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Maintenance Concept Study for Deep Subsea Tunnels: Rogfast Tunnel as a Case

By

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Abstract

Today, Norway has 1259 road tunnels, 1185 are categorized as inland tunnels and 41 are categorized as subsea tunnels. In fact, the number of subsea tunnels has doubled in the last 20 years and entering a more challenging era as deeper and longer underwater tunnels are either already built, in progress, or planned. Keeping such complex assets available at minimal operations and maintenance cost requires effective maintenance engineering analysis to be considered during the early design and project phase. Therefore, the purpose of this thesis is to explore the state of the practice of maintenance engineering for deep underwater tunnels, specifically in Norway. To explore that, a case study method has been applied where the Rogfast tunnel is purposefully selected and analysed. Rogfast will be the deepest and longest underwater tunnel in the whole world and it is currently in the middle of the project phase. The case study has focused on the five main aspects of maintenance engineering: technical hierarchy, consequence classification, failure mode analysis, maintenance data exchange, and reliability and availability analysis. The case study has utilized data from existing tunnels, e.g., Ryfylke tunnel, Mastrafjord tunnel and Karmoy tunnel, to extract failure modes, failure rate, mean time to repair. The findings indicate a lack in the current practice of maintenance engineering at the project phase, due to the domination of safety over other consequences like availability, operating cost, and environmental impact. Considering availability, operating cost, and environmental issues provide a more realistic image of the potential operating expenditures. It will also enable the need to collect specific data categories according to standardized technical hierarchy and data exchange framework and initiate analysis regarding potential failure modes, system reliability and availability, prioritizing maintenance concepts and tasks. Therefore, this thesis proposes and demonstrates a more customised technical hierarchy and consequence classification matrix to enable maintenance engineering analysis and maintenance data exchange. It is found that the Rogfast tunnel has a unique configuration due to the roundabout at Kvitsoy that might be utilized to gain a higher level of tunnel availability. It is also demonstrated how new trends and maintenance programs like condition-based, predictive and perspective maintenance can be explored. The methodology applied in this thesis complies with NORSOK Z-008 and is well known for oil and gas sector. However, it is customised in this thesis to fit the tunnel industry.

Acknowledgements

This thesis work marks the end of my two years of being a master student of the Industrial Asset Management program at University of Stavanger. It has brought me much joy, a few tears and has been challenging at times. I have learned a lot in this process, about road tunnels, maintenance engineering, and about myself.

I want to sincerely thank my supervisor Idriss El- Thalji, for his support and encouragement throughout my thesis work. He has given me great advice and understanding in times when I felt that it was all unachievable. Thank you!

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Lastly, I want to thank my family, friends and fellow students for supporting and motivating me during the final stages of my studies.

Tonje Skjølberg

Tonje Skjølberg

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List of abbreviations

AADT	Annual Average Daily Traffic
CCTV	Closed-Circuit Television
CMMS	Computerized maintenance management system
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode, Effect and Criticality Analysis
HSE	Health, Safety and Environment
M&E	Mechanical and Electrical
NPRA	Norwegian Public Roads Administration
O&G	Oil and gas
O&M	Operations and Maintenance
PIARC	Permanent International Association of Road Congresses (World Road Association)
RAM(S)	Reliability, Availability, Maintainability, Safety (for roads)
RFI	Request for Information
WO	Work Order

List of translations

English	Norwegian
Annual average daily traffic (AADT)	Årsdøgntrafikk (ÅDT)
County road network	Fylkesveinettet
Directorate of Public Roads	Vegdirektoratet
Driver and Vehicle Licensing Offices	Trafikkstatsjoner
Ministry of Transport and Communications	Samferdselsdepartementet
Municipal sub-plan	Kommunedelplan
National road network	Riksveinettet
Norwegian Public Roads Administration (NPRA)	Statens vegvesen (SVV)
Norwegian Road Supervisory Authority	Vegtilsynet
NPRA Guidelines (short: guidelines) Note: "Prescriptive guidelines"	Retningslinjer "Prescriptive guidelines" kan legges til ved behov for å skille retningslinjer fra veiledninger.
NPRA Guidelines (short: guidelines). Note: “Descriptive guidelines”	Veiledninger. "Descriptive guidelines" kan legges til ved behov for å skille veiledninger fra retningslinjer.
NPRA Specification	Normaler
Sag-curve	Lavbrekk
Tunnel cross-section (syn. cross-passage)	Tverrforbindelse
Tunnel run	Tunnelløp (hovedløp)
Zoning plan	Reguleringsplan

1 Introduction

This chapter presents the topic and problem of interest and their relevance to global and national tunnel industry. It first starts with defining the market share and market growth in tunnel industry followed by an overview of the technical challenges that faces inland and subsea tunnels. Then research gaps are identified, the research question is formulated, followed by thesis methodology, scope and limitations, and lasty the structure of the chapters.

1.1 Background

1.1.1 Global numbers about tunnel industry

Tunnels has become an increasingly important part of infrastructure across the world in the past decades. Rapidly increasing population and urbanization results in a need for efficient and safe ways of transportation. According to the Tunnel Market Survey conducted in 2019 by the International Tunnel Association (ITA) [1], there has been a shift in market share in the tunnel industry the past couple of decades. The survey conducted by ITA looks at several types of tunnels, categorized as metro, rail, road and others, where road tunnels represent 29% in kilometres and 40% in output, as shown in Figure 1 below. For a long time, Europe has held the largest market share of the tunnel sector, measured in total tunnel length constructed per year and in output. This have since around 2010 changed, and now China holds the biggest share of tunnelling market. It is important to highlight that these numbers include different infrastructure sectors, and that the railway sector makes up the largest part of tunnel constructions in China.

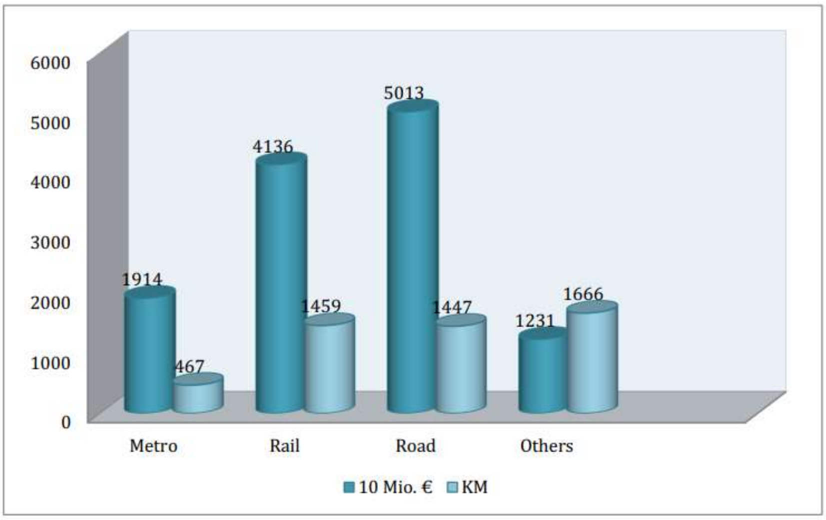


Figure 1. *Tunnel construction in 2019, breakdown by infrastructure sector [1]*

1.1.2 National numbers about tunnel industry

In the beginning of the year 2000, Norway had 757 road tunnels on the national road network, which was an increase of 22% from 1992 [2]. The first subsea tunnel in Norway, Vardø tunnel, was completed in 1982 and 18 years later, in 2000 there were 20 subsea tunnels in operation and three more under construction or completion [2], [3]. Today there are more than 1200road tunnels in Norway (exact 1259 tunnel objects as pr. 15.03.2022 [4]). Out of the 1200 road tunnels, 1185 are categorized as inland tunnels and 41 are categorized as subsea tunnels [4]. This means that in the last 20 years the number of subsea tunnels has doubled.

1.1.3 Challenges and Prospects of road tunnels

A variety of challenges was highlighted during initial meetings in the early stages of the thesis work, as a part of the thesis objective definition stage. Challenges related to tunnel maintenance, technical failure in tunnels and possible causes for technical failures have was highlighted.

The Coastal Highway Route E39 (*Norwegian: Ferjefri E39*) is the largest road project undertaken in modern history in Norway and is according to the Norwegian Public Roads Administration (NPRA) [5], possibly the largest ongoing road project across the world. The projects is in simple works the future prospect of roads going between Kristiansand in the south and Trondheim in mid-Norway. The overall aim of the project is to reduce travel time between the major cities along the west coast of Norway, by decommissioning ferry passes and constructing new road tunnels and bridges as means of crossing the fjords. Figure 2 below, shows the layout of the Coastal Highway Rout E39-project. In order to accomplish the project new technologies structural designs, and construction methods must be developed, some of which are still in the research stage [6].

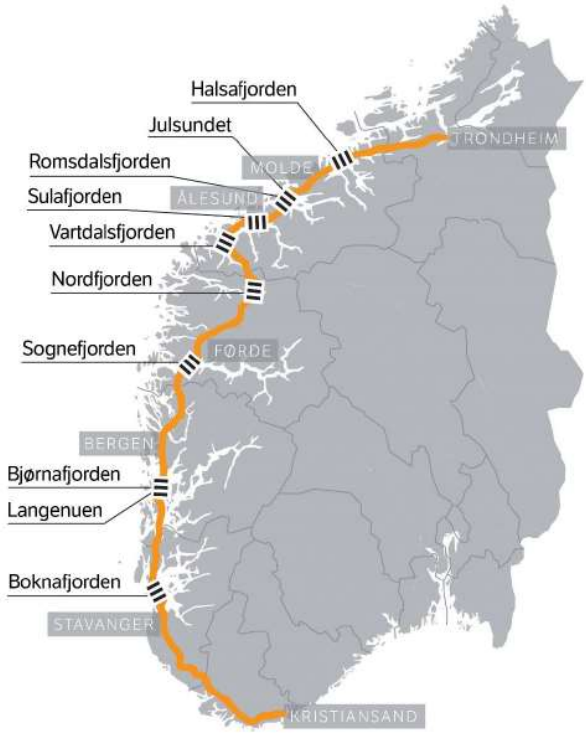


Figure 2. *Overview of "The Coastal Highway Route E39" - project [6]*

The focus on maintenance optimization in the infrastructure sector has been highlighted in recent years. The NPRA division for operations and maintenance has established a business development program referred to as "VU004 Forvaltning og vedlikeholdsstyring*"* (i.e., operations and maintenance (O&M) management). The program aims to develop and implement a new strategy, work processes, methods, and technology for O&M within the road sector [7]. As part of the VU004-program a benchmarking was initiated in 2019 to evaluate NPRAs present state-of-practice related to asset management and in 2021 a Market Survey (RFI) for procurement for a FDV solution was released. The purpose if the survey was to gather information about state of the art within ITS solutions for improving O&M management of the transportation sector, such as for bridges, tunnels, open roads, etc. [7]. In 2020 another R&D program called "SMARTere Vedlikehold" (i.e., smarter maintenance) was initiated in collaboration with Norwegian University of Science and Technology (NTNU) to improve maintenance of the Norwegian road network by developing new methods, technologies and products for the sector [8].

In tunnel operation, safety is the topmost important factor followed by availability. Some of the most widely discussed topics regarding road tunnels are traffic accidents and tunnel fires. NPRA has published several reports on traffic accidents in tunnels over the years, including data from subsea road tunnels. The last report published on traffic accidents by NPRA, accommodates for registered accidents during 2001-2006. It was shown that 97,5% (46 out of 48) accidents in subsea road tunnels occur in the middle sone of the tunnel, which is defined as 150 meters after the tunnel entrance and 150 meters before the tunnel exit [9], [10]. If an incident should occur, it is important that technical equipment, such as ventilation system, fire detection and monitoring systems, digital signs and communication systems are maintained to an acceptable level or sate at the time of the incident. It is not possible predict the exact moment at which an incident will occur, and hence it is very important that technical equipment that have safety related functions are operational and always working at acceptable level.

Based on experience, maintenance costs are in large parts determined by discissions that are made during design and building phases of tunnel projects [11]. The relationship between the project costs and level of decision influence is illustrated in Figure 3 below. Because of this it is important to consider maintenance in the design phase of the project.

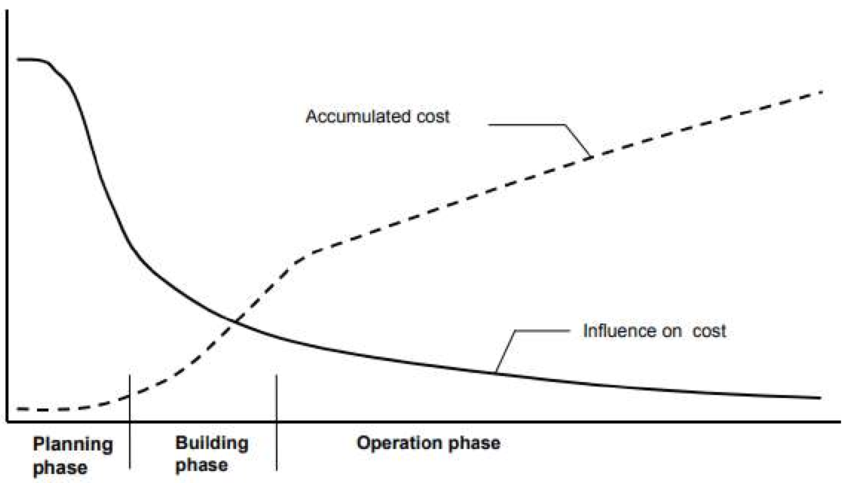


Figure 3. *Accumulated cost and corresponding level of influence on cost [11]*

1.2 Research needs and gaps

In order to get an overview on the state of the art within the topic of operations and maintenance for road tunnels, initial litterateur search and review has been conducted, using the database Scopus. The keyword “road *tunnel*” was used in all searches, because this is a good way of excluding literature that does deal with specifically road tunnels. Before searching for relevant literature, a search on the keyword "road *tunnel*" alone was made and resulted in 2173 hits. This information is included to show that the keyword "road *tunnel*" is a good keyword to combine with e.g. maintenance strategy, asset management etc. in order to retrieve limited and specific results. In Table 1 searched keywords, applied limitations, number of documents total and number of relevant documents for this thesis is described. The summation of total number of hits and total number of relevant hits excludes the initial search.

Table 1. Literature search in Scopus database

Search No.	Search Keywords	No. hits	No. relevant hits	Comment
1	TITLE-ABS-KEY ("road *tunnel*") AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (SUBJAREA , "ENGI"))	2173	-	Included to show that "road tunnel" gives many results
2	TITLE-ABS-KEY ("road *tunnel*" AND "maintenance *strateg*")	9	3	No limitations
3	TITLE-ABS-KEY ("road *tunnel*" AND "risk based maintenance")	1	1	No limitations
4	TITLE-ABS-KEY ("road *tunnel*" AND "asset management") AND (LIMIT-TO (SUBJAREA , "ENGI"))	6	2	Limited to engineering
5	TITLE-ABS-KEY ("public" AND "road *tunnel*" AND maintenance)	11	3	No limitations
	Total	**27** (2200)	**9**	

Out of these 9 relevant hits, there was a duplicate. It is important to note relevant hits from different keyword searches in some cases can result in the same publication. For example, the article *"Development of a cross-asset, reliability-based life cycle management"* was included in relevant hits for both keyword searches no. 2 and 4 *(tab.1)*. In Table 2 below, the induvial relevant publications are listed and duplicated relevant hits are accounted for. Hence the actual number of relevant hits (i.e. the total number of relevant hits) is 8.

Table 2. Relevant publications based on literature search

Author(s), title, publication year, source, cited by *(based on information from Scopus)*	**Document type**	**Search No.**
Petroutsatou, K., Maravas, A., Saramourtsis, A. A life cycle model for estimating road tunnel cost (2021) Tunnelling and Underground Space Technology, 111, art. no. 103858, . Cited 1 time.	Article	2
Grunicke, U.H., Stefan, C., van Linn, A., Weninger-Vycudil, A., Mellert, L.D. Traffic tunnels – Development of a cross-asset, reliability-based life cycle management (2020) Geomechanik und Tunnelbau, 13 (5), pp. 520-530. Cited 1 time.	Article	2 & 4
Hu, M., Yu, M., Chen, Q.R. The tunnel life-cycle evaluation framework design (2020) Life-Cycle Civil Engineering: Innovation, Theory and Practice - Proceedings of the 7th International Symposium on Life-Cycle Civil Engineering, IALCCE 2020, pp. 1507-1514.	Conference paper	2

Ng, M.F., Tummala, V.M.R., Yam, R.C.M. A risk-based maintenance management model for toll road/tunnel operations (2003) Construction Management and Economics, 21 (5), pp. 495-510. Cited 13 times.	Article	3
Honeger, C., Engelbogen, S., Pucher, M. Challenges with regard to road tunnel structures – Assessment management by Asfinag (2017) Geomechanik und Tunnelbau, 10 (5), pp. 507-515. Cited 1 time.	Article	4
Henning, J.E., Melby, K., Øvstedal, E., Amundsen, F.H., Ranes, G. Experiences with subsea road tunnels in Norway-construction, operation, costs and maintenance (2007) Yanshilixue Yu Gongcheng Xuebao/Chinese Journal of Rock Mechanics and Engineering, 26 (11), pp. 2226-2235. Cited 3 times.	Article	5
Mashimo, H., Ishimura, T. State of the art and future prospect of maintenance and operation of road tunnel (2006) 2006 Proceedings of the 23rd International Symposium on Robotics and Automation in Construction, ISARC 2006, pp. 299-302. Cited 7 times.	Conference paper	5
Wada, K. Maintenance and control of the Kanmon highway tunnel (1986) Tunnelling and Underground Space Technology incorporating Trenchless, 1 (3-4), pp. 315-322. Cited 2 times.	Article	5

Based on the literature study, there is no customized maintenance program for subsea tunnels, that comply with specific standard like NORSOK Z-008

1.3 Research question

The main purpose of the thesis is to answer the following question:
How to implement risk based maintenance (RBM) into deep subsea tunnel projects?

1.4 Methodology

The methodology of the case study consists of several steps based on the risk based maintenance approach described in NORSOK Z-008. The selected case is Rogfast tunnel, which is still in the project phase of its lifecycle. The thesis consists of the following activities:

- A literature study to get insight into the road tunnel sectors, maintencene and operation management within the sector and challenges related to this.
- Data collection of maintenance data for three case tunnels in Plania
- Development of technical hierarchy for technical equipment in road tunnels
- Development of consequence classification for technical equipment
- Develop FEMA for technical equipment in road tunnels
- Utilize RBD for RAM analysis for technical equipment in road tunnels
- Discuss the results from implementation of risk based maintenance approach for technical equipment in road tunnels

1.5 Scope of the thesis

The scope of the thesis is limited to illustrate how a risk-based maintencene approach can be used to develop maintenance concept for technical equipment in road tunnels. The selected technical systems for applying the method are (1) ventilation system and (2) drainage water pump system.

The focus of the thesis lies on subsea road tunnels. The Rogfast tunnel is selected as a case study, but because Rogfast is still in the project phase, three additional tunnels that are in the operational phase have been chosen for the purpose of data collection.

Limitations and delimitations

- **Data collection** - The number of case tunnels used to retrieve operational data are limited three tunnels, all of which are located in Rogaland County in Norway.
- **Tunnel type**: All case tunnels included in the analysis are subsea tunnels
- **Equipment** - Two types of technical equipment in road tunnels has been chosen for the analysis in chapter *5. Analysis and Results*. The two types are (1) jet fans/ventilators, which are used for both normal operation and in case of fire and (2) pumps, which are used for pumping drainage water.
- **Project phase** – the focus lies on the design phase of the tunnel life cycle. Data gathered from the three case tunnels are based on the operational phase of the tunnel life cycle.
- **Exclusions -** Structural integrity of the tunnel is not covered in this thesis. Spare parts evaluation will not be considered, even though it is an important part of the risk based maintenance approach defined in NORSOK Z008

1.6 The structure of the thesis

Chapter 2 provides the theoretical background needed to answer the research question. The chapter includes theories on road tunnels, maintenance management and risk-based management methodology based on NORSOK Z-008.

Chapter 3 describes the research methodology and design of the thesis. It describes the research steps taken in the thesis and how data has been collected.

Chapter 4 - describes the method and source of data collection, key information of three case tunnels proving in maintenance data and how data has been collected.

Chapter 5 contains the analysis and results of the case study, where the analysis process for each research step and results of the analysis' are provided. The chapter is divided into sub-chapters following the research steps described in chapter 3.

Chapter 6 - discusses the analysis and results from chapter 5, following the same structure as the previous chapter. An additional section discussing data quality and challenges related to the collected data is included in this chapter. Lastly, a recommendation for further work is presented.

Chapter 7 - concludes the thesis work and answers the research question presented in the introductory chapter, which is the underlying purpose of the thesis work.

2 Theoretical background

The purpose of this chapter is to provide a theoretical background on the topic, methods used and application of those methods. The theories presented in the chapter is based on extensive literature review. The chapter by introducing road tunnels, its lifecycle and some differences between inland and subsea tunnels, then moves on to maintenance

2.1 Road tunnels

Tunnels can be used in a variety of different ways, such as for road or rail traffic, utilities, sewage and water lines. A road tunnel can defined as a construction/built structure that lead the traffic in an underground or underwater passage [12]. Road tunnels are important parts of the infrastructure in modern society around the world, as it provides a way of bypassing both natural and man-built obstacles. There are many advantages of road tunnel structures, such as minimizing congestion, caused pedestrian movement, traffic, ferries, etc.

An overview of laws, regulations and manuals that applies to the Norwegian road sector is illustrated in Figure 4 below. Norwegian Public Roads Administration (NPRA) has developed and published manuals (i.e. handbooks) that are divided into a set of Norms (Vegnormaler, N), Prescriptive Guidelines (Retningslinjer, R) and Descriptive Guidelines (Veiledere, V), which are constantly updated.

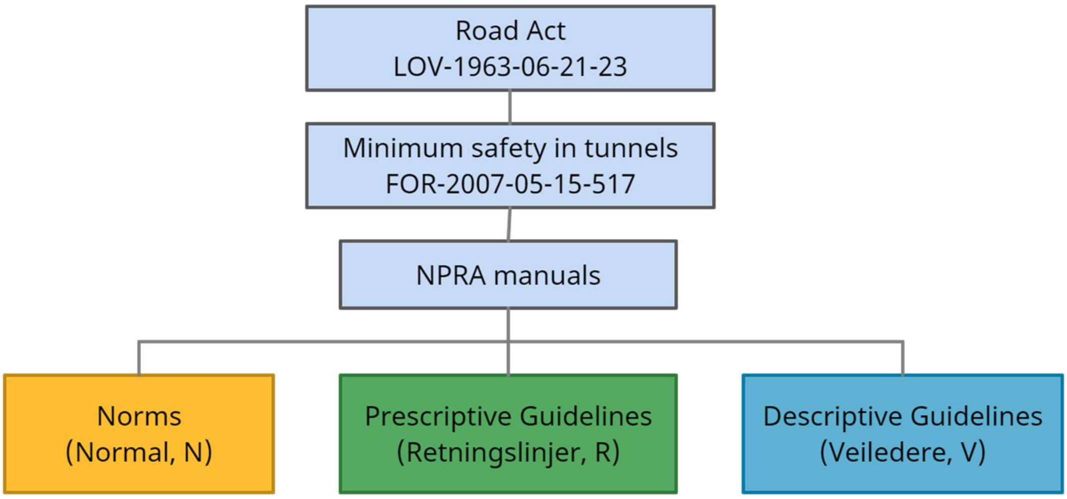


Figure 4. *Overview of laws, regulations and manuals*

2.1.1 Road tunnel life cycle

Road tunnels have long life cycles, with the operational phase being the longest. Based on to the guideline R760 covering management of road projects and on RoadRAMS report [13], [14], the life cycle of road tunnel projects has been derived and shown in Figure 5. The life cycle process diagram (*fig.5*) is quite general and therefore applies to most road projects, such as road tunnels, bridges and open road system. KS1 and KS2 are abbreviations for external quality assurance.

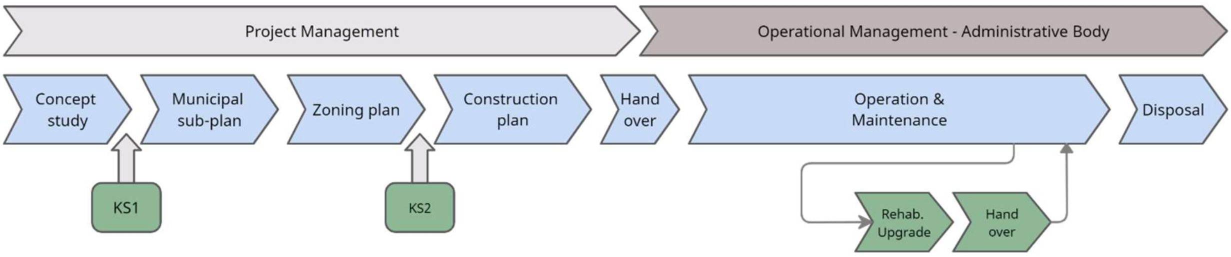


Figure 5. *Road tunnel lifecycle, created based on [13], [14]*

According to the norm N500 [12] the operational design lifetime of road tunnels are a total of 100 years. However, the tunnel can be divided into different categories, with varying requirements for length of design service life:

- 100 years for tunnel structure, including drainage- and surface water system, and guideways for cables embedded in the ground
- 50 years for water- and frost protection structures, technical infrastructure such as cables including guideways inside the tunnel
- 25 years for technical installations/equipment

2.1.2 Inland tunnels vs. underwater tunnels

Subsea tunnels (also called underwater tunnels) are in some ways different from conventional or land-based tunnels. Challenges inherited by underwater tunnels that does not apply to inland tunnels, are especially related to engineering geology, rock engineering and construction of the tunnel. For example during construction N500 [12], requires separate procedures for emergency preparedness at the construction site in order to handle landslide development, water intrusion and preparedness to make injections quickly. There are also some specific requirements regarding design of the drainage systems and pumpstations, which are according to [12]:

- As the drainage system in subsea tunnels are prone to overgrowth, it must be oversized by 50% or more compared to the dimensioning capacity in inland (non-subsea) tunnels. In cases where the slope is below 10 ‰, the capacity of the drainage system should be increased by 100%.
- It is necessary to make arrangements to enable water to be pumped out in both directions. In addition, in subsea tunnels/tunnels with sag-curves (*Norwegian: lavbrekk*), within each of the tunnel portals, a simple pumping station with associated manholes and drains must be placed, to capture and pump out surface water.

2.1.3 Road tunnel complexity

World Road Association (PIARC) states that "*Modern tunnels are complex technical engineering systems that have more in common with some industrial production plants than they do with the rest of the road network.*" [11]. Hence, it is argued that road tunnels can be considered a complex system, as there are many different parameters that interact with each other. According to the World Road Association (PIARC) [15] these interacting parameters can be categorized into subsets, which are illustrated in the Figure 6 below.

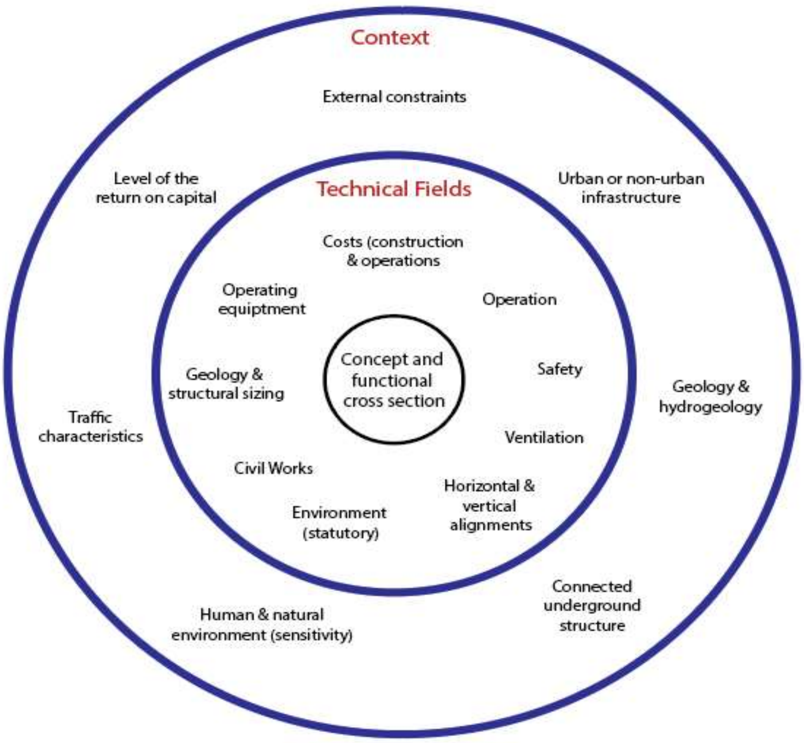


Figure 6. *Illustration based on main subsets of describing tunnel complexity [15]*

2.1.4 Technical equipment in tunnels

Road tunnels needs a lot of technical equipment to be functional and safe for traffic. N500 [12] specifies requirements that apply generally to all technical equipment, such as requirements for corrosion protection. In addition, there are a handful of requirements targeting each type of technical equipment and installation. As disclosed in limitations in *section 1.5*, the focus of thesis is on two specific types of technical equipment, namely jet/fans and pumps. The length of the tunnel is a critical factor during a technical failure for example power supply, ventilation or pump system in subsea road tunnels [10].

Ventilation systems in tunnels

There exist many different ventilation principles for road tunnels, such as natural ventilation, several different types of mechanical ventilation, such as longitudinal, massive point/point-flow extraction, fully- and semi-transverse ventilation systems [15].

Longitude ventilation normally consists of axial jet fans (also referred to as impulse ventilators), which is the most widely used ventilation principle in road tunnels [16]. In some road tunnels there are a combination of shaft ventilation (e.g., transverse) and jet fans combined. Jet fans are normally used for both normal operations use case and in a fire situation. In normal operation the ventilation system insures that the air quality of the tunnel is sufficient and in a fire situation ventilation system aims to make the environment as safe as possible for the users [15]. What is sufficient air quality is defined by the amount of air pollutants in the tunnel. Dimensioning concentration of NO2, NO, CO and particles based on requirements in N500 are shown in Figure 7 below.

Tabell 9.2 — Dimensjonerende konsentrasjoner av NO2, NO, CO og siktforurensning i tunneler

	Dimensjonerende konsentrasjoner	Forutsetninger
NO_x	C_{NOx} = 10 ppm	Ved 10 % tungtrafikk
NO_2	C_{NO2} = 1,5 ppm	Verdien er basert på en antatt NO_2 -andel på 15 % av NO_x. Der NO_2 -konsentrasjonen overstiger 0,75 ppm midt i tunnelen skal det utløses alarm på VTS, og ventilasjonsanlegget bør reguleres automatisk til maksimal kapasitet. Tunnelen skal stenges for trafikk hvis konsentrasjonen i midtpunktet ikke faller under 0,75 ppm i løpet av 15 min.
NO	C_{NO} = 8,5 ppm	Verdien er basert på en antatt NO-andel på 85 % av NO_x
CO	C_{CO} = 50 ppm	Dersom CO-konsentrasjonen overstiger 50 ppm skal tunnelen stenges for trafikk. Grunnen er at denne konsentrasjonen bare oppstår ved brann, stillestående kø eller ved alvorlig feil i ventilasjonsanlegget
Sikt	C_{PM10} = 1 000 µg/m^3	Vekt av svevestøv (PM_{10})
	$C_{PM2,5}$ = 500 µg/m^3	Vekt av eksospartikler $PM_{2,5}$

Figure 7. *Dimensioning concentrations of air pollutants for Norwegian road tunnels [12]*

Pumping system for drainage water

Drainage systems in road tunnels typically consists of pipes, sump, pumps, oil/water separators and control systems to assure safe and reliable handling of drainage water. Drainage system should be able to deal with surface water, water infiltration into the tunnel and leakage from other sources, such as accidental spills [17]. In theory tunnels can be impermeable, meaning no water ingression into the tunnel. During the operational phase tunnels are either impermeable or semi-permeable, meaning some ingress of water into the tunnel. The permeability of the tunnel depends on the lining of the tunnel, which will not be discussed further in this thesis (see limitations and delimitations in *section 1.5*). Ingress of water into the tunnel is not normally accepted, as it can lead to several damages to the tunnel structure over time and also it can impact functionality and lifetime expectancy of mechanical and electrical equipment [15].

The pumps used in tunnel drainage systems are usually vertical multistage centrifugal pumps. According to NPRA [18] the pumps have a life expectancy of 40 000 hours in operation, given that they only pump clean water. However, the wate water in tunnels are quite aggressive, meaning that the pumps will most likely not have the same life expectancy.

2.1.5 Road tunnel operations and maintenance

Maintenance in the road sector is to a large degree based on experience and manufacturer requirements for upkeeping of the different structural elements and technical equipment of the tunnel. NPRA has developed manuals for operations and maintenance of roads, such as "R610 Standard for operations and maintenance" [19]. However, this manual accounts for all elements of the national road network, and a specific manual regarding maintenance management in road tunnels has not been developed.

Sometimes it is necessary to close the tunnel for performing maintencene actions. According to NPRA [20], maintencene actions such as functional testing of traffic control equipment, tunnel and CCTV cleaning, control of emergency stations, fans and water supply, sludge removal and inspections of the tunnel structure. In Figure 8, tunnel closure of a 3500km road tunnel is shown. It shows how many hours a year the tunnel is closed, during a period of 100 years, which is equivalent to the design life of the funnel structure.

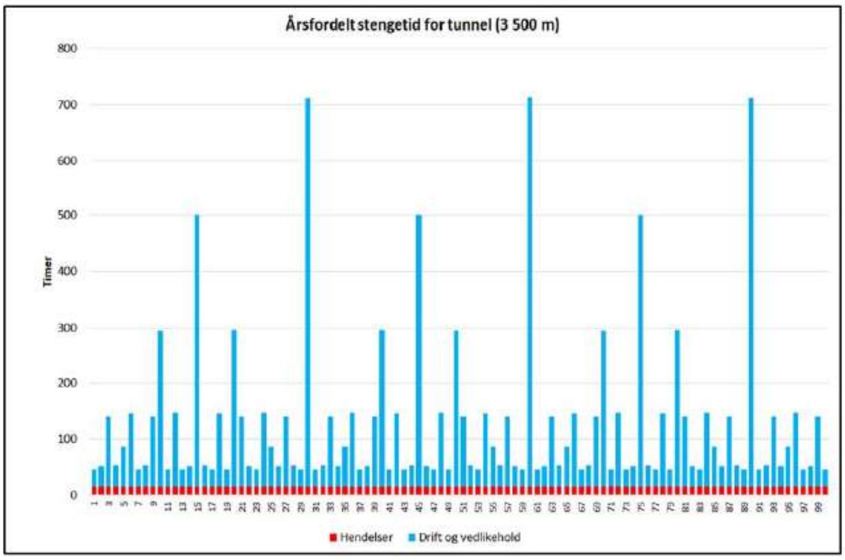


Figure 8. *Tunnel closing throughout 100 years [13]*

Preventive maintencene actions are important in order to keep the longevity of equipment life. Based on experience, replacement of electrical and mechanical (M&E) equipment in tunnels, usually happens after around 5-10 years [10]. This means that in some cases, technical equipment fails beyond repair 15-20 years before it has reached the end of its design life.

2.2 Theories about the topic

2.2.1 Maintenance Management

2.2.1.1 Maintenance philosophies

According to the standard EN 13306:2001 maintenance is defined as a "*combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function*" [21]. Maintenance is generally divided into two main categories, corrective- and preventive maintenance. Preventive maintenance can be defined as maintenance that is done at predetermined intervals or according to a prescribed set of criteria, with the intention to reduce likelihood of failures [21]. Corrective maintenance can be defined as maintenance that is preformed after a fault has been detected, with the intent of restoring the items state so that it can carry out is required function [21]. Preventive and corrective maintencene can be further divided into different maintencene philosophies, as illustrated in Figure 9 below.

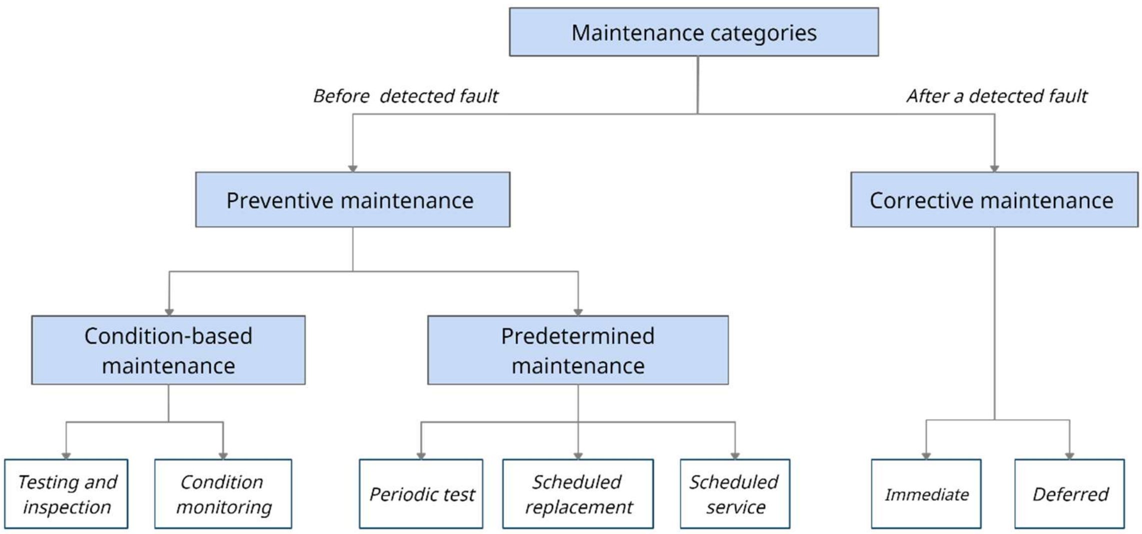


Figure 9. *Overview of maintenance philosophies based on [21], [22]*

Maintenance management techniques has developed a great deal over the recent years, as it has been affected by advancements in manufacturing processes and an increased focus on health, safety and environment [23]. A improved and extended overview of maintenance philosophies is included in Figure 10 below.

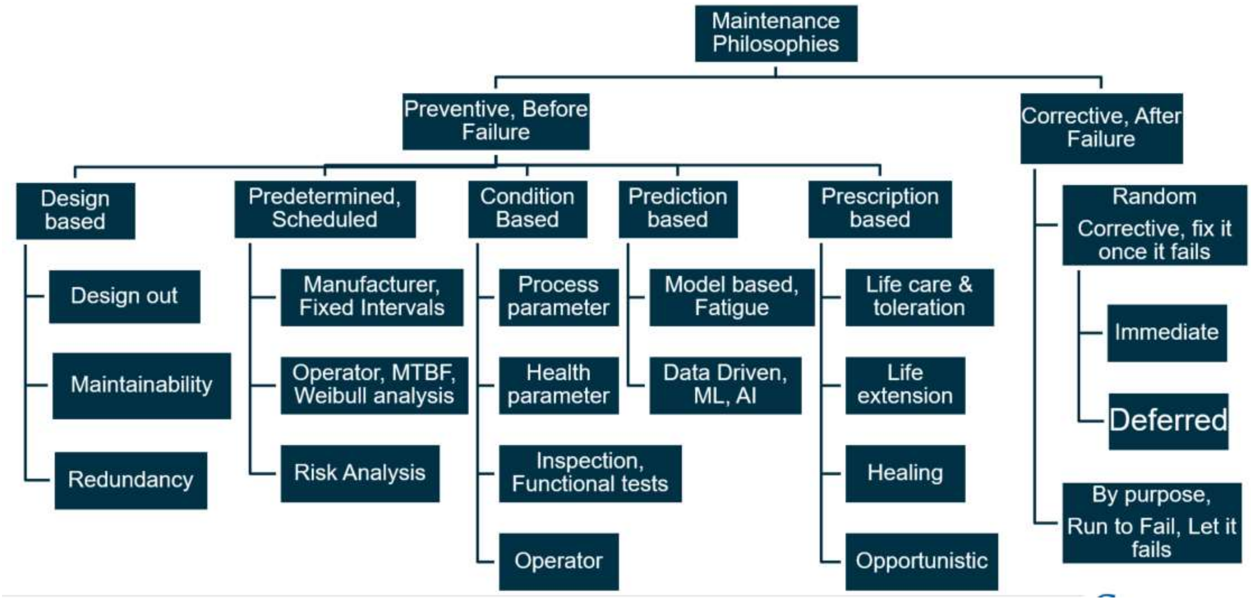


Figure 10. *Updated overview of maintencene philosophies [24]*

2.2.1.2 Maintenance management loop

In 1998 the Norwegian Petroleum Directorate (NPD) published a maintenance baseline study which presents a method for systematic self-assessment of maintenance management systems. The underlying intention behind the study was to provide a basis for strengthening and improve the decision-making processes in maintenance management [25]. Similar maintenance management loops have been developed later by different actors, such as DNV 2010 [26] and NORSOK Z-008 in 2017 [27], which is shown in Figure 11. It consists of inputs, outputs and management of work processes. It is intended to feedback information gathered from the outputs of the system, in order to revise and improve the maintenance management system.

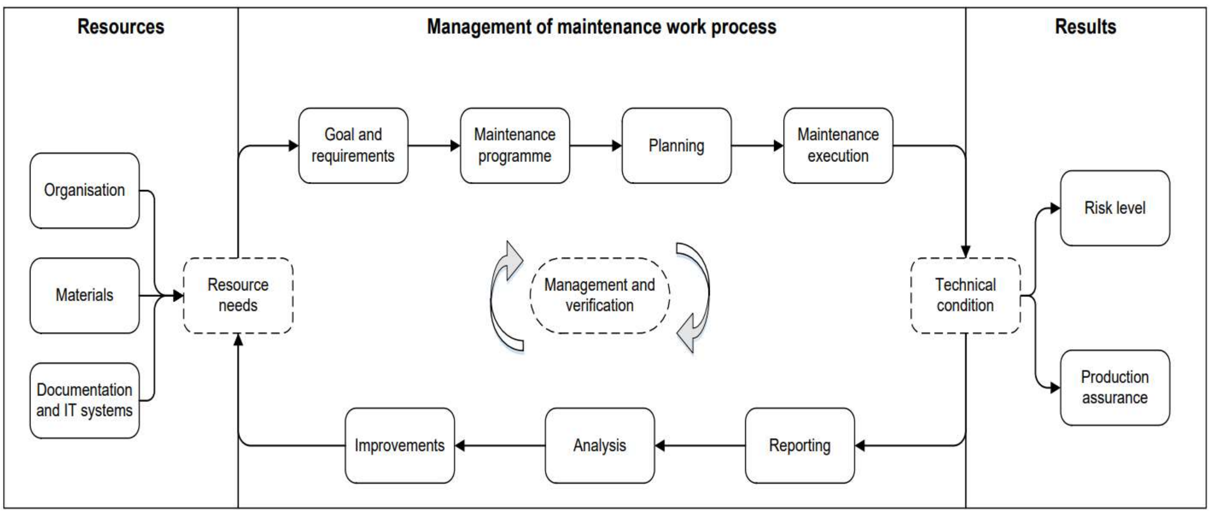


Figure 11. *Maintenance management process, described in NORSOK [27]*

2.2.2 RoadRAMS

As we have already established, road tunnels are complex technical engineering systems, that according to PIARC [11] has more commonalities with industrial production plants then they do with the rest of the road network. Based on literature review, there does not seem to exist a general maintenance program framework for the road sector, such as provided by NORSOK Z-008 for the oil and gas (O&G) sector. NPRA has however developed a report based on RAMS methodology called RoadRAMS (Norwegian: VegRAMS), which was part of the R&D project "Varige Konstruksjoner" (i.e., lasting structures) [28]. The RoadRAMS-report is a tool that aims to contribute to satisfy the requirements in the road standards (N100, N400 and N500) and states that future operation and maintenance must be taken into account the planning phase of the road project [13]. According to the report, the RoadRAMS approach should be applied in various phases of a road projects, as shown in Figure 12.

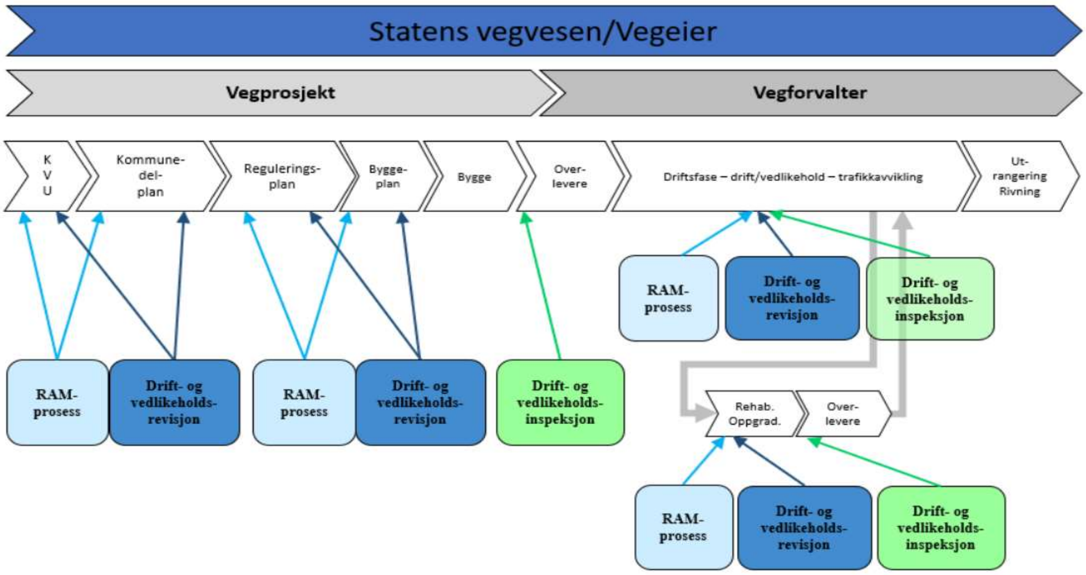


Figure 12. *Application of RoadRAMS in different phases of road projects [13]*

The RoadRAMS report was released in 2019, and has since then used in three different pilot projects, which are «Svegatjørn-Rådal», where an availability analysis was preformed, «Rogfast» where different alternatives for tunnel profiles where suggested, and «Møreaksen», where cost analysis, availability and analysis of certain «themes» where discussed [28]. Based on three pilots one of the major takeaways was that it has created a formal environment where operation and maintenance stakeholders can give input for new tunnel projects based on their experience, as well as providing quality checks on plan proposals purely based on operations and maintenance needs.

2.3 Theories about used methods and application

2.3.1 Risk-based Maintenance and NORSOK-Z008

The main objective of risk-based maintenance (RBM) methodology is to reduce overall risk that can result from unexpected failures of operating plants [23]. The RBM approach consists of two main phases, (1) risk assessment and (2) maintenance planning based on risk [23]. Planned maintencene activities are based on the assets risk of failure, hence the initial risk assessment creates the guiding principles for prioritizing maintenance activities in the planning phase. This means that high-risk equipment should be prioritized over low-risk equipment, in order to reduce the overall risk and probability of failure.

NORSOK Z008 describes a risk-based maintenance approach that can be applied for the purpose of optimising maintenance activates [27]. It provides guidelines and requirements for developing a technical hierarchy, consequence classification of equipment, maintencene management of technical barriers, methods for risk and reliability analysis and how to use this to aid maintenance decisions and evaluation of spare parts [27]. The key work process of the NORSOK standard is described in Figure 13. The standard can in principle be applied to any industry, however it was initially developed with the oil and gas (O&G) industry in mind.

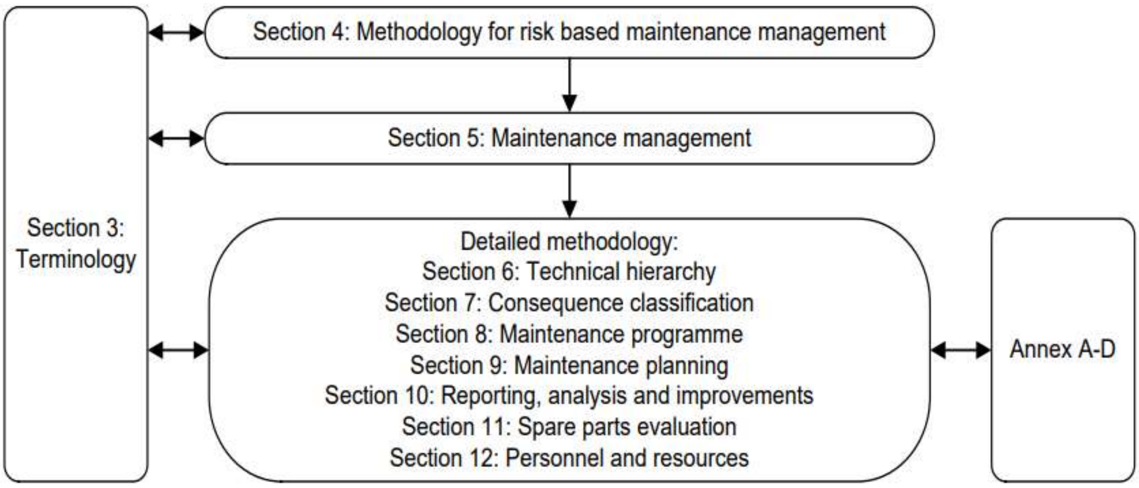


Figure 13. *Key work process of NORSOK Z-008 [27]*

NORSOK Z-008 can be used to optimize maintencene management during different stages of the project lifecycle, such as during the design phase, in preparation of operation and during the operational phase [27]. Hence, it can be used to establish, implement, update and optimise maintenance management systems. In order to use the NORSOK standard methodology to establish, implement or optimise a maintencene management system, information about the system and items that is part of the system such as drawings, P&IDs, tag lists and operational and maintencene data.

2.3.1.1 Technical Hierarchy and main functions

According to NORSOK Z-008 [27], the technical hierarchy shows the physical relationships between different hierarchical levels and provides an overview if the installations by giving physical items unique identifiers (e.g., tags). The technical hierarchy can be regarded as part of the system analysis (*2.3.1.1*) and should be established early in the design phase. A technical hierarchy can be used as input for subsequent parts of the risk-based maintenance approach such as defining equipment functions, preforming failure mode and effects analysis (FMEA), evaluation spare parts and planning maintenance work orders. ISO 14224:2016 [22] provides a taxonomy classification, defining hierarchical levels and descriptions that are useful when developing a technical hierarchy. Figure 14 shows an example of the workflow to develop a technical hierarchy.

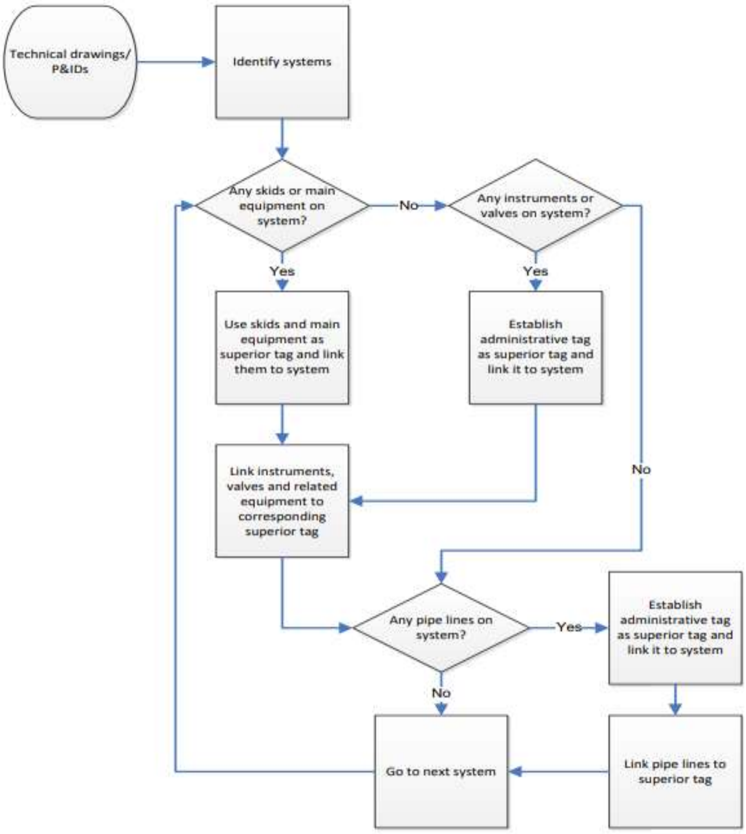


Figure 14. *Example of workflow to develop technical hierarchy [27]*

Based on the technical hierarchy, main functions (MF) and sub-functions for each equipment can be identified [27]. Identifying equipment functions is an important part of the risk-based maintencene approach as it is used in prioritising maintenance activities, based on effects of failures.

2.3.1.2 Consequence classification

Consequence classification is performed to identify critical equipment with regards to e.g., health, safety, environment, cost and production. Consequence classification is a qualitative analysis method [27], meaning it is based on knowledge, experience and/or expert judgement and evaluation. According to NORSOK [27] consequence classification, together with other information, provides input to equipment screening processes (equipment selection), development of PM programme, optimisation of maintenance concepts, prioritising of work orders and spare parts evaluations. Figure 15 provides the general process for consequence classification as described in NORSOK Z-008.

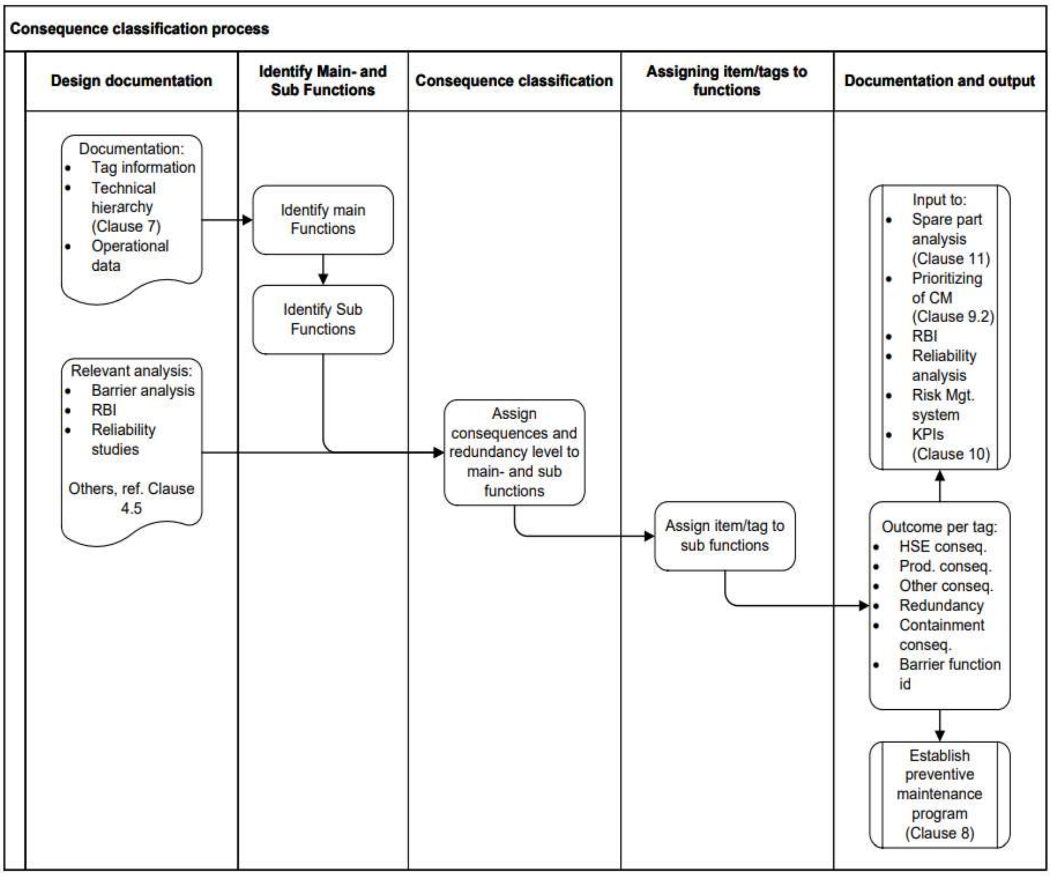


Figure 15. *Consequence classification process according to NORSOK Z-008 [27]*

2.3.1.3 Failure Mode and Effect Analysis (FMEA)

NORSOK Z-008 [27] states that General Maintenance Concepts (GCM) can be used in combination with classical reliability centred maintenance (RCM) approach can be used to express probability of failure based on maintenance experience. The standard defines a GMC as "*A GMC is a set of maintenance actions, strategies and maintenance details, which demonstrates a cost-efficient maintenance method for a defined generic group of items functioning under similar frame and operating conditions.*" [27]. However, if there is no applicable GCM, an FMECA/RCM/RBI analysis should be carried out.

Failure Mode and Effect Analysis (FMEA) is defined as a systematic qualitative analysis method [29] according to IEC 60706 [30], a reliability analysis method, that identifies failure modes and causes of all possible failures of an item. It can be used as an input to predict maintainability by identifying failure modes, frequencies and maintencene actions required based on these. The Figure 16 below, shows the general workflow of conducting an FMEA.

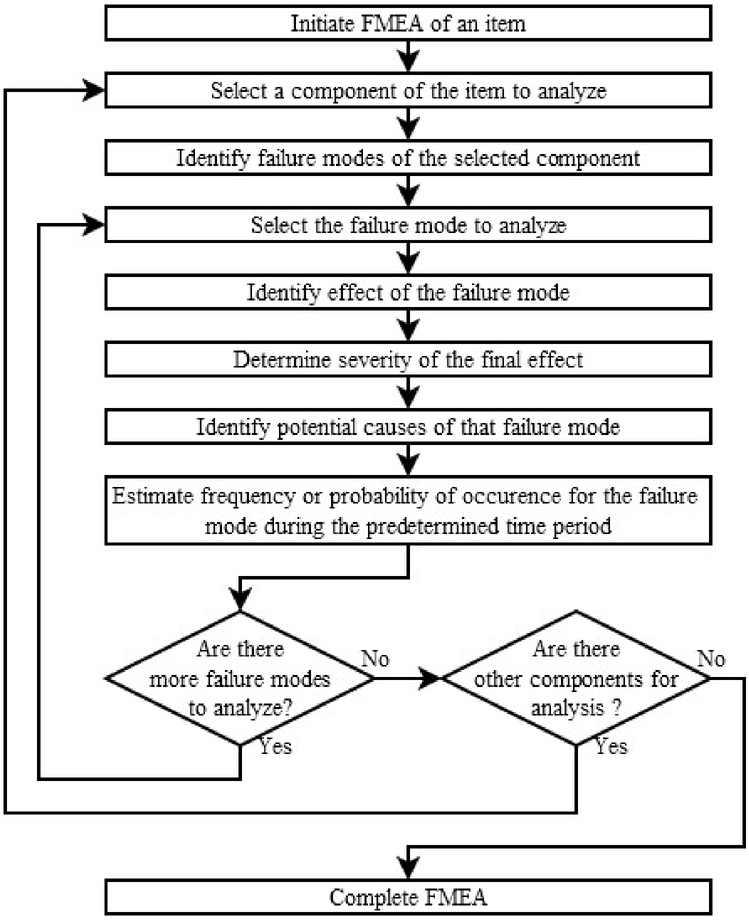


Figure 16. *The work flow of FMEA [31]*

There are two methods of identifying failure modes and effects: FMEA and FMECA. According to El-Thalji [32], an FMECA is a development of FMEA that adds additional factor called Risk Priority Number (RPN), which provides a measure of failure criticality. For an FMEA only defined failure modes and effects are needed [32].

2.3.1.4 Reliability Block Diagram (RBD) analysis

A reliability block diagram (RBD) illustrates the functional ability of a system and representing this as a logical diagram, which can be based on a fault tree or set up directly [33]. RBD can be composed of elements in series, parallel or a combination of both, as shown in Figure 17. A system composed of all elements in series, will only be functional if all elements are functional, and a system composed of all elements in a parallel structure will be functional if at least one element is functional [33]. The RBD is a good method for analysing reliability of a system.

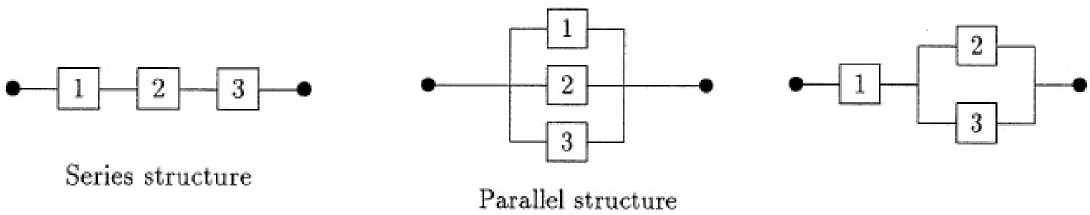


Figure 17. *Reliability block diagrams with different structures [33]*

3 Research methodology and design

This chapter describes the research methodology and design that has been established for the purpose of answering the research question. It described the research steps and methods for collecting data.

In order to anwer the research question *How to implement risk based maintenance (RBM) into deep subsea tunnel project*, a research methodology has been developed.

The methodological approach to the research conducted in this thesis is based on both quantitative data and qualitative data. Both primary and secondary data collection methods have been used. The qualitative data was primary collected, as it was retrieved from the maintenance management tool Plania, by the author. Other data and information gathered has been gained form other sources as secondary collection.

Table 3. Research methodology steps

Analysis step		**Description of main activities**
1	System analysis	Case tunnel of interest (Rogfast) location and layout. Overview of technical equipment
2	Technical hierarchy	Identify different levels and groupings of technical equipment in road tunnels (used as input to FMEA)
3	Work order analysis (Plania)	Systematically organize raw data collected from Plania from case tunnels (Ry, Ma, Ka). Retrieve failure modes, time between failure and time to repair (used as input to FMEA)
4	Consequence classification	Find relevant consequence classes, quantify class levels (used as input to FMEA)
5	Failure mode and effect analysis (FMEA)	Input results from step 2, 3, and 4 for specific equipment categories (jet fans, pumps)
6	RAM-analysis	Reliability block diagram analysis using software program Relyence® for three different scenarios
7	Maintenance concept study	Choose best option for maintenance concept for the chosen equipment based on the previous analysis steps

Initially, the intended research methodology was to collect data from three different case tunnels (qualitative primary data collection). The collected data would be utilized to retrieve information about failure modes, failure rates, etc., which again would be used in different parts of the analysis. However, issues related to data collection and utilization has had an impact on the originally intended research methodology. The main issues with the collected data are as follows:

- Poor data quality
- Lack of data
- Large variety in data between different tunnels

Data was collected from Plania. However, after an extensive amount of time and effort it was decided that the data would not be sufficient to use as the only data source input for the analysis process. Hence, other data sources (qualitative and secondary) have been used in addition to data retrieved form Plania.

Table 4. Research methodology and design

	Analysis step	**Data source**
1	System analysis	Literature review, internal documents and drawings retrieved from case company, Plania
2	Technical hierarchy	Literature review, Plania, NVDB, NPRA Vegkart
3	Work order analysis	This purely cased on data retrieved form Plania
4	Consequence classification	NORSOK Z008, ISO 14224, literature regarding road tunnels, contracts
5	Failure mode and effect analysis (FMEA)	Plania data, Internal documents, Literature
6	RAM analysis	Literature, technical drawings,
7	Maintenance concept study	Literature

4 Data collection

In the first part of this chapter the method of data collection is described. Then the case company and the case tunnels that has been used to collect maintenance data is described. Key information about the case tunnels and technical data for ventilation- and pump systems are gathered in tables presented in the case description sub-chapter. Lastly, a description of what and how data has been retrieved from the maintencene management tool Plania.

4.1 Case company

The Norwegian Public Roads Administration (NPRA) is an administrative body of Norwegian roads and a subject to The Ministry of Transport and Communications in Norway [34]. NPRA is organized into six divisions and a directorate, which is referred to as Directorate of Public Roads. The six divisions are (1) Construction, (2) Operations and Maintenance, (3) Road Users and Vehicles, (4) Transport and Society, (5) IT and (6) Shared Services, with main offices located in different locations in Norway. In addition to the main offices, NPRA also has over 70 Driver and Vehicle Licensing Offices spread around the country [34].

NPRA participates in international organisations, such as The Nordic Road Association (NVF), Conference of European Directors of Roads (CEDR) and World Road Association (PIARC). International cooperation contributes to acquire new knowledge, improve coordination of cross-border plans and contribute to development of rules and regulations within the sector .

4.2 Case Description

As the case tunnel of interest, Rogfast, is estimated to open in 2033 and is currently in the early construction phase of its life cycle, it follows that there are no operational data related to it. Because of this data has been collected from three tunnels, that has been in operation for a varying time period. The three case tunnels for data collections are as follows:

- Ryfylke tunnel (C1) *(Norwegian: Ryfylketunnelen)*
- Mastrafjord tunnel (C2) *(Norwegian: Mastrafjordtunnelen)*
- Karmoy tunnel (C3) *(Norwegian: Karmøytunnelen)*

Table X summarises key information for the three case tunnels, in which the information is gathered from Plania.

Table 5. Summary of key information for case tunnels

Information	Case 1 (C1)	Case 2 (C2)	Case 3 (C3)
Building no.	2319 A and 2319 B	1603	2205 B
Building name	Ryfylketunnelen mot Stavanger (A) Ryfylketunnelen mot Røldal (B)	Mastrafjordtunnelen	Karmøytunnelen, Rundkjøring
Opening year	2019		2013
AADT (total)	A: 2769, B:2808	8636	4200
AADT registered (year)	2021	2020	2020
Restriction class	a	a	-
Tunnel class	E	C	C
Tunnel profile (main)	T8,5	T11,5	-
Official length [m]	14500	4400	-
Max depth [m]	292	133	60
No. of runs	2	1	1
No. of "felt" in each run	2	2 and 3	2
Separated traffic	Yes	No	No
Roundabout (amount)	No	No	Yes (1)

Case 1: Ryfylke tunnel

Ryfylke tunnel is a part of Ryfast, which connects he two Nord-Jaeren and Ryfyke in Rogaland County [35]. The tunnel opened 30. December 2019, and has therefore been in operation for a short amount of time.

Case 2: Mastrafjord tunnel

Mastrafjord tunnel is a part of Rennfast, which is the main land connection between Rennesoy and Stavanger municipalities in Rogaland County. Rennfast consists of two tunnels; Byfjord tunnel and Mastrafjord tunnel, which both opened in 1992 and reduced the travel time between Rennesoy and Stavanger from 2,5 hours to 25 minutes [36]. Mastrafjord has been chosen as case 2, because it has a high number of registered work orders in Plania [37] and it will be partly replaced by Rogfast, as it is currently part of the travel route E39 going north from Stavanger.

Case 3: Karmoy tunnel

The Karmoy tunnel is part of a project called the T-connection (*Norwegian: T-forbindelsen*), which consists of three tunnel runs connected in the middle by a round about 60 meters under the mean sea level. The three tunnel runs are located under Karmsund, Fordesfjord and Hellevik in Karmoy municipality. Traffic goes in both direction in each run, and each run is 11,5m wide. The deepest point of the runnel lies 139 m under the sea level. The Karmoy tunnel is the only one of the chosen case tunnels that has a roundabout, which is the main reason it is interesting to look at.

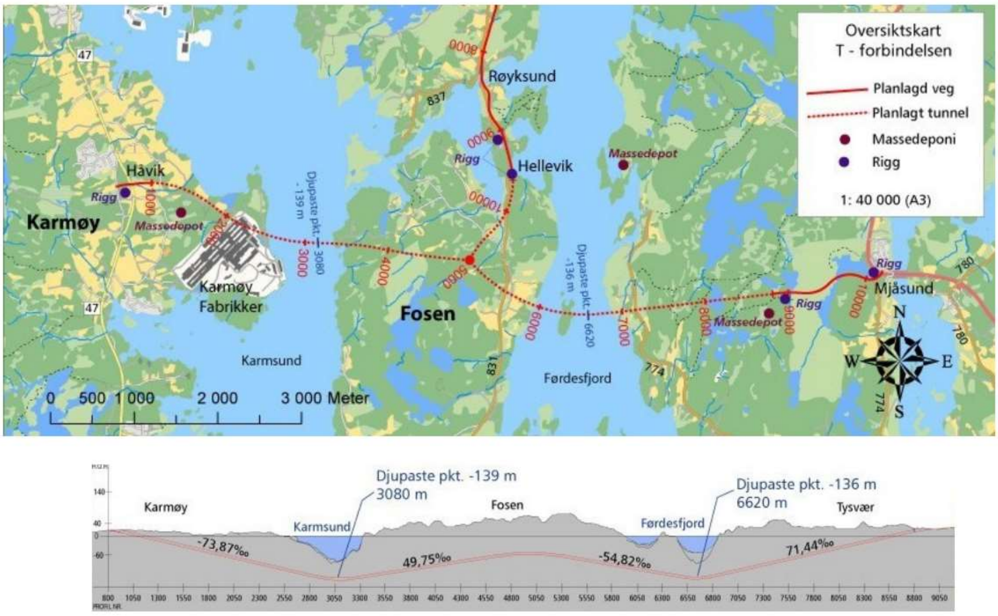


Figure 18. *Overview of Karmoy tunnel [38]*

AADT for Karmoy tunnel was estimated to be around 5000 vehicles/day in all three runs (both directions) in 2030 [38], however in Plania AADT is registrert to be 4200 vehicles/day as of now [37] . In Figure 18 below, the assumed number of vehicles a day is shown for the roundabout.

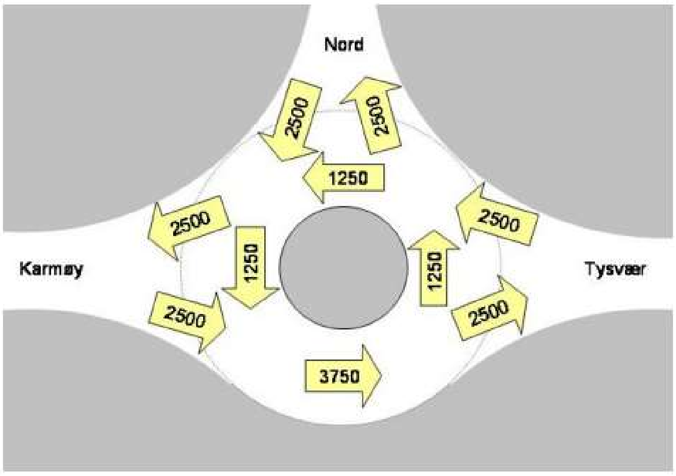


Figure 19. *AADT in the Karmoy tunnel round about [38]*

Equipment summary

The tables 6 and 7 gives a summary of available information about the jet fans and pumps in the case tunnels, gathered from Plania and NPRAs "Vegkart" [4], [37].

Table 6. Summary of technical data for fans/ventilators used in the case tunnels [4]

Property	C1 - Ryfylke	C2 - Mastrafjord	C3 - Karmoy
No. of jet fans	94	45	47
Effect	45 kW	37 kW	25 kW
Voltage	400 V	-	400 V
Vibration sensor	Yes	-	-
Established	2018	2015	2013
Producer, fan motor	VEM motors GmbH	-	-
Product name, fan motor	IE3-W41R 225 M4 FAN FV1	-	-
Supplier, fan motor	Energima	-	-
Producers, fan blade	Howden	-	-
Supplier, fan blade	Energima	-	-
Product name, fan blade	APA-1250/403-45	Mojet_AJ_1120-5	-
Producer, fan housing	Howden	-	-
Product name, fan housing	APA-1250/403-45	-	-
Supplier, fan housing	Energima	-	-

Project reference	Rv13 E09 Ryfylketunnelen Elektro	-	-
Owner	Stat, statens vegvesen	-	Fylkeskommune
Maintenance operator	-	-	Statens vegvesen
Start-up date	2020-01-31	2015-09-22	2013-11-04

According to Plania, there are no registered pumpstations in the round about section of Karmoy tunnel (C3). As other data collected form C3 are restricted to the roundabout section, technical data for pumps in C3 is not included in table X below. Information about the pumps in Mastrafjord tunnel (C2) is unreliable. In plania there is registered 6 pumps in total. In NPRAs roadmap [4], project reference is said to be “firewater tunnel” (Norwegian: Brannvann tunnel) and there are only four pumps registered and located in the tunnel portal (entrance). FDV documentation for pumps were available in Plania for Byfjord tunnel, and the documentation states that there are four fire water pumps, and two wastewater pumps. As the two tunnels (Byfjord- and Mastrafjord tunnel) are both part of Rennfast, and were finished at the same time, an assumption is made that they have similar equipment layout. Description of the two wastewater pumps is included in the Figure 7 below in parenthesis.

Table 7. Summary of technical data for pumps used in the case tunnels [4]

Property	C1 - Ryfylke	C2 - Mastrafjord
No. of pumps	19	6 *(2)*
Effect	45.5 kW	11 kW *(4kW)*
Established	2018	-
Producer, pump	Gruppo Aturia P.I.	Grundfos *(ABS)*
Name and make	-	Type: SE1.85.150.110.4.52H.C.N.51D *(AFP 1049.4-M40/4-D05*10)*
Project reference	E12 Ryfylke, Eiganes- og Hundvågtunnelen - Pumpeanlegg	Brannvann tunneler
Owner	Stat, statens vegvesen	Stat, statens vegvesen
Maintenance operator	Statens vegvesen	Statens vegvesen

4.3 Collection of data and information from Plania

Planía is the main tool NPRA uses to follow up on management, operation and maintenance of tunnels and other road “objects” that are periodically inspected. Plania can be used as a mobile app, via internet browser and on desktop. Throughout the duration of the thesis work, both browser- and desktop version of Plania has been utilized to gather information about the maintencene management system and for the purpose of data collection.

Plania Browser version

The browser version is easy to navigate and has been used to gather information about system structure used to develop technical hierarchy, retrieving documents for technical equipment and overall understanding of the Plania software.

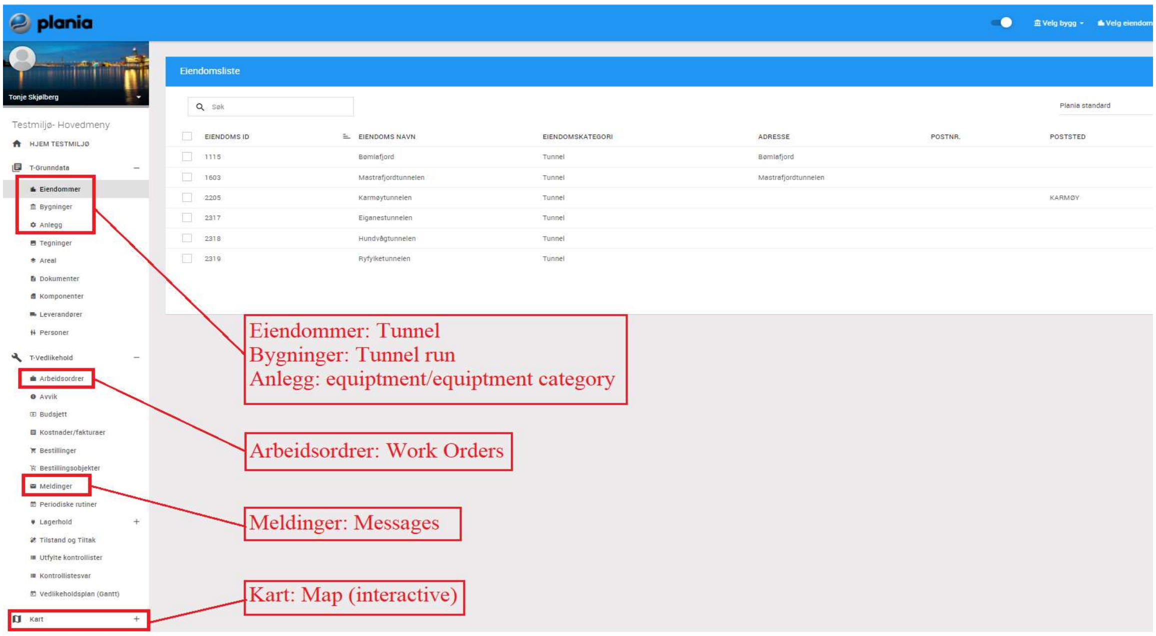


Figure 20. *Most used menus during thesis work in Plania browser version [37]*

Some references used in this thesis has been retrieved from the document archive that is integrated into Plania. This includes for example FDV documentation for the ventilators in Ryfylke tunnel. The documentation included in Plania does not seem to be complete or the Plania - version the author had access to during the work was limited to exclude certain documentation.

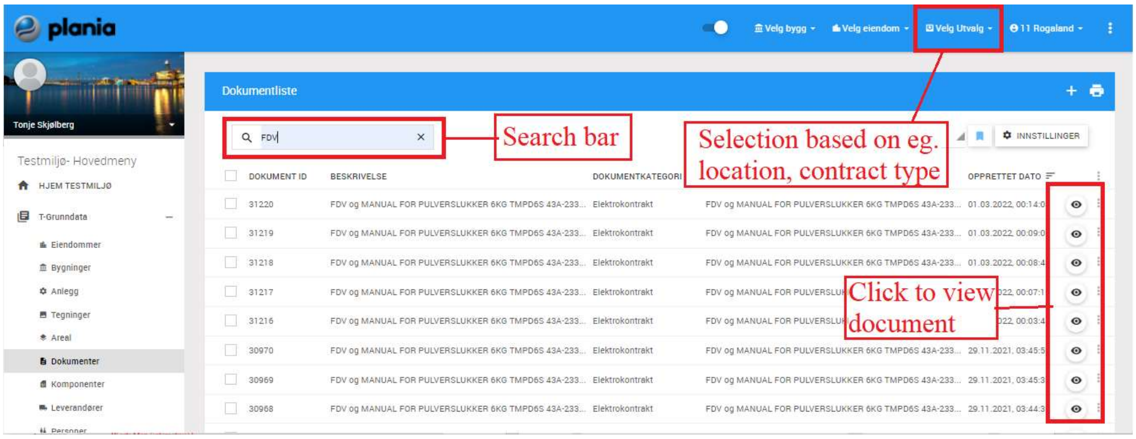


Figure 21. *Document library in Plania browser version*

Plania Desktop version

The Plania Desktop version has mainly been used to retrieve large amounts of raw data from three operational tunnels. It is easy to edit the user interface and then save this as a template, that can then be used for other inputs. The data collected from the case study tunnels (i.e., Ryfylke tunnel, Mastrafjord tunnel and the roundabout in Karmoy tunnel) is retrieved from plania desktop. However, the registered work orders mainly preventive maintenance in the form of inspections, controls and functional testing of equipment and not a complete history of all incidents occurring in the tunnels. After speaking with stakeholder from operational manager it was clear that there does not exist specific guidelines for registration in Plania, that applies to all users of the Plania software.

5 Analysis and Results

This chapter consists of seven steps that aim to apply the risk based maintenance approach proposed in NORSOK Z-008 for road tunnels. The analysis steps are systtem analysis, development of technical hierarchy, work order analysis, consequence classification, failure modes and effects analysis (FMEA), RAM analysis and maintencene concept selection.

5.1 System analysis

5.1.1 Tunnel location and layout

The selected case study is project E39 Rogfast, consisting of Boknafjord tunnel and Kvitsøy tunnel. Rogfast is a part of the project "Ferry Free E39", replacing the ferry crossing over Boknafjorden. When the tunnel construction is finished, it will pass through the three municipalities Randaberg, Bokn and Kvitsøy in Rogaland County in the south-west of Norway, as illustrated in Figure 22.

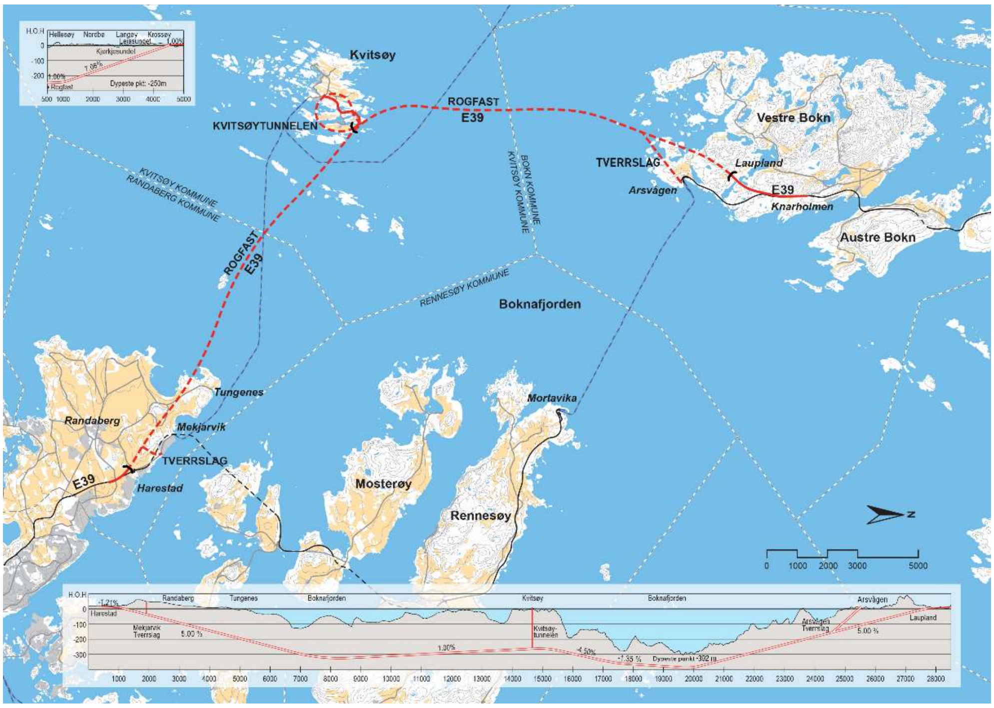


Figure 22. *E39 Rogfast tunnel project layout [39]*

Rogfast will be the longest and deepest subsea road tunnel in the world, with a total length of almost 27 km and a depth of 391 meters below mean sea level. The approximate driving duration is 20 minutes for passenger cars and 23 minutes for heavy transport at speed limit 80 km/t [40]. AADT is estimated to 13000 vehicles a day [41].

According to a presentation held in early 2021 by Espedal [42], the total construction time of Rogfast was initially estimated to last for about 10 years, meaning the Rogfast project would be finished in mid-2031. However, during an interview in the newspaper “veier24.no” [43], it was disclosed that due to a new model for estimating construction time, the new opening year for Rogfast is set to 2033. The project is currently in the early construction phase and construction work has already started for some parts of the tunnel. According to presentation by Espedal [42], the construction of the project is divided into the following main contracts, which is also illustrated in Figure 23:

- E15 Kvitsoy contract –construction started
- E02 Kvitsoy contract – planned construction start-up when E15-contract is finished
- E03 Randaberg contract – planned construction start-up summer 2022
- E04 Bokn contract – planned construction start-up winter 2022/2023

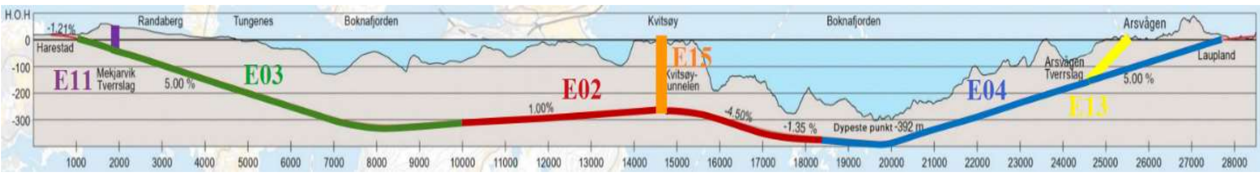


Figure 23. *Overview of different contracts for E39 Rogfast construction [42]*

The Rogfast tunnel has an intersection at Kvitsoy, consisting of two roundabouts and several tunnel ramps, as shown in Figure 24.

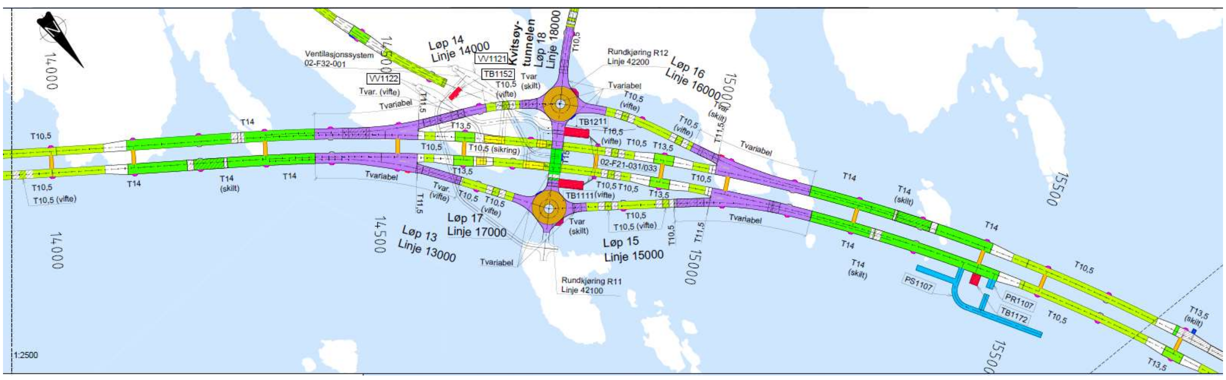


Figure 24. *Technical drawing showing midsection the tunnel*

5.1.2 Technical equipment

Due to lack of time and scope of work, it is not possible to go into detail on every single type of equipment that might be of interest in a reliability analysis. Hence, two categories of technical equipment have be chosen. The length of a tunnel is critical in case of technical failure in power supply, ventilation and pump system [10]. Hence, as jet fans/ventilators and drainage pumps both can be considered safety critical, they have been chosen as object of analysis.

5.1.2.1 Ventilation system

In Rogfast, the ventilation system consists of both shaft ventilation and jet fans. By looking at the work orders for the case tunnels, it was found that the equipment with the highest number of work orders is the ventilation system/fans/ventilators. Keep in mind that this includes both preventive maintencene actions (e.g., periodic maintencene such as inspection, control etc.) and corrective maintenance actions (e.g., repairs, replacement, etc.), and that the majority of the historical workorders for all the case tunnels are preventive maintencene

There are two main use case scenarios for the jet fans, normal operation and fire operation. The total number of required jet fans are based on net thrust requirement for the fire ventilation use case scenario.

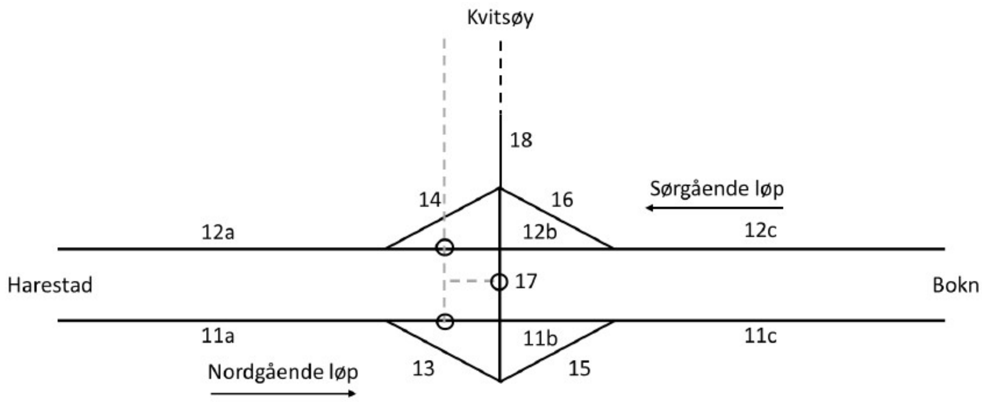


Figure 25. *Sectioning of Rogfast for ventilation dimensioning purposes [41]*

Tabell 5-1: Skyvkraftbehov skyvkraftbehov for brannventilasjon.

		Løp 11			Løp 12			Ramper				Kvitsøy-tunnelen
Tunnelstrekk		11a	11b	11c	12a	12b	12c	13	14	15	16	18
Netto skyvkraftbehov	[kN]	63.0	2.2	72.0	60.7	2.2	67.5	4.5	4.5	4.5	4.5	11.2
Antall vifter	stk	56	2	64	54	2	60	4	4	4	4	10

Figure 26. *Total number of impulse ventilators in Rogfast[41]*

Tabell 4-1: Største antall impulsvifter i bruk i hvert enkelt tunnelstrekk for driftsventilasjon i normalsituasjon ved dimensjonerende timestrafikk 10 år etter tunnelen åpnes

		Løp 11			Løp 12			Ramper				Kvitsøytunnelen
Tunnelstrekk		11a	11b	11c	12a	12b	12c	13	14	15	16	18
Netto skyvkraftbehov	[kN]	11.2	0.0	33.7	33.7	0.0	11.2	2.2	0.0	0.0	2.2	0.0
Antall vifter	stk	10	0	30	30	0	10	2	0	0	2	0

Figure 27. *Number of impulse ventilators in normal operational scenario in Rogfast [41]*

Table 8. Number of jet fans in different sections

Tunnel run sections	**Tunnel section**	**No. of fans (normal operation)**	**No. of fans (in case of fire)**
Tunnel run 11 (northbound)	11a	10	56
	11b	0	2
	11c	30	64
Tunnel run 12 (southbound)	12a	30	54
	12 b	0	2
	12c	10	60
Ramps (northbound)	13	2	4
	15	0	4
Ramps (southbound)	14	0	4
	16	2	4
Kvitsøy tunnel	18	0	10
	Total	**84**	**264**

5.1.2.2 Pumpstations and pumps

The pump type selected must be a standard multi-stage centrifugal pump. The pumps normally has the same dimensions from all suppliers [18]. In Figure 28 a technical drawing of the pump system in Rogfast is provided. It includes three types of pump stations, where type 1 and 2 are of interest. Each pump station of Type 1 contains thee "dry-set pumps" (Norwegian: Tørroppstillte pumper") and each pump station or Type 2 contains six combined "dry-set" and submersible pumps (Norwegian: "Kombi tørroppstilte og dykkede pumper"). In addition to the two types of pump stations mentioned, there are also two portal pump stations in each opening, the number of pumps in each of these portal pump stations is unknown.

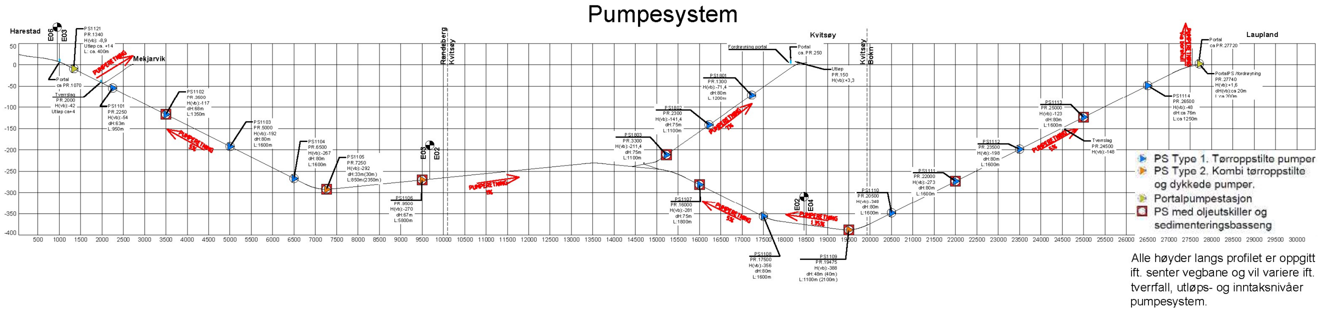


Figure 28. *Technical drawing of pump system layout in Rogfast*

Based on the drawing shown in Figure 28, there is a total of 14 pump stations of Type 1 and 3 of Type 2, which gives a total of 17 pump stations of these types.

Table 9. Number of pumps in different sections

Tunnel section	Pump station type	No. of pump stations	No. of pumps
Randaberg -Kvitsøy (0 – 10 km) 11A	Type 1	4	12
	Type 2	2	12
Kvitsøy (10km – 20 km)	Type 1	2	6
	Type 2	1	6
Kvitsøy Tunnel (14.5km – 18.5km) 18	Type 1	3	9
	Type 2	0	0
Kvitsøy – Laupstad (20km – 27.5km)	Type 1	5	15
	Type 2	0	0
	Total	**17**	**60**

5.2 Technical Hierarchy

The literature study revealed that a generic technical hierarchy for road tunnel equipment does not exist as per today. In the O&G industry there exists have standardized and generic methods for creating technical hierarchies for the system to be maintained. Standards such as NORSOK Z-008 and ISO 14224:2016 describes both the need for this type of systematic classification and guidelines on how to develop a technical hierarchy for a system.

Firstly, a reference for taxonomy is needed. ISO14224:2016 divides the system into different taxonomic classes and levels, which is shown in Figure 29. The taxonomy suggested in the ISO standard can to some degree be translated to road tunnels, with some small modifications. In Table 10 a structure for taxonomy levels and classes that could be used for road tunnels is suggested.

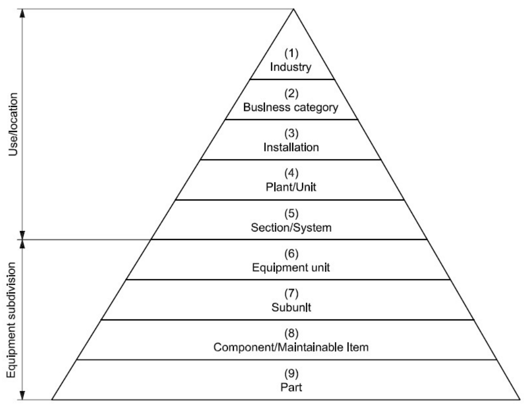


Figure 3 — Taxonomy classification with taxonomic levels

Main category	Taxonomic level	Taxonomy hierarchy	Definition	Examples
Use/location data	1	Industry	Type of main industry	Petroleum, natural gas, petrochemical
	2	Business category	Type of business or processing stream	Upstream (E and P), midstream, downstream (refining), petrochemical
	3	Installation category	Type of facility	Oil/gas production, transportation, drilling, LNG, refinery, petrochemical (see Table A.1)
	4	Plant/Unit category	Type of plant/unit	Platform, semi-submersible, hydrocracker, ethylene cracker, polyethylene, acetic acid plant, methanol plant (see Table A.2)
	5	Section/ System	Main section/system of the plant	Compression, natural gas, liquefaction, vacuum gas oil, methanol regeneration, oxidation section, reaction system, distillation section, tanker loading system (see Table A.3)
Equipment subdivision	6	Equipment class/unit	Class of similar equipment units. Each equipment class contains comparable equipment units (e.g. compressors).	Heat exchangers, compressors, piping, pumps, gas turbines, subsea wellhead and X-mas trees, lifeboats, extruders, subsea BOPs (see Table A.4)
	7	Subunit	A subsystem necessary for the equipment unit to function	Lubrication subunit, cooling subunit, control and monitoring, heating subunit, pelletizing subunit, quenching subunit, refrigeration subunit, reflux subunit, distributed control subunit
	8	Component/ Maintainable item (MI) [a]	The group of parts of the equipment unit that are commonly maintained (repaired/ restored) as a whole	Cooler, coupling, gearbox, lubrication oil pump, instrument loop, motor, valve, filter, pressure sensor, temperature sensor, electric circuit
	9	Part [b]	A single piece of equipment	Seal, tube, shell, impeller, gasket, filter plate, bolt, nut, etc.

[a] For some types of equipment, there might not be a MI; e.g. if the equipment class is piping, there might be no MI, but the part could be "elbow".

[b] While this level can be useful in some cases, it is considered optional in this International Standard.

Figure 29. *Taxonomy classification and levels and examples [22]*

The taxonomy levels from 1-6 is relevant and applicable for creating a technical hierarchy for the tunnels in this case. It would also be possible to include the subsequent levels (7-9) as well, but the problem is information retrieved from Plania, nor from NPRAs norms. Road tunnel specific sources (e.g., Plania, NPRA literature) rarely include any information about sub-units, components and parts. For example, in Plania (and NVBD) the equipment "fan/ventilator" is the lowest hierarchical level for the ventilation system and the equipment "pump" is the lowest hierarchical level for the drainage pump system. In other words, Plania (and NVBD) does not contain information about the components/parts, such as bearings, valves, impellers, etc. of the pumps and fans/ventilators. Another aspect worth mentioning is that in Plania sensors and measuring components do not seem to be connected to the equipment that they monitor.

Table 10. Translation of taxonomy classes and levels for road tunnels

Taxonomy class and level *ISO 14224:2016*		Suggested levels *for Road Tunnel*	Comment
1	Industry	Infrastructure sector	e.g., road, aviation, rail, sea
2	Business category	Infrastructure category	e.g., tunnel, open road, bridge
3	Installation/facility	Tunnel Asset	Individual tunnel
4	Plant/unit	Plant/unit	Technical equipment or structural elements
5	Section/system	System	e.g. ventilation system, pump stations
6	Equipment unit	Equipment unit	e.g. impulse ventilator/fan, pumps
7	Sub-unit	-	Not registered in NVBD or Plania
8	Component/MI	-	Not registered in NVBD or Plania
9	Part	-	Not registered in NVBD or Plania

Initially, an attempt on developing a Technical Hierarchy based on the suggested generic system as described in ISO12442:2016 was made, the hierarchy is inspired by Taha [44]. In Figure 30 below the highest levels (1-4), related to use/location are presented. In figure 31, the lower levels (level 4-6) are structured in the developed technical hierarchy. The categorization type within each level is based on Plania, NVBD and norm N500 [12], [37], [45]. The equipment groups “static equipment”, “rotating equipment”, etc. are based ISO 14224:2016 equipment categories. The reasoning behind categorising different types of equipment in this manner is that failure modes are similar within each category, even for different equipment.

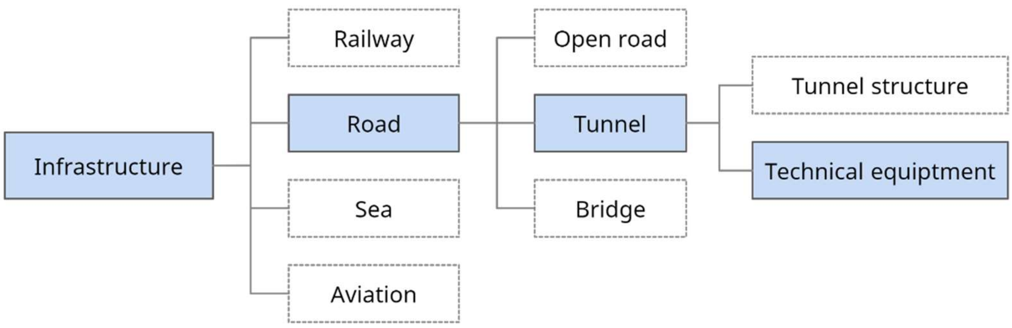


Figure 30. *Overview of higher levels of Technical Hierarchy (level 1-4)*

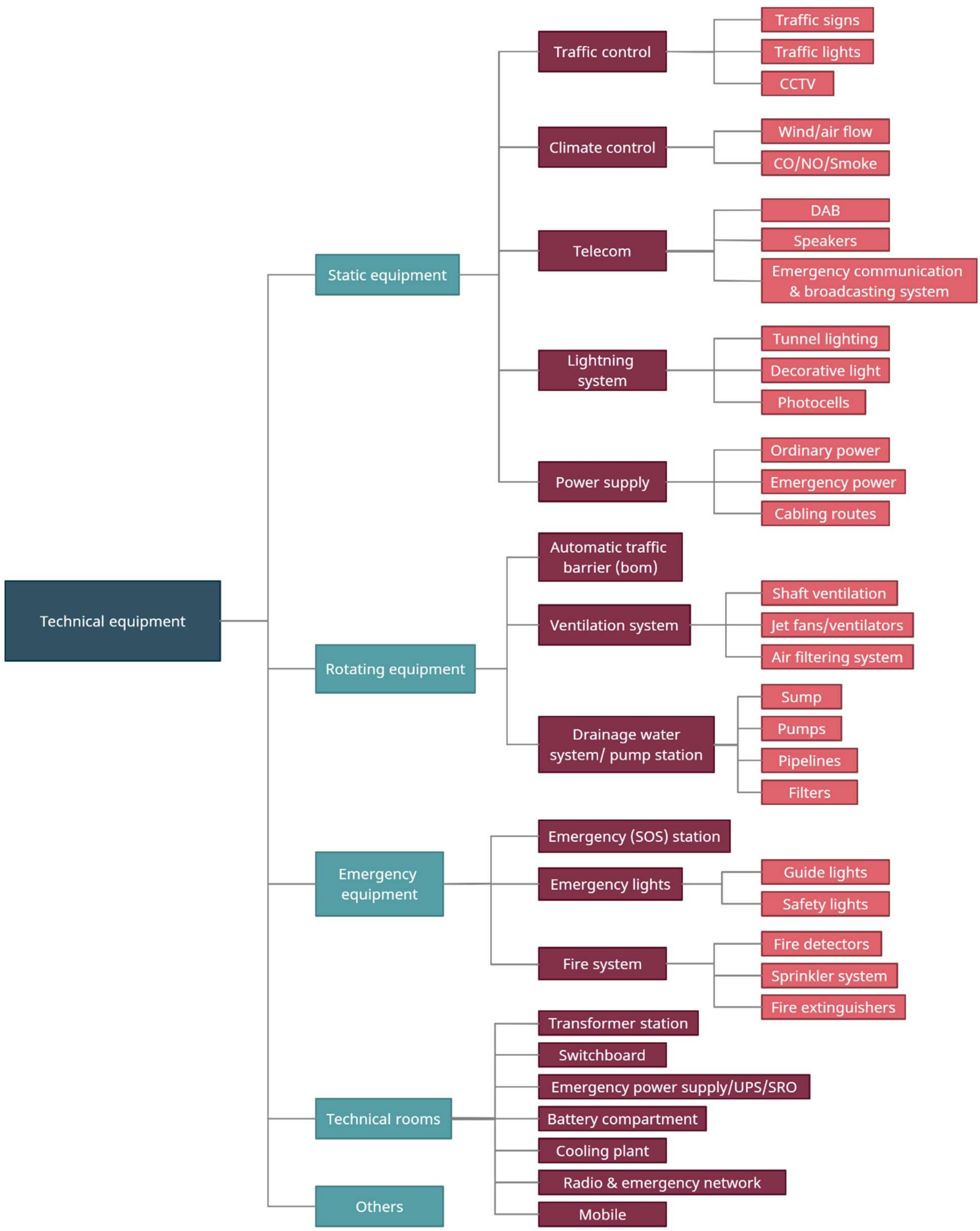


Figure 31. *Technical hierarchy of road tunnel, based on ISO 14224 taxonomy*

The main challenge, in the authors opinion with the structure of the equipment database (NVBD) is that there is no description of taxonomy level in NVBD, other than parent/child relationships between the different registered objects. A concrete example is that “278 Ventilajsonsanlegg” (i.e. ventilation system) and “212 Vifte/Ventilator” (i.e. fan/ventilator) are both listed as child nodes of “67 Tunneløp” (i.e. tunnel run), but at the same time, “212 Vifte/Ventilator” is a child node of “278 Ventilajsonsanlegg”. Another challenge related to specifically the ventilation system, is that in Plania, all fans/ventilators (“212 Vifte/Ventilator”) are grouped under the parent node “360 Ventilasjon” (i.e., ventilation) and not “278 Ventilasjosnanlegg” as it is described in the NVBD structure. In NVBD it is described that there should be one ventilation system (278) in each tunnel run, but it is not included in Plania. This is shown in Figure 32 below. The example marked source: Plania in the Figures 32 and 33 are based on equipment in the tunnel run 2319B Ryfylke tunnel towards Røldal.

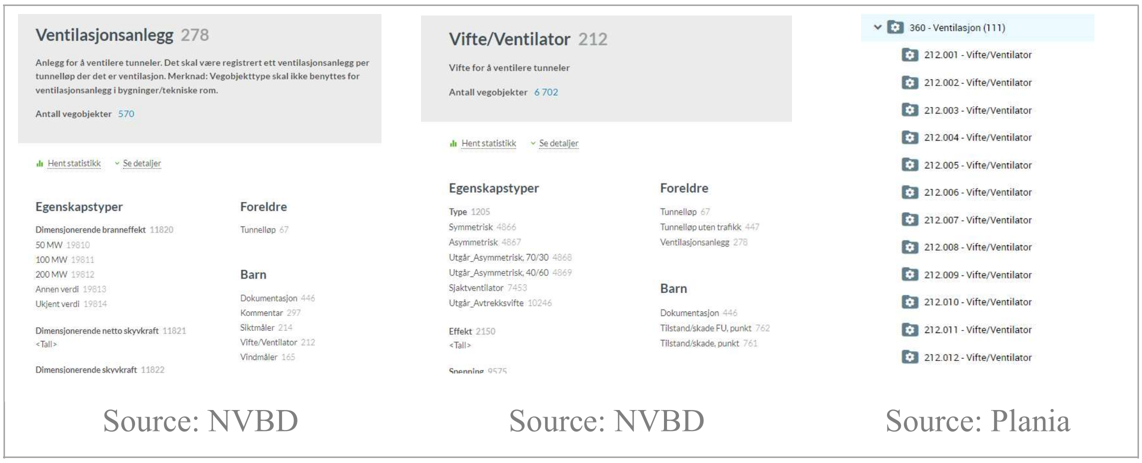


Figure 32. *Comparison of registration of ventilation system in NVBD and Plania*

If we look at the drainage water pumping system *(fig.33)*, “85 Pumpe” (i.e., pump) only have one parent node, which is the “210 Pumpstasjon” (i.e., pump station) and the pump station is child of tunnel run. Also, in plania both pump station and pumps are grouped under “385 Pumpstasjon” and given a tag. However, there is also an additional category “386 Pumper”, which can be seen used for Plania work orders such as functional control of pumps and control of sensors.

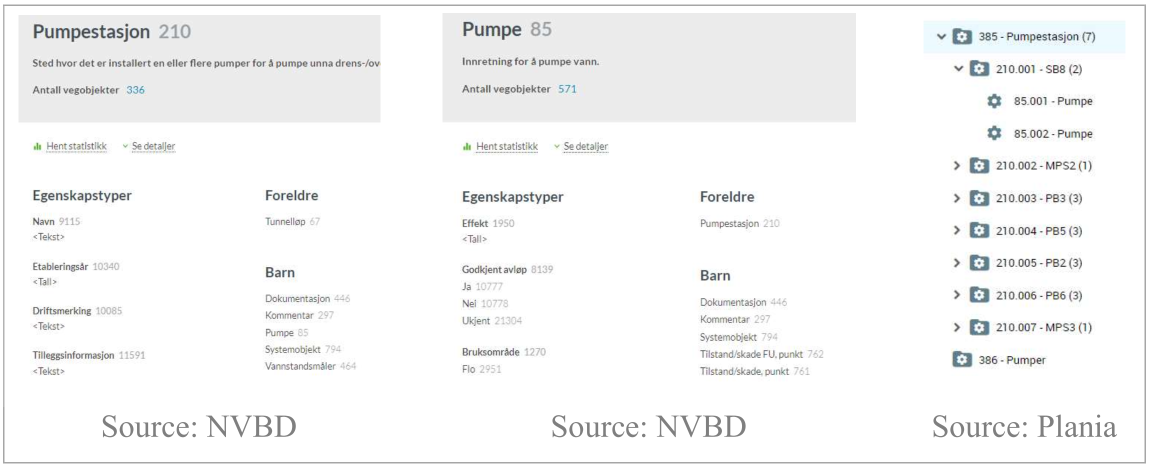


Figure 33. *Comparison of registration of pump system in NVBD and Plania*

The suggested technical hierarchy *(fig. 31)* might not be sufficient in describing equipment in tunnels as a basis of some types of risk analyses. Unlike O&G plants, much of the equipment in tunnels are spread out/placed in the longitudinal direction, and therefore the layout of the tunnel (intersections, gradient, cross connections, etc.), has an impact on how possible failures effect the same equipment types located in different section differently. Because of this, it is possibly more helpful to create the technical hierarchy of road tunnels based on longitudinal direction and not by taxonomy level such as described in ISO 14224:2016(E). Dividing the tunnel into longitudinal sections could prove to be more appropriate especially for those systems that consists of equipment distributed throughout the tunnel, such as ventilations system, lightning system, water draining system, fire detection and distinguishing systems, technical rooms, etc. In the figure below, the tunnel has been divided into sones based on Figure 25 in *section 5.1.2*, that shows how Rogfast is sectioned based on the ventilation system.

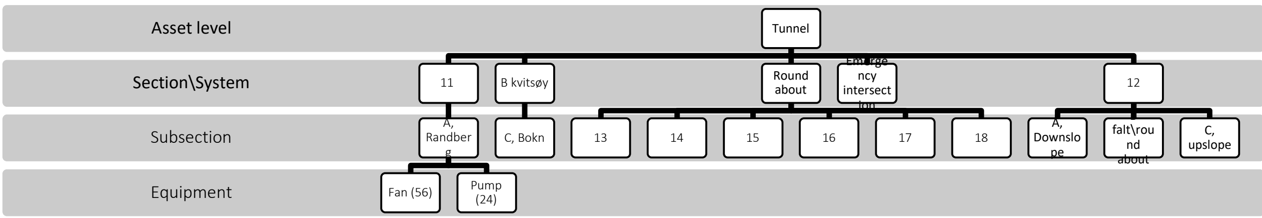


Figure 34. *Technical hierarchy based on longitudinal tunnel sones*

Main functions (MF) and sub-functions can be retrieved from a functional hierarchy, which is normally based on the technical hierarchy [27]. However, as the scope of the thesis is limited to two types of equipment, it will be sufficient to decide MFs directly (without functional hierarchy). In order to proceed with the subsequence analysis steps, MFs for jet fans and pumps must be established. According to NORSOK Z-008 [27], “pumping” can be used as MF for equipment that pumps liquids. There is no specific MF specified for fans in the standard, and hence “blowing” is suggested by the author as MF for the jet fans.

5.3 Work order analysis, Plania

Value can be gained by the business and industrial sector, by utilizing the feedback from collected maintenance data. In ISO14224:2016 [22], a feedback loop is presented to illustrate how to take advantage of data collection. Figure 35 below, illustrates that analysed data from failures and maintenance events by improving the O&M concept and proved insight leading to adjustment and modifications of O&M during the O&M phase of the system life. In addition, feedback can be used to improve both design and manufacturing of new systems.

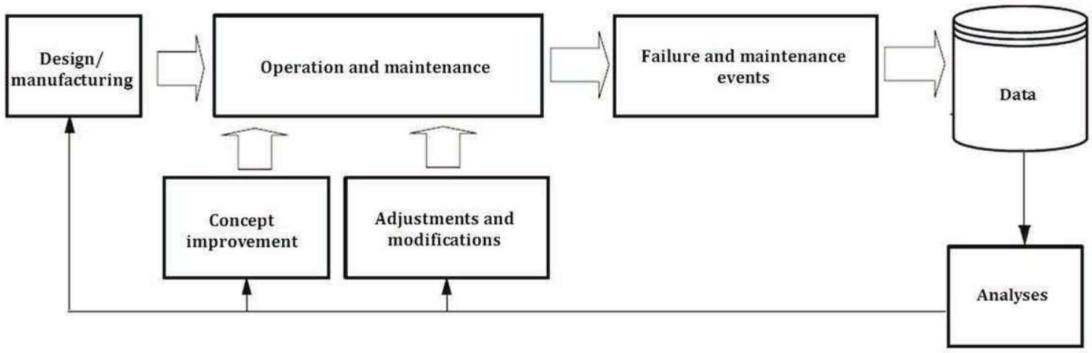


Figure 35. *Typical feedback of analysis from collected reliability and maintenance data [22]*

Relevant information retrieved from work orders (WOs) in Plania Desktop, that has been used to filter/sort data in excel during the analysis process are as follows:

- AO ID and Type = WO tag and types (i.e., corrective, planned, deviation, and message),
- Byggnr. and Byggnavn = building (i.e., tunnel) number and name
- ID and anlegg = installation number and name
- Beskrivelse = description of the work order
- Startdato, tidsfrist og ferdigdato = Start date, deadline and finished date

The first part of the work order analysis was about structuring the data, to get an overview of how WOs are structured. The aim is to find distribution of Planned Maintenance vs. Unplanned Maintenance, how many work orders are delayed and which equipment category has the most amount of work orders. The two graphs below (f*ig.36*) shows planned maintenance actions for the two tunnel runs in Ryfylke tunnel, based on its finished date. It is assumed that the WOs are registered as complete on the same day as the maintenance event occurred. There is a pattern that show a number of workorders are gathered and preformed at specific dates.

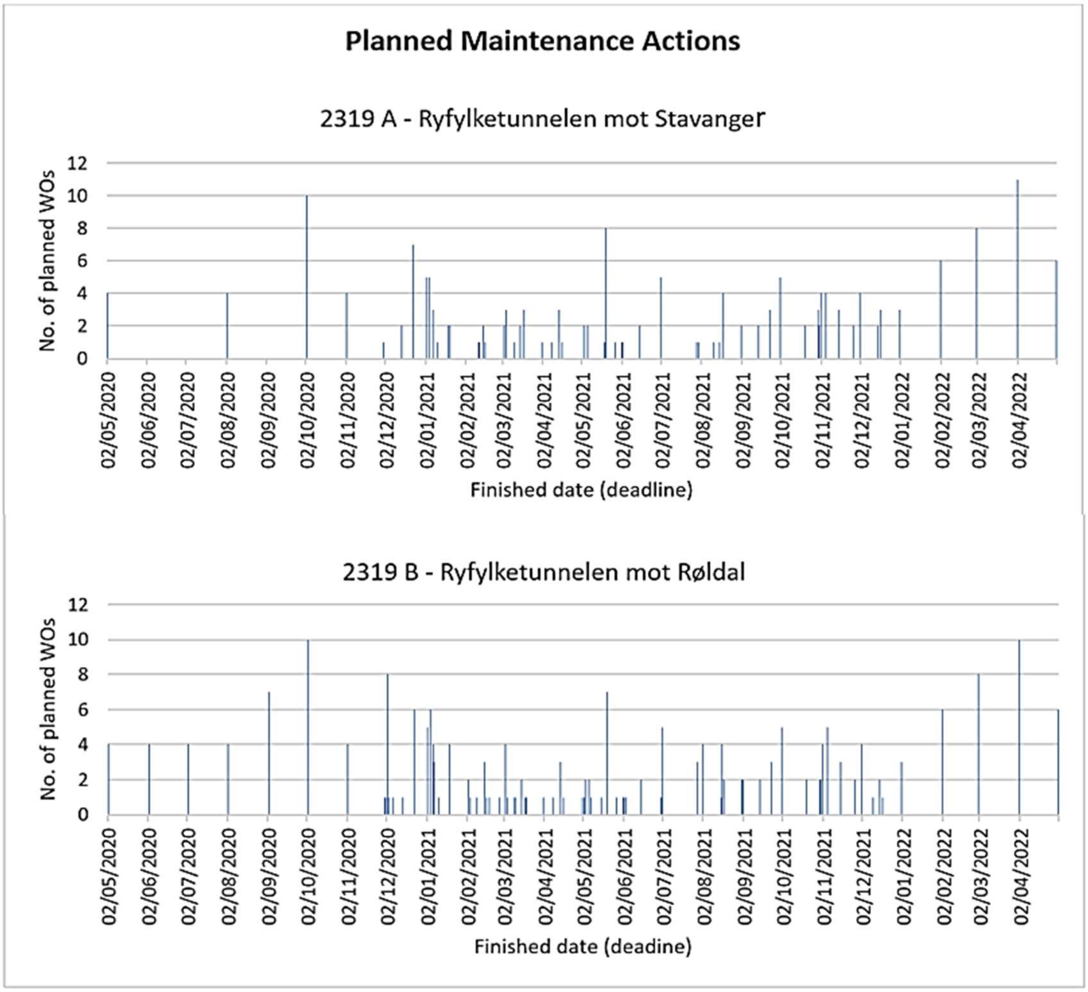


Figure 36. *No. of planned maintenance WOs based on finished date for Ryfylke tunnel*

The next part of interest was to look at the work orders delays. This was done by calculating the time between deadline and finish date. Out of a total of 460 work orders for Ryfylke tunnel (both runs) there was only 249 work orders that was registered as finished within their respective time limit (deadline). This means that 211 out of 460 workorders was delayed by 1 or more days, which is about 46% of all WOs registered for Ryfylke tunnel. The distribution of number of days delayed is showing in Figure 37 below.

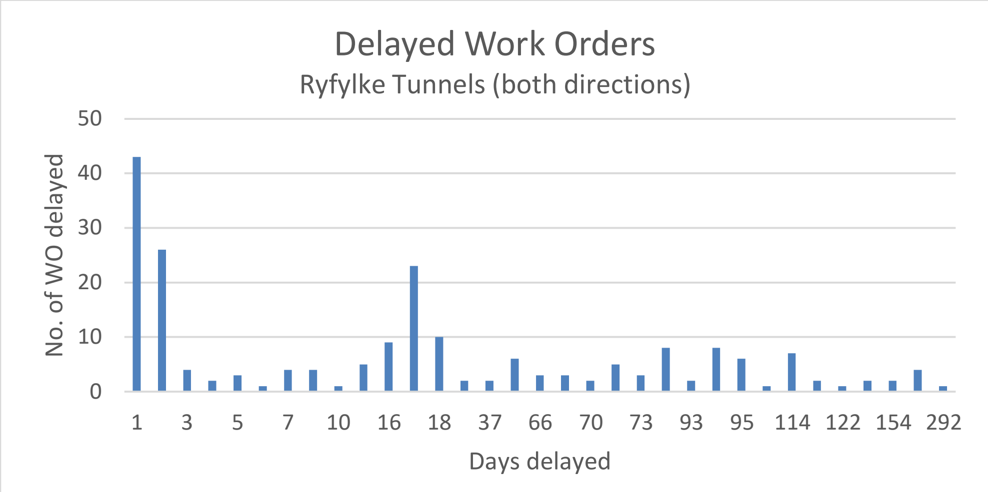


Figure 37. *Number of days delayed*

The third part of interest was to look at the distribution of WO types (i.e., corrective, preventive and message). In the Figure 38 below, preventive WOs are dominating. There are only a few corrective WOs registered for Ryfylke tunnel, which can probably be related to the fact that the tunnel opened in 2019.

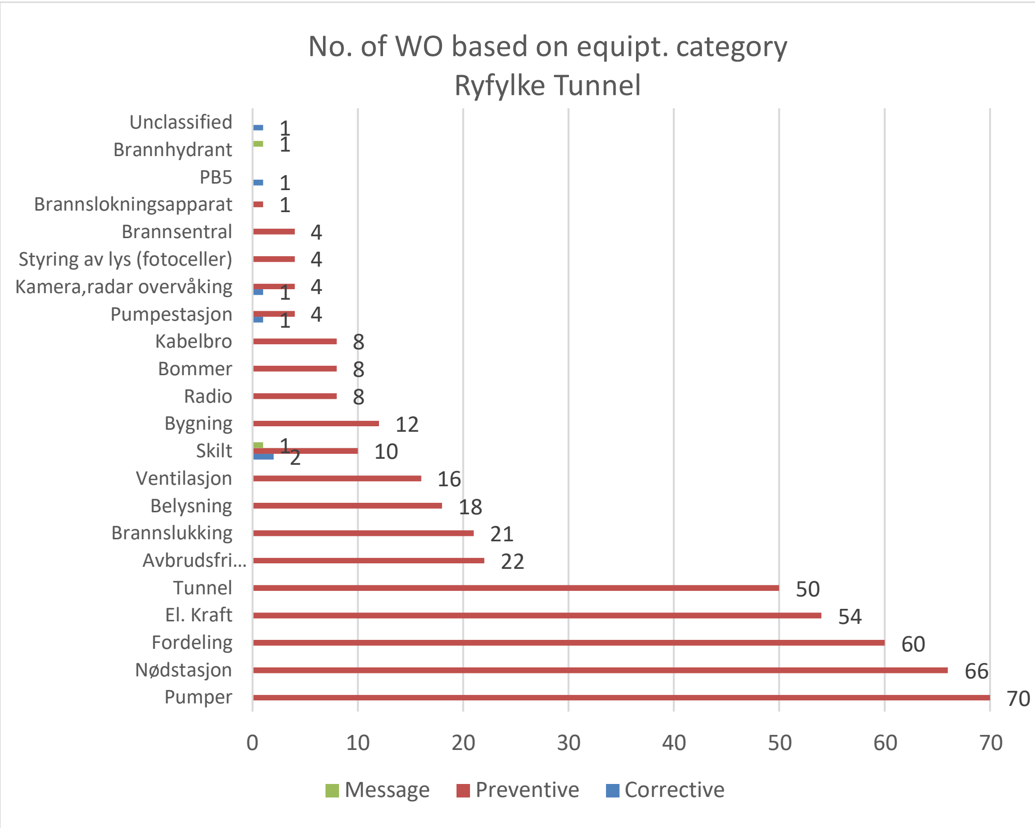


Figure 38. *No. of workorders sorted on equipment and WO type, from start of operational phase*

As the last part of the work order analysis an attempt was made on calculating failure rates for jet fans in Mastrafjord tunnel. Figure 39 below shows how this calculation was performed in excel. As a starting point the work orders were filtered on type “KO”, “ME” and “AV”, and hence excluding preventive maintenance actions, which were in most cases only inspections, controls, etc. There were 17 failures (corrective actions) in total, and the time interval from the first failure to occur until the last is 3543 days.

Type	Byggnr.	Byggnavn	Id	Anleggsnavn	Beskrivelse	Startdato	Tidsfrist	Ferdigdato	Time to repair	Time between failure	Days delay
KO	1603	Mastrafjordtu	212.924	Vifte/Ventilator	Kontroll av vifter, styring og Co	24/02/2011		15/08/2011	172	954	
KO	1603	Mastrafjordtu	360	VENTILASJON	Kontrollere og eventuelt skifte	26/03/2014	25/04/2014	30/07/2014	126	418	96
KO	1603	Mastrafjordtu	360	VENTILASJON	ingen brannventilasjon ved st	21/09/2015	17/11/2015	04/11/2015	44	505	-13
KO	1603	Mastrafjordtu	360	VENTILASJON	Utbedre feil på NO måler M2	23/03/2017	06/04/2017	27/04/2017	35	547	21
ME	1603	Mastrafjordtu	212.079	Vifte/Ventilator	Veglogg 818168 / 8364 7 defe	26/10/2018	30/11/2018	27/10/2018	1	3	-34
ME	1603	Mastrafjordtu	212.063	Vifte/Ventilator	Vifte 42 defekt	30/10/2018	28/02/2019	22/02/2019	115	-25	-6
ME	1603	Mastrafjordtu	360	VENTILASJON	Tunnelvifte nr 11	28/01/2019	21/03/2019	15/05/2019	107	-106	55
KO	1603	Mastrafjordtu	.		utbedre feil etter avvik	29/01/2019	31/08/2019	19/09/2019	233	-111	19
ME	1603	Mastrafjordtu	360	VENTILASJON	defekt sikkerhetsbryter Vifte 8	31/05/2019	30/06/2019	17/06/2019	17	73	-13
KO	1603	Mastrafjordtu	.		Feilretting etter tunnelinspeks	29/08/2019	13/12/2019	23/04/2020	238	-163	132
ME	1603	Mastrafjordtu	360	VENTILASJON	Ventilatorer merket feil, byttet	12/11/2019	29/02/2020	13/03/2020	122	-51	13
KO	1603	Mastrafjordtu	360	VENTILASJON	Utbedre avvik vibrasjonsvakte	22/01/2020	29/02/2020	12/03/2020	50	5	12
ME	1603	Mastrafjordtu	212.079	Vifte/Ventilator	Defekt Vibrasjonvakt	17/03/2020	17/04/2020	12/03/2020	-5	109	-36
AV	1603	Mastrafjordtu	212.014	Vifte/Ventilator	Utbedring av avvik	29/06/2020	29/06/2020	29/06/2020	0	0	0
AV	1603	Mastrafjordtu	212.014	Vifte/Ventilator	Utbedring av avvik	29/06/2020	29/06/2020	29/06/2020	0	0	0
ME	1603	Mastrafjordtu	212.071	Vifte/Ventilator	Defekt smøreplugg	29/06/2020	31/08/2020	21/09/2020	84	112	21
ME	1603	Mastrafjordtu	.		Vifte 34 og 35	11/01/2021	30/04/2021	27/04/2021	106	138	-3
KO	1603	Mastrafjordtu	.		Ingen styring på vifter	12/09/2021	24/09/2021	24/09/2021	12	-44463	0
								3543	0.0047982		
										MTBF	142

Figure 39. *Failure rate calculation*

Failure rates can, according to OREDA [46] be calculated using the following estimation:

Failure rate estimator λ = Number of failures / Aggregated time in service

λ = 17 / 3543 = 0.004782 failures a day.

The collected data is not extensive enough for this calculated failure rate to create the basis for decisions to be made in subsequent analysis steps. This is partly because there are very few corrective actions/registrert failures and, as Figure 39 above reveals, the failures are not based on the same jet fan each time. Hence, it was decided that the failure rates would be excluded for further use in analyses. For those sections where failure rates are required, assumptions and simplification shall be made instead.

5.4 Consequence classification of tunnel equipment

Consequence classification is useful in showing how loss of function of equipment can affect safety, environment, production, cost and others factors [27], and by that help determining critical equipment functions. Based on the literature study, a general consequence classification matrix specifically intended for road tunnel equipment does not exist and has therefore been developed in this part of the thesis.

Consequence categories will not be the same for road tunnels as in the O&G industry and thus it is not possible to use the general consequence classification matrices suggested in NORSOK Z008 and ISO 14224, without making some changes to them. The "Production" consequence category is not relevant for road tunnels, nor for other parts of the Norwegian road sector, as there is no production during the operational phase of road assets. The Figure 40 below shows the general consequence classification matrix from NORSOK Z008. ISO 14224 provides a similar matrix, but with safety, environment, production, and operational cost as consequence categories [22].

Table 1 - General consequence classification

Class	Health, safety and environment (HSE)	Production	Cost (exclusive production loss)
High	Potential for serious personnel injuries. Render safety critical systems inoperable. Potential for fire in classified areas. Potential for large pollution.	Stop in production/significant reduced rate of production exceeding X hours (specify duration) within a defined period of time.	Substantial cost - exceeding Y NOK (specify cost limit)
Med.	Potential for injuries requiring medical treatment. Limited effect on safety systems. No potential for fire in classified areas. Potential for moderate pollution.	Brief stop in production/reduced rate of production lasting less than X hours (specify duration) within a defined period of time.	Moderate cost between Z – Y NOK (specify cost limits)
Low	No potential for injuries. No potential for fire or effect on safety systems. No potential for pollution (specify limit)	No effect on production within a defined period of time.	Insignificant cost less than Z NOK (specify cost limit)

Figure 40. *General consequence classification according to NORSOK Z-008 [47]*

In the NPRA document for contractual provisions for operation [48], a set of consequence classes are given for the purpose reporting in case of accidental events during O&M activities. The consequence classes are related to events such as workplace accidents and injuries and "other unfavourable events". There are three categories of consequences described, which are human injury, material damage and environmental damage, which are each classified in five degrees of severity, as shown in the Figure 41 below.

Konsekvensklasse: Statens vegvesens klassifisering av skader som vist nedenfor

Konsekvensklasse	Personskade
K5	Død
K4	Alvorlig personskade med mulig varig mén
K3	Personskade med fravær over 10 dager
K2	Personskade med fravær inntil 10 dager
K1	Personskade uten fravær

Konsekvensklasse	Materiell skade
K5	> NOK 10 mill
K4	> NOK 5 mill
K3	> NOK 1 mill
K2	> NOK 250.000
K1	> NOK 50.000

Konsekvensklasse	Miljøskade
K5	Katastrofal miljøskade. Svært alvorlige og langvarige miljøskader. Regionale og/eller lokale konsekvenser med restaureringstid over 10 år.
K4	Kritisk miljøskade. Alvorlige og langvarige miljøskader. Lokale konsekvenser med restaureringstid 5-10 år.
K3	Alvorlig miljøskade. Betydelige miljøskader. Restaureringstid 1-5 år.
K2	Moderat miljøskade. Registrerbar skade. Restaureringstid inntil 1 år.
K1	Minimal miljøskade. Ikke registrerbar i resipient.

Figure 41. *Consequence classification according to NPRA for operational contracts [48]*

A suggestion for consequence classes suitable for equipment failures in road tunnels are (1) Safety, (2) Availability, (3) Operational and maintenance (O&M) costs, and (4) Environment. Hence the production consequence class is no longer an issue, and availability is introduced. Another alternative could be to merge the two classes safety and environment or follow the general classification of NORSOK Z008 and include the class health, safety and environment (HSE) instead. Because the desired output for road tunnel operation is to acquire the highest possible degree of safety and minimal downtime [49], the first suggestion for consequence classes is considered the most suitable option.

Safety

Safety is highlighted as the most important factor in road tunnelling, both during construction and in the operational phase. In the Figure 41, five consequence classes for personal injury are described. These should possibly be adjusted to more realistic levels based on qualitative and quantitative methods. For now, the suggestion levels of safety consequences from high to low are fatality, permanent injury, serious injury requiring absence, injury with medical treatment and lastly first aid, with no absence. These have been entered into the consequence classification matrix provided in Table 11 below.

Availability

Availability in road tunnels is mainly based on whether the tunnel is open to traffic or not, but changed traffic conditions, such as lowered speed limits, could also be considered to have an impact on availability depending on how we define availability. In report 143, NPRA [50] has divided tunnel closure into groups, based on cause of tunnel closure. The two main categories of tunnel closure are (A) planned tunnel closing and (B) unplanned tunnel closure. Each main category is further divided into sub-groups, describing the cause of the tunnel closing, as shown in Figure 42. According to the report [50], the definition of a "closed tunnel" will be different for tunnels with one and two tunnel runs. For single run tunnels, where traffic goes in both directions in the normal use case scenario, closing the tunnel means that all traffic must be rerouted. For two-run tunnels, where traffic goes in only one direction, closing the tunnel means that one out of two tunnel runs are closed while the other is still open. The traffic that normally would go through the closed tunnel run either needs to be rerouted to a different road or through the other open tunnel run. If the last scenario applies, the remaining open tunnel run would have to be two-way-regulated.

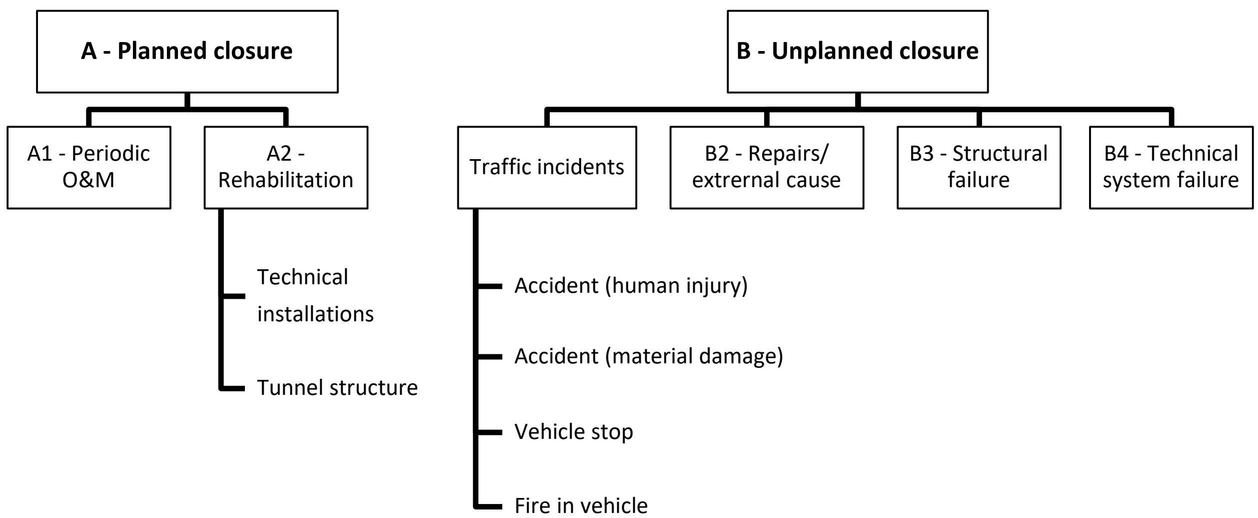


Figure 42. *Road tunnel closure causation*

Operation and maintenance (O&M) cost

According to Figure 41 the cost of material damage has already been quantified into cost elements, which can be used in the purpose of developing the consequence classification matrix for equipment in road tunnels. There are five intervals of cost consequences defined in the document for contractual provisions for operation [48], which are:

- Very low > 50 KNOK
- Low > 250 KNOK
- Medium > 1 MNOK
- High > 5 MNOK
- Very Heigh > 10 MNOK

Where KNOK is *1000 NOK and MNOK is *1 million NOK

Environment

In the suggested consequence class for environment according to [48], which is provided in Figure 41 above, environmental consequences are quite severe and might be hard to measure in case of equipment failure. Keeping in mind that the consequence classes suggested in the contractual provisions for operation [48] is based on events such as workplace accidents and injuries and "other unfavourable events", there is a possible need for modifying the scale of the consequences when the focus is on equipment consequence classification.

Based on NORSOK Z-008, ISO 14224:2016 and NPRAs contractual provisions for operation, a general failure consequence classification matrix for road tunnel equipment has been developed and is provided in Table 11 below.

Table 11. General failure consequence classification matrix for road tunnel equipment

Class	Consequence			
	Safety	**Availability**	**O&M cost**	**Environment**
Very High	Fatality	Long term tunnel closure > 6 weeks	> 10 MNOK	Catastrophic environmental damage. Very serious and long-term environmental damages. Regional and/or local consequences with restoration time > 10 years
High	Permanent injury	Midterm closure 1-6 weeks	5 – 10 MNOK	Critical environmental damage. Serious and long-term environmental damages. Local consequences with restoration time 5-10 years
Medium	Serious injury requiring absence	Closure 1-7 days	1 – 5 MNOK	Serious environmental damage. Significant environmental damages. Restoration time 1-5 years
Low	Injury with medical treatment	Detour < 2 hours	250 – 1000 KNOK	Moderate environmental damage. Registrable environmental damages. Restoration time up to 1 year
Very Low	First aid, no absence	Waiting > 2 hours	50 – 250 KNOK	Minimal environmental damage. Not registrable in recipient.

In addition to the failure consequence classification, NORSOK Z008 proposes to include expected failure frequency intervals. Expected failure frequencies can either be calculated based in company maintencene data/generic industry databases or estimated based in qualitative data and expert opinions [27]. The failure frequencies can then be given as intervals. Combining consequence classification and expected failure frequencies, gives a risk matrix that can be used to determine criticality level each type of equipment. A proposed risk matrix, combining the consequence classification matrix (*tab.11*) and a suggested set of expected failure frequency intervals, is given in Table 12 below. The suggested expected failure frequencies are only provisional, for the purpose of exemplifying the method, and should be updated based on either qualitative (e.g., expert opinion) or quantitative data (e.g., historical maintencene data).

Table 12. Risk criticality matrix for road tunnel equipment

Consequence	Safety	Fatality	Permanent	Serious	Medical treatment	First aid
	Availability	Closing > 6 weeks	Closing 1-6 w	Closing 1-7 days	Detour < 2 hours	Waiting > 2 hours
	O&M cost	> 10 MNOK	5 – 10 MNOK	1 – 5 MNOK	250 – 1000 KNOK	50 – 250 KNOK
	Environment	Catastrophic	Critical	Serious	Moderate	Minimal
Frequency	Less than 1 month	**VH**	**VH**	**VH**	**VH**	**VH**
	1 month to 1 year	**VH**	**VH**	**H**	**H**	**H**
	1 year to 5 years	**VH**	**H**	**M**	**M**	**M-L**
	5 years to 30 years	**H**	**M**	**M**	**L**	**VL**
	More than 30 years	**M**	**L**	**L**	**VL**	**VL**

5.5 Failure Mode and Effects Analysis (FMEA)

A Maintencene Concept Study Template have been developed in Microsoft Excel, with the purpose of selecting appropriate maintenance concepts of different technical equipment in road tunnels. The template includes the followings steps:

- Technical and functional hierarchy
- Consequence classification
- Failure modes and effect analysis (FMEA)
- Failure rate and active maintenance hours
- Maintencene concepts
- Spares and logistics

Limitations

Originally, all failure data was supposed to be retrieved from and based on historical data collected from Plania. This turned out to be specifically challenging, and thus much of the failure data presented in this part is gathered from other sources, such as FDV documentation for specific road tunnel equipment. Due to limited time and data, "Spares & Logistics" is not included in the analysis. It is however included in the Excel template, as it is considered an important step in the risk based maintencene approach described in NORSOK Z-008.

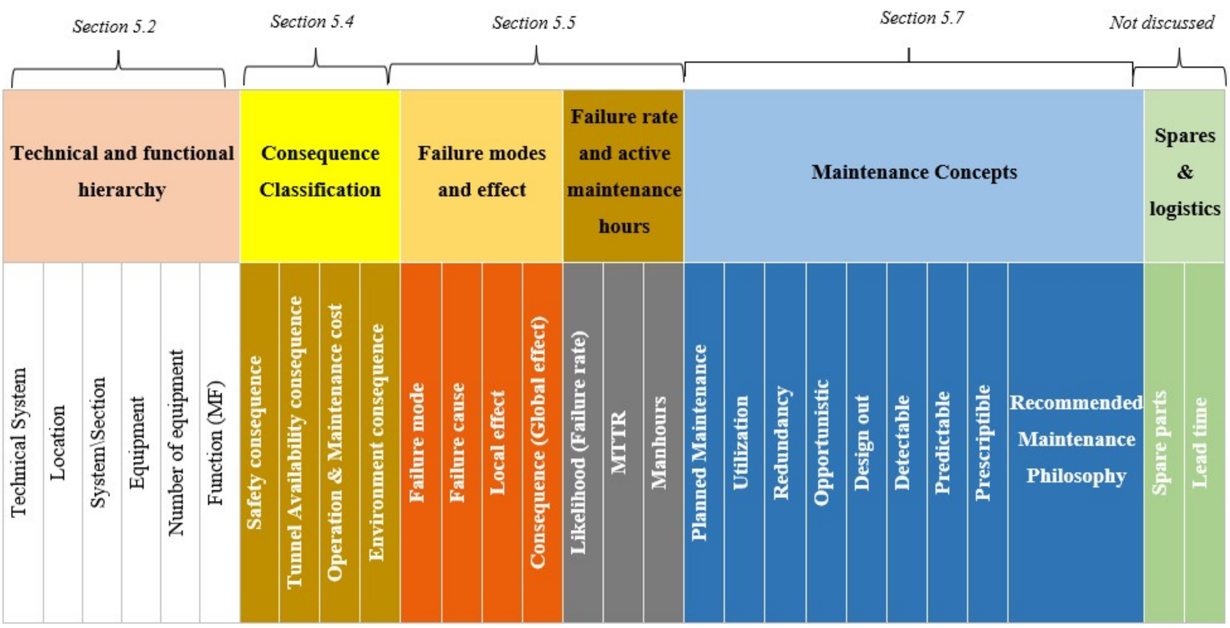


Figure 43. *Maintencene Concept Study template for road tunnel equipment, constructed in Microsoft Excel*

The first two steps, technical hierarchy and consequence classification, are described extensively in the respective sections *5.2* and *5.4*. The failure modes and effect analysis (FMEA) preformed and described in this sub-chapter.
As described in *section 2.3.1.3* of the theory chapter, an FMEA is a qualitative analysis method that can be conducted to identify failure modes and causes of all possible failures of an item.

5.5.1 Failure modes and effects

Failure modes are defined as the "*manner in which the inability of an item to perform a required function occurs*" [51]. In other words, a failure mode describes the specific way a failure occurs for the system, sub-system, component, etc., where failure means loss of required function. All failure modes have a cause, which is the reason why the failure occurred. According to ISO 14224 [22], the term "failure cause", which describes the underlying or root cause of the failure, is often confused with the term "failure mechanism", which describes the obvious or observed cause of a failure. It is not always an easy task to determine the failure cause or failure mechanism, as each failure mode can have several causes and the cause of failure may not be apparent at the time of the observation of the failure. As described in *section 5.2*, equipment level is the lowest available hierarchical level for this case study. Thus, the failure modes are based on equipment level.

Failure effects have been divided into local and global effects in the FMEA. The local effects describe the impact the failure mode has on the equipment itself and the global effect describes the impact of the specific failure mode on the entire system. Failure effects have been decided based on each failure mode.

Failure modes and possible failure causes are registered in Plania as descriptions (*"Beskrivelse"*), or comments (*"Kommentar"*), which are open text fields. Thus, the maintenance worker/personnel are free to write (or not write) failure mode or possible failure cause. This means that in some cases failure is only described as for example "Fan no. X defect", and no further descriptions are given on the failure.

Table 13 provides jet fan failure modes and possible causes based on FDV documentation [52] for jet fans in Ryfylke tunnel and historical maintenance data retrieved form plania. The two columns, "FDV" and "Plania" (*tab.13 and 14*) discloses where the failure mode and cause descriptions originates from. Most of the described failure modes are based on FDV, however a few have been found in historical data (i.e., Plania). There is no registered failure data from Ryfylke tunnel, neither in registered work orders nor in messages, related to either pump nor jet fans. This was expected as the tunnels the operational life is relative short compared to the lifetime of ventilation equipment, and considering replacement and repairs of technical equipment usually start 5 to 10 years after tunnel opening [10].

Table 13. Jet fan failure modes and causes, retrieved from Plania and FDV [52]

Failure mode	Possible failure cause	FDV	Plania
Minor vibration (can only be detected by vibration measurements)	Lose parts: externally and internally in motor	X	
	Bearing: lack of lubrication, wear, damaged bearing, loose bearing	X	
	Shaft imbalance	X	
	Defect fan blade	X	X
	Suspension, vibration dampers	X	
	Stator/rotor complication	X	
Major vibration (possible vibration sensor gives alarm signal)	Fan goes into transition mode shortly after fan is turned on and natural wind direction is in opposite direction, or fans blowing direction is recently changed from forward to backwards	X	
	Welded connections on fan casing have cracked or loosened	X	
	Foreign object attached on impeller or significant corrosion on fan blades	X	
	Fan balance weights loosened	X	
	Foreign objects in airstream causing damage to fan blades	X	
	Motor bearing defect	X	
	Bolts/screws and nuts loosened	X	
	Foreign objects blocking airstream on inlet- or outlet side and therefore forcing fan to work outside design mode	X	
Motor stop or motor protection switch off	Defect bearing, overlay in power supply, overloaded or burned engine, etc.	X	
High noise levels	Foreign objects blocking airstream on inlet- or outlet side and therefore forcing fan to work outside design mode and increased noise levels are observed	X	
	Defect silencer		X
Power consumption above expectations	Motor bearing could be broken	X	
Fan doesn't work	Motor could be defect/broken	X	X
	Power supply is interrupted	X	
Fan pair blows in opposite directions	Coupling mounted incorrectly		X

Documentation and information about the type and make of pumps for Rogfast is unknown. The failure modes listed in the Table 14 below, are mainly based on FDV documentation from Plania document library. The described pumps are produced by DP-Pumps[53], and are of the type vertical, multistep centrifugal pumps. They can be used for transportation and pressure increase of both cold and warm water, and can also be used to transport liquids with other viscosity than water.

Table 14. Drainage pumps failure modes and causes, retrieved from Plania and FDV [53]

Failure mode	Possible failure cause	FDV	Plania
Leak along the shaft	Running surfaces of the mechanical seal worn or damaged	X	
	New pump: seal stuck due to assembly	X	
	Mechanical seal mounted incorrectly	X	
	Elastomers affected by medium	X	
	Pressure too high	X	
	Shaft worn	X	
	Pump has been operating without water	X	
Leakage along the shroud at the top racket or at the pump foot	O-ring worn	X	
	O-ring not resistant to medium to be pumped	X	
	Too high tension on pump foot; it becomes oval	X	
Pump vibration or high noise levels	Coupling mounted incorrectly	X	
	Faulty setting of hydraulic assembly	X	
	There is no water in pump	X	
	No supply	X	
	Pump and/or motor bearings is defective	X	
	Available net positive suction head (NPSH) too low (cavitation)	X	
	Pump does not work in its working range	X	
	Pump standing on uneven surface	X	
Malfunction	Internal blockage in pump	X	
	Defect soft starter		X
Pump does not start	No voltage on the terminal clamps	X	
	Thermal motor safety switch triggered	X	
Motor running, but pump does not work	The pump shaft has been broken	X	
	The coupling between pump- and motor shaft is loose	X	
Pump supplies insufficient capacity and/or pressure	Outlet and/or inlet shut-off valve is closed	X	
	There is air in the pump	X	
	The suction pressure is insufficient	X	
	Pump rotates in the wrong direction	X	
	The suction line has not been vented	X	
	Air bubble in the suction line	X	
	Pump sucks air because of leakage in the suction line	X	
	Too little water consumption so air bubbles clog up in the pump	X	
	The diameter of the suction line is too small	X	
	Capacity of water meter in the supply line is too small	X	
	Foot valve blocked	X	
	The impeller or the diffuser is blocked	X	

	O-ring between impeller and diffuser is gone	X	
	O-ring not resistant to the medium to be pumped	X	

5.5.2 Failure rates and active maintenance hours

In the Maintencene Concept Study template *(fig.43),* "failure rate and active maintenance hours" is one of the steps in the workflow. The step includes finding the likelihood of failure (failure rate), Mean Time to Fail (MTTF) and manhours (active maintencene hours). This step is included in the template, as these factors are important in determining critical failure modes. However, these factors have not been filled due to lack of sufficient data quality.

Failure rate is defined as "*conditional probability per unit of time that the item fails between t and t + dt, provided that it has been working over [0, t]*." [22]. In other words, the failure rate states the likelihood of failure within the next time unit. Failure rates can be estimated by calculating number of failures divided by aggregated time in service [46]. MTTF can be calculated based in the failure rate, where failure rate = 1/MTTF.

As described in *section 5.3*, an attempt on calculating failure rate based on collected data was made. It was also attempted to gather information about failure rates from other sources, such as literature on specific road tunnel equipment and by using the OREDA database. However, due to the insufficient amount of data the calculated failure rates and failure rates from other sources not being comparable/applicable for road tunnel equipment, failure rates are excluded from further analysis.

The collected data was also not sufficient in calculating or deciding upon manhours or active maintenance hours, and hence it has been excluded from further analysis.

5.5.3 Result of FMEA

Firstly, the failure modes and causes established based on the tables 13 and 14 in *section 5.5.1*, then local and global effects was decided based on each failure mode. In table 15 below shows the result of the developed FMEA for road tunnel equipment types of pumps and jet fans.

Table 15. Developed FMEA worksheet for road tunnel equipment

Technical and functional hierarchy					Consequence Classification				Failure modes and effect			
Technical System	**System\Section**	**Equipment**	**Number of equipment**	**Function (MF)**	**Safety consequence**	**Availability consequence**	**O&M cost consequence**	**Environment consequence**	**Failure mode**	**Failure cause**	**Local effect**	**Consequence (Global effect)**
Rotating equipment	Drainage water pumping system	Pump	60 (total no.)	Pumping	L	L	M	VL	Leak along the shaft	mechanical seal worn or damaged, seal stuck due to assembly (new pump), mechanical seal mounted incorrectly, pressure to high, shaft worn	loss of efficiency, corrosion	loss of effeciency, to high waste water levels
									Leakage along the shroud at the top bracket or at the pump foot	worn O-ring, O-ring not resistnat to pumped medium, to high tension on pump foot	loss of efficiency, corrosion	loss of effeciency, to high waste water levels
									Pump vibration or high noise levels	coupling mounted incorrectly, faulty setting of hydraulic assembly, no supply, no water in pump, pump and/or motor bearings defective, pump standing onuneven surface	increased mechanical load, damage to other components	loss of effeciency, to high waste water levels
									Malfunction	internal blockage, defect softstarter	unable to perfom MF	to high waste water levels
									Pump does not start	no voltage on terminal clamps, thermal motorsafety switch triggered	unable to perfom MF	to high waste water levels
									Motor running, but pump does not work	pump shaft has been broken, coupling between pump- and motor shaft is loose	unable to perfom MF	to high waste water levels
									Pump supplies insufficient capacity and/or pressure	outlet and/or inlet shut-off valve closed, air in pump, suction pressure insufficient, pump rotates in the wrong direction, impeller or diffuser is blocked	loss of efficiency, damage to other components	loss of effeciency, to high waste water levels
Rotating equipment	Ventilation system	Jet fan/ventilator	264 (total no.)	Blowing	M	M	L	VL	Fan doesn't work	defect/broken motor, power supply interrupted	unable to perfom MF	loss of effeciency, to high levels of CO/NO/PM
									Minor vibration	loose parts in motor, damaged/loose bearing, defect fan blade, suspesnsion, vib. damper stator/rotor complication	increased mechanical load, fatigue of other components	loss of effeciency, to high levels of CO/NO/PM
									Major vibration	transition mode, welds/fan casing loose or cracked, foreign object on impeller, corrosion on blades, fan balance weights loose, foreign object in air stream blocking airstream/causing damage to blades, motor bearing defect, loose bolts/screews/nuts	increased mechanical load, damage to other components	loss of effeciency, to high levels of CO/NO/PM
									Motor stop or motor protection swtich of	defect bearing, overloaded/burnt engnine	unable to perfom MF	loss of effeciency, to high levels of CO/NO/PM
									High noise level	foreign objecst blocking airstream in inlet or outlet side, defect silencer	noise pollution	noise pollution
									Power consumtion above expected	motor bearing could be broken	increased fatigue and vibration	increased electrical costs
									Fan pair blows in opposite directions	Coupling mounted incorrectly	decreased MF efficency	loss of effeciency, to high levels of CO/NO/PM

5.6 RAM analysis

Reliability block diagram (RBD) analysis is included to suggest a new alterative for RAM analysis that can be implemented into the RoadRAMS methodology. It has been conducted, using the online software tool Relyence, to study reliability of tunnel equipment given the tunnel layout. RBD analysis has been conducted for three different cases of tunnel layouts, to show how the sectioning of the tunnel affects the tunnel reliability and availability. It was decided by the author, in compliance with the university supervisor, that a simplified approach should be used for conducting the RBD analysis, with the purpose of showing an example of how this type of analysis can be used with regards to technical equipment in road tunnels.

The following steps is taken in Relyence RBD software tool to analyses reliability of the ventilators and drainage pumps in Rogfast tunnel:

1. Scenario description - create simplified a model of the tunnel, based on three different scenarios
2. Data entry and simulation – enter data into Relyence RBD software. Run calculation/simulation
3. Result of analysis

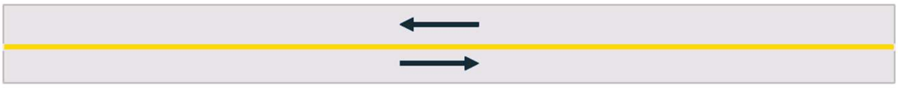
In order to complete the RBD analysis the following assumptions have been made:

- Failure rate for each equipment have been set to 1
- Failure distribution: exponential
- It is assumed that if one equipment fails the lane will not be available, hence equipment redundancy is unaccounted for. This assumption is unrealistic, as the tunnel will be operable despite failure of one jet fan or one pump. The assumption is made to show how the tunnel layout will affect overall reliability.

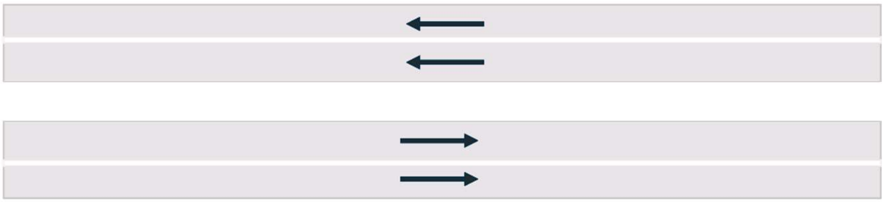
5.6.1 Scenario description

Three different scenarios presented below. The scenarios are simplified generic models, with the intention of showing how the tunnel layout affects reliability. The three figures are added to give a better understanding of the layout of the three scenarios.

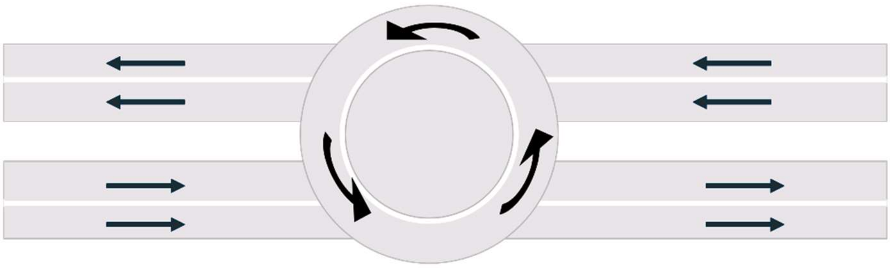
Scenario 1: A generic tunnel consisting of only one tunnel run and two lanes, meaning that traffic goes in both directions in the same tunnel run. There are no intersections in the tunnel.



Scenario 2: A generic tunnel consisting of two tunnel runs, where tunnel run has two lanes. Traffic moves in one direction only. There are no intersections in the tunnel.

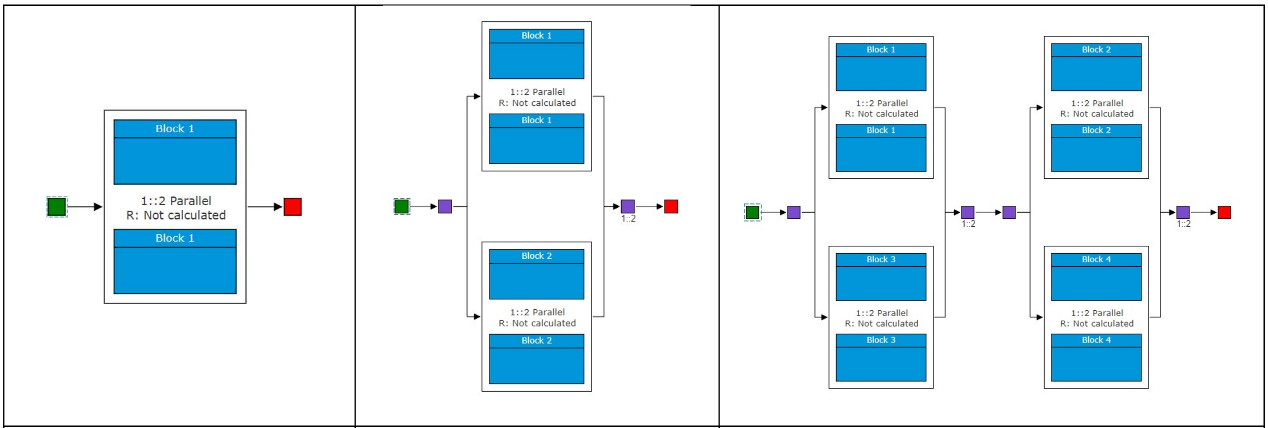


Scenario 3: A generic tunnel consisting of two tunnel runs, where each run has two lanes. Traffic moves in one direction only. There is one intersection in the middle of the tunnel length. For simplicity it is assumed that no equipment is located in the intersection.



5.6.2 Data entry and simulation

Firstly, the reliability block diagrams (RBD) are created in the software.



Scenario 1	Scenario 2	Scenario 3

Figure 44. *RBD made in Relyence of the three scenarios*

The next step would be to decide how many jet fans and pumps are placed in the tunnel and enter this information in the "Quantity" field in Relyence. The layout of the technical equipment (i.e., jet fans and pumps) are described in section *5.1.2*. In case of fire, all jet fans (264) will be operative and in normal operative use case there will be a total of 84 jet fans in use. The pump stations are categorised as type 1 and type 2, which contains respectively 3 and 6 pumps each. There is a total of 14 pump stations of Type 1 and 3 pump stations of Type 2, giving a total of 60 pumps altogether. In the tables 13 and 14 in section *5.1.2*, jet fans and pumps have been divided into sections based on the layout of the tunnel, which would be used as information in the RBD analysis. The purpose of performing the RBD analysis is to make an example how this type of analysis can be used with regards to technical equipment in road tunnels, and hence a simplification is made in terms of quantity of equipment. Input values that have been entered are as follows:

- Quantity: 40
- Quantity required: 40
- Failure Distribution: Exponential
- Failure rate: 1
- Repairable: No

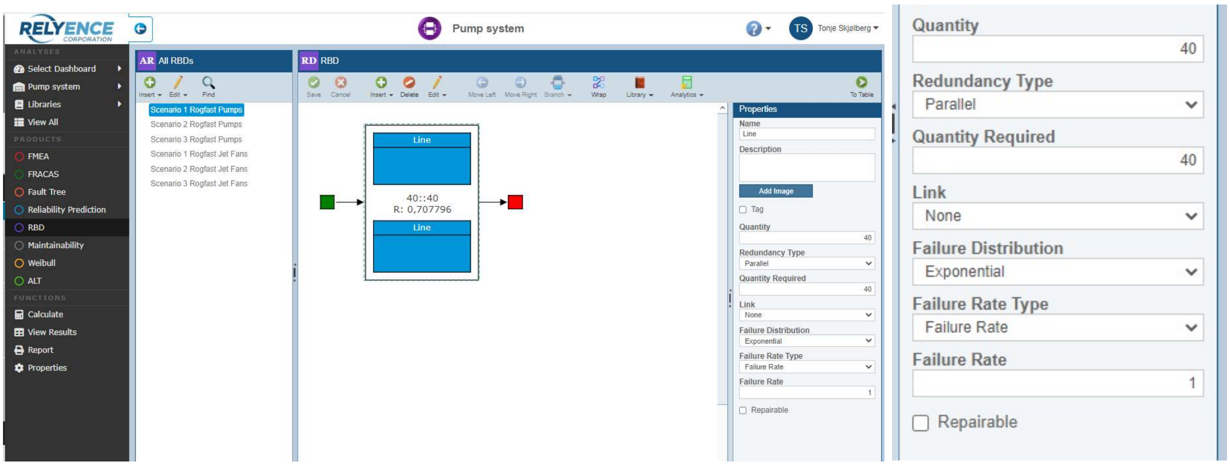


Figure 45. *Entry of input values in Relyence*

The system is set to non-repairable, meaning if the equipment fails it will be replaced and not repaired. The reason for this is that analysing a repairable system requires data that can be used to find Mean Time to Repair (Hours), which found by registering manhours for repairs, as suggested in the Maintenance Concept Study template.

The last step is to simulate the RBD. The properties used for the simulations are shown in figure X below, these are unchanged for the three different scenarios. Note, the “End time” under “Time-Based Metrics” have the unit hours.

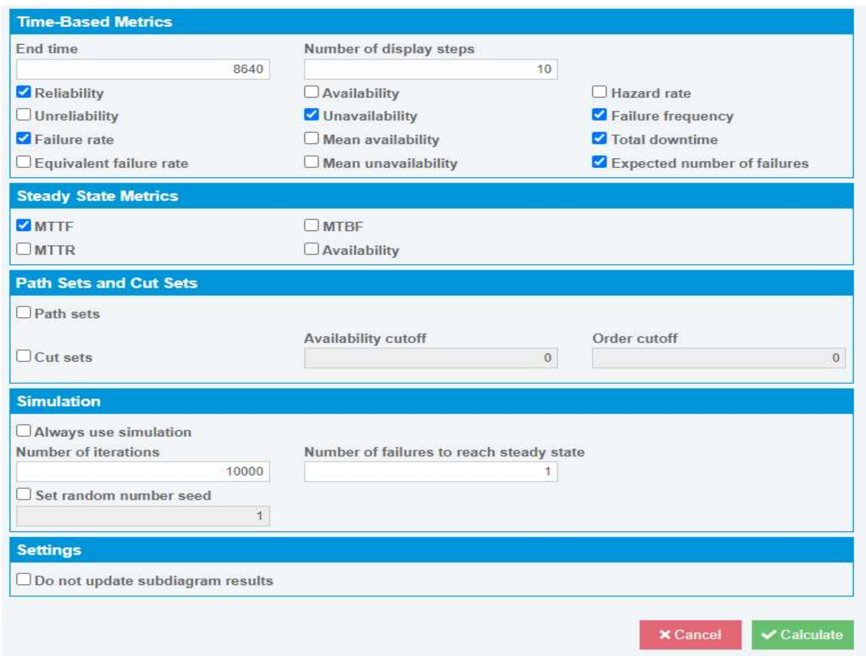
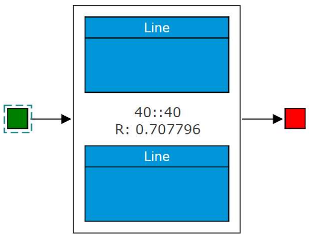


Figure 46. *Properties of simulation*

5.6.3 Results of RBD analysis

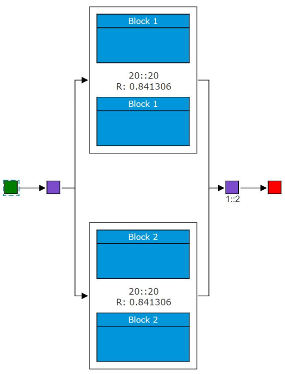
Figures 47 – 49 below, provides the results of the simulations made in Relyence. Comparing the results are important to understand the relevance and benefits of the analysis. Changes in reliability, unavailability, failure frequencies, total downtime and expected number of failures metrics of interest.

It is apparent based on the result that unavailability equals expected numbers of failures. This is because of the assumption that if one item fails, then the tunnel run (path) is unavailable. As time passes, reliability of the whole system decreases, which is true for all scenarios. Reliability of the system decreases at a higher rate for scenario 1, than for other two scenarios. This is related to the layout of the RBD, as scenario 2 and 3 has redundancy of availability of the tunnel (i.e., if one tunnel run closes, traffic is redirected to another run). It can be observed that failure frequency, total downtime and unavailability/expected number of failures increases with time for all three scenarios.



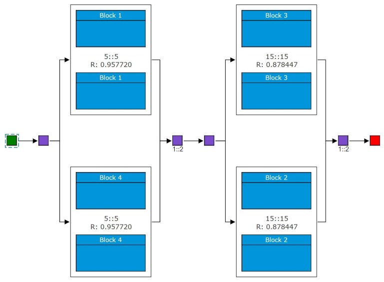
Time	Reliability	Failure Rate	Unavailability	Failure Frequency	Total Downtime	Expected Number of Failures
0	1.000000	40.000000	0.000000	40.000000	0.000000	0.000000
864	0.966030	40.000000	0.033970	38.641215	14.759466	0.033970
1728	0.933215	40.000000	0.066785	37.328588	58.367313	0.066785
2592	0.901514	40.000000	0.098486	36.060549	129.843573	0.098486
3456	0.870890	40.000000	0.129110	34.835586	228.241567	0.129110
4320	0.841306	40.000000	0.158694	33.652234	352.646773	0.158694
5184	0.812727	40.000000	0.187273	32.509081	502.175736	0.187273
6048	0.785119	40.000000	0.214881	31.404759	675.975012	0.214881
6912	0.758449	40.000000	0.241551	30.337952	873.220147	0.241551
7776	0.732685	40.000000	0.267315	29.307383	1093.114694	0.267315
8640	0.707796	40.000000	0.292204	28.311822	1334.889262	0.292204

Figure 47. *Result of scenario 1*



Time	Reliability	Failure Rate	Unavailability	Failure Frequency	Total Downtime	Expected Number of Failures
0	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000
864	0.999707	0.673720	2.934902e-004	0.673523	0.084954	2.934902e-004
1728	0.998846	1.314144	0.001154	1.312628	0.670550	0.001154
2592	0.997448	1.923591	0.002552	1.918681	2.233961	0.002552
3456	0.995540	2.504171	0.004460	2.493001	5.227685	0.004460
4320	0.993149	3.057806	0.006851	3.036856	10.080530	0.006851
5184	0.990300	3.586254	0.009700	3.551469	17.198557	0.009700
6048	0.987020	4.091120	0.012980	4.038017	26.965995	0.012980
6912	0.983331	4.573879	0.016669	4.497635	39.746121	0.016669
7776	0.979255	5.035883	0.020745	4.931416	55.882106	0.020745
8640	0.974816	5.478379	0.025184	5.340412	75.697831	0.025184

Figure 48. *Result of scenario 2*



Time	Reliability	Failure Rate	Unavailability	Failure Frequency	Total Downtime	Expected Number of Failures
0	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000
864	0.999816	0.424302	1.843801e-004	0.424224	0.053326	1.843801e-004
1728	0.999271	0.833752	7.286520e-004	0.833145	0.422382	7.286520e-004
2592	0.998380	1.229120	0.001620	1.227129	1.412448	0.001620
3456	0.997155	1.611123	0.002845	1.606540	3.317654	0.002845
4320	0.995608	1.980431	0.004392	1.971734	6.421250	0.004392
5184	0.993752	2.337668	0.006248	2.323062	10.995876	0.006248
6048	0.991598	2.683418	0.008402	2.660872	17.303817	0.008402
6912	0.989158	3.018226	0.010842	2.985502	25.597268	0.010842
7776	0.986443	3.342605	0.013557	3.297288	36.118585	0.013557
8640	0.983464	3.657033	0.016536	3.596558	49.100535	0.016536

Figure 49. *Result of scenario 3*

As shown in Figure 50 below, the improvement in reliability from scenario 1 to 2 and 3 is clearly large. There does not seem to much difference between scenario 2 and 3 regarding reliability. However, looking the comparison of Total Downtime, the difference between scenario 2 and 3 is much more noticeable. This means that even though it does not seem like the reliability is much higher for scenario 3, the effect of the improved reliability (i.e., reduction in total downtime) is quite noticeable when comparing scenario 2 and 3.

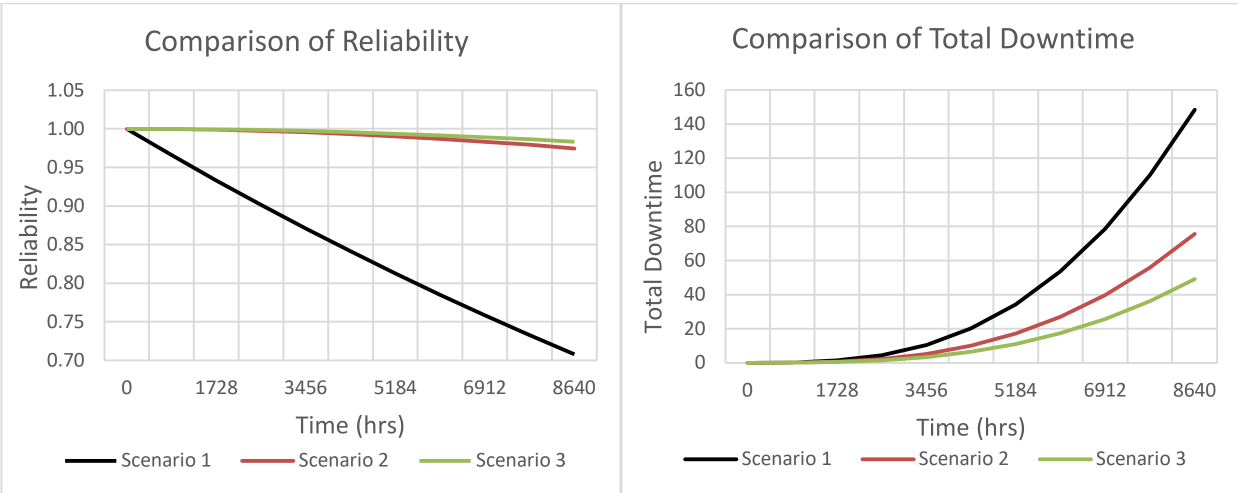


Figure 50. *Comparison of results for the three scenarios: Reliability and Total Downtime*

As a summary, scenario 2 (redundancy in tunnel) shows high improvements in terms of reliably and downtime and scenario 3 (redundancy with roundabout) shows a minor improvement in reliability, but a medium downtime. It is important to note that AADT (traffic flow) has not be taken into consideration in the simulation, as it was not part of the scope. However, if AADT had been taken into account, there would probably have been a larger difference of reliability between scenario 2 (without roundabout) and scenario 3 (with roundabout). Hence, it can be argued that scenario 3 would be the preferred options when considering reliability.

5.7 Selection of maintenance concept

5.7.1 Description of analysis

The selection of maintenance concepts or techniques for each type of equipment is based on consequence classification and FMEA. The maintenance philosophies that are included in the Maintenance Concept Study template describes how maintenance events should be triggered, based on the equipment failure modes.

Table 16. Maintencene Concepts from the Maintenance Concept Study template

Maintenance Concept							
Planned Maintenance	**Redundancy**	**Opportunistic**	**Design out**	**Detectable**	**Predictable**	**Prescriptible**	**Recommended Maintenance Philosophy**

According to El-Thalji [24], the maintencene philosophies included in the template, can be defined as follows:

- **Planned Maintenance** is predetermined and aims to schedule maintenance events to a time when the equipment is idle (i.e., not in operation), so that the maintencene event does not interrupt the equipment function to the overall system. Scheduled maintenance can either be preventive or corrective.

- **Redundancy** refers to redundancy of an item (e.g., equipment), where the aim is to keep the uptime even if one item has failed. Hence, redundancy can be achieved by having more than one equipment required to uphold the equipment function. There are two types of redundancy, active and passive or standby redundancy. Active redundancy is when more equipment than require operate at a lower capacity (e.g., 50%), such that if one fails the capacity of the other(s) will increase. Passive redundancy is when at least one additional equipment is on standby, i.e., not in operation but can be activated in case of failure of equipment in operation.

- **Opportunistic** maintenance is a prescription based maintencene philosophy, that aims to utilize the next possible planned maintenance event or the “right time” to perform a given preventive maintencene. The maintencene action can be done on an item or the items environment. Opportunistic intervals for road tunnel maintenance can for example be during night-time, when the traffic is low.

- **Design out** philosophy is based on user knowledge (user notes analysis) and failure root causes, that initiates redesign actions a specific hierarchy level of the system (e.g., at system, equipment or component level). It aims to remove the possibility of the failure mode occurring, by changing the design.

- **Detectable** maintenance philosophy depends on condition monitoring. The equipment condition is measured by instruments (e.g., sensors), which is used to trigger the maintencene events.

- **Predictable** maintenance depends on condition monitoring, diagnosis and prognosis to predict when a possible failure occurs, based on evaluation of health and degradation of the item. Prognosis analysis can be either data-driven or physics based and require a high level of knowledge about failure mechanisms. For example, for pumps and fans, usage rate data can be used to determine loading on the equipment.

- **Prescriptible** philosophy is preventive and aims to provide operators an option to either (1) heal or (2) deaccelerate degradation of the equipment heath until the next maintenance evet. This can be done by using several methods, such as changing operating loads and/or operating condition. It depends on condition monitoring, diagnosis and prognosis to make good decisions.

Each maintenance philosophy is graded from 0-2, which tries to establish how applicable the philosophy of interest is to the specific failure.

0 – maintenance philosophy is not applicable
1 – maintenance philosophy is suitable to some degree
2 – maintencene philosophy is suitable

5.7.2 Result: Recommended Maintenance Concept

The result of the maintenance concept analysis is included in Table 17 below. For the purpose of showing the method of the maintencene concept analysis, only one critical failure mode has been chosen to perform analysis on for each equipment type. One failure mode for each equipment category has been chosen based on qualitative judgement of criticality and possible failure causes and effects have been listed. Each maintenance concept has been evaluated and given a grade between 0-2, which creates the basis for the recommended maintencene concepts.

Table 17. Maintenance concept evaluation for pumps and jet fans

Worksheet: Maintenance Concept Study Template

Technical and functional hierarchy				Failure modes and effect				Maintenance Concepts							
System\Section	Equipment	Number of equipment	Function (MF)	Failure mode	Failure cause	Local effect	Consequence (Global effect)	Planned Maintenance	Redundancy	Opportunistic	Design out	Detectable	Predictable	Prescriptible	Recommended Maintenance Philosophy
Drainage water pumping system	Pump	60 *(total no.)*	Pumping	Pump vibration or high noise levels	pump and/or motor bearings defective	increased mechanical load, damage to other components	loss of effeciency, to high waste water levels	2	2	1	1	2	1	2	The pump is reccomended using condition-based maintenance (detection), and a redundant sysetm shall be considered.
Ventilation system	Jet fan/ventilator	264 *(total no.)*	Blowing	Fan doesn't work	defect/broken motor, power supply interrupted	unable to perfom MF	loss of effeciency, to high levels of CO/NO/PM	1	2	1	0	2	1	2	For the jet fan it is reccomneded having a redundant system. In addtion condition monitoring (detectable) is reccomended.

Recommendation for pumps:

The chosen failure mode for the pumps are vibration/high noise levels. The recommended maintencene concept for the pumps is to use condition-based maintencene (i.e., detection). An additional recommendation for considering a redundant system has been made.

Recommendation for jet fans:

The chosen failure mode for the jet fans is that the fan does not work (i.e., fail to start). The recommended maintencene concept for the jet fan is having a redundant system. By having either active or passive redundancy, the possible failure effects can be reduced. In addition to redundancy, condition monitoring is recommended to be able to monitor the jet fan health.

6 Discussion

This chapter discusses the analysis and results from chapter 5 and states which limiting factors occurred in each step. Then limitations and challenges regarding data quality is discussed. Lastly, some suggestions for future work, based on the results of this thesis is provided.

6.1 General discussion

A drawback using of only Scopus as primary database for literature search, is that it is not linked to Brage – which is NPRAs publishing platform of choice (other than their own web-page). This means that scientific research conducted by or in cooperation with NPRA will most probably not be present in the Scopus database. NRPA has their own database in Brage, where all reports, handbooks, articles, etc. are published and stored.

6.2 Discussion related to analysis steps

In order to answer the research question *"How to implement risk based maintenance (RBM) into deep subsea tunnel projects?"*, the analysis and results of the research steps undertaken in this thesis will be discussed. The empirical findings obtained by the analysis steps show that risk based maintenance approach can be implemented for deep subsea tunnel projects by developing customised technical hierarchy, consequence classification matrix, FMEA, reliability block diagram for the road tunnel configuration, and selecting the appropriate maintenance concept based on the result. However, the main challenge throughout the duration of the thesis has been related to the data quality, and therefore the number one criterion for implementing risk-based maintenance in road tunnels is to improve data quality related to maintencene and operational management. This is discussed further in *section 6.3*.

6.2.1 System analysis and Technical Hierarchy

Two different layouts of technical hierarchy have been presented – the first (*fig.31*) is based on NORSOKZ008 and ISO14224 and the second (*fig. 34*) is based on tunnel layout and sones. The two technical hierarchies has their pros and cons. The first, standard hierarchy that was presented would probably create a better basis for structuring of databases, CMMS programs etc. The problem of using the standard industry setup for the technical hierarchy occurs when it is used in risk assessments and analysing consequences of failure for equipment. When many technical equipment's are placed in the longitudinal direction of the tunnel, and probability of occurrences is somewhat based on longitudinal location, it is derived that reliability and risk properties related to equipment will slightly vary based on its location. For example, looking at the ventilators and use case description of these, it apparent that in the last part of the tunnel (upwards slope) require a higher flow rate and more ventilators in operation. Hence, the failure data for ventilators placed in the upwards slope, will not mirror those in the flat part or downwards slope. Road tunnels are becoming more and more advanced, which makes the fact that there does not exist a generic hierarchical structure for road tunnel equipment, even more problematic.

Limitation:
Developing the technical hierarchy for road tunnel equipment has been a very challenging and time-consuming process. As mentioned in *section 5.2,* the main challenge in developing a technical hierarchy is related to the structuring of the equipment in the NVBD database and Plania. There is no description of taxonomy levels for road tunnels, other than parent/child relationships between the different registered objects. Further research and knowledge based expert opinions are needed to solve this challenge.

6.2.2 Consequence classification of tunnel equipment

The consequence classification was developed based on the method in NORSOK Z008 and consequence classes and severity levels in NPRAs document for contractual provisions for operation. Availability was introduced as a new failure consequence, as it was not mentioned in NORSOK nor in NPRA literature. As a suggestion, the description of a generic consequence classification method for tunnel equipment should be included in NPRA literature, such as RoadRAMS. There is no literature describing knowledge transfer from the O&G industry and implementing the risk based maintenance approach described in NOSOK Z008 for the road sector and thus, this analysis gives original insight into consequence classification for road tunnel equipment.

Limitations:
The severity of the consequences in the developed consequence classification matrix (*tab. 11*) are mainly based on the document for contractual provisions for operation [48], in which the focus lies on events such as workplace accidents and injuries and "other unfavourable events". For example, the severity of environmental consequences is high and because of this, environmental

consequences will in most cases be classified as low or very low for equipment failures. Thus, for purpose of classifying consequences of equipment failure, that the severity level should be considered scaled down. This would require more research and historical failure data for tunnel equipment, which is also the reasoning for not scaling severity levels in this thesis.

6.2.3 FMEA

FMEA has proven to be a good tool to use in systemising operation and maintencene of equipment in other industrial sectors, such as in the oil and gas sector. The developed FMEA has been tailored specifically for road tunnel equipment. The result of the FMEA proves gives a better understating of failure modes, causes and effect of failures for the selected technical equipment in tunnels, which increases quality of the decision-making process for choosing maintencene concepts for each equipment type.

Limitations:
Because of the lack of data, it was not possible to complete all parts of the FMEA, such as failure rates and active maintenance hours, as was initially expected. Failure modes and possible causes are, as mentioned in the analysis chapter, registered in open text fields in Plania. This will in many cases result in inadequate information about the equipment failure. A suggestion for solving this problem is to identify possible failure modes and causes for each equipment type based on manufacturer documentation supported by expert judgements and then include these in a drop down menu in the CMMS software. This would result in a fixed set of failure modes and causes for each equipment type, which would be easier to manage, both during maintencene planning and activities. Furthermore, information such as failure rates and active maintenance hours would be more reliable if based on a fixed set of failure modes and causes.

6.2.4 RAM analysis

Reliability calculations were performed for the ventilation system and for drainage pump system on equipment level. Three different scenarios was described and analysed. The RBD analysis is included in this thesis with the purpose of showing a potential method of calculating reliability for the tunnel equipment, based on tunnel failure rates of technical equipment. The results of the analysis showed having a redundant system (e.g., two tunnel runs or roundabout), results in improved reliability and a decrease in total downtime. The method could be involved and used for investigating safety critical equipment to give an additional source of information about the equipment lifecycle, other than manufactory specification for the different equipment. This also means that information on equipment life becomes more location-oriented and tailored for the individual tunnel.

Limitation:
Failure rates retrieved form Plania, was not a good enough to draw conclusions based on due to insufficient data quality. Hence, failure rates used in the analysis could not be extracted form historical maintenance data, and a failure rate was therefore assumed. There is not a high enough quantity of data to make good estimations/statistical calculations on failure rates, for example one single ventilator does not contain enough datapoints or registered WOs to get reliable results. The failure rates calculated based on Plania, is based on different equipment of the same type, hence it does not give a realistic result.

6.2.5 Maintenance concept selection

The maintenance concept selection shows that the technical hierarchy, consequence classification and FMEA can be used to make qualitative decisions on proposed maintenance philosophies for specific equipment types. One failure mode for each equipment type (i.e., pumps and jet fans) was selected based on the FMEA and then each maintenance philosophy was evaluate with the purpose of reducing the risk of that specific failure mode. This can be a good basis for developing a more tailored maintenance management program for technical equipment in road tunnels.

Limitation:
Again, the biggest challenge for this analysis step is related to data quality. If failure rates for each failure mode had been available, it would be possible to choose the most critical failure modes to mitigate. For example, if failure rates provided information that a specific failure rate occurs often, it would affect how the maintencene philosophies was evaluated. Maybe the best solution in such a case would be to design out the failure mode (if possible).

6.3 Limitations and challenges related to data quality

The data quality of collected data from Plania was not good enough. There were several issues that occurred in relation to data collection. In section 5.3, it was disclosed that based on the collected data, it was not possible to calculate reliable failure rates. If we had higher data quality, meaning more consistent data, registered failure modes, etc. and a higher quantity of data the historical maintenance data would be a good source of input for the methods of analysis preformed in this thesis.

It should have been possible start filtering data based on work order type (=corrective), equipment type and tag and failure modes. Then the filter selection could be sorted based on dates (e.g., start date, finished date). This would create a good starting point for calculating failure rates and MTTF for specific equipment types and also for specific failure modes for each equipment type. By doing this we would have sufficient information to conduct FMEA analysis, where it would be possible to categorize criticality of equipment based on quantitative analysis. This again would be used as input in decision-making processes in the design phase of the tunnel project.

Throughout the whole life cycle of an asset (e.g., road tunnel), many decisions are made, and these decisions will normally affect both economy and safety of the project. In order to reach the best possible decisions, they should be based on good methods/models which again is based on high quality data. Several of the analysis types completed in this thesis, such as FMEA or RBD, relies on equipment data. This means that unreliable or insufficient data, will in turn yield unreliable analysis results. Table 18 below, describes what equipment data should be recorded for maintenance management according to ISO 14224 [22], in order to achieve reliable analysis results that can be further used to make good, knowledge-based decisions in maintenance management. The column "Theory" marks what types of data that should be available in order to follow a risk based maintenance approach, and the column "Case study" marks which data types have been available during this thesis work.

Table 18. Equipment data to be recorded based on ISO14224 [22]

ISO 14224:2016	Theory	Case study
Equipment location (e.g., tag number)	X	X
Equipment classification (e.g., equipment class, type and system)	X	
Installation data	X	X

Manufacturer's data	X	X
Design characteristics	X	X
Surveillance period	X	
Accumulated operating period	X	
Number of demands	X	X
Operating mode	X	
Common cause failure rate (frequency)	X	
Equipment unit	X	
Subunit		
Maintainable item		
Failure impact on equipment function	X	
Failure mechanism	X	
Failure cause	X	
Detection method	X	
Failure on plant operation	X	
Failure date	X	X
Maintenance category	X	X
Maintenance activity	X	
Downtime	X	
Active maintenance time	X	
Maintenance man-hours per discipline	X	
Date of maintenance action	X	X
Maintenance impact on plant operations	X	

6.4 Generalization

In this thesis jet fans and drainage pumps has been evaluated following the risk based maintencene approach in NORSOK Z-008. The chosen equipment of interest (i.e. jet fans and drainage pumps) are both some of the most critical equipment types found in tunnels. As the method is applicable for these equipment types, the method could and should be used for other equipment types as well.

The case study Rogfast can be considered to the most complicated road tunnel in the under construction in Norway as per now. If it is possible to apply the risk based maintenance methodology to the most complicated subsea road tunnel, it follows that it can also be applied for other road tunnels.

Risk based maintenance based on NORSOK Z-008 is a general methodology and as it is applicable to many different sectors. As it has been shown that it is applicable for road tunnels, it should also be possible to generalize and evolve the adopted steps in this thesis to other parts of the infrastructure sector, such as for brides and open roads.

Suggestion based on ISO 14224 is valid for any maintencene system that is usually utilized by actors in other sectors. As it is general and if the infrastructure sector adopts the methodology, well developed and tried CMMS programs can be utilized by actors in the infrastructure sector.

6.5 Future work

Utilizing the risk-based maintenance approach described in NORSOK Z-008, based on this thesis work seem to have benefits for the road sector.

Future research work originating from the results of this thesis work should include:

- Details and requirements in related to data collecting for failures and maintenance management for road tunnel is needed.
- Explore RAM analysis in more detail. Due to a variety of limitations, it is not possible to make conclusions on reliability of technical equipment based on the RAM analysis.
- A future CMMS software should be restructured, based on technical hierarchy for technical equipment. As structural element of road tunnels was not considered in this thesis work, there is also a need for developing a technical diarchy for the tunnel structure as well as for technical equipment.
- Spare parts evaluation for road tunnel equipment following principles in NORSOK Z-008
- Cost analysis for road tunnel equipment following principles in NORSOK Z-008

7 Conclusion

The purpose of this thesis is to explore how can risk based maintenance be implemented for deep underwater tunnel. Based on the analysis and the empirical findings, it can be concluded that risk-based maintenance, with its way of thinking and recommended engineering analysis, is required for deep underwater tunnels. Comparing oil and gas installations (where risk based maintenance is dominant) and road tunnels shall not lead to underestimating the need and benefits of applying risk based maintenance for tunnel industry, as oil and gas installation are further complex and maintenance hard to be managed at utilisation phase within a proper engineering consideration at project phase. In fact, the analysis shows that deep underwater tunnels are quite complex systems and getting even more complex with new trends and targets, which makes operations and maintenance a critical aspect to be managed. So, there is a need to implement risk based maintenance for deep underwater tunnel and it can be implemented as demonstrated in this thesis.

The answer regarding how to implement risk-based maintenance for deep underwater tunnel, is to follow NORSOK Z-008 standard with some customisations, when it comes to creating technical hierarchy, consequence classification matrix, preforming failure mode and RAM analysis and exploring new maintenance programs and technologies,

Even though, the case study analysed in this thesis was to demonstrate how risk based maintenance can be implemented and not to provide exact or final (ready for use) of figures in term of consequences, reliability and availability, some conclusions can be drawn up based on this case as follows:

- The tunnel sections (entry, downslope, upslope, exit, roundabout) shall be considered as the section or system level while building the technical hierarchy.
- The consequence classification categories and matrix shall be developed based on comprehensive discussion with all relevant stakeholders.
- The RAM analysis shall be performed for different tunnel configuration (no redundancy, redundancy, multi-stage redundancy) at project phase. In fact, it can be concluded, based on the simple RAM analysis, that redundancy and the roundabout can enhance the reliability and tunnel downtime.

- The maintenance concepts and new maintenance programs shall be explored during project phase to check their benefits and avoid keep doing the maintenance in the same traditional way.

Even though, the case study presented in this thesis answer and demonstrate how to implement risk based maintenance, it is worth to conclude that an effective CMMS is required to enable the implementation of risk based maintenance and its analytics.

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Appendices

Appendix 1 - Project plan

	Month																				
	FEB				MAR					APR				May					June		
Week #	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
TASK																					
Problem understanding and description	■																				
Literature review	■	■	■	■				■			■										
Framework development	■	■																			
Data collection		■	■																		
Data analysis			■	■																	
Revise the framework and Case study description				■	■																
Solutions generation					■	■															
Data collection and analysis, Part 1						■	■														
Data collection and analysis, Part 2							■	■													
Data collection and analysis, Part 3								■	■												
Verify the proposed solution									■	■											
Writing the data and analysis chapter										■	■										
Demonstrate the proposed solution											■	■	■								
Discuss the proposed solution and the whole case study												■	■	■							
Draw up the conclusions and further work												■	■	■							
Deadline for first submission														■							
Thesis revision, Technical and academic checks															■	■	■	■	■		
Final submission to university																				■	

Appendix 2

Tonje Skjølberg

Worksheet: Maintencene Concept Study template for road tunnel equipment

Date: 15/6-22

Technical and functional hierarchy						Consequence Classification				Failure modes and effect				Failure rate and active mainten. hours			Maintenance Concepts									Spares & logistics	
Technical System	Location	System\Section	Equipment	Number of equipment	Function (MF)	Safety consequence	Tunnel Availability consequence	Operation & Maintenance cost consequence	Environment consequence	Failure mode	Failure cause	Local effect	Consequence (Global effect)	Likelihood (Failure rate)	MTTR	Manhours	Planned Maintenance	Utilisation	Redundancy	Opportunistic	Design out	Detectable	Predictable	Prescriptible	Recommended Maintenance Philosophy	Spare parts	Lead time