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Risk assessment of strait crossing bridges

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Preface

This is a master thesis written during the spring of 2015 at the Norwegian University of Science and Technology (NTNU), Department of Production and Quality Engineering. The thesis is written in cooperation with the Norwegian Public Road Administration (Statens Vegvesen) regarding their project “Ferjefri E39”. The reader of this thesis is assumed to have some basic knowledge about risk assessment, but some explanation of the theory is given to ensure that all readers can understand the content of this master thesis.

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Acknowledgment

I would like to thank Professor Mary-Ann Lundteigen (NTNU) and Inger Lise Johansen (Statens Vegvesen) for their valuable guidance and inspiring discussions throughout this Master thesis. I would also like to thank Trine Forsnes for carefully proof reading the final draft of this thesis. Special gratitude is directed to Andreas Anthonsen Jahn and my entire family for their unconditional support.

M.K.F

Summary and Conclusions

The purpose of this thesis is to try to provide an overall risk picture for the planned strait crossing (SC) bridges on coastal highway E39 between Trondheim and Kristiansand in Norway. The thesis starts off by explaining the concepts and solutions of SC bridges to understand what the National Public Road Administration (NPRA) is planning to accomplish with the coastal highway E39. The SC bridges cannot be compared to any other bridge structures in the world, which will lead to some challenges. The biggest challenge with these crossings is the depths of the fjords.

General risk assessment theory is briefly explained. In addition the general practice for the NPRA and other relevant applications are presented to get an understanding of what have been done when it comes to risk assessment of bridges and tunnels. The necessity of a new approach to risk assessment for SC concepts is discussed.

Hazard identification methods are described and discussed. Some of the methods described are used to identify the hazards and hazardous events for the three different SC concepts. It has been distinguished between hazards related to location/environment and hazards related to construction.

Some knowledge about risk metrics and risk acceptance criteria is presented. It is discussed how to establish risk acceptance criteria for the SC concepts. This discussion is based on theory and the use of acceptance criteria from other applications. One preliminary conclusion of the discussion says that the NPRA should learn from other applications, but be careful not to copy directly from others.

It is suggested that the NPRA modify their plan processes to make a better environment for risk assessment. A new and general approach to risk assessment for SC concepts is suggested. This approach is more detailed and structured than the existing procedure at the NPRA, and should be applicable to all the different concepts. To exemplify the approach a case study of a submerged floating tunnel crossing Halsafjorden is performed.

The conclusion of this thesis is that a change in routines regarding risk management is necessary for the NPRA to ensure the safety of SC concepts. An improved risk assessment approach with substantial risk acceptance criteria needs to be established. The solutions suggested in this thesis are a step in the right direction, but there are still numerous challenges, especially regarding the risk acceptance criteria, that need to be solved before a full risk picture of the SC bridges is achieved.

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Chapter 1

Introduction

1.1 Background

In 2010 a commission to investigate the potential for eliminating all ferries along the coastal highway E39 in Norway was given to the Norwegian Public Road Administration (NPRA). The purpose of this commission was to clarify the technological challenges and possibilities, and to explore the benefits for the local community and businesses. There are eight ferry connections that cross eight relatively wide and deep fjords. There will be built either underwater tunnels or bridges, collectively called strait crossing (SC) bridges, to eliminate all the ferry connections on E39 (SVV, 2012b).

These SC bridges will be of an entirely different scale than any other bridge structure built in the world today, and this will naturally lead to some challenges. The fjords are not that wide compared to other fjords, but the depth of the fjords on E39 is the real challenge. The depths of the eight fjords vary from about 500 meters to about 1300 meters. There are also a lot of other challenges, like ship traffic and environmental conditions, that need to be solved to cross all of these fjords. Existing bridge technology needs to be modified if these fjords are going to be crossed by fixed connections. The NPRA is trying to apply the knowledge from offshore structures to bridge structures. One possible solution for these deep fjords is to use buoyancy of floating elements to carry the load of the bridge, like it is done with some oil platforms (Skorpa, 2013).

Since these kinds of structures have never been built before, it is impossible to know everything beforehand, which will create a lot of uncertainty. The use of new technology combined with high uncertainty will require some thorough analyzes regarding risk. There is not much tradition for risk assessment in the NPRA today, and that needs to change. The NPRA has a procedure for risk assessment (V721, 2007), but it is vague and it looks like it is not used consistently. It could be argued that there is a need for a new and better risk assessment approach within the NPRA to ensure the safety of these challenging structures that are planned on E39.

The NPRA should try to gain knowledge from other industries that are more experienced with risk assessment, like the offshore industry or the Norwegian National Rail Administration (NNRA). However, it would a challenge for the NPRA to pick the relevant knowledge for their use from the different industries. A risk assessment should evaluate the risk that SC bridges may inflict on the people using them. When performing a risk assessment there is need for a risk limit: what kind of risk is tolerated? This is called a risk acceptance criterion, and it is used as a base for comparison with the results from a risk assessment. The challenge for the NPRA is to determine this criterion. The SC bridges will make life easier for people using highway E39, but it will also make them more vulnerable. If the structure fails, a vulnerable society will emerge because there will be no other alternatives for crossing the fjord anymore. In addition, a failure might cause harm to people using the bridge. This creates a conflict between the vulnerability of the society and the potential harm to people. The question is if the NPRA have to choose between those two factors when creating a criterion, or if it is possible to include both factors in the same criterion.

1.2 Objectives

The overall objective of this master thesis is to try to provide an overall risk picture for the planned SC bridges on coastal highway E39. To fulfill this overall objective five smaller objectives have been formulated and treated:

1. Define and clarify the concepts relating to SC bridges.
2. Carry out and document a brief literature survey related to risk assessment of existing

concrete structures. The survey should include both today's practice by the NPRA and approaches from other relevant applications

3. Identify the hazards and hazardous events related to SC bridges
4. Suggest possible risk metrics and risk acceptance criteria for SC bridges
5. Outline an approach to risk assessment of SC bridges, and exemplify the approach with a case study of Halsafjorden

1.3 Limitations

This thesis has limited its focus to the risk factors that can arise in the operating phase of the SC bridges. The thesis is only considering the hazards and hazardous events that can be present when the SC bridges are in use by the public. The author is only evaluating these crossings on a rough, overall level since the NPRA are in such an early stage of the project, where neither the final concept nor design is determined.

1.4 Structure of the Report

A general introduction of the SC concepts and solutions are presented in chapter 2. The purpose of the SC project is presented, and the three different crossing solutions are described. Chapter 3 gives a brief introduction to the theory of risk and risk assessment. It presents some of the most relevant existing literature regarding risk assessment of tunnels and concrete structures. Chapter 4 introduces the key concepts associated with hazards, and methods to detect and classify hazards. In addition the hazards of the three different SC concepts are identified. Chapter 5 discusses the use of risk metrics and risk acceptance criteria for SC bridges. Some knowledge about risk metrics and risk acceptance criteria is also given in this chapter. Chapter 6 presents a suggested approach to risk assessment of SC bridges, exemplified with a case study. The chapter gives some suggestions on how the NPRA should structure their plan processes. Conclusions and recommendations for further work are found in chapter 7. All the acronyms used in this thesis are provided in appendix A.

Chapter 2

Straight crossing concepts and solutions

This chapter gives a brief explanation of the strait crossing project on coastal highway E39. The concepts and the proposed solutions to cross the fjords along E39 are presented and discussed.

2.1 Strait crossing

In 2010 the Norwegian Public Road Administration (NPRA) got a commission from the Ministry of Transport and Communications to investigate the potential for eliminating all ferries along the coastal highway E39 between Kristiansand and Trondheim. On this highway there are eight ferry connections (see Figure 2.1), and most of these fjords are very wide and deep. It will require huge investments in addition to groundbreaking innovation to eliminate all the ferry connections. The strait crossing (SC) bridges that will replace the ferries require much longer spanning structures than previously installed in Norway. The purpose of this project is to clarify the technological challenges and possibilities, and to explore the benefits for the local community and businesses (SVV, 2012b).

Figure 2.1 presents all the eight ferry connections along E39. However, the last ferry connection is not really a part of this project. The crossing of Boknafjorden is already in operation, and an underwater tunnel is going to be built. The process of building SC bridges for the remaining seven ferry connections have not started yet. Therefore, Bokanfjorden is not considered in this thesis.

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Figure 2.1: The ferry connections along coastal highway E39 (Skorpa, 2013)

All of the seven fjords along E39 in Norway are unique and different from other straits, sounds or inlets in the world. Many of the fjords are exposed to waves and wind from the North Sea. In addition, many cruise ships, and other ships visit these fjords every year. Therefore it is important to not restrict ship traffic with a SC bridge. The largest ships that visit these fjords will require a free height of more than 70 meters. All the fjords vary in width from about two kilometers to about eight kilometers, which are not extreme values when it comes to width. Wider straits and fjords have been crossed before, so that is not the biggest challenge with the straits along E39. The real challenge is the depth of the fjords. The fjords along E39 are extremely deep; they vary from about 500 meters to about 1300 meters. The deepest fjord is Sognefjorden with a maximum depth of 1250 meters. These depths are obviously a challenge when it comes to building SC bridges (Skorpa, 2013). The characteristics for each of the seven fjords are found in Table 2.1.

Table 2.1: Characteristics og the fjord along E39

Crossing	**Witdh [km]**	**Depth [m]**
Halsafjorden	2.0	500
Moldefjorden	1.6	500-600
Storfjorden	3.4	500
Voldafjorden	2.5	600
Nordfjorden	1.7	300-500
Sognefjorden	3.7	1250
Bjørnafjorden	6.0	500-600

The challenge with these SC bridges is that they are not comparable to any bridge structures built in the world today. There has never been a bridge project with as many challenges as the crossings along E39. Width, depth, ship traffic and environmental conditions are some of the most important challenges that need to be solved to cross these fjords. If it is going to be possible to cross these fjords, existing bridge technology has to be modified and new technology has to be developed. The offshore industry can be of great help regarding new technology development. The knowledge from offshore structures can be applied to bridge structures. An example of this is using buoyancy of floating elements to carry the load of the bridge, like it is done with some oil platforms. This technology makes it possible to look at the fjord as a possibility, instead of just an obstacle (Skorpa, 2013).

This project will bring some uncertainties into the light. The largest uncertainties have been discussed several times in conversations with the NPRA. Some of the most significant uncertainties that were discussed are presented in Table 2.2.

Table 2.2: Uncertainties regarding SC bridges

Main uncertainty factors	**Will create uncertainty regarding:**
Groundbreaking technology	• Calculations models - Analysis and verification • Data - Is it possible to extrapolate values from smaller existing bridges? • Can all hazards and hazardous events be predicted? • The relevance of regulations and standards
Environmental impact	• Measurements of waves, wind and currents (large spread in measured values) • Are the assumptions conservative enough?
Time horizon (100 years)	• Climate • The development of traffic, both vehicles and ships • The life of the structure (fatigue etc) • Future laws and requirements

The NPRA has used Sognefjorden as a pilot study for developing new concepts for crossing of the fjords along E39. Sognefjorden is considered the most challenging and difficult fjord to cross, and therefore it has been used as a pilot study. From this study three main alternatives of SC bridges for the fjords along E39 have been developed:

- Suspension bridge
- Floating bridge
- Submerged floating tunnel

These main alternatives may create up to 30-40 different alternatives or more. They are only limited by the imagination. All of these may look different from location to location. A suspension bridge over one fjord may look completely different from a suspension bridge over another fjord. There are three main alternatives, but it is important to remember that these can be utilized in numerous different ways. There might be in fact over 40, or more, different concepts in total to chose from. This is because all the fjords are unique when it comes to depth, length and geological conditions. The three main alternatives can also represent many different options based on the choice of solution for anchoring, trace, height, material etc. Therefore it is necessary to find different concepts and solution that best fit the characteristics of each fjord. The three SC bridge concepts can be used in different ways and they can be combined (see Figure 2.13) to get the best solution for the fjord in question (Skorpa, 2013).

2.2 Suspension bridge

2.2.1 Concept

This concept involves either a suspension bridge in one span or a suspension bridge in several spans on floating foundations. A main span of 3700 meters is required for a suspension bridge in one span crossing Sognefjorden (Figure 2.2). Since many of the fjords, especially Sognefjorden, have steep slopes into the fjords it is required that the main span of the bridge have the same length as the width of the fjord. A traditional suspension bridge cannot be built over any of the strait crossings along E39. For this concept to work it is essential to think outside the box and try to take advantage of the solutions from the offshore industry like a tension leg platform (shown briefly in Figure 2.5) (Isaksen et al., 2013; Oosterlaak et al., 2013).

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Figure 2.2: Suspension bridge with a span of 3700 meters (Ellevset, 2013)

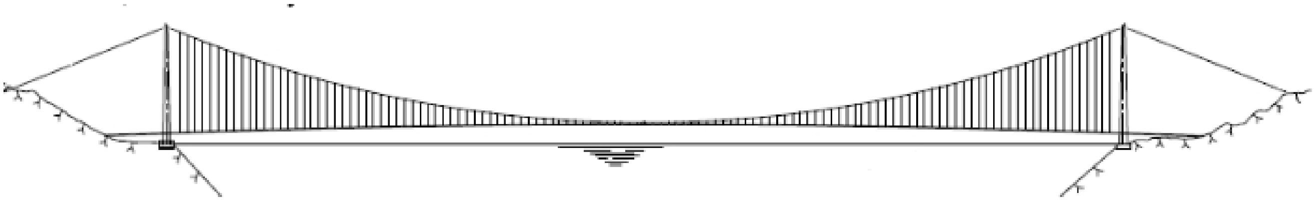

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Figure 2.3: Sketch of a one span suspension bridge (Isaksen et al., 2013)

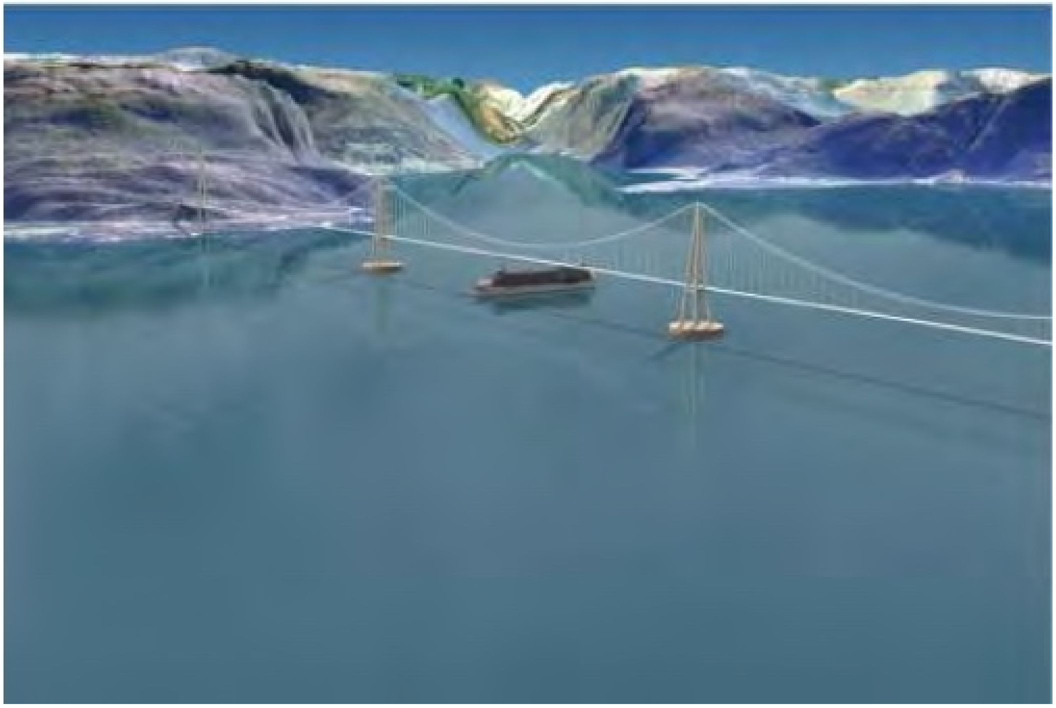

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Figure 2.4: A three span suspension bridge on floating patons (Ellevset, 2013)

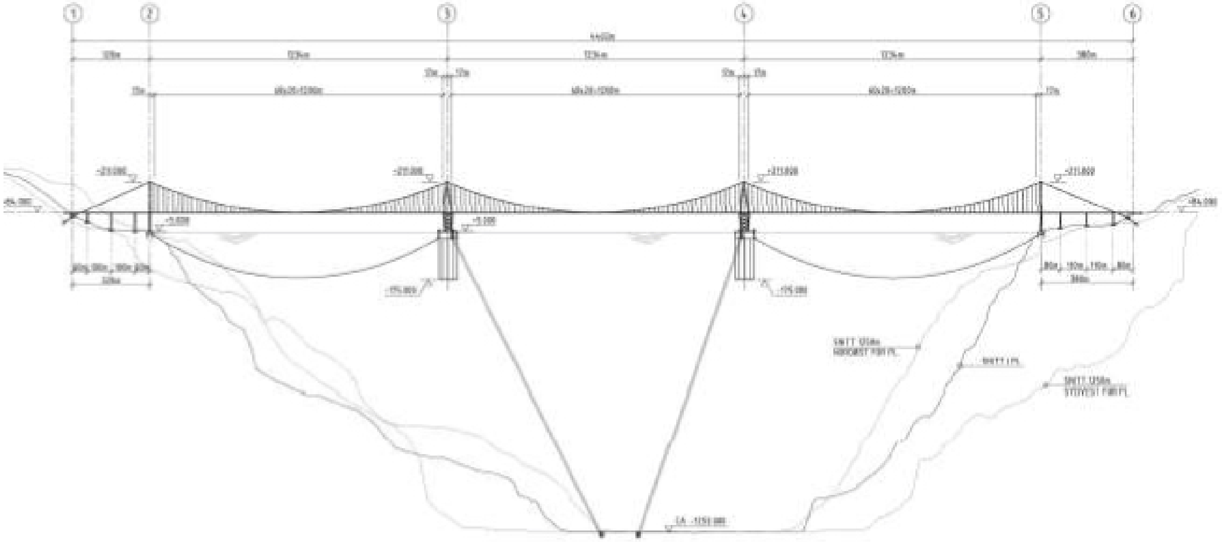

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Figure 2.5: Sketch of the three span suspension bridge (SVV, 2012a)

2.3 Floating bridge

2.3.1 Concept

This concept involves traditional floating bridges with or without anchoring to the seabed. Since the fjords along E39 are extremely deep it can be difficult to anchor to the seabed in most cases. The two floating bridge solutions that are best fit for the fjords in Norway are a floating bridge with anchoring to the ends (Figure 2.6 and Figure 2.7) of the bridge or a floating bridge with side-anchoring (Figure 2.8). For these solutions to fulfill the needs of the Norwegian fjords, traditional floating bridge solutions has to be combined with other solutions, like a high-bridge over the vessel passage (SVV, 2012a).

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Figure 2.6: A suggestion of a floating bridge with end anchoring for Storfjorden (SVV, 2012a)

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Figure 2.7: A suggestion of a floating bridge with end anchoring for Bjørnafjorden (SVV, 2012a)

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Figure 2.8: A suggestion of a floating bridge with side anchoring (SVV, 2012a)

2.4 Submerged floating tunnel

2.4.1 Concept

The idea behind a submerged floating tunnel is to lead traffic through a tube that is submerged under water. A submerged floating tunnel is supposed to float 20 to 30 meters below the surface (Figure 2.10), and is therefore not the same as a submerged tunnel since it is not located on the seabed. This concept will be anchored to the mountain at the ends. In addition to this the tunnel can either be anchored to floating pontoons at the surface, as shown in Figure 2.9, or in tension rods to the bottom of the fjord, as shown in Figure 2.12 (SVV, 2012a).

It is estimated that a ship will collide with the submerged floating tunnel once every ninth year. That is not that often, but the tunnel is supposed to withstand a ship collision if it happens. One idea is that the tunnel will be equipped with a so-called "weak link" that acts as security protection if a larger ship collides with one of the pontoons. This weak link between the pontoons and the pipe (where the cars will drive) will break when triggered by a ship of a certain size. The pontoon will break loose and float away while the rest of the bridge is intact. There are several challenges with this idea, but the biggest challenge will be to make the weak link robust enough to withstand normal stress but at the same time weak enough to break when needed (Rambøll, 2014).

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Figure 2.9: The submerged floating tunnel seen from above (SVV, 2012a)

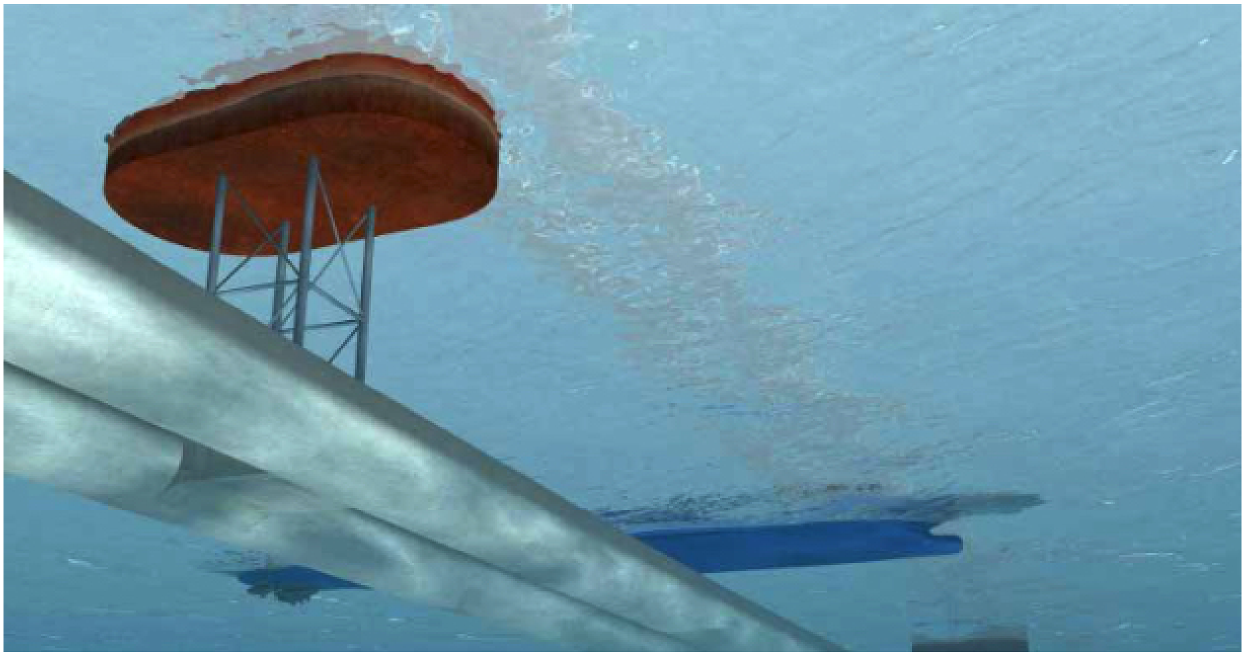

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Figure 2.10: The submerged floating tunnel seen from below (SVV, 2012a)

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Figure 2.11: Cross-section of the submerged floating tunnel (SVV, 2012a)

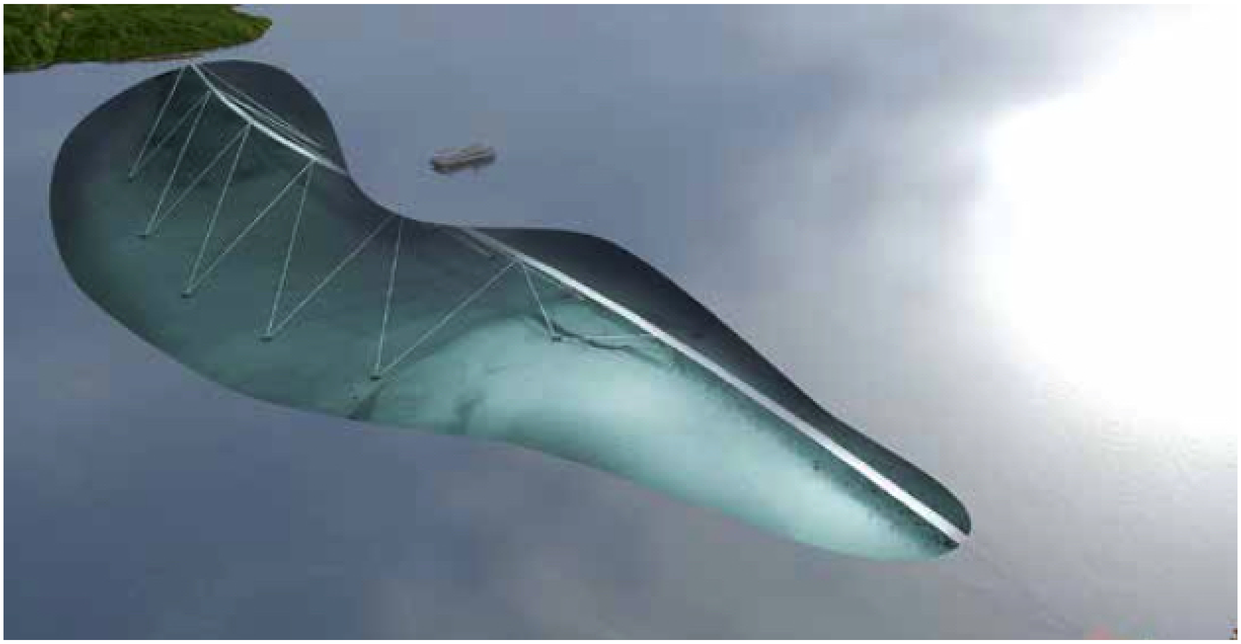

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Figure 2.12: The submerged floating tunnel anchored to the seabed (SVV, 2012a)

2.5 Concept combinations

As already mentioned all of these concepts can be combined in numerous different ways to best fit the needs of the specific fjord. Figure 2.13 is an example of such a combination.

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Figure 2.13: A combination of a submerged floating tunnel and a floating bridge (SVV, 2012a)

Chapter 3

Risk and risk assessment

This chapter presents some general theory regarding risk assessment. Later on in the chapter the existing procedures for risk assessment of tunnels and concrete structures (typically a bridge) are explored to see what modifications must be done to do a proper risk assessment of strait crossing (SC) bridges.

3.1 General concepts and approaches

Risk is a word that can be interpreted in several different ways. However, a definition formulated by Kaplan and Garrick (1981) is a generally accepted definition of risk. They define risk as the answer to three basic questions:

1. What can happen?
2. How likely is it?
3. If it does happen, what are the consequences?

The main idea of a risk analysis is to identify the possible hazardous events, calculate the likelihood of them occurring, and try to avoid or reduce the risk if possible. The word risk has become important in the world today. There is risk involved in everything people do, and it is important that this risk is minimal. A good rule is to try and have the risk as low as reasonably possible at all times. This is important for all types of risk, but especially of the risk to human beings. To better understand risk some definitions of common terms in risk assessment are given below.

☞ **Hazard:** A source of danger that may cause harm to an asset

Rausand (2011)

☞ **Hazardous event:** The first event in a sequence of events that, if not controlled, will lead to undesired consequences (harm) to some assets.

Rausand (2011)

☞ **Risk reduction:** Measures taken to either reduce the frequency of one or more hazardous event, or measures taken to avoid or reduce the consequences of a potentially hazardous event.

Rausand (2011)

☞ **Risk acceptance criteria:** Criteria used as a basis for decisions about acceptable risk.

Rausand (2011)

☞ **Safety barrier:** A physical or engineered system or human action that is supposed to prevent, control, or mitigate energy released from reaching the assets and causing harm.

Rausand (2011)

In Norway, NS 5814 (2008), ISO 31000 (2009) and NORSOK Z-013 (2010) are the most known standards for risk assessment. NORSOK Z-013 (2010) is directed at the offshore industry, but it can also be used as a general guideline for risk assessment in other industries. It provides detailed guidance for different stages (like design, operational etc.) of a facility/structure. NS 5814 (2008) sets requirements for the elements that may be included in a risk assessment process. These three standards complement each other well, but they still differ. For example, the ISO 31000 (2009) standard is a generic standard of risk management, while the NORSOK Z-013 (2010) standard provides detailed guidance on analysis of risk and emergency preparedness (Johansen, 2010b). The main steps in a risk assessment according to NORSOK Z-013 (2010) is represented in Figure 3.1.

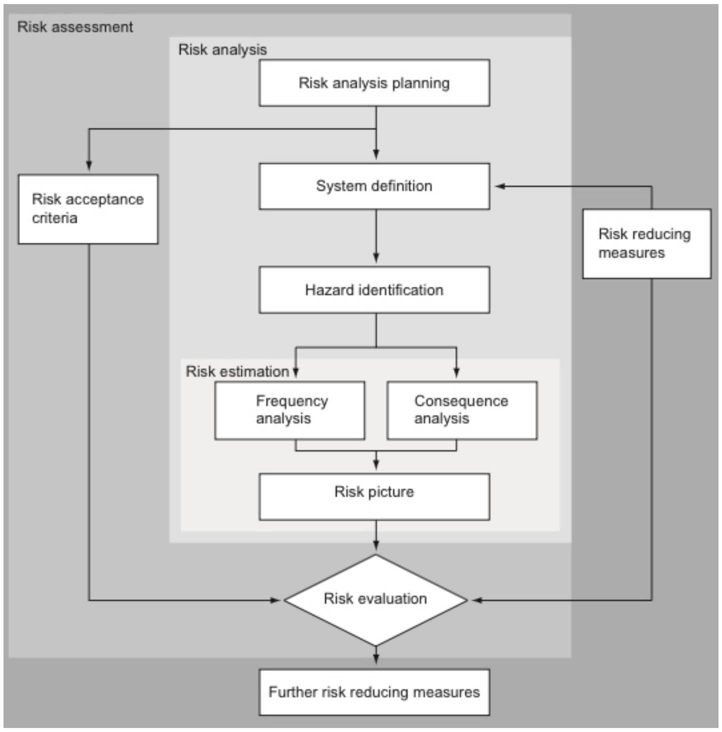

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Figure 3.1: NORSOK Z-013's interpretation of risk assessment and risk analysis (Johansen, 2010b)

This representation complements well with the definition described by Kaplan and Garrick (1981). The three questions cover the risk analysis part of Figure 3.1. Risk assessment is the whole picture consisting of a risk analysis and an evaluation of the findings of this analysis. Figure 3.2 is a figure from Lair et al. (2004) (this report is introduced in more detail in 3.2.3), which illustrates the structure of risk management. This complies well with the representation NORSOK Z-013 (2010) presents in Figure 3.1. It is easy to see that the risk analysis is an important part of the risk assessment, but just performing a risk analysis is not enough in itself. An evaluation of the risk is also necessary to get the full extent of the risk picture.

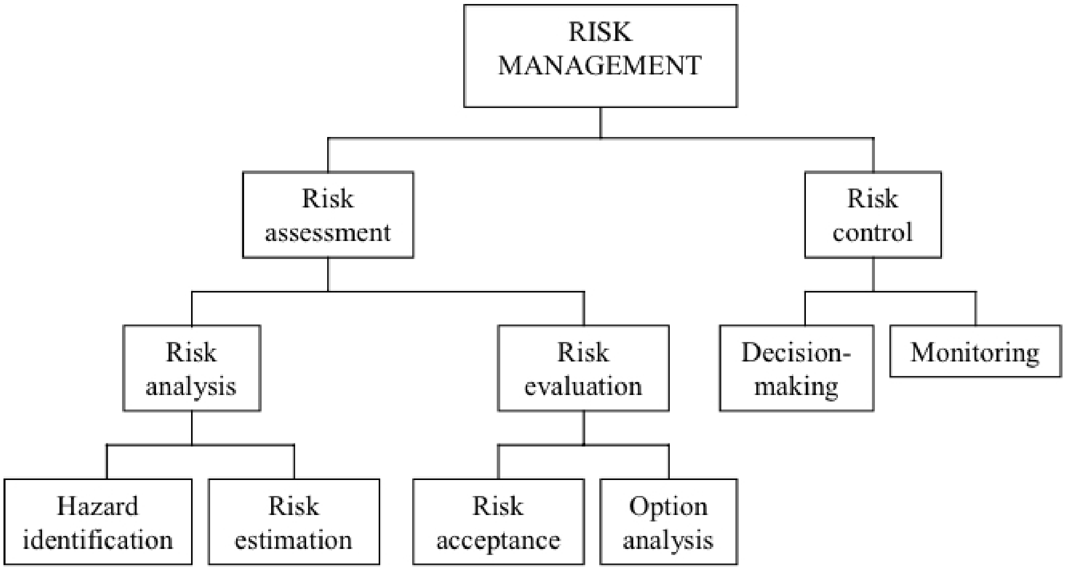

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Figure 3.2: A possible structure of Risk Management (Lair et al., 2004)

There are many models, tools and approaches that can be used to perform a risk analysis. Performing such an analysis is a challenging and time-consuming task. There are three main types of analysis; hazard identification, causal analysis and consequence analysis. Figure 3.3 illustrates the fundamentals of risk analysis in a so-called bowtie diagram. The three basic questions from Kaplan and Garrick (1981)'s definition should be answered regardless of the method. The first question can be answered with a hazard identification method (see Chapter 4 for more information about hazard identification). If the identified hazardous events are events that cannot occur, it will be a need for a casual analysis, like a Fault Tree Analysis (FTA). A fault tree is a logic diagram representing the interaction between a potential hazardous event and the causes of this event (more information about fault trees are found in Rausand (2011)). The causal analysis can answer the second question. However, analyzing the causes is not enough to fully comprehend the risk picture, and a consequential analysis is needed to understand the possible extent of these hazardous events. An Event Tree Analysis (ETA), which is a preferred method for a consequential analysis, can answer the third question. An event tree is a logic diagram representing all the potential consequences of a hazardous event (more information about event trees are found in Rausand (2011)).

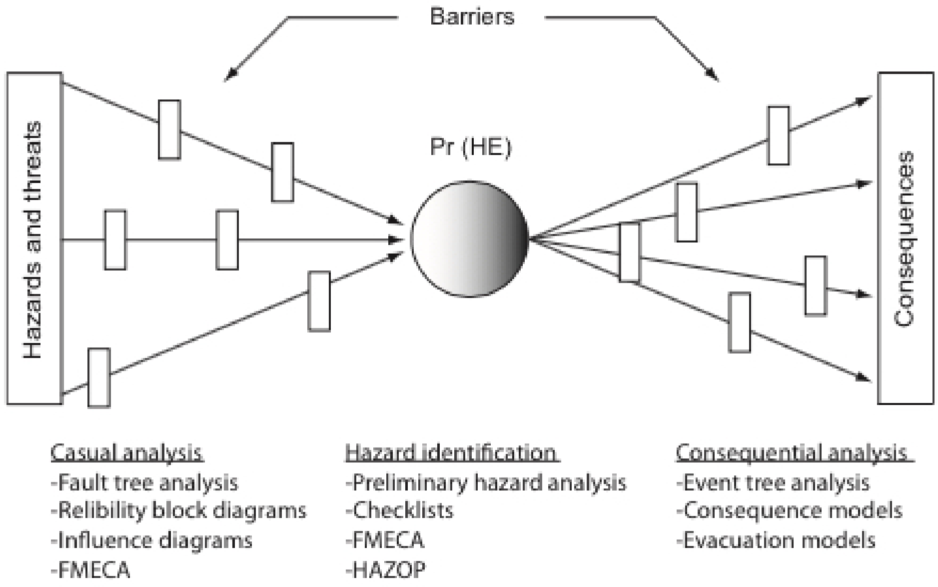


Figure 3.3: The bowtie diagram (Johansen, 2010b)

3.1.1 Barriers

In most systems there is some kind of protection equipment or features to protect the environment, people and other assets from harm if something goes wrong. This equipment or these features are referred to as barriers. The bow-tie model in Figure 3.3 shows that barriers can either be in place to prevent the probability of hazardous events, or to reduce the consequences of the hazardous event. The preventive barriers are called proactive barriers, while the reductive barriers are called reactive barrier. Examples of proactive barriers related to cars can be driver-training, traffic signals and antilock braking system (ABS), while some examples of reactive barriers can be seatbelts, airbag systems and headrests (Rausand, 2011).

The Management Regulation (PSA, 2014) by The Petroleum Safety Authority (PSA) in Norway talks about the regulations regarding barriers in the offshore industry in section five. The regulations states that barriers should be established and that these barriers should at all times be able to:

1. Identify conditions that can lead to failures, hazards and accident situations
2. Reduce the possibility of failures, hazards and accident situations occurring and developing
3. Limit possible harm and inconveniences

To properly do an analysis of the operational phase of a system, which is the main focus of this thesis, it is important to know what the barriers are and how good they are supposed to be. This information is needed to evaluate the potential risks that can occur in the operational phase of the SC bridges. A barrier will usually have some performance requirements that have to be fulfilled. These requirements are a sort of acceptance criterion, which means that the barrier will not be considered safe if it does not meet the criterion.

3.2 Risk assessments for road infrastructures

This section gives a brief overview over what has been done, and not been done, regarding risk assessment of concrete structures, like bridges, that have been built so far. This has to be done to find a good approach for risk assessment of SC bridges. The three SC bridge alternatives that the NPRA has come up with will require that known solutions will be executed in new ways. These bridges will be nothing like the bridges that have been built before, therefore the theory has to be modified. To do a proper risk analysis of these bridges, it is important to consider everything that has been done before (risk analysis of tunnels, roads, bridges etc.), and see how this can be combined and modified to fit the scope and scale of the SC bridges. For a project like this risk analysis has to be done in different stages. The purpose of risk analysis at an early stage is to help choose the design of the concepts for the different crossings. In addition it is meant to help highlight all the hazards and treats. There are different traditions when it comes to risk analysis, but for bridges there is no special tradition for a systematic use of risk analysis, like there is for the offshore industry with the NORSOK Z-013 (2010) standard. The existing traditions for risk analysis of bridges are mostly limited to ship collisions, which Gamborg Hansen et al. (2012a) and Gamborg Hansen et al. (2012b) are examples of.

3.2.1 General practice by the NPRA

A risk assessment will typically be performed at different stages of the project. For the NPRA the stages of risk assessment in projects are not that clear. Figure 3.4 illustrates the different stages of a project at the NPRA.

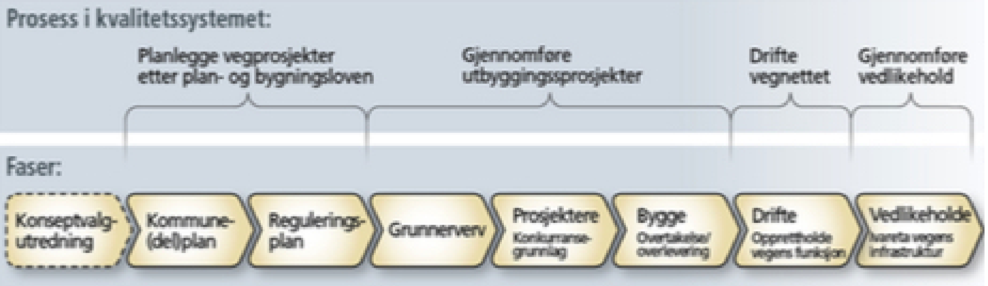


Figure 3.4: An illustration of the plan processes at the NPRA (R760, 2012)

A "konsekvensutredning (KU)" ("consequence assessment") is supposed to be executed in the stage called "kommuneplan". This is the only time when it is explicitly mentioned that a risk analysis should be performed in projects at the NPRA. The KU takes a lot of factors into account, so it is difficult to know the part of the risk analysis in this assessment. What significance has the risk analysis compared to all the other factors considered in the assessment? It is unclear how the risk analysis should be used actively and how to emphasis it when making decisions. The author would recommend separating the risk analysis from the KU to make it more visible and significant. Generally the risk assessment will be more detailed towards the end of the project, but the risk analysis is only included one time in the NPRA's structure. It is therefore necessary to start thinking differently to come up with a better solution. This will be explored further in chapter 6.

The NPRA has a vision of a transport system that does not lead to loss of life or permanent injury. This vision is called the zero vision. Today the road traffic risk in Norway is among the lowest in the world. If Norway wants to continue to reduce the number of fatalities and injuries, in line with the zero vision, it requires a proactive approach to traffic accidents SVV (2006). Risk assessment can be a good contribution to this. The NPRA has on that occasion written a manual for risk evaluation of road traffic (V721, 2007). The most relevant chapters (for this thesis) from this manual are chapter 2 "Generell modell for risikovurderinger" ("General model of risk assessments") and chapter 3 "Risikovurdering av planer" ("Risk evaluation of new concepts/structures"). The manual presents a general model that should be used for performing a risk assessment at the NPRA. It is a general and simple model that is based on HAZID (hazard identification, another version of HAZOP which will be described more in chapter 4). The model is illustrated in Figure 3.5. The manual was written in 2007, and at that time risk assessments of new concepts were executed in different ways and with various scopes at the NPRA. The consequential analysis done for major projects involved calculations of changes in accident costs as a result of new road systems. However, documented risk assessments were rarely done at that time. There were no requirements to implement safety evaluations in the planning phase at this time, but the document recommended that it should be a part of the procedure for the implementation of small and large projects from then on. The manual gives a description of how each step in the risk assessment should be executed for new concepts in chapter 3 "Risikovurdering av planer" ("Risk evaluation of new concepts/structures") (V721, 2007).

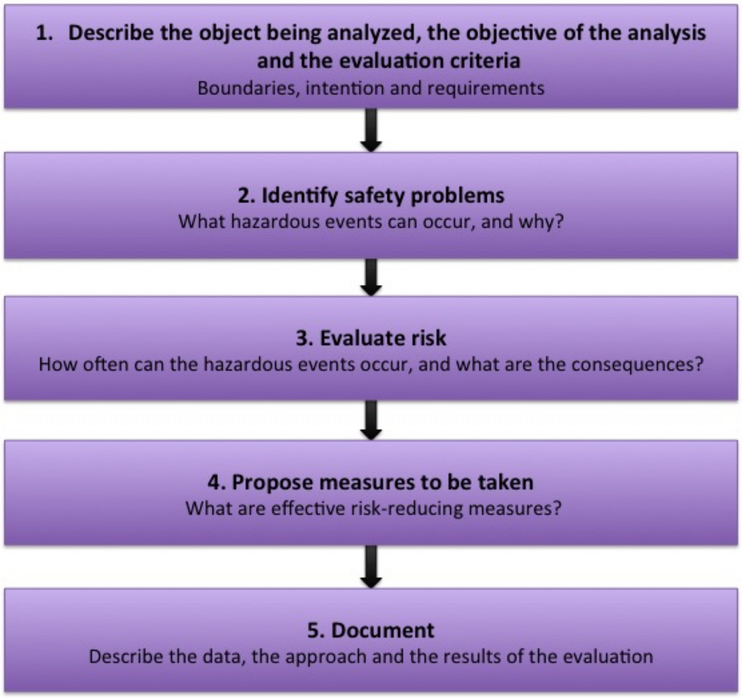


Figure 3.5: The risk assessment model at the NPRA adapted from V721 (2007)

3.2.2 Tunnels

There are generally more requirements regarding risk analysis of tunnels than for bridges. The EU Directive 2004/54/EC, which concerns minimum safety requirements for tunnels in the Trans-European Road Network (TERN), is the EU directive that influences the safety in road tunnels in Norway. The purpose of this directive is to ensure that tunnels have a safety level that is equal to or better than the minimum allowable level for the users with requirements that are intended to prevent critical events that can put human lives, the environment and the tunnel construction in danger, and to ensure protection in the event of an accident (Samferdselsdepartementet, 2007). This regulation provides some safety measures, but these measures are mainly functional requirements since the tunnels vary a great deal.

In addition to the EU directive the NPRA has a manual for risk analysis of road tunnels in Norway. This is a guideline with the purpose: "to describe when a risk analysis is necessary and provide a description of the types of analyzes that are appropriate for the various purposes, as well as an introduction to how the analysis can be carried out" (Wienche et al., 2007). The guideline mentions three different analyzes: preliminary risk analysis (PHA), detailed risk analysis and statistical risk calculation. It is assumed that a PHA is always carried out in advance of a detailed risk analysis. The identification of safety problems that have been carried out in the PHA does not need to be repeated because it will also be relevant in the detailed risk analysis. The proposed procedure for the PHA and the detailed risk analysis is the same as the general model for risk assessment at the NPRA, which is presented in Figure 3.5. However, the procedure in Wienche et al. (2007) tries to solve the challenges regarding of acceptable risk, in addition to being more descriptive.

The difference between the PHA and the detailed risk analysis is the thoroughness. Often, the PHA gives an adequate picture of the causes of unwanted events, but sometimes it is desirable to go into more detail.

3.2.3 Concrete structures

In 2004 a project called Lifecon (Life Cycle Management of Concrete Infrastructures for Improved Sustainability) issued a deliverable (Lair et al., 2004) about "Methods for optimization and decision making in lifetime management of structures". This deliverable is divided into three parts, where one part addresses risk assessment and control. This part of the deliverable is supposed to help cope with the lifetime risk of concrete facility management. Lifecon has four principal viewpoints that should be implemented in the risk management approach; human conditions, economy, culture and ecology. The author of this thesis interprets these viewpoints as how Lifecon categorize risk. The viewpoints may correspond to the different types of consequences that should be avoided. The understanding of the procedure Lifecon suggests is that it will help to avoid or reduce risks that can harm people, culture, economy and ecology in some way. Looking at the risk picture of a concrete structure it can be useful to have these viewpoints in mind. To exemplify, if there is a risk that the structure will collapse, all the viewpoints will be in danger. A collapse can harm humans, the culture, economy and/or ecology. When looking at this procedure, it is obviously essential to keep these viewpoints in mind when analyzing and evaluating the risk.

The risk part of this deliverable presents a proposed generic risk management procedure. This procedure is built upon Lifecon's principle of being predictive and integrated. The procedure can be summarized in four steps:

1. Identification of adverse incidents
2. Analysis of the identified adverse incidents:
    - Deductively, in order to find causes
    - Inductively, in order to find consequences
3. Quantitative risk analysis
4. Risk-based decision-making (and continuous updating of risk database)

The idea behind this procedure is to make the facility owners aware of the risks throughout the lifetime of the facility. This procedure is meant to be logical and easy in order to deal consistently with the risks. In the risk analysis part of this procedure there are many methods that can be used to get a good analysis. The methods differ in numerous ways, and the choice of method depends on variables like resources, expertise, phase of the project, risk category, source data and the nature of the problem among other things. The methods recommended by Lair et al. (2004) are Preliminary Hazard Analysis (PHA), Hazard and operability (HAZOP) study, Failures Modes, and Effects Analysis (FMEA), Event Tree Analysis (ETA) and Fault Tree Analysis (FTA). Some of these methods will be discussed in more detail in chapter 4. If risk is treated qualitatively then step one, two and four are enough. If there is need for a quantitative analysis step three has to be executed. In this step methods like ETA and FTA are used as in step two, but here estimations about probabilities of the basic events has to be included. In the last step judgments have to be made about the acceptability and significance of the risk. From this decisions have to be made on how to proceed with the risk identified. This step is about checking if the risk is acceptable or not according to the risk criteria used. If the risk is not acceptable measures must be taken. Lifecon talks a little about risk acceptance, but they do not provide any solution for it. They bring up some interesting questions relating to the potential problems with setting a risk acceptance criterion, but this will be discussed a little further in chapter 5 (Lair et al., 2004).

Lifecon risk procedure is meant as a general guideline for risk assessment. Risk evaluation depends on the company's preferences and strategy. Therefore most of the responsibility will be left to the end user. This procedure does in fact not say anything about how to do it. It does not give a solution to how one should do a risk assessment, it is only a general approach where the user has to choose the methods and risk acceptance level itself. The idea is to implement the procedure into the company's existing management system and utilize it in the best way suited for the company. This risk procedure is in other words not a strict regulation, but more of a guideline that might be a good jump-start for a risk assessment of a facility (Lair et al., 2004).

Lifecon's procedure is not that different from the risk assessment model at the NPRA. The Lifecon procedure seems to have a more "correct" risk language (based on the risk literature that the author has read), and is more to the point than the NPRA model. The NPRA procedure looks too vague compared to Lifecon. However, both procedures try to communicate the same message. An implication is that the NPRA has been inspired by the Lifecon procedure, but structured theirs more after their own liking and understanding. It is said that the NPRA was a part of the Lifecon project, which makes it likely that their model was inspired by Lifecon's procedure.

3.3 Discussion

The theory presented in this chapter is a good starting point for coming up with a risk assessment approach of SC bridges. It can be assumed that the existing procedure at the NPRA will not be good enough to cover all the challenges with the SC bridges, because the existing procedure are not designed to fit these challenges. Compared to for example NORSOK Z-013 (2010), today's practice at the NPRA is too vague, and it does not go into specifics about what to do for each step. The NORSOK Z-013 (2010) is a detailed standard for risk assessment in the offshore industry, and a similar one should be made for concrete structures on land, like bridges. The existing traditions for risk analysis for bridges are mostly limited to ship collisions, and this will not represent the whole risk picture. Gamborg Hansen et al. (2012a) and Gamborg Hansen et al. (2012b) are examples of risk analyzes that are limited to ship collisions. These analyzes have an exclusive focus on ship collision which results in an incomplete hazard identification. In addition there is paid little attention to uncertainty and assumptions, and the risk acceptance criteria are insufficient in these analyzes. These risk analyzes do not have a complete bow-tie mentality, and to carry out an adequate risk assessment a risk analysis should be more clearly linked to the entire bow-tie model (Figure 3.3).

Since there is not much tradition for risk assessment at the NPRA, it is natural to think that a more detailed and explanatory procedure would help implement risk assessment into their routine. The NPRA have always been interested in learning from the Norwegian National Rail Administration (NNRA) and the EN 50126 (1999) standard, since they have much longer traditions for risk management than the NPRA. It makes sense to be inspired by the NNRA since they are more closely related to the NPRA than other industries. This is because they are both in the transportation sector. In addition the risk for third persons are similar for the NNRA and the NPRA. Third persons are more vulnerable in the transportation sector than in the offshore industry. This makes the NNRA a good basis for comparison. The NPRA may also learn something from their own constructions. When building road tunnels and underwater tunnels an extensive risk analysis is executed. An example is the risk analysis report by Hokstad et al. (2012). This analysis is a good example of a good risk analysis, and the NPRA should implement the knowledge from this analysis to the SC bridges.

To conclude, the NPRA needs to modify their existing risk procedure to properly assess the risk of SC bridges. It is important that a risk procedure for these bridges will catch all the hazards and uncertainties. In addition, it is essential that this new procedure will look at all possible perspectives. There is more at stake than harm to humans with this project. There are many things that can go wrong, and consequences affecting other aspects than human lives have to be considered as well. The consequences if one of these bridges fails in any way may be more damaging than for existing bridges. A modified, and more thorough procedure that will cover all the potential hazards and consequences needs to be presented for the SC bridges. This procedure should first and foremost be based on the existing procedure at the NPRA. It should then be modified and improved by the knowledge from applications with more experience, like the NNRA, tunnel analyzes and the offshore industry. A solution to this issue is explored further in chapter 6, were a new risk assessment approach for the NPRA is suggested.

Chapter 4

Hazards and hazard identification

This chapter tries to introduce the key concepts associated with hazards, and methods to detect and classify hazards. If this part is done thoroughly and correct it will lay a solid foundation for the rest of the risk analysis. This part is especially important in an early phase of a project, which is the case for the SC bridges along E39. It can be argued that the regular methods for risk assessment of bridges, like V721 (2007), Lair et al. (2004), Gamborg Hansen et al. (2012a) and Gamborg Hansen et al. (2012b), are too weak in identifying hazards and hazardous events. If that is the case, those methods will definitely not be good enough for the SC bridges. It is impossible to know if the regular methods will be able to identify all the hazards of a SC bridge, since these structures have never been built before. There is great deal of uncertainty with these new bridges, and the regular methods might not cover that. This is why hazard identification has been given more focus in this thesis than causal and consequential analysis.

☞ **Hazard identification:** The process of identifying and describing all the significant hazards, threats, and hazardous events associated with a system.

Rausand (2011)

In the book by Rausand (2011) a list of all the objectives of hazard identification is presented. This list is reproduced below.

(a) Identify all the hazards and hazardous events that are relevant during the lifetime of the system

(b) Describe the characteristics, and the form and quantity, of each hazard

(c) Describe when and where in the system the hazard is present

(d) Identify possible triggering events related to each hazard

(e) Identify which conditions that the hazard could lead to a hazardous event

(f) Identify potential hazardous events that could be caused by the hazard

(g) Make operators and system owners aware of hazards and potential hazardous events

4.1 Hazards associated with bridge structures

There will never be exactly the same kind of hazards for different systems. It depends on a lot of factors, like location, structure, weather etc. In another Lifecon deliverable (Sarja, 2004), a table (table 12) of typical hazards for concrete structures is given. This illustrates the most typical hazards that can be identified for a standard concrete structure, like a bridge. These hazards are divided into four categories: mechanical, physical, chemical and biological. The most relevant hazards, according to the author, for the structures analyzed in this thesis has been listed below.

Physical:

- Temperature changes
- Freezing - melting cycles
- Traffic
- Running water
- Turbulent water

Mechanical:

- Static loading
- Cyclic or pulsating loading
- Impact loading

Chemical:

- Soft water
- Carbon dioxide
- Sulphur dioxide
- Nitrogen dioxide
- Oxygen + water

Biological:

- Microorganisms
- Plants
- Animals
- People

A report by PIARC (2015) discusses risk-based management for bridges around the world. This report provides an illustration of typical hazards that can affect a bridge, which can be compared to the list of hazards above. Those hazards are illustrated in Figure 4.1. Combining the findings from these two reports (Sarja, 2004; PIARC, 2015) can be helpful in establishing a checklist for

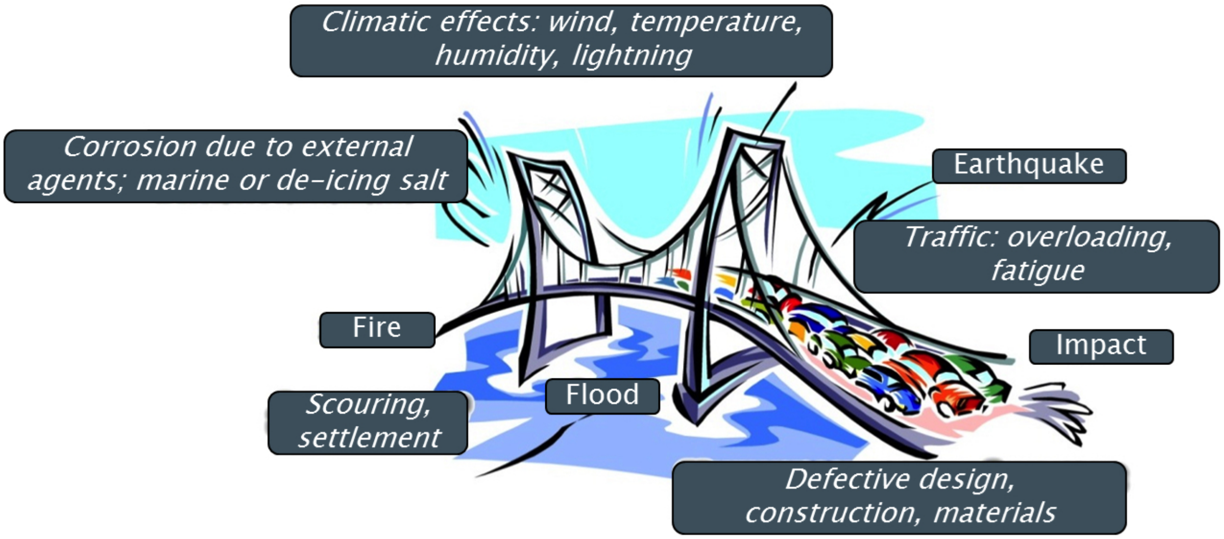


Figure 4.1: Typical hazards for a bridge (PIARC, 2015)

hazards related to SC bridges. In the identification of hazards for the three different SC bridge concepts these reports have been used as an inspiration.

4.2 Methods for hazard identification

There are many different methods for identifying hazards, and in the book by Rausand (2011) a selection of hazard identification methods is provided. Some of the most common and useful methods from this book, according to the author, are listed below.

- Checklist and Brainstorming
- Preliminary Hazard Analysis (PHA)
- Failure Modes, Effects, and Criticality Analysis (FMECA)
- Hazard and Operability (HAZOP) Study
- Structured What-If Technique (SWIFT)

4.2.1 Checklist and Brainstorming

In some industries, like the offshore industry, there are lists of generic hazards that can be used to identify hazards. For industries that do not have list like these, an idea could be to look at the list from other industries for inspiration. In addition to these lists teamwork and brainstorming can help to come up with more hazards and details about the events (Rausand, 2011). Some advantages are that it does not overlook common and obvious problems, and non-system experts can use it. It can, however, miss hazards that have not been seen previously in addition to being limited to previous experience. A complete list of advantages and disadvantages can be found in Rausand (2011).

4.2.2 Preliminary Hazard Analysis (PHA)

This is a simple method used in the design phase to identify hazards. It is a preliminary method because the result often gets updated when more detailed risk analyses are performed. A PHA gives a good overview of all the hazards in a system. It is often combined with a risk matrix (often used in relation to ALARP, see chapter 5), which sorts the hazards by frequency and consequence (Rausand, 2011). Some advantages are that it is simple to use, a good method to use in the early phases of a project and it is a versatile method that cover a range of problems. However, it does not assess risks of combined hazards or coexisting system failure modes. A complete list of advantages and disadvantages can be found in Rausand (2011).

4.2.3 Failure Modes, Effects, and Criticality Analysis (FMECA)

A FMECA is supposed to identify all the potential failure modes for all the components in a technical system. Then the causes of these failure modes have to be identified, before determining the effects that each failure mode has on the whole system. FMECA is a simple method where a specific worksheet should be filled out. This method is highly component based, and does not look at how these failures effect things outside the technical system (Rausand, 2011). Some advantages are that it is widely used, easy to understand, and it is flexible. However, the benefits of this method depend on the experience of the analyst, and it is time-consuming and expensive. A complete list of advantages and disadvantages can be found in Rausand (2011).

4.2.4 Hazard and Operability (HAZOP) Study

A HAZOP will identify deviations and dangerous situations in a process. This method is best suited for teamwork. The structure is based on guidewords that are supposed to help guide through the process. It is usually executed with several meetings of brainstorming with the help of the guidewords. The result of the HAZOP is usually reported in a specific worksheet, which gives a good overview of the result (Rausand, 2011). Some advantages are that it is widely used, and it is highly effective for both technical faults and human errors. However, this method is dependent on the knowledge of the leader and the team, in addition to being time consuming. A complete list of advantages and disadvantages can be found in Rausand (2011).

4.2.5 Structured What-If Technique (SWIFT)

SWIFT is executed in the same way as a HAZOP, a team having sessions of brainstorming. The difference is the guidewords, which SWIFT does not use. In this method the team come together to ask and answer a lot of what-if questions. This method is often considered a simplified HAZOP. SWIFT is usually documented in a specific worksheet (Rausand, 2011). Some advantages of this method are that it is flexible and quick. However, it is not that thorough and foolproof, in addition to being highly dependent on checklists being prepared in advance. A complete list of advantages and disadvantages can be found in Rausand (2011).

4.3 Identification of hazards and hazardous events

The methods chosen to identify hazards in this thesis are a combination of checklist/brainstorming and a PHA. A HAZOP would be the method most preferred, but since the author is doing this almost alone and in a limited time period, this method is not suitable in this case. A HAZOP is a good tool because it involves different people with different points of views. It is a good method to catch all the hazards and treats. The author has once been a part of a HAZOP at a summer internship, and it was a good and structured way of identifying hazards. It is a common method in the oil and gas industry in Norway, which emphasizes that HAZOP is a good method for identifying hazards. The HAZOP is a method that the author would recommend if it is possible to execute. In this case a HAZOP will, as mentioned, be time-consuming and hard to conduct with few people. A checklist and PHA would therefore be a good alternative in this case. These two methods combined will cover the most important hazards and treats.

In subsections 4.3.1 and 4.3.2 the hazards for the three SC bridge concepts are introduced. The hazards have been found by looking at existing risk assessment of bridges and tunnels. In addition to this, several sessions of brainstorming with the supervisors at NTNU and the NPRA have been conducted to try and find all the possible hazards. The author has tried to divide the hazards into two categories. One category for hazards that are environmental and location dependent, and one for hazards that are construction dependent. This means that some hazards, like the weather, are dependent on the location and can cause harm to the construction if it is positioned at that location. Some environmental/location-based hazards are also listed under hazards related to the specific construction if they are considered as hazards that can cause significant damage to the construction if present.

4.3.1 Hazards related to location and environment

There are some hazards that will depend on the location and the environment. The presence of these hazards depends on the fjord and the crossing place for the bridge (depth, openness, steepness, width, etc.). The hazards identified as environmental and location dependent is listed below.

- Wind
- Waves
- Swells from ocean
- Ice
- Current
- Landslides resulting in a tsunami
- Underwater landslides
- Earthquake
- Scour

4.3.2 Hazards related to structure

Suspension bridge

- Terrorism
- People
- Many vehicles at the same time
- Heavy vehicles
- Ships
- Planes and helicopters
- Corrosion and carbonization (depends on the material)
- Obstructions in the road
- Deformations and vibrations (may be because of wind)
- Ice
- Landslides resulting in a tsunami

Floating bridge

- Terrorism
- People
- Many vehicles at the same time
- Heavy vehicles
- Ships
- Planes and helicopters
- Obstructions in the road
- Corrosion and carbonization (depends on the material)
- Waves
- Current
- Landslides resulting in a tsunami

Submerged floating tunnel

- Sudden change of light when driving into and out of the tunnel
- Terrorism
- People
- Many vehicles at the same time
- Heavy vehicles
- Leakage from cargo
- Ships or falling anchor/objects
- Submarines
- Closed space
- Marine growth
- Corrosion and carbonization (depends on the material)
- Steep incline
- Obstructions in the road
- Current
- Underwater landslides
- Swells from ocean

The reason "ships or falling anchor/objects" are mentioned among the hazards is because these hazards depend on the type of submerged floating tunnel. If the tunnel is anchored to floating pontoons at the surface (Figure 2.9), ships will be a hazard, but if the tunnel is anchored to tension rods to the bottom of the fjord (Figure 2.12), ships will not be a hazard (except for submarines). Then falling objects and anchors will be a more significant hazard than ships.

These lists are not considered to be complete checklists, but more of a good starting point for a checklist of hazards for SC bridges. They are based on the existing risk assessments for tunnels and bridges, like Gamborg Hansen et al. (2012a), Gamborg Hansen et al. (2012b) and Hokstad et al. (2012), in addition to lists of typical hazards for bridges found in both Sarja (2004) and PIARC (2015). The author have extended the existing knowledge of hazards for bridges by combining all of these references to form more complete lists of hazards for SC bridges. Lists like these have not been found anywhere for SC bridges (as far as the author knows), and they would therefore be considered to be a good supplement to what is used today.

4.3.3 Hazardous events

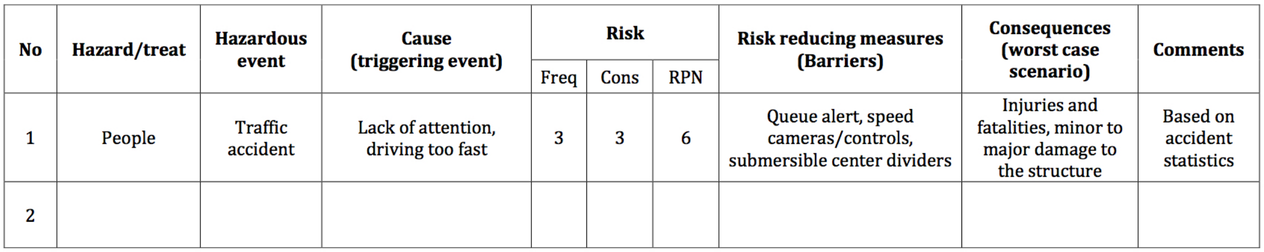
A list of the most relevant hazardous events that may apply for all the structures are listed below.

- Fire
- Explosion
- Traffic accident
- Ship collision
- Collapse of structure
- Water leakage into the structure (tunnel concept only)

4.3.4 PHA

For the PHA, only the layout of the PHA worksheet that should be used is presented (Table 4.1) in this chapter. A PHA for each of the three different concepts is not made. The worksheet presented is a simplified version of the PHA worksheet found in Rausand (2011). A thorough PHA with this layout is made in chapter 6 for the case study of Halsafjorden.

Table 4.1: PHA worksheet layout



No	Hazard/treat	Hazardous event	Cause (triggering event)	Risk			Risk reducing measures (Barriers)	Consequences (worst case scenario)	Comments
				Freq	Cons	RPN			
1	People	Traffic accident	Lack of attention, driving too fast	3	3	6	Queue alert, speed cameras/controls, submersible center dividers	Injuries and fatalities, minor to major damage to the structure	Based on accident statistics
2									

RPN is an acronym for "risk priority number", and is the frequency and consequence number added together. It rates the risks, so the hazard with the highest RPN is the most dangerous hazard. The frequency and consequence numbers usually comes from a classification of these two factors. The classification of frequencies is often defined in rather broad classes, like improbable, remote, possible, occasional and fairly normal (Rausand, 2011). The classification of consequences is often defined after the severity, like minor damage, damage, major damage, severe loss, catastrophic (Rausand, 2011). The comments column is a new factor added by the author, which is meant to describe how the frequency and consequence numbers are determined.

Chapter 5

Risk metrics and risk acceptance criteria

5.1 General concepts

Risk metrics are measurements of risk, usually risk relating to people. A risk metric can often be used as a risk acceptance criterion (recall definition from chapter 3).

When a risk analysis is performed an evaluation of the risk is needed. This is where the risk acceptance criteria come into play. The result of the risk analysis usually gets compared to the stated risk acceptance criterion to see if the risk identified is acceptable or not. However, this is not as easy as it might sound. How do we set an acceptable criterion? It is worth mentioning that not everyone agrees that comparing the result of a risk analysis to an absolute acceptance criterion is a good idea. These viewpoints are empathized by the following quote from Aven and Vinnem (2004):

> We believe that we can do better if cost-effectiveness (in a wide sense) is the ruling thinking rather than adoption of pre-defined risk acceptance limits. This means a closer resemblance with the ALARP principle as adopted in the UK and other countries, but is not a direct application of this practice.

However it is common to use acceptance criteria, and therefore it is natural to discuss the possibilities of such criteria for the NPRA. The SC bridges along E39 cannot be compared to anything that has been built so far, so how do we know what will be acceptable risks for these constructions? What kind of factors should be considered? Should the focus be on human safety or structure safety? Or is it possible to set limits that will ensure both construction and human safety? This chapter will discuss the challenges and possible solutions regarding acceptable risk for SC bridges. In addition some knowledge about the different principles of risk metrics and risk acceptance criteria will be presented.

5.1.1 Risk metrics

In most cases risk metrics are measures of risk to people. Risk to humans is often divided into two, individual risk and group risk. The most common and relevant risk metrics relating to human risk are Individual Risk per Annum (IRPA), Localized Individual Risk (LIRA), Potential Loss of Life (PLL) and Fatal Accident Rate (FAR).

Individual Risk per Annum (IRPA)

☞ **IRPA:** The probability that an individual will be killed due to a set of hazards (a) during one year's exposure.

Rausand (2011)

This measure is based on the observed number of fatalities in a particular time period for a particular group of people which are exposed to the same hazards (a). This is expressed by equation 5.1 (Rausand, 2011).

$$IRPA = \frac{\text{observed number of fatalities due to hazards (a)}}{\text{total number of persons exposed in that one year}} \tag{5.1}$$

Localized Individual Risk (LIRA)

☞ **LIRA:** The probability that an average unprotected person, permanently present at a specified location, is killed in a period of one year due to an accident at a hazardous installation.

Rausand (2011)

It is assumed that the person is always present at the given location for a year. It can be argued that LIRA is a geographic risk measure instead of an individual risk measure because it remains unchanged regardless if a person is in that spot or not. The location-specific properties that LIRA possesses are the reason this measure is only used for land-use planning. The total LIRA at location (x,y) due to accident of type A_i is presented in equation 5.2, where λ_i = frequency of accidents (Rausand, 2011).

$$LIRA_{x,y} = \sum_{i=1}^{m} \lambda_i \cdot Pr\left(\text{fatality at}(x,y)\middle|A_i\right) \tag{5.2}$$

Potential Loss of Life (PLL)

☞ **PLL:** The expected number of fatalities within a specified population (or within a specified area A) per annum.

Rausand (2011)

PLL is one of the most used measures of group risk. It is a simple measure that does not distinguish between one accident that can cause 100 deaths and 100 accidents each causing one death over the same time period. PLL does not reflect on the contrast between the strong reactions from society to rare and major accidents and the silent acceptance of the highly frequent small accidents. If all members of a population are assumed to have the same IRPA, the PLL can be calculated with equation 5.3, where n_i = number of people affected, λ_i = frequency of accidents and p_i = probability that an average person will be killed if an accident of type$i$should occur (Rausand, 2011).

$$PPL = n_i \cdot \lambda_i \cdot p_i = n_i \cdot \text{IRPA} \tag{5.3}$$

Fatal Accident Rate (FAR)

☞ **FAR:** The expected number of fatalities in a defined population per 100 million hours of exposure.

Rausand (2011)

Far is one of the most common risk indicators for occupational risk in Europe. The meaning of FAR is as follows: If 1000 people work 2000 hours per year during 50 years, their cumulative exposure time will be 10^8 hours. FAR is the expected number of fatalities among these 1000 people working under the same conditions for their whole life. The value of FAR can be calculated with equation 5.4 (Rausand, 2011).

$$FAR = \frac{\text{expected number of fatalties}}{\text{number of hours exposed to risk}} \cdot 10^8 \tag{5.4}$$

5.1.2 Risk acceptance criteria

A risk acceptance criterion can be either quantitative or qualitative. The criterion can be based on a lot of factors, like requirements from authorities, standards, norms, experience and theoretical knowledge. What is meant by acceptable risk will depend on a lot of factors. It is mostly a conflict between the benefits gained from the activities that cause the risk, and the consequences of the potential hazardous events that can occur because of the risk. Risk acceptance criteria will simplify the decision making process, and will usually be considered a tool for making decisions regarding risk (Johansen, 2010a). There are many different approaches that are used to determine acceptable risk, but some of the most commonly used principles are ALARP, GAMAB, MEM and the Precautionary principle.

The ALARP Principle

ALARP stands for "as low as reasonably practicable". This principle divides risk into three levels:

1. An unacceptable level
2. An ALARP level
3. An acceptable level

The three risk levels of ALARP are described in Figure 5.1. In the ALARP level the costs should be substantially greater than the benefits for risk reducing measures not to be made, the costs should be grossly disproportionate to the benefits. The point is to always try and reduce risk if it is practical and beneficial (HSE, 2001).

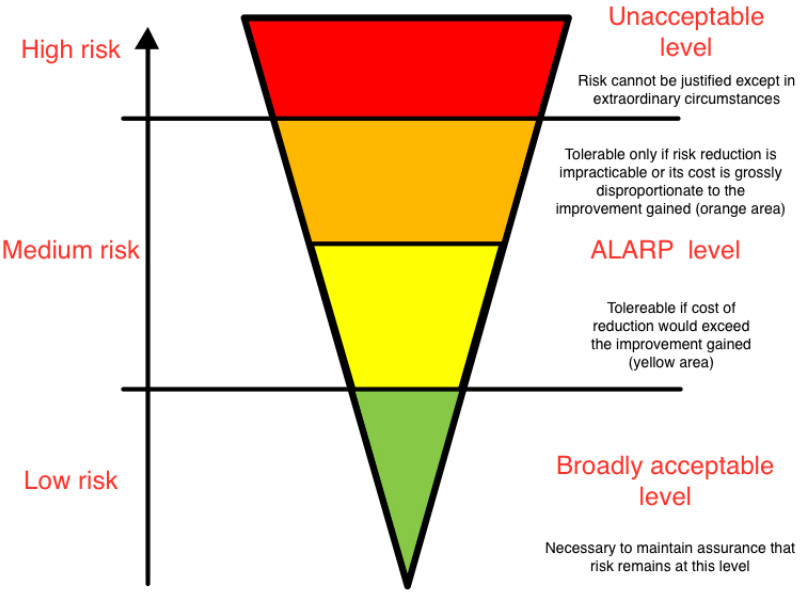
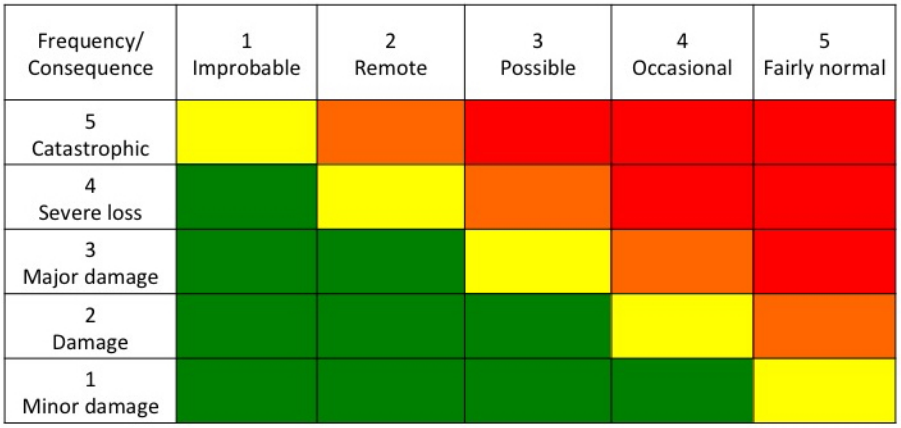


Figure 5.1: The ALARP principle (adapted from HSE (2001))

A risk matrix is often used in combination with ALARP and a PHA, as briefly mentioned in subsection 4.2.2. The matrix illustrates the frequency and consequences of hazardous events and the categorization of these factors is explained briefly in subsection 4.3.4. In combination with ALARP, the risk matrix is dived into the different colors for ALARP, which is represented in Figure 5.1. An example of an ALARP based risk matrix is given in Figure 5.2, with the same frequency and consequence categories used in Rausand (2011). The categories for frequency and consequence should be adapted to the situation. In combination with a PHA the hazards identified will be put into the matrix according to the frequency and consequence numbers.



Frequency/ Consequence	1 Improbable	2 Remote	3 Possible	4 Occasional	5 Fairly normal
5 Catastrophic	🟨	🟧	🟥	🟥	🟥
4 Severe loss	🟩	🟨	🟧	🟥	🟥
3 Major damage	🟩	🟩	🟨	🟧	🟥
2 Damage	🟩	🟩	🟩	🟨	🟧
1 Minor damage	🟩	🟩	🟩	🟩	🟨

Figure 5.2: A typical risk matrix based on ALARP (Rausand, 2011)

The GAMAB principle

GAMAB is a French acronym for "globalement au moins aussi hon", which means "globally at least as good." The principle states that any new project should be at least as good as existing solutions. This principle has been used in France to make decisions about transportation systems, which means that new systems are required to be as safe as the existing ones. This principle uses existing technology as the point of reference, which means that with this principle a risk acceptance criterion does not need to be established since this is defined as the present level of risk (EN 50126, 1999).

The MEM principle

MEM is a German principle that stands for "minimum endogenous mortality." This principle uses the probability of dying of natural causes as a reference to acceptable risk. Endogenous mortality is an expression for death caused by internal causes, like illness. This principle says that a new or modified technological system should not cause a significant increase of IRPA for any person. Often, especially in the railway standards, this significant increase means more than 5%. If a system causes the IRPA to increase more than 5% the risk is considered unacceptable. MEM gives a universal quantitative risk acceptance criterion that is developed from the minimum endogenous mortality rate (EN 50126, 1999).

The Precautionary Principle

☞ **The Precautionary Principle:** Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

UN (1992)

This principle does not give any quantitative number as a criterion, which the risk discovered can be compared with. The acceptance of risk is instead based on the proportionality between the severity of potential consequences and the precautionary measures taken. This principle primarily concerns uncertainty. If there is any reason to believe that modifications to a system can lead to harm to users, and the knowledge of the relationship between hazards and consequences is limited, this principle should be implemented (Rausand, 2011).

5.2 Acceptance criteria for SC bridges

Establishing risk acceptance criteria for SC bridges is the most challenging task of this thesis. From a RAMS perspective the NPRA has two overarching goals for the E39 project: availability and safety (the A and S in RAMS). It is from these letters that the criteria for reliability and maintainability (R and M) of components and systems are derived. Availability and safety should be vital in the screening and selection of concepts, and overall requirements should therefore be established at an early stage. The requirements will provide guidelines for a technology qualification process. The challenge is to define an appropriate level of detail in relation to the uncertainty in the early stages. For the transport and communication sector, failures can affect both individual people and society. This is the challenge when establishing a criterion, because it can create a conflict between the vulnerability of society and the potential harm to people.

What is most the important? Harm to humans is often the priority when acceptance criteria are established, but what about society? Will not risk in relation to these SC bridges lead to a vulnerable society? If the structure fails a vulnerable society will emerge because there will be no other alternatives for crossing the fjord anymore. This vulnerability is about how much downtime we tolerate relative to the consequences it has for society. This is equal to the availability of the bridge. It is challenging to establish a risk acceptance criterion that will cover all the important aspects, like availability and safety to people. It might be useful to divide the risk acceptance criteria into individual risk and societal risk for this sector, but it might not be so easy to distinguish the boundaries between these two risks. It is possible to learn from other applications, but good justifications for selected acceptance criteria are unfortunately rare. The benefits of copying criteria from other applications can be limited, but it can provide an indication that it is possible to learn from. This section will discuss this a little further by looking at existing applications that can be of use in addition to some new ideas.

Structural reliability requirements

What the NPRA currently accept regarding structural reliability is briefly mentioned in their N400 (2009) manual about bridge engineering. N400 (2009) says that they cannot ignore hazardous events that have an annual probability of $1 \cdot 10^{-4}$, which implies that they "accept" hazardous events with a lower probability. This means that their structures should be designed to withstand hazardous events with an annual probability of $1 \cdot 10^{-4}$ or higher. If events like that occur, it may result in loss of bearing capacity. This probability can be interpreted as a risk acceptance criterion, but it really should not be. It should be handled as a "selection" criterion instead, but that does not make much sense either because it does not say anything about the overall risk. How many hazardous events may occur that could, if not properly managed, lead to a loss of structural integrity? If they want to use this criterion they should at least use $1 \cdot 10^{-5}$ as the author understands is used in the offshore industry. This would create a buffer, which could make it safer. If there are many of these events (with probability of $1 \cdot 10^{-4}$ or less), the total frequency of all of these events might easily be higher than $1 \cdot 10^{-4}$. If they used $1 \cdot 10^{-5}$ as a criteria for the frequency of each individual event instead, the total frequency of all these events (the sum) could be compared to $1 \cdot 10^{-4}$ to see if it is acceptable. This would set a more stringent requirement to each individual event, which could ensure that the total frequency of all these events would be less than $1 \cdot 10^{-4}$. If the total frequency is higher than the criteria, they have to take some measures that will decrease the frequency of that consequence. The consequence in it self cannot be reduced, but the frequency of it can. This kind of probability measure may in some cases be treated as a measure of availability, which might be a little strange. This measure will have repercussions for both availability and safety, but how is unclear in today's guidelines. In the Storebælt project in Denmark they used this kind of probability measure as a measure of availability. Storebælt is an approximately 18 km suspension bridge built over the Storebælt strait in Denmark. Their criteria said that the probability that the unavailability is larger than one month should be $4 \cdot 10^{-4}$ or less per year. However, this acceptance criterion is not that clear with respect to safety. Does it represent the tolerance for unavailability according to safety, or does it represent the tolerance according to costs and benefits?

Implementation of the zero vision

With regards to safety the NPRA has said that it should be as safe to travel on the SC bridges as it is on regular roads. On regular roads the zero vision applies, which states that the transport system should not lead to any loss of life or permanent injury. This vision is not really an acceptance criterion in itself, but rather an expectation to move downwards in the ALARP zone to continuously try to improve the safety. A good way to try to strive towards this vision for the SC bridges is to use the GAMAB and ALARP principle. An idea is to have the GAMAB principle as a base since the first priority is to make the SC bridges as safe as regular roads. For this to work it will be necessary to find a criteria that will represent an average regular road. This however is not that easy. How do we quantify the regular roads to represent a number that we can compare with the SC bridges? Should it be based on statistics relating to how many people get badly injured or die in the transport system in Norway yearly? If that is an alternative, should it be the average of all roads in Norway, or should it be certain selected roads? It is not easy to say what is right, but the idea of looking at statistics for injuries and casualties in road traffic is a good start. It is just a matter of how this data should be used. In addition to the GAMAB principle, the ALARP principle should be used as well. First the GAMAB principle should be used to determine if the SC bridges are as safe as regular roads. However, GAMAB only states that the global risk must be equal or better than previous risks. This gives the NPRA the opportunity to tolerate an increased risk for the SC bridges if they reduce the risk on the rest of coastal highway E39. This will depend on how they define the system, but the use of GAMAB should ensure that the total risk on E39 will not increase with the addition of the SC bridges. Second, the ALARP should be used to try and reduce the risk even further, if it is practical, to strive towards the zero vision. The zero vision makes ALARP highly ideal for the NPRA, because this principle will always try to strive for better solutions if the benefits are larger than the costs. Alternatively, a principle that is very similar to ALARP, called ALARA could be implemented to strive towards the zero vision. ALARA states that risk should be as "low as reasonably achievable", which means that it does not have a broadly acceptable level like ALARP (Johansen, 2010a). This implies that the ultimate goal of ALARA is to strive to reach the bottom of the upside down triangle of ALARP, which is zero. This might be a better principle to ensure the implementation of the zero vision.

Comparison with ferries

The SC bridges are supposed to replace ferries. Therefore it would be natural to believe that travelling on these bridges should not be any more dangerous than the ferry. With that said it could be a good idea to look at accident statistics for ferries. In 1997 SINTEF did a risk analysis of ferries in Norway (Hokstad et al., 1997). The SINTEF analysis could be combined with today's ferry statistics (V620, 2012) to find an assumed accident rate for today's ferries. In Hokstad et al. (1997) SINTEF suggests risk acceptance criteria for individual risk for the overall ferry connections in Norway. The fact that ferries should not be any more dangerous than other public transportation is a basis for these criteria. In addition, they use ALARP on top to always try and reduce the risk if possible. SINTEF argues that the average individual risk should not exceed 2 fatalities per billion-passenger kilometers, and if it exceeds 0.5 fatalities per billion passenger kilometers, risk-reducing measures should be initiated if it is beneficial (ALARP). They also suggested that an accident with 10 or more fatalities should not happen more than once per 100 years, and that an accident with 100 or more fatalities should not happen more than once per 10 000 years. ALARP should be used to try to reduce the risk of these potential accidents if it is beneficial. It can be assumed that ferries have not become any more risky than they were in 1997, so the average number of accidents found in the SINTEF report should not have increased. The numbers from Hokstad et al. (1997) would have to be adjusted to fit the number of ferry connections today. From all of these assumptions the NPRA can assume an accident rate for an average ferry by comparing these two reports. This accident rate can then be set as a risk acceptance criterion for a SC bridge. However, it is questionable if ferry statistics are a good basis for comparison. There are a lot of underlying assumptions to this method, and that entails a lot of uncertainty. It would be a much better approach if the SINTEF report was more up to date. The author is therefore unsure if this is a reliable and good method for establishing a risk acceptance criterion for SC bridges.

Knowledge from other applications

When it comes to safety, the NPRA definitely has something to learn from other industries, like the offshore industry, or the Norwegian National Rail Administration (NNRA), as well as from risk analyzes performed on road tunnels. In an article by Gudmestad and Emesum (2013) at the University of Stavanger the design basis for SC bridges are discussed. They relate the safety of a SC bridge to the offshore industry. They recommend that the construction and maintenance workers should be protected as well as the workers in the offshore industry. The FAR level for these workers should be equal to five, which means that there will be five fatalities for every $1 \cdot 10^8$ hours worked on the project. For the average person using the bridge they recommend a FAR level of 1-2, but this does not make much sense since the FAR level is based on 10^8 working hours. The FAR level is only a valuable measure for people who work on the bridge. According to Gudmestad and Emesum (2013), an average person using the bridge should be protected at the same level as new roads where the roadways are divided by barriers. However, the NPRA should always strive towards zero fatalities regardless of the FAR level. These recommendations can be combined with the MEM principle. In the offshore industry a third person (people not directly involved in the activities) is not as vulnerable as they would be at the SC bridges. If an offshore installation collapses it would not lead to many consequences for other people than those who work there. If a SC bridge (and bridges in general) collapses it may affect people on ships and on land. It is therefore important that the safety of third persons related to the SC bridges are safeguarded and not forgotten.

The NNRA has a much longer tradition for risk assessment than the NPRA. The NNRA has a safety manual (JBV, 2013) that describes their practices regarding safety management. The NNRA and the NPRA are both in the transportation and communication sector, which might make it beneficial for the NPRA to learn from the NNRA. The safety manual divides the risk acceptance criteria into three different categories that has to be fulfilled at all times: societal risk, individual risk and the ALARP principle.

1. **Societal risk:** The maximum total risk the NNRA accepts every year. They accept a maximum of 11 fatalities per year for the railway network
2. **Individual risk:** To ensure that individuals are not exposed to disproportionate risks. Divided into two categories, one for people hired at the NNRA and one for passengers and third persons:
   - For hired personnel: FAR < 12.5
   - For passengers and third persons: Probability of death per year should be $1 \cdot 10^{-4}$
3. **ALARP:** When the risk is not considered unacceptable the ALARP principle should be applied. Risk reducing measures are desirable unless the costs are significantly higher than the benefits.

The tradition for risk assessment for road tunnels is much stronger than for any other road structures in Norway. The Wienche et al. (2007) guideline presents how to do a risk assessment for a road tunnel. It is argued that this procedure is not good enough to ensure the safety of road tunnels, but it is definitely better than the existing procedures for concrete road structures mentioned earlier. The NPRA can definitely learn something from these assessments, and it is therefore worth mentioning the criteria that have been applied for those applications. The results from the risk analysis of tunnels will usually present the difference in number of fatalities and severely injured for the different tunnel solutions. Selection of a final solution may then be based on four different criteria (Wienche et al., 2007):

1. **Change in risk:** An evaluation of how much risk reducing effect and what risk reducing effect the different alternatives have compared to the "zero fatalities" alternative (the zero vision). The safest alternative or the most effective measure is usually chosen, typically

reduction in the number of fatalities or severely injured.

2. **Cost-effectiveness:** In the cost-effectiveness analysis the expected cost in Norwegian kroner per expected lives saved or severely injured is calculated as a result of the choice of solution or implementation of measures. The most cost effective solution or measure is selected.
3. **Limit Cost = marginal utility:** This principle can be used to assess how much to invest in risk reduction. The marginal utility can be measured in the statistical value of a life lost or severely injured. One will then invest in security until the cost is equal to or exceeds the value of one life and/or severely injured.
4. **Cost-benefit analysis:** In a complete cost-benefit analysis all the effects of a measure in Norwegian kroner are valued. The value of the Norwegian krone is then used to measure the importance of the various consequences against each other. If the estimated expected value of all the consequences of a measure is positive, the measure is economically profitable.

These criteria can be an inspiration to the NPRA. They should not copy them, but they could be used as an indication. The FAR level for hired personnel is, according to the author, a little too high. The FAR level from the offshore industry would be a much better alternative. It is clear that none of the applications of risk acceptance criteria mentioned in this section is a perfect match for the NPRA. There are many applications to learn from, and the ideal approach would be to pull out the most suitable factors from all applications and make their own criteria customized to their scope. This is explored a little further in the subsection below.

5.2.1 Recommendation

A clear recommendation for establishing risk acceptance criteria for SC bridges is not presented in this thesis. This is because establishing a risk acceptance criterion is a question of value and must therefore be discussed and incorporated within the NPRA. The author is rather offering valuable input that can be used in such a discussion. The process of establishing a criteria can be compared to a "build-your-own" concept, where the NPRA have to pick the pieces they find useful from other applications and put those pieces together to form their own customized criteria. As a basis the NPRA should use the GAMAB principle. They have clearly stated that the SC bridges should be as safe as regular roads, which the GAMAB principle represents. The problem is how to compare regular roads with SC bridges. There is need for a quantitative value that represents the limit for acceptable risk on regular roads, as a reference road. This value can be an indicator of whether the SC bridge is safe enough. However this would, according to the author, not be enough. There should be more criteria in place to ensure the safety of these bridges. ALARP is a principle that should be an underlying factor in a company's risk strategy, like it is in the NNRA. Applying ALARP (alternatively ALARA) in the "background" will help the NPRA strive towards the zero vision. The author strongly believes that the NPRA could learn a lot from the offshore industry, the NNRA and from road tunnel experience. Many of the SC bridge concepts are based on technology used offshore, and since they have long and reliable traditions with risk it would be natural to adapt some of their experiences. Some of the safety requirements for the offshore industry might be too conservative for SC bridges, but in the authors opinion it might be better to be a little too safe. However, it is important to discuss the relevance of the experience from the offshore industry. According to Aven et al. (2003), the transportation sector should be careful to apply the thinking that has been used in the oil industry. Aven et al. (2003) is not sure if the experience from the oil industry is appropriate for the NPRA. It can be argued that the NNRA and road tunnel experience are a better fit since they are more closely related to the NPRA, as they are both in the transportation sector. In addition they have a lot of the same priorities regarding risk (like risk of third persons), which will make it easier to adapt their experience to the NPRA. The author believes that the NPRA could benefit if they tried to combine the experience from the offshore industry, the NNRA and road tunnels. A preliminary recommendation (from the author) is to combine GAMAB, ALARP and the knowledge from the offshore industry, the NNRA and road tunnels to establish a solid risk acceptance criterion for SC bridges.

It is important to remember that a risk acceptance criterion will never be able to make a structure safe from all kinds of hazardous events. There will always be some events that we cannot predict, and that the risk acceptance criterion will not offer protection from. If risk is considered a product of two uncertain factors, like the probability of the occurrence of a scenario (P) and the consequences of that scenario (C), the risk will be subjected to uncertainty. An alternative solution that has a high P and a low C can have the same risk as an alternative solution that has a low P and a high C, which are not necessarily comparable (Lair et al., 2004). This is some of the problems that may arise with risk, and risk acceptance criteria. It will always be some uncertainty when it comes to risk, it just depends on how much we tolerate and how we relate to it. To be able to know how much we tolerate, it can be a good idea to try and present the possible uncertainties in a table to get an overview. A table like Table 2.2 could be a good starting point for exploring the potential uncertainties of SC bridges.

Chapter 6

Approach to risk assessment of SC bridges

In chapter 3 the plan processes at the NPRA (Figure 3.4) were introduced. In reply to the unclear structure regarding risk analysis, the author has made a simplified figure (Figure 6.1). This figure illustrates where a risk analysis should be executed in different stages of the project. In the pre-concept stage a risk analysis should be performed to distinguish between all the different concepts. A new and little more detailed risk analysis should be performed in stage two to choose the best concept. In stage three an even more detailed risk analysis should be done to finalize the design. Then a thorough quantitative risk analysis should be done in stage four to ensure the feasibility of the concept. Stage three and four can be combined to make a simpler process model. The point of this figure is to show that for every stage in the project, up until the building phase, the risk analysis needs to be increasingly more detailed and correct. This should be done to be sure that the end product is safe and meet the risk acceptance criteria. In the building phase it is important to do quality control to make sure the construction meets the acceptable risk level determined in the risk analyzes. In the operational phase it is necessary to perform regular tests and do maintenance to make sure the bridge is safe. It is essential to monitor and update the assumptions and barriers determined at the beginning of the project.

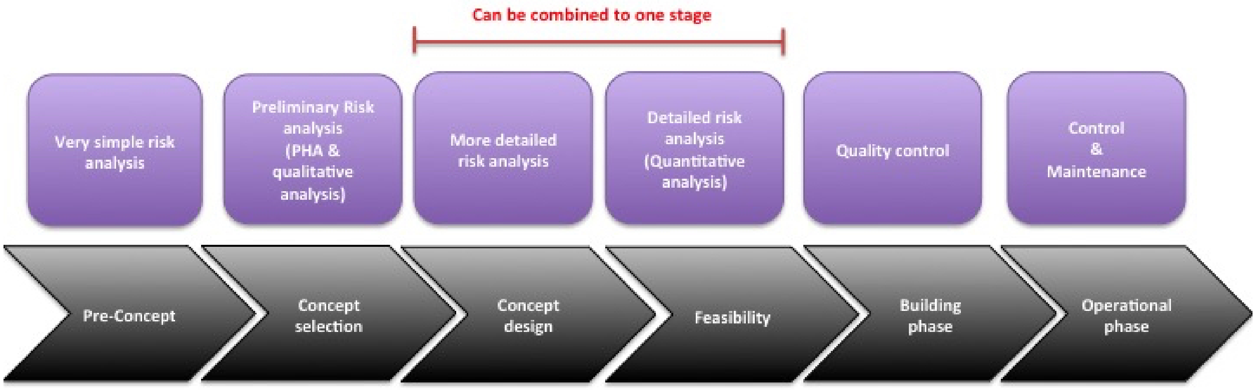


Figure 6.1: A suggestion to the structure of plan processes

This thesis focuses on the early stages of the project. The approach suggested in this chapter is meant to help choose between the three concepts in an early stage for all the different fjords. A more detailed, and thorough quantitative risk analysis will be needed after this stage, which is not done in this thesis. There will in other words be a simple approach, with no need for quantitative data, to help find the best concept for the different fjords.

6.1 Overarching approach for the three concepts

This approach is based on the NPRA's existing procedure. The existing procedure is a good starting point, but it is a little vague. Here, the old procedure at the NPRA is taken a small step further by making it more structured and strict, with some inspiration from other existing procedures like Lair et al. (2004) and NORSOK Z-013 (2010). However, the real challenge with the risk assessment approach for the SC bridges is to establish risk acceptance criteria, as discussed in chapter 5. The main focus of this approach is to identify all possible hazards, and establish risk acceptance criteria that will ensure safety for both humans and the environment. A proposed approach to risk assessment for SC bridges is illustrated in Figure 6.2.

The new approach has five steps, just like the old one, but the content of these steps have changed a little. The only step that has not changed at all is step one. Step two has been rephrased to make it more specific. This step is now more or less self-explanatory, it clearly

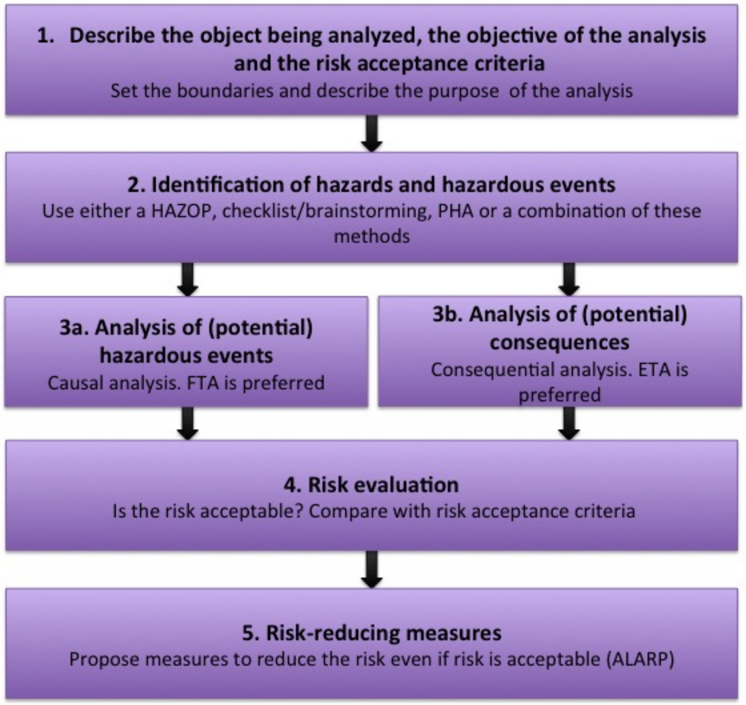


Figure 6.2: Suggested approach to risk assessment for SC bridges

states which methods should be used to identify the hazards and the hazardous events. Step three has been divided into two sub-steps. In the old procedure this step was meant for evaluating risk, but it did not say anything about how it should be evaluated. In the new approach, it is clearly stated that in this step an analysis of hazardous events and an analysis of consequences should be performed. It is also stated which analysis methods should be used for both of them. In chapter 3 it was stated that the risk procedure by Lair et al. (2004) did not give an answer to what methods should be used in the risk assessment. This new approach answers this question by suggesting specific methods for the steps where an analysis should be carried out. The risk evaluation in the new approach is moved down to step four. It is easier to evaluate the risk if causal and consequential analyzes are done first. In this step risk acceptance criteria is introduced. This is mentioned in other standards, like NORSOK Z-013 (2010), but it is not mentioned anywhere in the existing procedure by the NPRA. In this step the results from all analyzes performed should be compared to a risk acceptance criterion. One underlying assumption of this approach is that a solid and safe risk acceptance criterion is established for SC bridges beforehand. In step five risk-reducing measures should be suggested, which is the same as step four in the existing procedure. The only difference is that in the new approach risk-reducing measures should be suggested based on the ALARP principle. In the last step in the existing procedure, the complete risk analysis should be documented. This has not been included in the new approach because it should be a known fact that a risk analysis should be documented.

This is a general approach that can be used in all the different stages of a project. For the early stages it is important to thoroughly identify hazards and hazardous events. It is not necessary for causal and consequential analysis to be as detailed in the early stages of the project, but these analyzes should be performed early to understand the causal relationships and possible consequences of the hazards. For the later stages, when a more detailed risk analysis is required, quantitative analysis should be done for step 3a and 3b. In step 3a and 3b causal and consequential analysis should be performed for the most critical hazards and hazardous events found in step 2. This means that it is not necessary to make a fault tree for all the different hazardous events, just the most critical ones. The same goes for the construction of event trees when analyzing the consequences of potential hazardous events.

This approach can in general be used for all the three SC concepts. The most significant difference between these concepts will be some of the hazards. Many of the hazards will be the same for the various concepts, but the consequences will be different. An example is that a suspension bridge in one span will be more sensitive to wind than a suspension bridge with several spans of pontoons. It is important that the characteristics of each concept are clearly defined when performing a risk analysis to ensure that all the potential hazards get identified. This approach will work for all the three concepts, but it is essential that the approach is adjusted to complement the characteristics of each concept.

6.2 Case study: Halsafjorden

The author has chosen to do a case study of a submerged floating tunnel (SFT) crossing Halsafjorden. The reason for this is because Halsafjorden is considered to be the easiest fjord to cross, which makes the fjord ideal for testing out a SFT for the first time. In addition, the author thinks the SFT concept is the most exciting concept, and would therefore like to explore it a little further. In the fall of 2014 the author did a project in the course TPK5160 where a risk analysis of an underwater tunnel was performed. This case study is partly inspired by that project since an underwater tunnel has a lot of the same characteristics as a SFT. The steps in the new approach suggested above have been followed as closely as possible for this case study. Step four and five are limited to a brief discussion in this case study since the risk acceptance criteria is not clearly established because the project is in such an early stage.

Step 1: System description

The object being analyzed is a submerged floating tunnel (SFT) crossing Halsafjorden. The system analyzed contains the whole tunnel in it self. The SFT analyzed is anchored to the mountain at each end, and anchored to floating pontoons at the surface, as illustrated in Figure 2.9. The system boundaries are determined with inspiration from Amundsen and Engebretsen (2008). The boundary is set to 50 meters before both entries to the tunnel; in addition the environment (the fjord and the landscape) within a 50-meter radius of the tunnel is included. The analysis looks at the system in normal operating condition, and omits the planning, construction and decommissioning phase, as well as maintenance. The purpose of this analysis is to identify hazards and hazardous events, and analyze the causes and consequences of the most critical events.

Step 2: Identification of hazards and hazardous events

When identifying hazards and hazardous events for the SFT, checklist/brainstorming and PHA are the methods used. The checklist/brainstorming for the SFT is done in subsection 4.3.2, and the identified hazardous events are found in subsection 4.3.3. The checklist/brainstorming results have been put into a PHA, which can be found in Appendix B. The data in the PHA are assumptions based on a variety of reports, like Hokstad et al. (2012), LMG Marin (2012), Gamborg Hansen et al. (2012a) and Gamborg Hansen et al. (2012b). The author has chosen to round up the numbers when in doubt, so the PHA illustrates the worst possible scenarios. The frequency and consequence categories used in the PHA are based on Hokstad et al. (2012). The consequence categories in Hokstad et al. (2012) are formulated as consequences with harm to humans, but with some small modifications by the author this categorization can now be used for both humans and the structure. The frequency categories are given in Table 6.1, while the consequence categories are given in Table 6.2.

Table 6.1: Frequency categories (adapted from Hokstad et al. (2012))

1. Extremely rare	2. Very rare	3. Seldom	4. Frequent	5. Very Frequent
Rarer than once every 1000 years	Once every 101-1000 years	Once every 11-100 years	Once every 2-10 years	At least once per year

Table 6.2: Consequence categories (adapted from Hokstad et al. (2012))

1. LL	2. L	3. M	4. H	5. HH
Slightly injured	Severely injured	1-4 fatalities	5-20 fatalities	Over 20 fatalities
Minor damage	Major damage	Severe damage, 1-4 months of unavailability	Partial collapse, 5-20 months downtime	Total collapse, over 20 months downtime

If the PHA result is put into an ALARP based risk matrix (as in Hokstad et al. (2012)) with the above frequency and consequence categories, the most critical hazardous events would be fire, traffic accidents and ship collisions (orange and red zone in the matrix). The author has chosen to base this matrix on the report by Hokstad et al. (2012) to give an example on how it could be done. Whether or not this is the right way to categorize a risk matrix for SC bridges is debatable. The risk matrix is found in Appendix B. The hazard identification process with the checklist and PHA shows that a lot of the hazards can depend on one another. An example could be that movements in the bridge due to currents or swells can lead to difficult driving conditions, which again can be the cause of car accidents. This can be seen as common cause failures or cascading failures, which means that if one hazardous event occur it can cause other hazardous events.

Step 3a: Analysis of hazardous events

In this step a casual analysis should be performed on the most critical events from the risk matrix. This should be done for all the critical events, in this case that would be all the events in the red zone because that is the unacceptable region. In this case study the orange zone of the ALRAP zone is also included. The author has chosen to limit the analysis to only one critical event in this case study. For a full and thorough risk analysis, a casual analysis should be done for all the critical events. The critical event exemplified with a casual analysis in this step is traffic accidents, more specifically rear-end collisions. The author has chosen this critical event because according to Ringen and Sperrevik (2013) 42% of traffic accidents in Norwegian road tunnels are rear-ended collisions. In addition, analyzes of ship collisions have been explored pretty well already in Gamborg Hansen et al. (2012a) and Gamborg Hansen et al. (2012b). In this casual analysis a fault tree have been used to illustrate (no data) the possible causes of a rear-end collision. The fault tree can be found in Appendix C.

Step 3b: Analysis of consequences

In this step a consequential analysis should be performed on all the critical events analyzed in step 3a. Since this case study is limited to only analyzing one critical event, the consequential analysis will only analyze the consequences of a rear-end collision. The consequences will be analyzed with an event tree. In this analysis relevant data for regular underwater road tunnels are used because they have the most resemblance to SFT. The data and assumptions for the analysis are given in Table 6.3 and Table 6.4.

Table 6.3: Data table

What	**Value**	**Reference**
Number of accidents in the period 2005-2012 in Norwegian road tunnels	1549	Ringen and Sperrevik (2013)
Percentage of accidents resulting from rear-end collisions	42%	Ringen and Sperrevik (2013)
Percentage of underwater tunnels in Norway	3%	RHA (2012)
Percentage of heavy vehicles on Norwegian roads	10%	Wienche et al. (2007)
Percentage of heavy vehicles carrying dangerous goods	3%	Madslien et al. (2013)

Table 6.4: List of assumptions

- 70% chance of hitting the tunnel wall or oncoming traffic when experiencing a rear-end collision
- 60% of the underwater tunnels in Norway have a speed limit of 70 km/h or higher
- 90% of the underwater tunnels in Norway have a speed limit of 50 km/h or higher
- A collision at high velocity, will hurt more than at low velocity
- Being hit by a vehicle heavier than 3.5 tons will hurt more than being hit by a regular passenger car
- The percentage of heavy vehicles is equal to the percentage of vehicles over 3.5 tons
- The consequences depend only on the velocity, the size of the car that hits the rear-end of a car, and if the car that gets hit collide into the tunnel wall/oncoming cars
- Only look at the car being hit, not events that follow from this

From this data the frequency of rear-end collisions in underwater tunnels per year can be estimated as shown in equation 6.1.

$$\text{Rear end accidents} = \frac{1549}{8} \cdot 42\% \cdot 3\% = \underline{\mathbf{2.44\ \ per\ year}} \tag{6.1}$$

This analysis is based on a lot of assumptions, which will lead to a lot of uncertainty. The intention of this analysis is to provide an illustrative example to show how it can be done. For a more thorough risk analysis more reliable data and less assumptions should be provided. The event tree constructed from the data in Table 6.3 and Table 6.4 can be found in Appendix D. From this tree it is possible to calculate the probability that a person will die from a rear-end collision. With this probability it is possible to calculate the frequency of fatalities as a result of rear-end collisions. The tree also explores the possibility of numerous fatalities if the vehicle hitting the rear-end is 3.5 tons and carrying dangerous goods. This should however be further developed with a separate event tree for fires as a result of a rear-end collision, which is not done in this thesis.

Step 4: Risk evaluation

The acceptance criteria for SC bridges must be incorporated into the NRPA and discussed based on the points suggested in section 5.2. This is why the author has chosen to use the traditional risk matrix in this case study. The matrix is not a full-worthy risk acceptance criteria and it does not address a lot of the fundamental issues. However, it is a good starting point for an initial screening. Risk acceptance criteria for SC bridges should not have a strict interpretation of either being acceptable or unacceptable, but rather be a starting point for ALARP considerations. In the red and orange zone there is a need for much stronger arguments for rejecting a risk reducing measure in relation to cost. This is how the zero vision can be somewhat implemented with the use of ALARP. Alternatively the ALARA principle may be used, to ensure that all the events below the unacceptable limit will always strive towards zero risk. This might in fact be a better principle to use if the zero vision should be upheld.

There is often a conflict between safety and availability when doing a risk analysis. This is exemplified in the PHA and fault tree by a potential traffic accident caused by accelerations and deformations. This risk could be reduced in several ways, like operational restrictions that says that the bridge must be closed under difficult conditions. This will create lower risk but at the same time a lower availability. An alternative would be to introduce design changes (make construction more robust), but this would cost money and it may also have side effects. In the context of ALARP it can be evaluated qualitatively, or both safety and availability can be converted to a value in money. The main point is that it is important to see everything as a whole, which this new approach is meant to help doing.

The results from the event tree can be used to find the frequency of each of the consequence categories. In this case it would be the most interesting to look at the frequency of "numerous fatalities" (NF). The total frequency of NF in this event tree is the sum of all frequencies of the events that could lead to numerous fatalities. This total frequency should be compared to a risk acceptance criterion to see if the total frequency of events that can lead to numerous fatalities is acceptable. For a thorough risk analysis there could be more than one event tree. The total frequency of NF consequential events can be found by adding together all the frequencies of the events leading to numerous fatalities from all the different event trees.

In Hokstad et al. (2012) the results from the analysis is compared to a refrence tunnel, and this is how it is determined if risk is acceptable or not. This is not a bad approach, but the question is, is it enough? Another question is how to define a reference tunnel. What would be considered a standard and safe tunnel? For simplicity, the author concludes that in this case study the hazardous events in the red and orange zone of the risk matrix are not acceptable and risk-reducing measures need to be taken.

Step 5: Risk-reducing measures

The conclusion in step 4 require that risk-reducing measures will be made for the hazardous events in the red and orange zone of the risk matrix. Some risk reducing measures are already proposed in the PHA in Appendix B, but to summarize the most relevant measures for the critical events is discussed in Table 6.5.

Table 6.5: Risk-reducing measures for the critical events

Measure	**Effect**
ITV surveillance	Can provide a quick overview of an accident situation and alert emergency services. If a fire occurs, ventilation can be increased to reduce dangerous smoke.
Queue alert	Can prevent the spread of fumes if a fire starts in a car. Can prevent rear-end collisions.
Speed cameras/controls	The speed limit may be adhered, and this can reduce accidents caused by speeding
Submersible center dividers	Can prevent front collisions (and collisions in general). It must be possible to raise them if an accident occurs so traffic can pass
Emergency shelter room	Motorists and passengers can stay there until evacuated. May have sluices at the entrance to remove fumes
Climbing lanes	Vehicles can pass slow and heavy vehicles safely. It can also let vehicles steer safely away from potential obstructions in the road
VTS coverage in the area	One might expect that a VTS system will reduce the ship collision rate by 60% (Gamborg Hansen et al., 2012b)
Changeable signs	Can prevent accidents by lowering the speed limit when there is a lot of traffic. Can be used to notify that the tunnel is closed if an accident or a fire occurs to prevent more cars driving into the tunnel

Chapter 7

Summary and Recommendations for Further Work

7.1 Summary and Conclusions

This master thesis has looked into risk assessment of strait crossing (SC) bridges for the NPRA. Since it is important that SC bridges are safe for users and the environment, a thorough risk assessment is required. Five objectives were stated in section 1.2, and all of them have been answered to the author's best ability.

The first objective of this thesis was to define and clarify the concepts relating to SC bridges. In chapter 2, the SC project on coastal highway E39 is presented and discussed. The SC bridges they want to build will eliminate the ferry connections along this highway. This chapter meant to clarify the SC concepts and solutions.

The second objective was to carry out and document a brief literature survey related to risk assessment of existing concrete structures. Chapter 3 presented some general theories about risk assessment. Today's practice at the NPRA was presented and compared with other applications, like Wienche et al. (2007) and Lair et al. (2004). The chapter concluded that the NPRA's existing procedure is not good enough for SC bridges. There is a need for a more structured and thorough approach to better implement a tradition for risk assessment at the NPRA, in addition to ensuring the safety of SC bridges.

The third objective was to identify the hazards related to SC bridges. In chapter 4, key concepts associated with hazards, and methods to detect and classify hazards were introduced. What kinds of methods are best suited for identifying hazards for SC bridges were discussed. Checklist/brainstorming and a PHA are used in this thesis to identify the hazards and the hazardous events. The hazards have been divided into hazards related to location/environment, and hazards related to the different constructions. The three concepts have many hazards in common, but there are also some differences in regards to consequences. The lists of identified hazards are found in chapter 4.

The fourth objective was to suggest possible risk metrics and risk acceptance criteria for SC bridges. Knowledge about risk metrics and risk acceptance criteria was presented in chapter 5. It was discussed how to best establish a risk acceptance criteria for SC bridges. A clear recommendation was not given because a risk acceptance criterion is a question of value and should be discussed and incorporated into the NPRA. However, a preliminary recommendation was given in addition to a list of valuable inputs that can be used in such a discussion at the NPRA. One preliminary conclusion was that the NPRA should learn from other applications, but be careful not to copy directly. This discussion is found in chapter 5.

The fifth and last objective was to outline an approach to risk assessment of SC bridges, and exemplify the approach with a case study of Halsafjorden. In chapter 3 the necessity of a new approach to risk assessment for SC concepts was discussed. In chapter 6 it is suggested that the NPRA modify their plan processes to create more awareness and focus on risk assessment. A new general approach to risk assessment for SC bridges was presented. This approach is more detailed and structured than the NPRA's existing procedure, and it should be applicable for all the different concepts. An example of this approach was done with a submerged floating tunnel crossing Halsafjorden. This example is simple because it is in the early stage of the project. A more detailed and thorough risk analysis should be performed at later stages.

7.2 Recommendations for Further Work

When preparing for this master thesis some questions were raised regarding risk assessment of SC bridges. In addition, this master thesis was written within a limited period of time, so some of the findings should be explored further. Based on this some recommendations for further work are listed below.

- It is essential to know the safety barriers of a system when doing a risk assessment. This leads to the question; what are the barriers of a SC bridge? This issue should get some attention, and typical barriers of a SC bridge should be identified and discussed.
- The risk acceptance criteria issue should be explored further to be able to establish a criteria that will ensure the safety of SC bridges from all potential hazards.
- A solid and stable risk strategy needs to be implemented at the NPRA. A process that will lay a solid foundation and be the beginning of a tradition for risk assessment at the NPRA needs to be established.
- Official regulations and standards regarding risk assessment should be updated, or established, to include more details around procedures for concrete structures, like SC bridges. Some requirements to these kinds of bridges should be established in international standards and regulations.

Appendix A

Acronyms

ALARA As Low As Reasonably Achievable

ALARP As Low As Reasonably Practical

ETA Event tree analysis

FAR Fatal Accident Rate

FTA Fault tree analysis

IRPA Individual Risk per Annum

LIRA Localized Individual Risk

NNRA Norwegian National Rail Administration

NPRA Norwegian Public Road Administration

PHA Preliminary Hazard Analysis

PLL Potential Loss of Life

SC Strait crossing

SFT Submerged floating tunnel

Appendix B

PHA and risk matrix for submerged floating tunnel

Table B.1: PHA for submerged floating tunnel crossing Halsafjorden

No	**Hazard/treat**	**Hazardous event**	**Cause (triggering event)**	**Risk**			**Risk reducing measures (Barriers)**	**Consequences (worst case scenario)**	**Comments**
				Freq	Cons	RPN			
1	Sudden change of light	Traffic accident	Blurred vision, panics	3	3	6	Enhance with more natural light	Injuries and fatalities, minor to major damage to the structure	Based on Hokstad et al. (2012)
2a)	Terrorism	Explosion	Bomb, traffic accident	1	5	6	ITV surveillance, emergency shelter room	Fatalities, total collapse	Based on Hokstad et al. (2012)
2b)		Collapse/leakage	Explosion/fire	1	5	6		Fatalities, total collapse	
3	People (human error)	Traffic accident	Speeding, not paying attention, driving too fast/slow, impatience etc.	3	3	6	Queue alert, speed cameras/controls, submersible center dividers	Injuries and fatalities, minor to major damage to the structure	Based on Hokstad et al. (2012)
4a)	Many vehicles at the same time	Traffic accident	Inattentive driving, falling asleep in front of the wheel, driving too fast/slow, driving mistakes (opposite lane)	4	3	7	Submersible center dividers, queue alert, speed cameras/controls, climbing lanes, ITV surveillance, emergency shelter room, changeable signs	Injuries and fatalities, minor to major damage to the structure	Based on Hokstad et al. (2012)
4b)		Brann	Traffic accident	5	3	8		Injuries and fatalities, severe damage to the structure	
4c)		Explosion	Traffic accident	2	4	6		Injuries and fatalities, partial to total collapse of the structure	
4d)		Collapse/leakage	Fire/explosion	1	4	5		Injuries and fatalities, total collapse	
5a)	Heavy vehicles	Traffic accident	Driving too fast/slow, inattentive driving	4	3	7	Submersible center dividers, require more frequent controls of trailers, speed cameras/control, climbing lanes, ITV surveillance, emergency shelter room	Injuries and fatalities, minor to major damage to the structure	Based on Hokstad et al. (2012)
5b)		Fire	Brakes (downhill) and motor (upward) overheats, trailers that do not meet EU requirements, traffic accident, leakage of flammable liquid	5	4	9		Injuries and fatalities, partial to total collapse of the structure	
5c)		Explosion	Traffic accident, fire	2	4	6		Fatalities, partial to total collapse of the structure	
6a)	Leakage from cargo	Fire	Traffic accident, technical failure vehicle	2	4	6	Require more frequent controls of trailers, emergency shelter room	Injuries and fatalities, partial to total collapse of the structure	Based on Hokstad et al. (2012)
6b)		Explosion	Traffic accident, technical failure vehicle	2	4	6		Injuries and fatalities, partial to total collapse of the structure	
7	Ships	Ship collision	Poorly marked, inattentive, narrow passage, barely visible pontoons, driving too fast	3	4	7	ITV surveillance, describing signs, update nautical charts, lower speed limit for ships, VTS coverage in the area	Injuries and fatalities, partial to total collapse of the structure	Based on Gamborg Hansen et al. (2012a) and Gamborg Hansen et al. (2012b)
8	Submarines	Ship collision	Poorly marked, inattentive, difficult to see the structure, driving too fast	2	4	6	ITV surveillance, describing signs, update nautical charts, lower the speed limit for submarines, VTS coverage in the area	Injuries and fatalities, partial to total collapse of the structure	Based on Gamborg Hansen et al. (2012a) and Gamborg Hansen et al. (2012b)
9	Closed space	Traffic accident	Driver gets panic, claustrophobia	3	3	6	Natural light, establish a non claustrophobic environment	Injuries and fatalities, minor to major damage to the structure	Based on Hokstad et al. (2012)
10	Marine growth	Damage to the structure (collapse/leakage)	Structure is under water	3	3	6	Regular maintenance and control, antifouling claddings, polymer coating	Severe damage to the structure	Educated guess by the author
11	Corrosion and carbonization	Damage to the structure (collapse/leakage)	Structure is under water	3	3	6	Regular maintenance and control, cathodic protection, corrosion inhibitors	Severe damage to the structure	Educated guess by the author
12a)	Steep incline	Traffic accident	Driving too fast / slow, bad brakes, undersized brakes and engines, inattentive, technical breakdowns	5	3	8	Make the inclines as flat as possible, require more frequent controls of trailers and cars, ITV surveillance, emergency shelter room	Injuries and fatalities, minor to major damage to the structure	Based on Hokstad et al. (2012)
12b)		Fire	Brakes (downhill) and motor (upward) overheats, traffic accident	5	4	8		Injuries and fatalities, partial to total collapse of the structure	
12c)		Explosion	Traffic accident, fire	2	4	6		Injuries and fatalities, partial to total collapse of the structure	
12d)		Collapse/leakage	Fire, explosion	1	4	5		Injuries and fatalities, partial to total collapse of the structure	
13	Obstructions in the road	Traffic accident	React too slow, inattentive	4	3	7	More frequent controls of the road, climbing lanes, meeting points	Injuries and fatalities, minor to major damage to the structure	Based on Hokstad et al. (2012)
14a)	Current/swells from ocean	Traffic accident	Structure fluctuates, people get scared/panicked	2	3	5	Solid anchors that can withstand the swells/current	Injuries and fatalities, minor to major damage to the structure	Based on LMG Marin (2012)
14b)		Collapse/leakage	Structure fluctuates	2	4	6		Injuries and fatalities, partial to total collapse of the structure	
15	Accelerations / deformation	Traffic accident	Currents, swell, waves	2	3	5	Solid structure that can withstand deformation	Injuries and fatalities, minor to major damage to the structure	Based on LMG Marin (2012)
16a)	Underwater landslides	Traffic accident	Structure fluctuates, people get scared/panicked	2	3	5	Solid anchors that can withstand the swells/current	Injuries and fatalities, minor to major damage to the structure	Based on LMG Marin (2012)
16b)		Collapse/leakage	Structure fluctuates	2	4	6		Injuries and fatalities, partial to total collapse of the structure	

Frequency/ Consequence	1 Extremely rare	2 Very rare	3 Seldom	4 Frequent	5 Very frequent
5 HH	🟨 2a), 2b)	🟧	🟥	🟥	🟥
4 H	🟩 4d), 12d)	🟨 4c), 5c), 6a), 6b), 12c), 16b), 14b)	🟧 7, 8	🟥	🟥 5b), 12b)
3 M	🟩	🟩 14a), 15, 16a)	🟨 1, 3, 9, 10, 11	🟧 4a), 5a), 13	🟥 4b), 12a)
2 L	🟩	🟩	🟩	🟨	🟧
1 LL	🟩	🟩	🟩	🟩	🟨

Figure B.1: Risk matrix for submerged floating tunnel crossing Halsafjorden

Appendix C

Fault tree of submerged floating tunnel

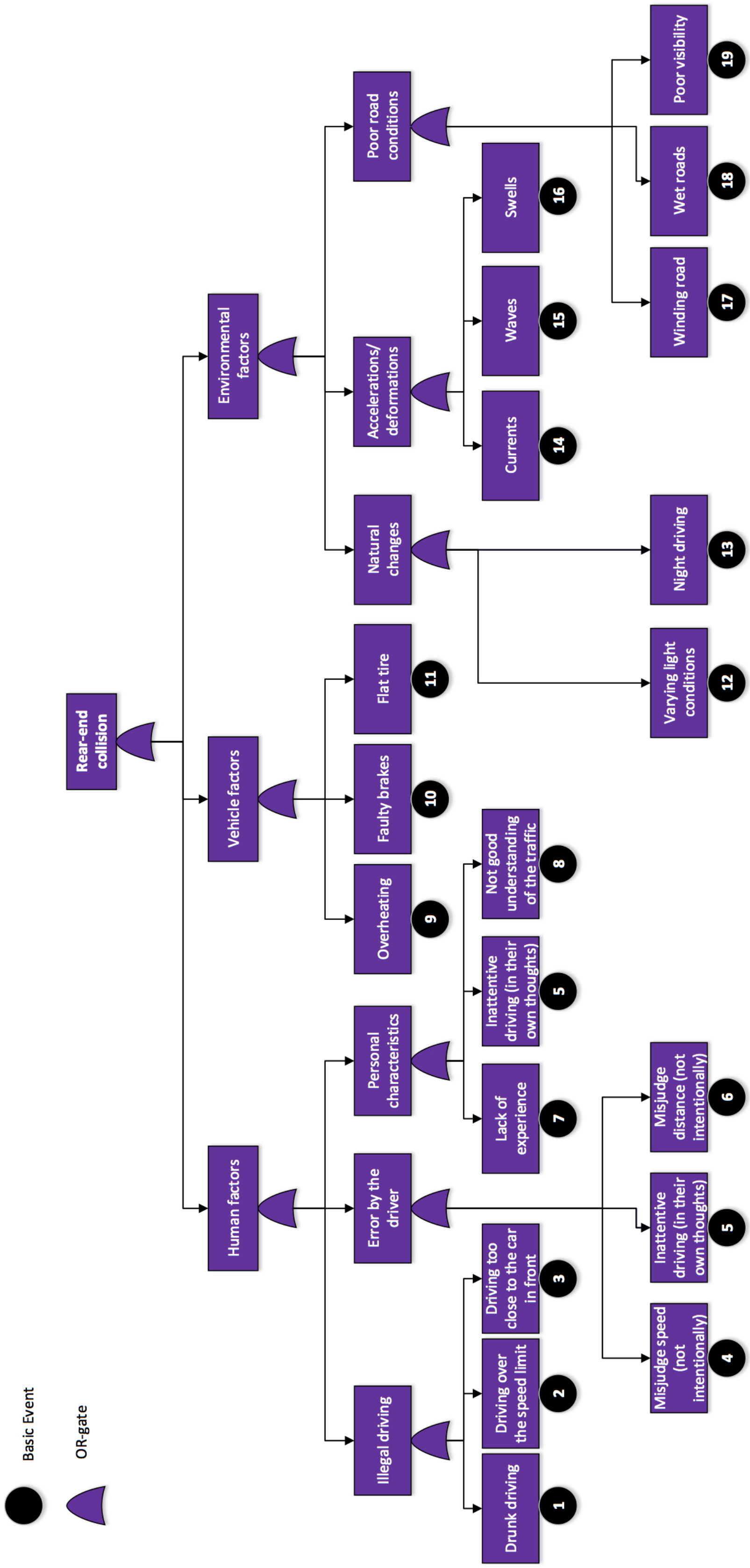


Figure C.1: Fault tree analysis of rear-end collisions

Appendix D

Event tree of submerged floating tunnel

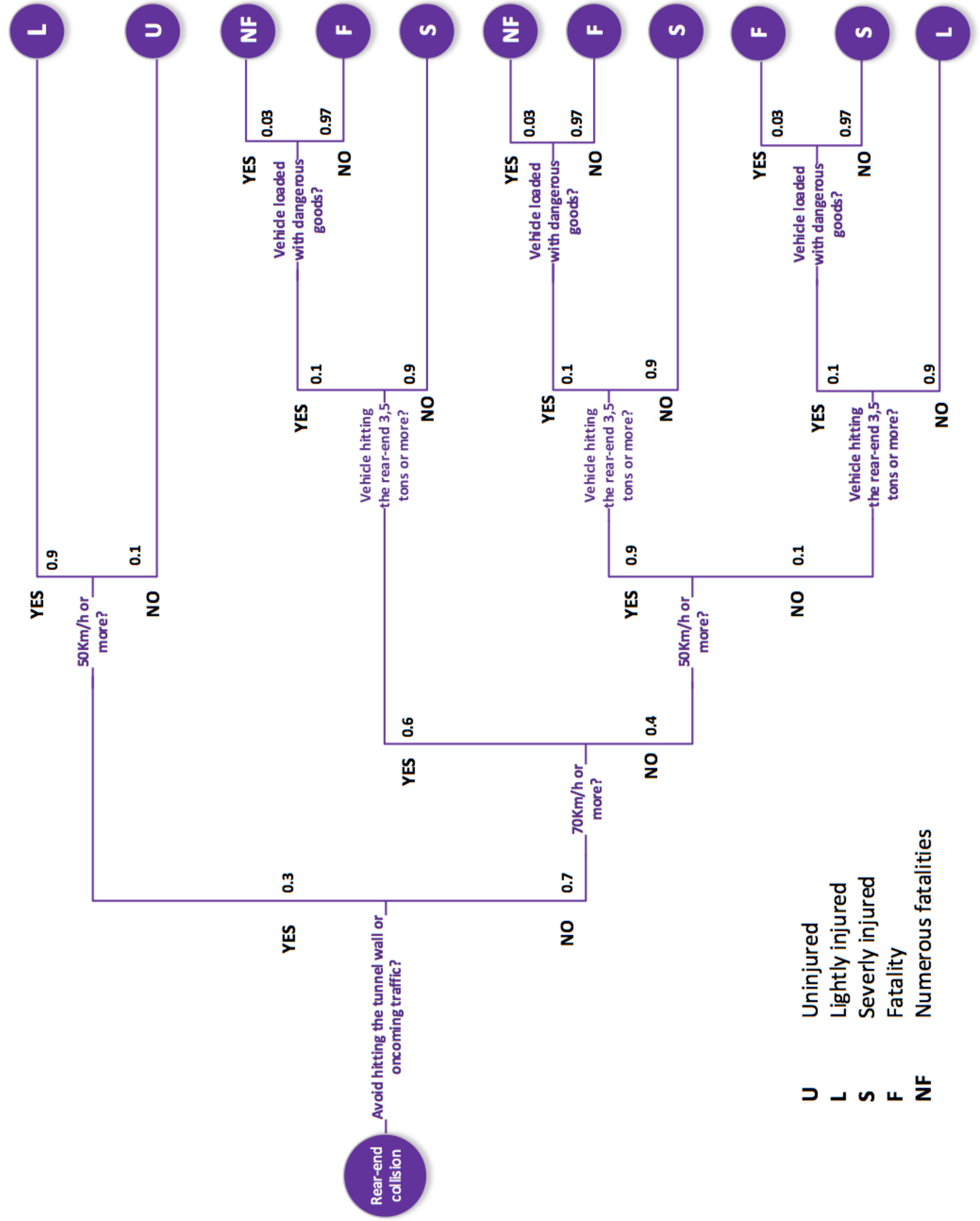


Figure D.1: Event tree analysis of rear-end collisions

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