of my knowledge, is designed specifically for the railway system. There are some software developing programs have been developing by some researchers using C# and JAVA which are designed to be applicable only in particular case study or in similar cases. There are still the lack of standard and the lack of comprehensive usability. Using the existing commercial RCM tool available for other transportation industries such as aviation and naval may seem promising because of the size and complexity of the systems. However, there are also differences in those systems and in railway system such as documentation, input, related standards, some criticality factors. Thus, there are efforts on supporting system development.

Simulation could also be applied for planning scheduled maintenance programs in order to be able to verify and validate the results of the plan without having to go into action. In the event of an error, simulation makes it easier to review and update maintenance plan. It also reduces the probability of negative events from improperly assigned works.

Dynamic nature of defect developing, factors, operation context, and operation requirements, are needed to be included for more effective maintenance program.

The goal of this study is to provide comprehensive information about RCM framework, but the study does not include specific information and has not been applied in the real world. Future research should be applied to case studies which will contribute useful information to develop relevant theory.

APPENDIX: IRB APPROVAL

Institutional Review Board
FWA00000351
IRB00001138, IRB00012110
Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

UNIVERSITY OF CENTRAL FLORIDA

NOT HUMAN RESEARCH DETERMINATION

August 4, 2020

Dear Sarita Rattanakunuprakarn:

On 8/4/2020, the IRB reviewed the following protocol:

Type of Review:	Initial Study
Title of Study:	Application of Reliability Centered Maintenance in Railway Tracks
Investigator:	Sarita Rattanakunuprakarn
IRB ID:	STUDY00001963
Funding:	None
Grant ID:	None
Documents Reviewed:	• HRP-250-FORM-Request for NHSR_SR.docx, Category: IRB Protocol; • References.pdf, Category: Other;

The IRB determined that the proposed activity is not research involving human subjects as defined by DHHS and FDA regulations.

IRB review and approval by this organization is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these activities are research involving human in which the organization is engaged, please submit a new request to the IRB for a determination. You can create a modification by clicking **Create Modification / CR** within the study.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Adrienne Showman
Designated Reviewer

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