NTNU

Norwegian University of
Science and Technology

MAINTENANCE STRATEGIES IN CIVIL ENGINEERING

OVERVIEW AND APPLICATION IN “FERRY FREE E39”

Razieh Amiri

Reliability, Availability, Maintainability and Safety (RAMS)
Submission date: June 2016
Supervisor: Anne Barros, IPK

Norwegian University of Science and Technology
Department of Production and Quality Engineering

MAINTENANCE STRATEGIES IN CIVIL ENGINEERING

OVERVIEW AND APPLICATION IN "FERRY FREE E39"

Supervisor: Professor Anne Barros

Author: Razieh Amiri

Department of Production and Quality Engineering

JUNE 2016

Norwegian University of Science and Technology, Trondheim, Norway

PREFACE

This project has been written towards the fulfillment of the Master degree in Reliability, Availability, Maintainability and Safety (RAMS) program in Production and Quality Engineering department at Norwegian University of Science and Technology (NTNU) in spring 2016.

This report is targeted for readers with fundamental knowledge on reliability, maintenance and safety knowledge. It is assumed to have a relative familiarity with concepts such as risk, reliability and maintenance activities.

Trondheim 10.06.2016

Razieh Amiri

ACKNOWLEDGEMENT

I would like to appreciate my dear supervisor, Anne Barros for continuous supervision, supports and valuable comments regarding the project. Her help facilitate me to be able to make this happen.

My sincere thanks to Hai Canh Vu for the valuable help in clarifying the doubts.

I extend my heartfelt thanks to my family for their immense support throughout my Master degree course and also to my boyfriend Sina for his encouragement and motivation.

SUMMARY

This report focuses on the maintenance activities in civil engineering considering the used case "Bjørnafjorden" as a part of "Ferry Free E39" project. Civil engineering is one of the oldest sectors in engineering, and its importance has been increasing in the last decades because of the advancement in modern civilization. Furthermore, maintenance activities have always been an integral part of civil industries. Especially in the large scale projects like "Bjørnafjorden", the role of maintenance will be more crucial and vital due to the fact that even a slight fault in a small component can lead to a loss of millions of money.

Based on this purpose, first classical and Risk-Based Maintenance (RBM) methods are presented as the maintenance strategies that are used in civil engineering. Classical maintenance strategies, which are preventive-policy based, are categorized as on-demand and periodical types. The maintenance intervals used in these strategies are claimed based on the reliability-based method considering the influencing factors on the structures. Furthermore, Risk-Based Maintenance (RBM) method, as another maintenance strategy, assesses the maintenance intervals considering the level of risks in the structures. The risk value in this method can be claimed based on the experts' judgments and condition assessment data.

Further, "Bjørnafjorden" is a part of "Ferry Free E39" project. The unique characteristics of this fjord make this project very huge. SVV (Statens Vegvesen) suggested three concepts as the possible solutions to this project: 1) Floating bridge (FB), 2) suspension bridge supported by tension leg platform (TLP), and 3) submerged floating tunnel bridge (SFTB). In order to assess the maintenance performance in these three concepts, qualitative comparison and sustainability-based methods are presented as the two maintenance strategies that can be used in the new bridge concepts. The main criteria in qualitative comparison methods are introduced as maintainability and maintenance-related risks. Further, in sustainability-based method, the maintenance performance can be analyzed by the sustainability score. The presented strategies can provide SVV with some inputs to make decision and choose an appropriate concept regarding the maintenance.

Key words: Maintenance, Bridge Structures, Risk, Reliability

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchical Process
CF	Consequence Factor
FB	Floating Bridge
FORM	The First Order Reliability Method
IOM	Inspection, Operation and Maintenance
IPN	Inspection Priority Number
LCC	Life Cycle Cost
MMO	Maintenance, Modification and Operation
OF	Occurrence Factor
RAP	Reliability Assessment Panel
RBI	Risk-Based Inspection
RBM	Risk-Based Maintenance
RSM	Response Surface Method
SFTB	Submerged Floating Tunnel Bridge
SORM	The Second Order Reliability Method
SuBETool	Sustainable Build Environment Tool
SVV	Statens Vegvesen
TLP	Suspension Bridge Supported by Tension Leg Platform

TABLE OF CONTENTS

PREFACE I

ACKNOWLEDGEMENT III

SUMMARY V

LIST OF ABBREVIATIONS VII

1 CHAPTER-1 INTRODUCTION 1

1.1 BACKGROUND 1

1.2 SCOPE AND OBJECTIVE 3

1.3 LIMITATIONS 4

1.4 THE REPORT STRUCTURE 4

2 CHAPTER-2 BASIC DEFINITIONS 6

2.1 RELIABILITY 6

2.2 FAILURE 7

2.3 SAFETY 8

2.4 LIMIT STATES 8

2.5 DURABILITY 9

2.6 SERVICEABILITY 9

2.7 MAINTENANCE 10

3 CHAPTER-3 MAINTENANCE METHODS IN BRIDGE STRUCTURES 11

3.1 CLASSICAL MAINTENANCE STRATEGIES 11

3.2 RISK-BASED MAINTENANCE (RBM) METHOD 14
3.2.1 RELIABILITY ASSESSMENT PANEL (RAP) 17
3.2.1 CONDITION ASSESSMENT 18
4 CHAPTER-4 PROPOSED APPROACHES FOR THE PROJECT: FERRY FREE E39 21
4.1 FLOATING BRIDGE (FB) 21
4.1.1 PROPOSED MAINTENANCE STRATEGY 23
4.1.1.1 MOORING/ANCHORS 24
4.1.1.1.1 IOM STRATEGY 24
4.1.1.1.2 EVALUATION OF THE PROPOSED IOM STRATEGY 25
4.1.1.1.3 OPTIMIZATION RECOMMENDATIONS 26
4.1.1.2 CONCRETE 26
4.1.1.2.1 IOM STRATEGY 26
4.1.1.2.2 EVALUATION OF THE PROPOSED IOM STRATEGY 27
4.1.1.2.3 OPTIMIZATION RECOMMENDATIONS 28
4.1.1.3 STEEL 28
4.1.1.3.1 IOM STRATEGY 28
4.1.1.3.2 EVALUATION OF THE PROPOSED IOM STRATEGY 34
4.1.1.3.3 OPTIMIZATION RECOMMENDATIONS 34
4.1.2 DISCUSSIONS 35
4.2 SUSPENSION BRIDGE SUPPORTED BY TENSION LEG PLATFORM (TLP) 36
4.2.1 PROPOSED MAINTENANCE STRATEGY 38
4.2.2 DISCUSSIONS 39

4.3 SUBMERGED FLOATING TUNNEL BRIDGE (SFTB) 40

4.3.1 PROPOSED MAINTENANCE STRATEGY 41

4.3.1.1 IOM STRATEGY 42

4.3.1.2 EVALUATION OF THE PROPOSED IOM STRATEGY 45

4.3.1.3 OPTIMIZATION RECOMMENDATIONS 45

4.3.2 DISCUSSIONS 45

5 CHAPTER-5 MAINTENANCE MODELS FOR NEW BRIDGE CONCEPTS 46

5.1 QUALITATIVE COMPARISON METHOD 46

5.1.1 MAINTAINABILITY 46

5.1.2 MAINTENANCE-RELATED RISKS 47

5.2 SUSTAINABILITY-BASED METHOD 49

6 CHAPTER-6 DISCUSSION AND CONCLUSION 57

7 REFERENCES 61

LIST OF FIGURES

Figure 1-1: Overview of the location of the bridge, and specifically Bjørnafjorden (Google Map) 2

Figure 2-1: Possible Realization of the Load and the Strength of an Item (Rausand and Høyland). 7

Figure 3-1: Time-Dependent Bridge Performance as Affected by Defects, Deterioration, and Damage, and Maintenance and Renewal (Aktan, Farhey and Brown). 19

Figure 4-1: Floating Bridge (FB) Design (Canh Vu). 22

Figure 4-2: Illustration of the "Curved Bridge" alternative (two separate bridge girders and two footway/ bicycle tracks) (Pederese, Innebern and Andersen). 22

Figure 4-3: Illustration of the "Strait bridge" alternative (one bridge girder and one footway/bicycle track) (Pederese, Innebern and Andersen). 23

Figure 4-4: Suspension Bridge Supported by Tension Leg Platform (TLP) Design (Canh Vu). 36

Figure 4-5: Suspension Bridge Supported by Tension Leg Platform (TLP) Design (Canh Vu). 37

Figure 4-6: The overview of the main components in TLP concept (Canh Vu). 37

Figure 4-7: Model for safe operation of marine installation showing typical delivery model (NORSOK N-005). 39

Figure 4-8: Submerged Floating Tunnel Bridge (SFTB) Design (Canh Vu). 40

Figure 4-9: An overlook into Submerged Floating Tunnel Bridge (SFTB) Design (Canh Vu). 40

Figure 4-10: Concept cross section of SFTB and relevant elements for operation and maintenance (Ludescher and Pederesen). 41

Figure 4-11: Scheme for development of inspection plan (Ludescher and Pederesen). 42

Figure 5-1: Correlation between Three Maintenance-Related Risks, Traffic Disturbances, Environment Pollution and People Safety (Canh Vu).. 48

Figure 5-2: Influence of Design Decisions on Life Cycle Impacts and Costs (Kohler and Moffatt). 51

Figure 5-3: Design Stages of a Building (Andrade, Vieira and Bragança). 51

Figure 5-4: Core indicators and additional indicators (Bragança, Vieira and Andrade). 53

LIST OF TABLES

Table 3-1: OF rating 0scale for RBM inspection (NCHRP Report 782). 15

Table 3-2: CF rating scale for RBM inspection (NCHRP Report 782). 15

Table 3-3: Risk matrix for a typical highway bridge (NCHRP Report 782). 16

Table 3-4: Maximum interval inspection categories (NCHRP Report 782). 17

Table 4-1: Summary of the inspection plans for the mooring and anchors elements (Pederese, Innebern and Andersen). 24

Table 4-2: Total estimated operation and maintenance cost for 16 and 20 mooring lines respectively for 100 years service life (Pederese, Innebern and Andersen). 25

Table 4-3: Summary of the inspection plans for the concrete elements (Pederese, Innebern and Andersen). 27

Table 4-4: Survey and material test related to visual inspection (Pederese, Innebern and Andersen). 30

Table 4-5: Inspections (Pederese, Innebern and Andersen). 31

Table 4-6: Initial Maintenance Plan, service life < 100 years (Pederese, Innebern and Andersen). 33

Table 4-7: Main categories of maintenance activities (Ludescher and Pederesen). 44

Table 5-1: Sub-indicators describing environmental impact indicator (Bragança, Vieira and Andrade). 52

Table 5-2: Indicators describing energy impacts (Bragança, Vieira and Andrade). 53

Table 5-3: Indicators describing life cycle costs (Bragança, Vieira and Andrade). 53

Table 5-4: The Correlation between the Priority Levels and Value Criteria (Alwaer and Clements-Croome). 54

Table 5-5: Sustainability values interpretations (Alwaer and Clements-Croome)............... 56

LIST OF EQUATIONS

Equation 2-1: Reliability Function of an Item (Rausand and Høyland). 6

Equation 2-2: Reliability Function of a Bridge/Structure Member (Rausand and Høyland). 6

Equation 2-3: Probability of Failure (Ghosn) 8

Equation 3-1: Inspection Priority Number (NCHRP Report 782). 16

Equation 5-1: Sustainability Score (Larsson). 55

CHAPTER-1 INTRODUCTION

1.1 BACKGROUND

Civil engineering is one of the oldest sectors in engineering. It has always been existing since humans decided to make a roof above. The importance of civil engineering has been increasing in the last decades because of the advancement in modern civilization (What is Civil Engineering?, [http://civil.columbia.edu/what-civil-engineering]).

Maintenance activities, such as repair and breakdown maintenance, have always been an integral part of civil industries. In the current trend, maintenance plays a very important role in many industries like civil engineering (Maintenance in History, [http://www.leanexpertise.com/TPMONLINE/articles_on_total_productive_maintenance/tpm/tpmprocess/maintenanceinhistory.htm]). Especially in the large scale projects, the role of maintenance will be more crucial and vital due to the fact that even a slight fault in a small component can lead to a loss of millions of money.

This report is written concerning the maintenance strategies which can be used in "Ferry Free E39" project. The project includes an action plan to build a Highway bridge crossing many rivers, lakes and fjords including "Bjørnafjorden". The location of the project is in Norway and it will be a connection of Kristiansand, South-Norway to the Mid-Norway, Trondheim, shown in Figure1-1. Hence, this project has some unique characteristics such as 1100 km total length, and some practical difficulties because of the location. This project can be considered as one of the largest scale projects in the world (Coastal Highway Route (Ferjefri)E39, [http://www.vegvesen.no/vegprosjekter/ferjefriE39/English]).

For this purpose, the classical maintenance strategies are first discussed in the report. Then, a greater overview of "Bjørnafjorden" used case from "Ferry Free E39" project is provided. There are some difficulties to cross "Bjørnafjorden" because of its depth and location. Bjørnafjorden is a fjord in Hordaland county in Norway. It runs through the municipalities of Austevoll, Fusa, Os, and Tysnes. The large island of Tysnesøya and many small, surrounding islands such as Reksteren lie along the south side of the Bjørnafjorden and the Bergen Peninsula and the mainland lie along the north and east sides of the fjord. The 30-kilometre fjord is about 10 kilometers wide and its maximum depth is 583-600 meters below sea level (Coastal Highway Route (Ferjefri)E39, [http://www.vegvesen.no/vegprosjekter/ferjefriE39/English]). Figure 1-1 shows the location of this fjord. There are three possible concepts which Statens Vegvesen (SVV), the Norwegian public roads administration, proposed as the possible solutions to this project, Floating bridge (FB), suspension bridge supported by tension leg platform (TLP) and submerged floating tunnel bridge (SFTB). Each are introduced and explained regarding the maintenance strategies and their discussable issues. Then, qualitative comparison and sustainability-based methodologies are presented to assess the maintenance performance for each possible concepts and provide input for SVV to make decision and to choose an appropriate concept regarding the maintenance.

Figure 1-1: Overview of the location of the bridge, and specifically Bjørnafjorden (Google Map)

[https://www.google.no/maps?espv=2&biw=1242&bih=585&q=bj%C3%B8rnafjorden&bav=on.2,or.r_cp.&bvm=bv.124088155,d.bGg&ion=1&sns=1&um=1&ie=UTF-8&sa=X&sqi=2&ved=0ahUKEwjf87ShoJ3NAhUBiiwKHdlPDywQ_AUIBygC]

1.2 SCOPE AND OBJECTIVE

The objective of this project is to present the maintenance strategies that could be used in civil engineering. Besides this, the used case of “Bjørnafjorden”” project will be discussed.

First, the classical strategies, which are used for many structures, are presented. Then, the three possible concepts to cross “Bjørnafjorden” in a bigger project titled, “Ferry Free E39” are given. These concepts were designed by Statens Vegvesen (SVV), the Norwegian public roads administration. Furthermore, two possible methodologies are introduced in order to assess and compare the maintenance performance in the proposed concepts. These methods can be helpful in order to find the most relevant maintenance in the civil industries. In this report, the primary focus is on the bridge structure.

Briefly, the objectives can be mentioned as below:

- Give an introduction about maintenance and its importance in civil engineering
- Describe the basic terms used in this report
- Present classical maintenance strategies used in civil engineering
- Discuss the “Bjørnafjorden” project and the three possible proposed concepts from this project
- Discuss the maintenance strategies in the 3 concepts and propose methodology to lead the discussion
- Provide future perspectives

Therefore, the main objectives of these projects are expected to answer the following three questions:

- ❖ **Question 1:** What are the classical maintenance strategies in civil engineering?
- ❖ **Question 2:** What can be the future maintenance strategies in civil engineering?
- ❖ **Question 3:** Which kind of inputs can be obtained from this report to be used in SVV regarding the “Bjørnafjorden” project?

1.3 LIMITATIONS

In this report, a used case, “Bjørnfjorden”, from the “Ferry Free E39” project, which is still in the planning and pre-design phase will be dealt with. This project is about a highway bridge structure in “Bjørnfjorden” with unique characteristics such as extraordinary length and location. There are three possible concepts for this project which are still under consideration. These concepts are analyzed and assessed from the maintenance perspective in order to find the best. For this purpose, there are two possible maintenance strategies introduced, and there are many questions regarding this project which should be explored.

This project is prone to have uncertainties in its decision making. These uncertainties and lack of data can be considered as few limitations in this report.

1.4 THE REPORT STRUCTURE

This report includes 8 chapters. The 1st chapter provides an outline of the project work, objectives, limitations and the report arrangement. The 2nd chapter consists of the required basic definitions for this report. In the 3rd chapter, the theory and literature works, starting with the maintenance importance in the structures is explained. It is followed by the introduction of classical maintenance strategies and Risk-Based Maintenance (RBM) methods in civil engineering. Chapter 4 includes the literature review of the used case, “Ferry Free E39” concepts and maintenance proposals, provided by SVV. In the 5th chapter, two new methods are proposed to discuss the maintenance strategies. Chapter 6, 7 and 8 explain the discussion, conclusion and references of the report respectively.

To illustrate more in detail:

Chapter 1:

- Role of maintenance in this industry
- Main project objectives, scope and limitation
- Report structure in more detail

Chapter 2:

- Basic required definitions

Chapter 3:

- Literature study about maintenance
- Classical maintenance and Risk-Based Maintenance (RBM) methods, used in the structures

Chapter 4:

- Introduction about the “Ferry Free E39” as the used case in this project
- Three possible concepts of this project and proposed maintenance strategies for them, to be able to analyze the discussable issues

Chapter 5:

- Qualitative comparison and sustainability-based methods as two strategies to assess the maintenance performance in the three “Ferry Free E39” concepts

Chapter 6 and 7:

- Respectively, discussion and conclusion on the discussed issues in the report, besides providing perspectives and references

CHAPTER-2 BASIC DEFINITIONS

2.1 RELIABILITY

For a system, reliability is defined as its ability to perform its required functions throughout the working life while serving the purpose they have been made for. Reliability is normally represented by the probability that the structure can carry out its intended functions without any failure during a specified proportion of time and specified conditions. (Rausand) (EN 1990). Based in the Equation 2-1, reliability is the probability that a component will not fail during the intended time duration (Rausand and Høyland).

$$R(t) = Pr(T \geq t) \qquad (2\text{-}1)$$

- R (t): Reliability function of an item
- T: Time to failure of the member
- t: Specific functioning time
- Pr (T ≥ t): Probability (Pr) or likelihood that the time to failure of the bridge goes above the specific functioning time

In order to use the reliability concept for the structures, structural reliability concept is defined. It is done considering the physical perspectives of the reliability. According to this concept, reliability is the probability that the strength is higher than the load applied (Rausand and Høyland). Equation 2-2 defines the definition of structural reliability.

$$R = Pr(S > L) \qquad (2\text{-}2)$$

- R: Reliability function of a bridge/structure member
- S: Strength of the member
- L: Applies load of the member
- Pr (T ≥ t): Probability (Pr) or likelihood that strength is greater than the load

Reliability is getting more significant while increasing the complexity in the components in most of the industries. This importance is due to the effect that reliability assessment can have on the company's progress. Increasing the reputation due to more reliable structures is one of the main concerns in the industries. Because it can result in more cost-effective structures and lead to a better satisfaction. Therefore, predicting reliability can be an advantage in todays' competitive business world (MIL-HDBK-338B). Therefore, a reliability assessment is necessary to be done as one of the first steps in the design process. Reliability mostly rely on serviceability and durability of the structure (ES ISO 2394: 2012). These two concepts are explained in more detail in the fifth and sixth sections.

2.2 FAILURE

Generally, failure means the state when specific objectives of a component or a system are not met (Rausand and Høyland). From the structural point of view, *"when an element is no longer performing its intended function to carry loads safely and reliably, and also unable to maintain serviceability, it is defined as failure"* (NCHRP Report 782). Structures collapse and fail to work when they carry the load much more than the capacity they were designed to bear. (Rausand and Høyland). Figure 2-1 shows the failure definition based on the structural reliability concept. As it can be seen, failure happens when the applied load would be more than the strength and capacity of the structure.

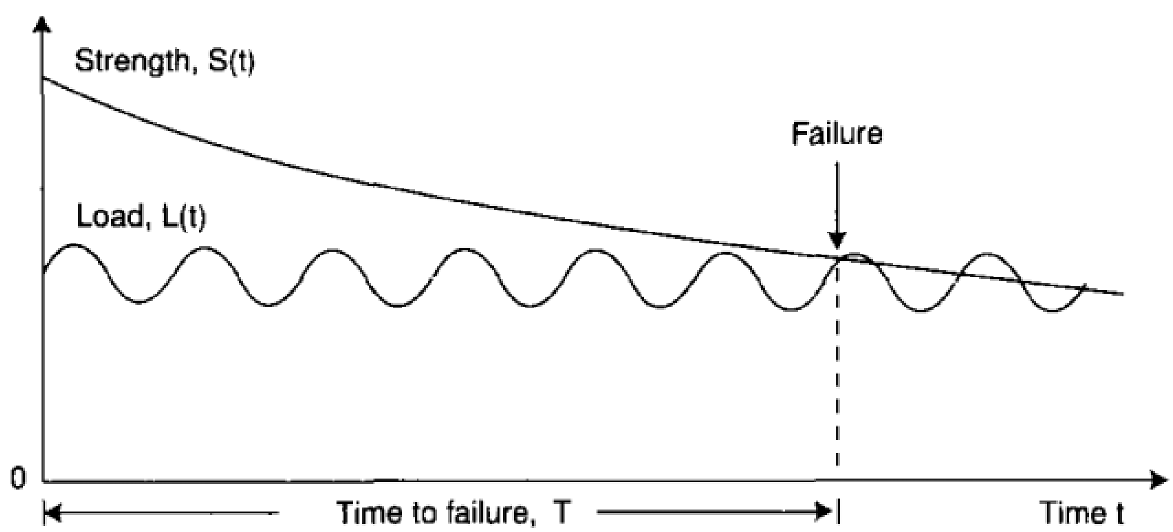

Figure 2-1: Possible Realization of the Load and the Strength of an Item (Rausand and Høyland).

Therefore, it can be possible to define the failure probability as the probability that the applied load would be more than the structure capacity. Based on structural reliability concept, failure can also be represented by the equation 2-3 (Ghosn):

$$Pf = \Phi(-\beta) \tag{2-3}$$

- P_f: Probability of failure
- Φ: Normally distributed cumulative distribution function
- B: Reliability index

As it can be seen in the Equation 2-3, probability of failure can be calculated as the normally distributed cumulative distribution function in terms of reliability index (Ghosn). Reliability index is explained in more detail in section 3.1 named “Typical Maintenance Strategies”.

2.3 SAFETY

In general terms, safety means “the condition of being protected from danger, risk, or injury” (Rausand and Høyland). This is helpful in order to explain safety in the structural reliability framework.

Based on the structural reliability definition, safety is defined as a situation when structure demand is always less than the structure capacity (Rausand and Høyland).

2.4 LIMIT STATES

Limit states is considered as a border line to distinguish between the desired and undesired states of the structure (ES ISO 2394: 2012). Bridge limit states are defined based on the physical definition of reliability. Based on the (ES ISO 2394: 2012), the set of limit states in structures can be explained as two types explained below.

- Ultimate limit states
- Intermediate or serviceability limit state

Ultimate limit states are the states concerning the safety of the structure such as collapse and bridge members' failures.

Intermediate limit states are defined as the serviceability related issues such as vibration, cracking and deflection. Serviceability concepts are defined in more detail in section 2.6.

2.5 DURABILITY

Specific to civil engineering, durability is a condition in which reliability requirements for the structural components have been met. Hence, the whole bridge structure stays fit in its natural condition during the working period provided that proper maintenance has been performed (ES ISO 2394: 2012).

Durability of a structure highly depends on maintenance programs and the structure design. Structure design is important, as it may lead to deterioration that can sometimes remain undetected during maintenance activities (ES ISO 2394: 2012). Based on (ES ISO 2394: 2012), there are factors mentioned which should be considered in the durability concept:

- Intended use
- Performance criteria
- Environmental condition
- Composition, properties and material performance
- Members shape and structural details
- Maintenance during the design

2.6 SERVICEABILITY

Serviceability is one of the two limit states in the structures which are explained in section 2.4. Serviceability shows the structural performance. Based on (ES ISO 2394: 2012), serviceability can be categorized as unacceptable deformation, local damage or excessive vibration.

In (ES ISO 2394: 2012), exceeding a serviceability limit state is considered reversible and can lead to failure in the following cases:

- The first time it is exceeded, if no excess is acceptable.
- The excess value is acceptable but the time in undesired state is longer than specified.
- The excess is acceptable, but the number of times that it is exceeding is larger than specified.
- Combination of the above criteria.

2.7 MAINTENANCE

Maintenance is defined as the entire set of activities performed during the life of the structure in order to enable it to fulfill the requirements for durability. It can be regular inspections, inspections on special occasions (e.g. after the earthquake), up gradation of protection systems or repair of structural elements (ES ISO 2394: 2012).

CHAPTER-3 MAINTENANCE METHODS IN BRIDGE STRUCTURES

Generally, proposing an effective maintenance method is a vital issue in most of the industries like civil engineering. Maintenance in bridge structures is also one of the important issues in the civil engineering (Lepore). A proper maintenance plan can be helpful not only to keep the bridge in good condition throughout its life time, but also to decrease the relative costs in the structures through optimization of resources (Lepore).

In this part, first, the classical and typical methods of maintenance are introduced and explained. Then, in the second part, Risk-Based Maintenance (RBM) method is discussed as another approach for the maintenance planning.

3.1 CLASSICAL MAINTENANCE STRATEGIES

Maintenance methods in bridge structures are mostly based on the preventive policy. The objective of this is to retain the bridge in the maintainable structure by performing predetermined maintenance in prearranged and fixed intervals (Chen and Duan). There are two types of preventive maintenance. It can be on-demand or periodical (cyclic) maintenance (Chen and Duan).

On-demand preventive maintenance or so-called preventive-corrective maintenance is performed when deterioration signs are detected during the routine or maintenance inspections. The purpose of this kind of maintenance is to restore the structure in good condition to compensate the deteriorations caused. In other words, they are mostly needed when the maintenance demands show up. For instance, wearing surface repair, snow and ice removal, electrical or mechanical repairs and sidewalk repairs can be cited as examples (Chen and Duan).

Another type of preventive maintenance is periodical (cyclic). Preventive periodical maintenance is a kind of maintenance which is routinely performed without observing the demand (Chen and Duan). Examples can be bridge washing, bridge painting, structural members painting, bearing lubrication, sweeping, crack sealing and other similar activities. Although, it is worth mentioning that maintenance activities can sometimes fall into both groups depending on the bridge characteristics (Chen and Duan).

There are some factors that influence the arrangement of intervals for this kind of maintenance. Environmental circumstance, bridge structure, bridge location, bridge age and the used components in the bridge can affect the choice of maintenance intervals (Chen and Duan). Structural reliability concept takes these factors into consideration to find the most proper maintenance intervals. This concept is based on the structural reliability theory. It is a quantitative tool to assess the safety in structural systems.

The objective of this method is to find the reliability values and structure lifetime laws in order to propose an optimal maintenance and inspection intervals. This method finds the limit states of the system and different failure modes of components by using four ways described later. In this method, it is possible to find the reliability for the system structure. Structural reliability provides us with the lifetime performance of the structure. As a result, it shows us the proper and efficient time to perform maintenance inspections based on the reliability of the structure.

The first step in structural reliability is to estimate the reliability index value, mentioned in the Equation 2-3 (Probability of failure). This value makes it possible to analyze the whole bridge reliability and to find the bridge design codes by the process calibration of the codes.

Reliability index has an important role in the structural reliability method. The main role of reliability index is to make a balance between costs and risks, to make the perfect safety criteria and also to outline suitable calibration methods and proper cost estimation. This value can be a number between 2 and 4 (Ghosn). The reliability index value increases when the importance of the structure increases. For instance, if it has some extraordinary characteristics, a higher reliability index is considered to consume higher construction costs. Hence, cost-benefit analysis should also be considered in order to find the best target for the reliability index value (Ghosn). There are many ways to calculate the reliability index value. The First Order Reliability Method (FORM), the Second Order Reliability Method (SORM) and many Monte Carlo schemes (Ghosn).

By assessing the reliability of the structure, it will be possible to analyze the reliability. There are four general methods in order to analyze the bridge reliability as a system. Each of the four methods, which are mentioned below, has been discussed shortly in this project.

1. Resistance and Load modeling Method
2. Reliability of bridge structural system Method

3. Response surface Method (RSM)
4. Generic Algorithm

Resistance and Load modeling method focuses to make a balance between the structure resistance and the applied load to the structure through the physical reliability point of view.

In the second method, reliability of bridge structural system, first it is required to analyze and find the dependencies between the members of the structures. The relations between the members can be helpful to model the structure system in order to apply the required calculations. Members' structure can be dependent in series, in parallel or in a combination of both. The dependency comprises of a concept which is named ductility. In mechanical engineering, ductility is generally explained as the ability of solid material to stretch out in a specific tension. This concept is also commonly used in earthquake engineering (Eurocode 8 - Section 6). Ductility is literally defined as "the ability of structure or part to sustain large deformation beyond the yield point without breaking". Ductility level of structure components are an important issue in structural reliability concept, as it helps to realize the effectiveness of the whole system (Eurocode 8 - Section 6). In other word, it is the proportion of maximum displacement to displacement during the first yield. In the series structure, ductility has no influence on the structure reliability. However, in the parallel systems the correlation coefficients rise if the ductile member reliability reduced (Ghosn).

Response surface Method (RSM) is mostly used when it is not so much clear and possible to formulate the reliability equations for the members' structure (Ghosn).

Additionally, Generic algorithm is mostly recommended in the large scale projects in which material and geometric nonlinearities in the structures is considered. Generic algorithm can be used as the best approach to perform structural reliability method in huge projects. (Ghosn).

The good point about the preventive approach is that it enable the managers to have a reasonable estimate about the maintenance inspections. However, it might not be the most efficient method. This method is not be able to sustain throughout the life time of the structure. Therefore, Risk-Based Maintenance (RBM) method is introduced in the next part. By considering the risk level in the structures, RBM can be the supplement method for fulfilment of maintenance objectives.

3.2 RISK-BASED MAINTENANCE (RBM) METHOD

Risk-Based Maintenance (RBM) method of the bridge can provide the maintenance managers with more data about the structure of the bridges. These methods can help to find the most proper maintenance planning.

Risk-Based Maintenance (RBM) in one of the strategies which can help to find the most appropriate maintenance inspection intervals. In RBM, it can be possible to increase or decrease the intervals between the maintenance inspections based on the risk of failures (NCHRP Report 782). In the standard NCHRP, it is proposed as a guideline for RBM inspection in structure of the bridges.

The purpose of proposing this method is to address the best maintenance inspection intervals that fits the failure risk best. This is a qualification method through which it is possible to propose an appropriate inspection. The duration is found using the rate of occurrence of failures and their consequences (NCHRP Report 782). In other words, the RBM objective is to perform maintenance inspections where and when it is needed. Therefore, it can lead to optimization of the resources.

According to (NCHRP Report 782), RBM is defined as planning the maintenance inspection based on the risk levels of the structure.

In RBM method, first, a reliability assessment is required. Reliability assessment relies on the answers of the three important questions based on reliability concept.

1. What can go wrong?
2. How likely is it to happen?
3. What are the possible consequences if it happens?

The purpose of the first question is to find the possible damage modes and the element attributes which are initially needed for the method. The second question reveals the key factors to find the Occurrence Factor (OF) for the RBM method. These factors can be categorized as one of the rates in the Table 3-1 which provides a scale for OF rates.

Table 3-1: OF rating 0scale for RBM inspection (NCHRP Report 782).

Level	Category	Description
1	**Remote**	Remote likelihood of occurrence, unreasonable to expect failure to occur
2	**Low**	Low likelihood of occurrence
3	**Moderate**	Moderate likelihood of occurrence
4	**High**	High likelihood of occurrence

The third question is concerning factor assessment to find the Consequence Factor (CF). CF can be claimed by arranging the possible consequence scenarios, besides expert elicitation. CF rating scales are shown in the Table 3-2.

Table 3-2: CF rating scale for RBM inspection (NCHRP Report 782).

Level	Category	Consequence on safety	Consequence on serviceability	Summary description
1	**Low**	**None**	**Minor**	Minor effect on serviceability, no effect on safety
2	**Moderate**	**Minor**	**Moderate**	Moderate effect on serviceability, minor effect on safety
3	**High**	**Moderate**	**Major**	Major effect on serviceability, moderate effect on safety
4	**Severe**	**Major**	**Major**	Structural collapse/ loss of life

In order to find the answer to all the three questions, it is possible to use the condition assessment data and also a reliability assessment panel (RAP). Both topics are explained in the sections 3.2.1 and 3.2.2.

After answering the three questions, it is possible to find the Inspection Priority Number (IPN) for the inspection scope. IPN can help to find the maximum inspection interval based on the risk matrix shown in the Table 3-3. IPN is defined as the multiplication of occurrence factor (OF) and consequence factor (CF) as shown in Equation 3-1:

$$\mathrm{IPN} = \mathrm{OF} * \mathrm{CF} \tag{3-1}$$

- IPN: Inspection Priority Number calculated for a bridge member
- OF: Occurrence factor for a bridge member
- CF: Consequence factor for a bridge member

Table 3-3: Risk matrix for a typical highway bridge (NCHRP Report 782).

4	III	II	II	I
3	III	III	II	II
2	IV	IV	III	II
1	V	IV	III	III
OF / CF	1	2	3	4

After finding the IPN in the provided risk matrix, from the Table 3-3, the maximum inspection intervals are shown precisely in the scale of month in the Table 3-4.

Table 3-4: Maximum interval inspection categories (NCHRP Report 782).

Category	Maximum Interval
I	12 months or less
II	24 months
III	48 months
IV	72 months
V	96 months

This process should be performed for all the failure modes detected by the RAP, expert elicitation and also condition assessment data. It can be possible to make a matrix as the Table 3-3 including all the members of the structure. It provides a visual overview of the maintenance inspection intervals required for all the structure parts as a whole system.

3.2.1 RELIABILITY ASSESSMENT PANEL (RAP)

Reliability Assessment Panel (RAP) is an important element in RBM method, as it helps to indicate the frequency and consequence of the failures in this method. It can be used in all the steps (NCHRP Report 782, 2014).

According to (NCHRP Report 782, 2014), RAP usually involves six types of specialists, introduced as below:

1. Bridge inspection expert
2. State program manager or bridge management engineer
3. Bridge maintenance engineer
4. Material engineer
5. Independent experts
6. Facilitators

The purpose of this panel is to analyze each component's importance. And also, to differentiate each structure so that the logical qualitative values are chosen based on the expert judgments and experts' knowledge (NCHRP Report 782, 2014).

3.2.1 CONDITION ASSESSMENT

A subjective and precise condition assessment can be very helpful in any structure including highway bridges (Aktan, Farhey and Brown). An accurate look through serviceability, safety and also more cost-effective maintenance and management can be named as the most important results of this method. These results can be used for performing the RBM method for a structure (Aktan, Farhey and Brown).

"Condition assessment means measuring and evaluating the state properties of constructed facility, and relating these to the performance parameters" (Aktan, Farhey and Brown). Defect, deterioration and damage identification would also be done first from global perspectives and also from region and local viewpoints. The desirable life time of a bridge is estimated to be between 75-100 years, and it is expected to perform the service during this expected life time (Aktan, Farhey and Brown).

In condition assessment process, first a list of acceptable limit states would be provided. Then, based on this criteria the present damages would be recognized. After localizing and qualifying these damages, it is possible to assess their possible effects (Aktan, Farhey and Brown). The better results would be achieved if condition assessment would be along with health monitoring and field laboratories (Aktan, Farhey and Brown). The final results of condition assessment help to have a better look into the evaluation of structural reliability and rational management (Aktan, Farhey and Brown).

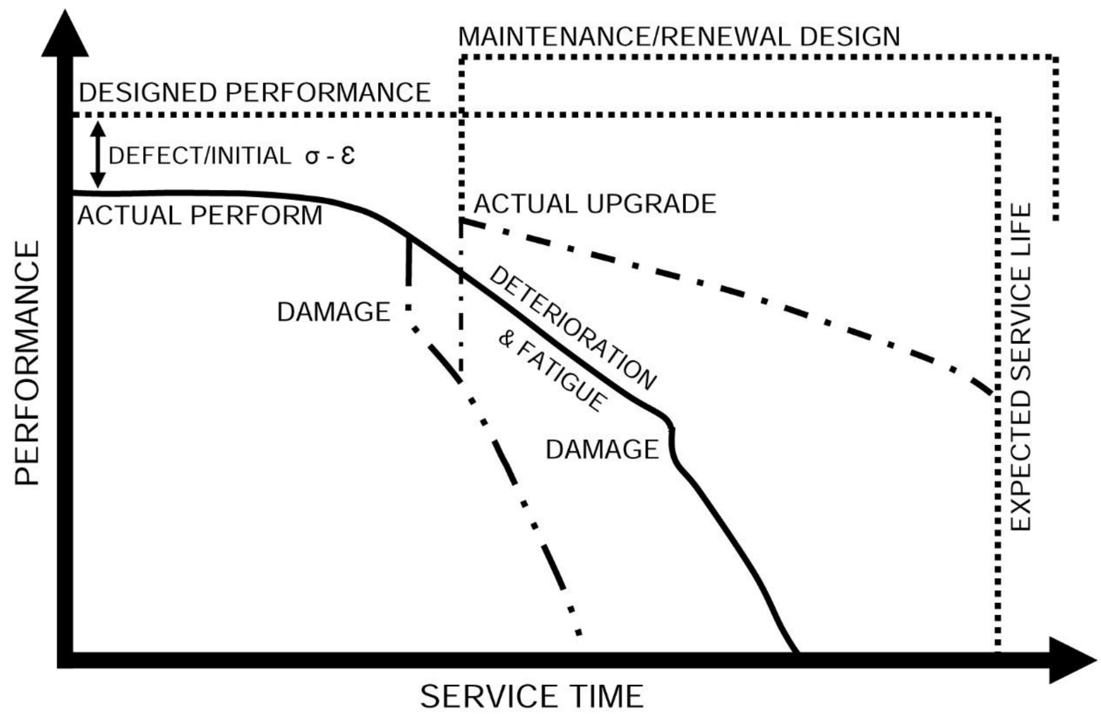

Figure 3-1: Time-Dependent Bridge Performance as Affected by Defects, Deterioration, and Damage, and Maintenance and Renewal (Aktan, Farhey and Brown).

As it can be seen based on the Figure 3-1, this method can be used when the actual performance of the structure begins.

The first thing should be done in this concept is structural-identification in the structure system. Based on the structural-identification, it will be discussed either to go with bridge-type-specific or bridge-specific condition assessment (Aktan, Farhey and Brown). It is required to explain shortly about these two concepts, bridge-type-specific and bridge-specific condition assessment

Bridge-type-specific condition assessment concern assessing the bridge conditions regarding the type of the bridge, the soil material where bridge is placed and mostly about the material type of the bridge (Aktan, Farhey and Brown).

Furthermore, bridge-specific condition assessment is mostly included in the condition assessment of the bridge components excluding its type and material. But mostly regarding the components' mechanism (Aktan, Farhey and Brown).

In condition assessment, destructive testing is the only tool to determine the actual damaged impacts on limit states. It is also reveal the defects, deterioration and damages on the structural capacities and failure modes (Aktan, Farhey and Brown).

This method provides maintenance managers and bridge engineers with a great deal of information about serviceability, safety and defects, deterioration and damages in the structures (Aktan, Farhey and Brown). The results enable them to estimate the maintenance and renewal time, shown in the Figure 3-1. These concepts play important roles in the financial and economic requirements of the structures (Aktan, Farhey and Brown).

CHAPTER-4 PROPOSED APPROACHES FOR THE PROJECT: FERRY FREE E39

"Ferry Free E39"project is a highway bridge project building in Norway with exceptional characteristics. This highway bridge involves an extraordinary total length around 1100 km which crosses over rivers, lakes and fjords (Coastal Highway Route (Ferjefri)E39, [http://www.vegvesen.no/vegprosjekter/ferjefriE39/English]). This bridge connects Trondheim city in Mid-Norway to the city in South Norway, named Kristiansand. "Bjørnafjorden" is a part of "Ferry Free E39" project which has a unique location, length and depth and it is still in the planning stage. Statens Vegvesen (SVV), is the Norwegian public roads administration, which is working on this project. This administration proposed three possible concepts for this project. Floating bridge (FB), suspension bridge supported by tension leg platform (TLP) and submerged floating tunnel bridge (SFTB) are the three main concepts that will be discussed in the following (Coastal Highway Route (Ferjefri)E39, [http://www.vegvesen.no/vegprosjekter/ferjefriE39/English]). SVV analyzes and assesses these concepts and proposed some Inspection, Operation and Maintenance (IOM) strategies for each concept.

This chapter has two main sections based on the three concepts. In each section, first, an overview and the proposed Inspection, Operation and Maintenance (IOM) strategies are presented. Then, the questionable and discussable points are pointed out. This section aims to provide the relevant information made by SVV or relevant companies about the three bridge proposals for "Bjørnafjorden".

This report does not provide detailed descriptions of the maintenance strategies for each concept. If the reader would like to have more detailed information regarding them, the intended references and documents can be referred according to the reference list at the end of this report, in "REFERENCES" chapter.

4.1 FLOATING BRIDGE (FB)

As one of the proposed concepts for the Ferry Free E39 project, the Floating Bridge (FB) design has two design alternatives: "Curved Bridge" and "Strait Bridge" (Pederese, Innebern and Andersen). Figure 4-1 and Figure 4-2 illustrate the curved bridge alternative and Figure- 4-3 shows the strait bridge design.

Figure 4-1: Floating Bridge (FB) Design (Canh Vu).

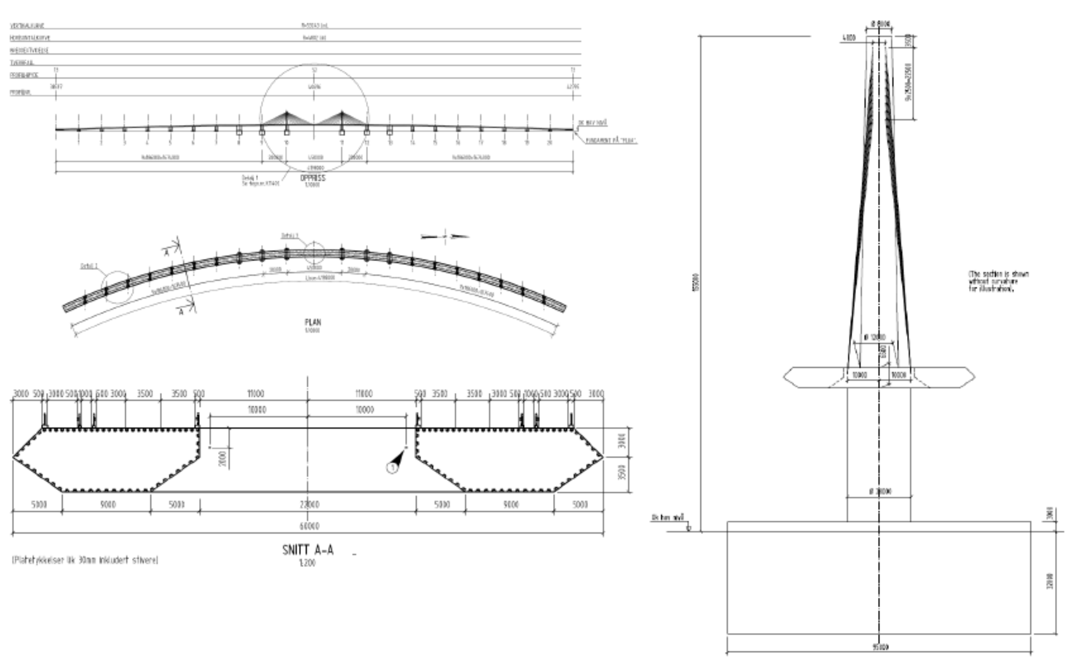

Figure 4-2: Illustration of the "Curved Bridge" alternative (two separate bridge girders and two footway/ bicycle tracks) (Pederese, Innebern and Andersen).

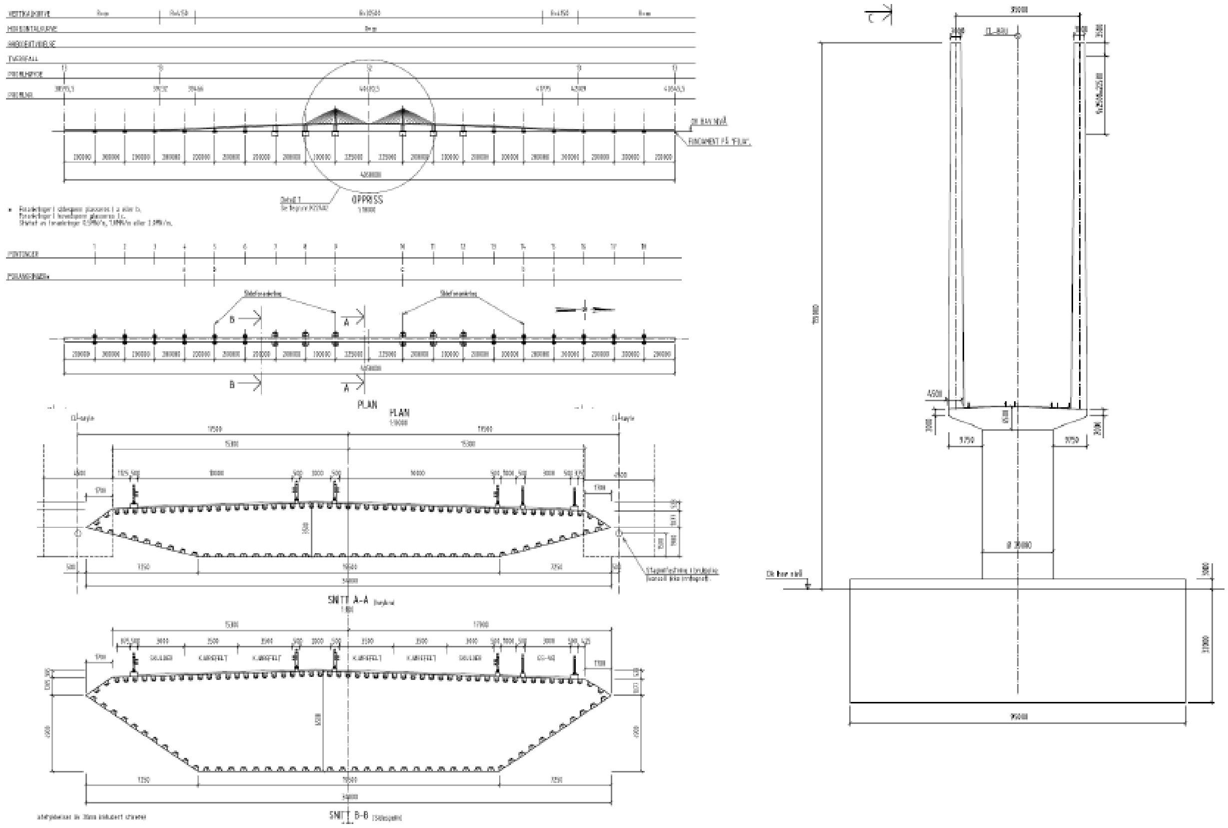

Figure 4-3: Illustration of the "Strait bridge" alternative (one bridge girder and one footway/bicycle track) (Pederese, Innebern and Andersen).

Both of the curved and strait alternatives are possible to be chosen for the project objectives. However, the proposed IOM strategy for both can be considered as the same for them. Therefore, in the proposed maintenance strategy, there are not separate maintenance strategies proposed for each of these two alternatives.

4.1.1 PROPOSED MAINTENANCE STRATEGY

The maintenance strategy for the FB design concerns three main parts of the structure: anchor/mooring, concrete and steel parts. Each part has been discussed and evaluated separately from the intended standards (Pederese, Innebern and Andersen), as listed below (Canh Vu):

- NOT-GEN-004 Operation and maintenance - Anchors.
- NOT-GEN-006 Operation and maintenance - Steel structures.
- NOT-GEN-007 Operation and maintenance - Concrete elements.

In the references for each part, the required personnel, equipment and material are presented by proposing the Inspection, Operation and Maintenance (IOM) strategies. The main IOM actions mentioned in the references are presented briefly in the following with the three main focuses: Inspection, Operation and maintenance. For each IOM strategy, there are evaluations analyzed in two different criteria, “cost” and “traffic disturbance and safety”. Further, there are some optimization recommendations includes in the documents.

4.1.1.1 MOORING/ANCHORS

4.1.1.1.1 IOM STRATEGY

Inspection: The inspection plan for the mooring and anchors include three planned inspections and the accidental inspection in case of any accident. Planned inspections are named as Annual, complete periodical and replacement (Pederese, Innebern and Andersen). More details have been provided in the mooring standard (Pederese, Innebern and Andersen). Table 4-1 shows a short overlook through the inspection plans for mooring and anchors.

Table 4-1: Summary of the inspection plans for the mooring and anchors elements (Pederese, Innebern and Andersen).

Inspection Designation	Interval (Year)	Type
Annual	1	Visual Inspection
Complete periodical	5	Detailed Inspection
Replacement (Full)	25	Full Replacement
Accidental	N.A.	Visual Inspection After Accident

Operation: Operation is defined as the continuous monitoring by having minimum and maximum tension, and also mean value of bridge offset values. Operation needs tensioning tools and maintenance crew (Pederese, Innebern and Andersen).

Maintenance: Maintenance plan has not been explained here separately for this part.

4.1.1.1.2 EVALUATION OF THE PROPOSED IOM STRATEGY

Traffic Interruption and Safety Evaluation: There is no specific evaluation based on traffic interruption and safety. There are just some points mentioned that should be considered in the IOM plans (Pederese, Innebern and Andersen), as below:

- Inspections should be done during the night time in a short duration.
- In case of any accident inspection, immediate close down is required.
- Heavy and small transportation should be provided for the anchor handling tug and hoisted down to pontoon from truck respectively.

Cost Evaluation: The detail cost evaluation for IOM plan has been done in (Pederese, Innebern and Andersen). Total cost for 100years duration, depend on number of lines used in the structure. They can vary from 16 to 20 lines. This variation can affect the estimated cost from respectively approximately 632000000 NOK (Norwegian Kroner) to 776000000 NOK. Table 4- 2 shows the total estimated costs both for the structure with 16 and 20 lines.

Table 4-2: Total estimated operation and maintenance cost for 16 and 20 mooring lines respectively for 100 years service life (Pederese, Innebern and Andersen).

Operation	Cost each action (NOK)	Total Cost for 16 lines (NOK)	Total Cost for 20 lines (NOK)
Annual inspection of mooring lines	12 000	15 360 000	19 200 000
Main inspection of mooring lines (5 year)	1 220 000	312 320 000	390 400 000
Storage of spare equipment	10 000	1 000 000	1 000 000
25 year inspection and line replacement	5 164 400	247 891 200	309 864 000
Agrement AHTS	300 000	30 000 000	30 000 000
Agreement ROV boat	250 000	25 000 000	25 000 000
Total 100 years	-	**631 571 200**	**775 464 000**

4.1.1.1.3 OPTIMIZATION RECOMMENDATIONS

In this part, some points have been mentioned which should take into consideration in order to do the IOM optimization recommendations from (Pederese, Innebern and Andersen). These points are:

- More detail plan can be made by using probabilistic methods.
- In order to decrease the cost of inspections and being more cost effective, systems should be fully accessible from the shore so that use of ROVs are possible.
- Strict fatigue requirement and environmental condition should be achievable for approximately 35 year.
- Tradeoff between increased corrosion and fewer replacement should be evaluated and optimized based on the cost.
- In order to achieve higher availability it is recommended to use closed socket design (Limit factor= wire segments [LE=30-35 years]).
- In order to increase service life and redundancy in the system bridge life time should be higher than the typical offshore installations while using nonstandard designs.

4.1.1.2 CONCRETE

4.1.1.2.1 IOM STRATEGY

Inspection: Three types of inspections are suggested for the concrete parts. Annual, Principal and special inspections are arranged for the intervals of 1 year, 5 years and 15 years respectively (Pederese, Innebern and Andersen). More details have been provided in the concrete standard (Pederese, Innebern and Andersen). Table 4-3 shows the summary of the concrete standard regarding the inspection.

ROV is Remotely Operated Vehicle which is used to remove the vegetation from the component located under the sea and also to perform the inspections under the sea level. Annual inspections are carried out from the ship only for the components located above the sea level and there is no ROV required (Pederese, Innebern and Andersen).

Further, in chloride inspections, first sampling and analyzing the concrete's dust are performed, then chloride testing is carried out either by field method such as Rapid Chloride Testing (RCT) or by laboratory method (Pederese, Innebern and Andersen).

Table 4-3: Summary of the inspection plans for the concrete elements (Pederese, Innebern and Andersen).

Inspection Designation	Interval (Years)	Type
Annual	1	Visual Inspection
Principal	5	Remotely Operated Vehicle (ROV) (detail) Inspection
Special	15	Chloride Inspection

Operation: Three operations are explained as 1) replacement of sacrificial anodes during the life time of structure, 2) removing marine vegetation and 3) algae generally and from pontoons in order to make them visible for inspections (Pederese, Innebern and Andersen).

Maintenance: Two maintenance activities have been defined in this scope. First, in case of using surface coating, they should be replaced during the structure life time. Also, concrete repairs should be first inspected and then repaired depending on the damage (Pederese, Innebern and Andersen).

4.1.1.2.2 EVALUATION OF THE PROPOSED IOM STRATEGY

Traffic Interruption and Safety Evaluation: Two elements have important roles in this evaluation, first of which is bridge design and then the secondary structures. There are two alternatives proposed in order to reduce the traffic disturbance in (Pederese, Innebern and Andersen).

- The best way is all the IOM work by access from the sea with ships.
- The second best way which can lead to some traffic disturbance is to access from the bridge girder to the pontoons.

Cost Evaluation: There are two most important factors regarding to the cost evaluation (Pederese, Innebern and Andersen):

- Sacrificial anodes and coating in concrete surface: with estimated life time of 25 and 30 years respectively
- Inspections: with estimated 2500000-500000NOK cost per day

4.1.1.2.3 OPTIMIZATION RECOMMENDATIONS

Some points have been mentioned which should take into consideration in order to do the optimization. These points are listed as below from (Pederese, Innebern and Andersen):

- In order to increase the durability, chloride sampling are recommended to be planned.
- The principal inspections is recommended to be performed during the winter because of the lower cost of ROV companies compared to summer. As winter is the low season for them.
- To ensure the satisfactory durability properties, high quality data about chloride diffusion reinforcement and reliable life expectancy are recommended to be measure and documented before the construction.
- Performing some concrete test samples before the construction is also recommended.
- In order to achieve the required durability, it is important to take additional actions based on the evaluation results.

4.1.1.3 STEEL

4.1.1.3.1 IOM STRATEGY

Inspection: However the inspection scope has not been explained separately, there are 7 types of inspection proposed listed below (Pederese, Innebern and Andersen). More precise information about the inspections is given in Table 4-5.

- Principal inspections
- Principal inspections of cable systems
- Hand over inspections
- Warranty inspections

- Yearly inspections
- Special inspections
- and, Non-scheduled (routine) inspections

Operation: Besides the inspections which is shown in more detail in Table 4-5, there are four main operation activities (Pederese, Innebern and Andersen):

- Measurement and survey
- Material tests
- Structural monitoring (Monitoring + Evaluation)

Survey and material testing related to visual inspections (6 out of the seven inspection types except the non-scheduled inspections) are shown in Table 4-4.

Regarding the structural monitoring, there are two main components (Pederese, Innebern and Andersen):

- The sensors as the structural monitoring component to data acquisition and data transmission
- The required analyses as the data evaluation component to evaluate the data from achieved relevant information

Table 4-4: Survey and material test related to visual inspection (Pederese, Innebern and Andersen).

Inspection type	Survey	Material test	Condition rating	Capacity rating
Hand-over inspection	Yes	No	No	No
Guarantee inspection	Yes	No	No	No
Yearly inspection	No	No	No	No
Principal inspection	Yes	No	No	No
Principal inspection, stay cable systems	Yes	No	No	No
Special inspection	Yes, for selected components	Yes, for selected components	Yes, for selected components	Yes, for selected components

Table 4-5: Inspections (Pederese, Innebern and Andersen).

Inspection type	Frequency	First time	Description
Routine inspection and maintenance [Separate inspections on bridge parts (inspection "themes") Primary steel and coating Yearly Before taking bridge in operation Roadway]	Yearly	Before taking bridge in operation	Primary steel and coating
	Weekly	Before taking bridge in operation	Roadway and footway/bicycle track. Incl. drainage and barriers/railings
	Weekly	Before taking bridge in operation	Stay cable system
	Weekly	Before taking bridge in operation	Expansion joints
	Monthly	Before taking bridge in operation	Overhead sign structures and signs
	Weekly	Before taking bridge in operation	Mechanical installations
	Weekly	Before taking bridge in operation	Electrical systems, incl. lighting
	Yearly	Before taking bridge in operation	Access facilities and I&M equipment
	Tests as appropriate	Before taking bridge in operation	Structural Health Monitoring System
Hand-over Inspection [Entire bridge]	One time	Before hand over of project	Visual inspection Registration of defects and deficiencies
Guarantee inspection [Entire bridge]	One time	Before end of agreed guarantee period	Visual inspection related to remedy of defects and deficiencies
General inspection [Entire bridge]	Yearly	Within 1 year after hand over	Visual inspection
Principal inspection	5 year interval	Within 1 year after hand over	Visual inspection
Principal inspection, stay cable systems	5 year interval	Within 5 year after hand over	Visual inspection
Special inspection [On selected bridge parts/ component]	As needed	As needed	Visual inspection by use of special methods and equipment

Maintenance: There are four kinds of maintenance planned for steel structures based on (Pederese, Innebern and Andersen).

- **Routine maintenance :** including cleaning, debris removal, litter removal, vehicle damage repair, lighting check and maintenance, graffiti removal, pothole repair, check and maintain functionality of doors, hatches, locks, sensors, cameras, signs, lifts, weather stations, drainage inlets, firefighting system, emergency, telephone system etc. (Pederese, Innebern and Andersen).
- **Scheduled and/or replacement maintenance:** The initial scheduled maintenance activities are explained in Table4-6.
- **Repair and rehabilitation:** The maintenance works that are not covered during the maintenance and replacement maintenance procedure, would be performed as repair and rehabilitation works. These activities are performed based on the normal design and construction standards (Pederese, Innebern and Andersen).
- **Operation and maintenance manual:** The operation and maintenance manual are unique for the project. SVV provides the detailed manual existing procedures and instructions (Pederese, Innebern and Andersen).

More details about the requirements and the intervals are provided in the reference (Pederese, Innebern and Andersen).

Table 4-6: Initial Maintenance Plan, service life < 100 years (Pederese, Innebern and Andersen).

Component	Service life	Non-scheduled maintenance	Scheduled maintenance	Replacement
Coating of primary steel structures	30	As needed	After 15 and 25 years	30 years
Waterproofing of bridge deck (isolation)	40	None	None	40 years
Wearing course	40	As needed	As needed	40 years
Safety barriers and railings	50	As needed	As needed	50 years
Drainage	50	As needed	As needed	50 years
Cable stay system	75	As needed	As needed	> 100 years for total system
Bearings	50	None	After 25 and 40 years	50 years
Buffers (if any)	50 (non-movable components)	None	After 20 and 35 years	50 years
Systems: • Electrical • Mechanical	30	As needed	As needed	30 years
SHMS	10 – 20 (sensors: 10 Infrastructure part: 20)	As needed	As needed	10-20 years
Secondary steel elements (access facilities etc)	60	As needed	After 30 and 45 years	60 years
Lifts in towers	30	As needed	After 20 years	30 years

4.1.1.3.2 EVALUATION OF THE PROPOSED IOM STRATEGY

Traffic Interruption and Safety Evaluation: Some mitigations and IOM, repair and replacement actions considering traffic disturbance are explained in the reference (Pederese, Innebern and Andersen). Disturbance periods in weeks per major maintenance / replacement work are also specified in (Pederese, Innebern and Andersen) for both different FB design, Strait and curved.

Cost Evaluation: Based on (Pederese, Innebern and Andersen), the cost is mainly due to six elements in the structure,

- Coating on steel surfaces (10-20%)
- Roadway surfacing (10-20%)
- Cable stay system (5-10%)
- Electrical system (5-10%)
- Secondary structures (5-10%)
- Bearings and expansion joints (curved bridge alternative: 0-1%, strait bridge alternative: 5-10%)

4.1.1.3.3 OPTIMIZATION RECOMMENDATIONS

In this part, some points are mentioned which should take into consideration in order to do the optimization (Pederese, Innebern and Andersen). These points are as below:

- Connection between column and pontoon
- Connection between tower and bridge girder (strait bridge alternative)
- Dehumidification
- Mobile self-propelled inspection gantry
- Stay cable anchorages
- Lift in towers
- Stay cable traveler
- Platform and rails on the outside of towers and columns
- Roadway surfacing
- Structural health monitoring system

More detail about the recommendations regarding these concepts are provided in the reference (Pederese, Innebern and Andersen).

4.1.2 DISCUSSIONS

Regarding the mooring/anchoring part:

- There is no precise maintenance plan provided in the document of (Pederese, Innebern and Andersen).
- There is not specific evaluation for the traffic interruption and safety done. There are just some points and recommendations mentioned that should be considered in the IOM plans of the mooring systems.
- In the reference, (Pederese, Innebern and Andersen), it is recommended to perform the probabilistic methods to get more detail plans regarding the mooring system. Therefore, probabilistic methods can be considered as a recommendation for the future work.

Regarding the concrete part:

- There are not an exact cost evaluation for the concrete parts. E.g. it said the inspection costs are 250000-500000NOK per day but it didn’t mentioned how many days are needed to inspect all the concrete structures.
- The specific maintenance intervals are not mentioned for the concrete parts.

Regarding the steel part:

- There are not detailed cost evaluations for proposed steel IOM strategy done.

4.2 SUSPENSION BRIDGE SUPPORTED BY TENSION LEG PLATFORM (TLP)

In this concept, it is discussed about the planned suspension bridge supported onto floating foundations across “Bjørnafjorden” (Aker Solution). This concept has been proposed based on the structure of marine installations. This bridge foundation structure considered is a steel structure of type Tension Leg Platform (TLP) with the service life of 100 years. Figure 4-4 and Figure- 4-5 provide an overlook of this concept. Figure 4-6 provides more detailed look into the components used in the structure of this concept.

As a maintenance strategy, (Aker Solution) provides “Asset Integrity Management” based on the new revision of (NORSOK N-005) offshore standard for this concept. This strategy for a TLP bridge foundation structure rely on the two parts below (Aker Solution) (Canh Vu):

- Foundation (hull, tether, foundation at seabed), shown in Figure 4-6.
- Integrity management with risk-based inspection.

This model is discussed in more detail in the following sub-section.

Figure 4-4: Suspension Bridge Supported by Tension Leg Platform (TLP) Design (Canh Vu).

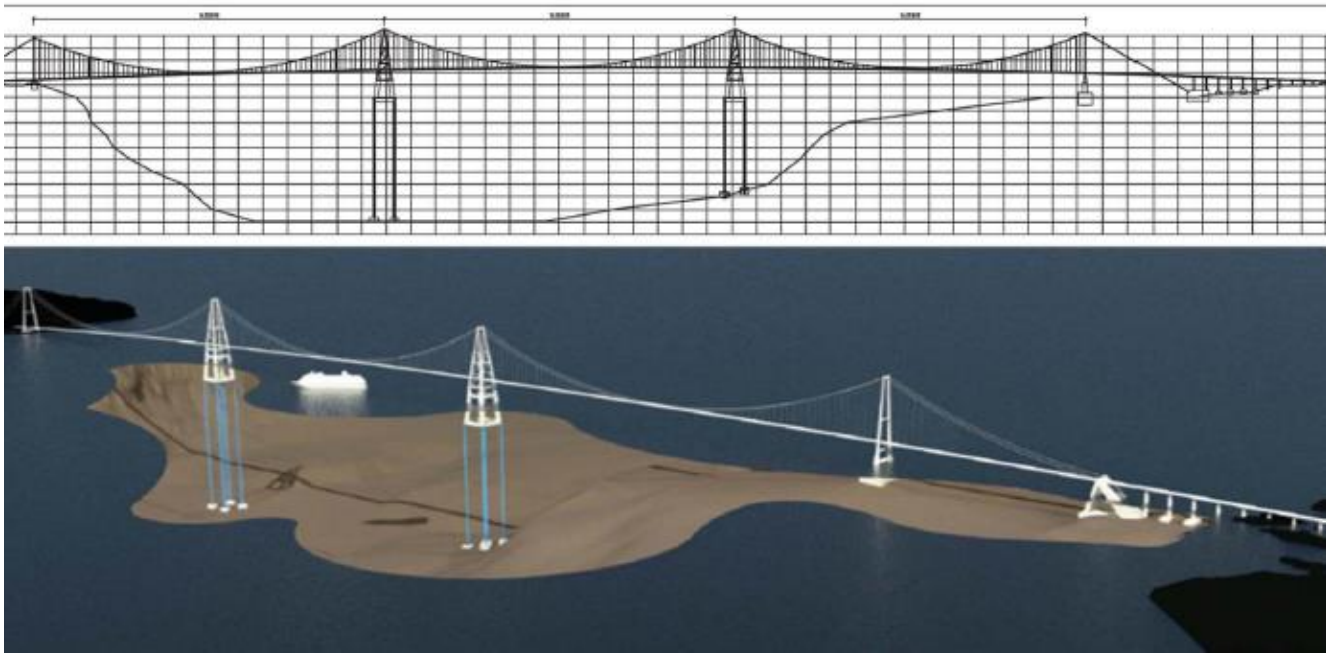

Figure 4-5: Suspension Bridge Supported by Tension Leg Platform (TLP) Design (Canh Vu).

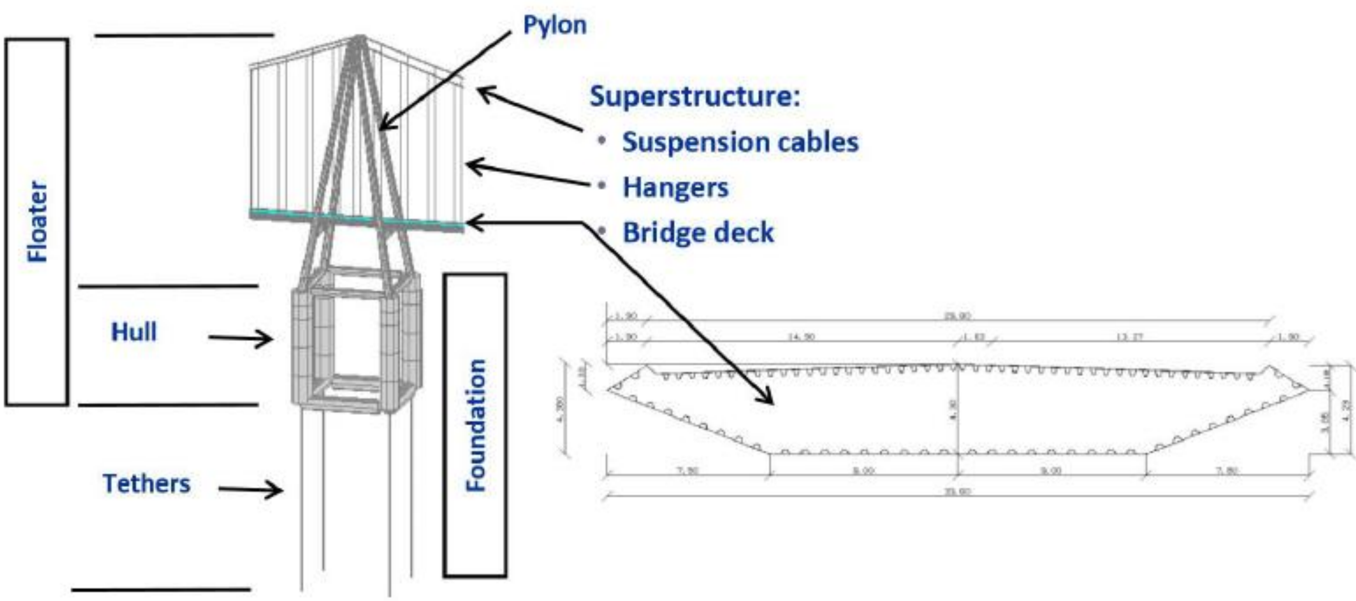

Figure 4-6: The overview of the main components in TLP concept (Canh Vu).

4.2.1 PROPOSED MAINTENANCE STRATEGY

The maintenance strategy proposed for TLP design is based on the integrity management model. The Flow chart for this strategy is shown on Figure 4-7.

The process, shown in Figure 4-7, is explained quite in detail by (Aker Solution). The typical delivery model based on the Figure 4-7, implies that the asset owner/operator sets up an organization which typically will consist in the following:

- Operator to set the terms (blue)
- An integrity contractor maintaining the analysis models, performing analyses and evaluate findings (red)
- An inspection contractor planning and executing inspections (green)
- Data management contractors (yellow)

(Aker Solution) consider these three points important that they should take into consideration:

- Quality deliverables during design and construction
- Design principles and measures for tether system
- Corrosion protection

In this model IOM strategy have been explained based on the three following points:

- Inspection strategy
- Repair and replacement
- Maintenance , modification and Operation (MMO)

More information about these concepts and more details in this model are provided in the intended reference made by (Aker Solution).

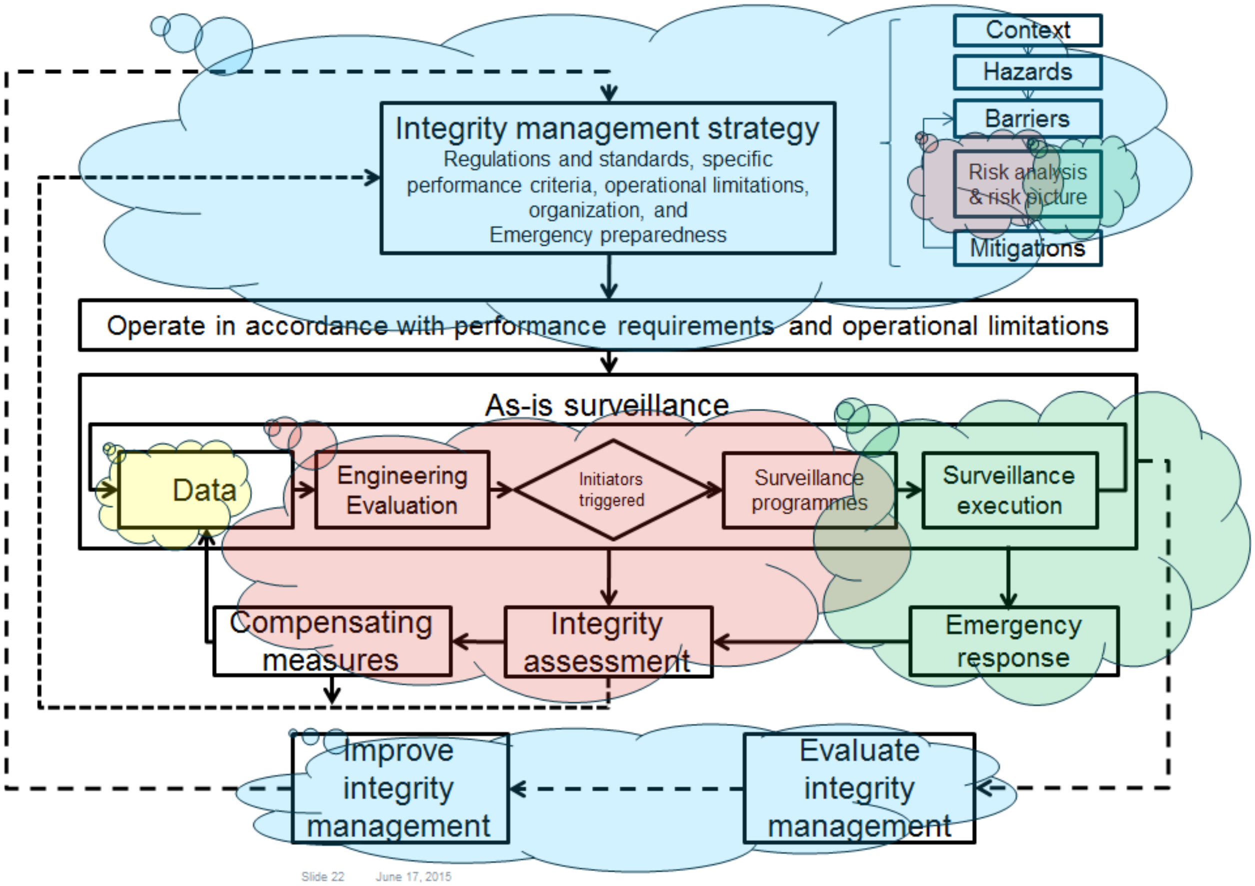

Figure 4-7: Model for safe operation of marine installation showing typical delivery model (NORSOK N-005).

4.2.2 DISCUSSIONS

1. The strategy look more generic compared to the strategies proposed for the other two concepts. For instance, it did not provide the precise data regarding the requirement, intervals, and durations etc.
2. No evaluation on the proposed strategy is done. It is opposite to FB concept that is evaluated from two perspectives, cost and traffic disturbance.
3. There is not any optimization recommendations provided for this strategy.

4.3 SUBMERGED FLOATING TUNNEL BRIDGE (SFTB)

Submerged Floating Tunnel Bridge (SFTB) is presented based on the tunnels and offshore structures. SFTB can be considered as a high standard concept regarding the safety (Ludescher and Pederesen). Figure 4-8 and 4-9 illustrate an overlook to this concept.

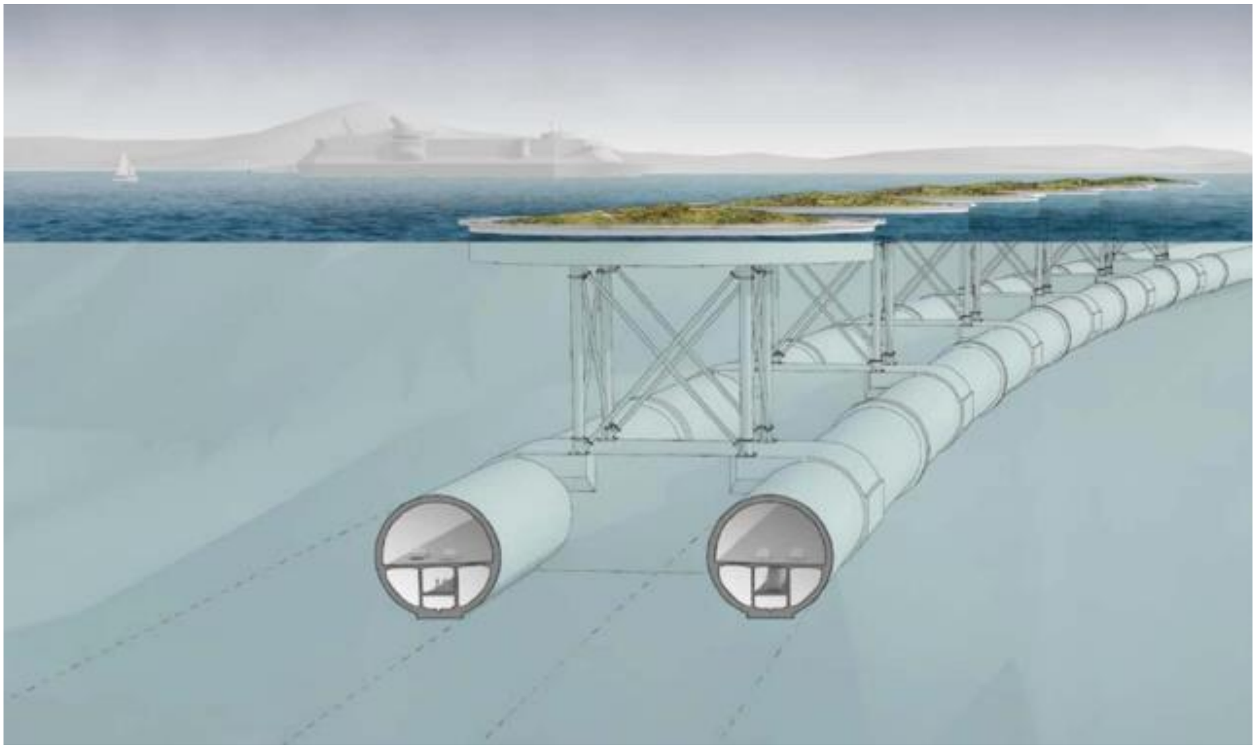

Figure 4-8: Submerged Floating Tunnel Bridge (SFTB) Design (Canh Vu).

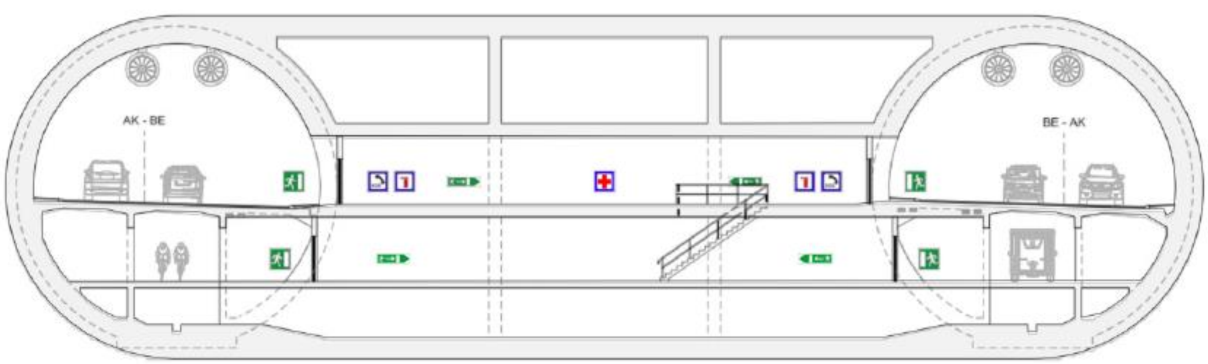

Figure 4-9: An overlook into Submerged Floating Tunnel Bridge (SFTB) Design (Canh Vu).

4.3.1 PROPOSED MAINTENANCE STRATEGY

The maintenance strategy gives the relevant elements and systems required for operation and maintenance plans, by proposing the IOM strategy and evaluation for each (Ludescher and Pederesen). Figure 4-10 shows the relevant elements for the strategy visually. As a summary of maintenance strategy, the Operation and Maintenance consists of:

— Detailed descriptions of the maintenance of concrete structures.

— Compatibility of maintenance with operation.

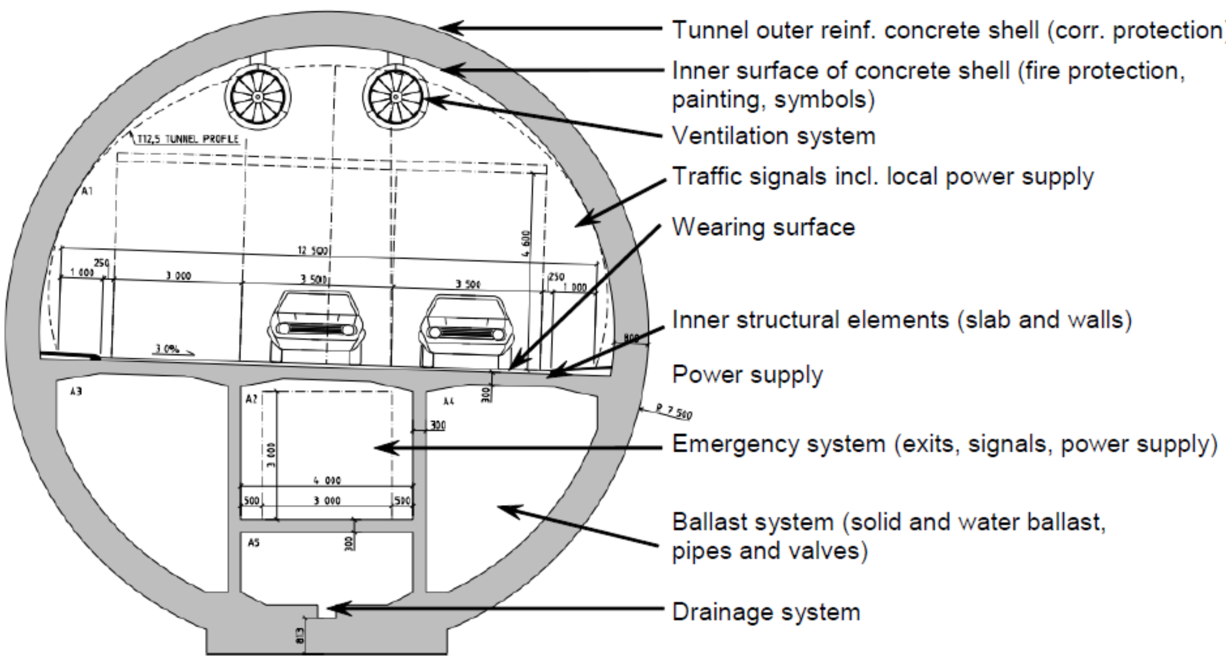

Figure 4-10: Concept cross section of SFTB and relevant elements for operation and maintenance (Ludescher and Pederesen).

The main IOM actions, mentioned in (Ludescher and Pederesen), would be presented briefly as Inspection, Operation and Maintenance and Monitoring. In the following, evaluation and some optimization recommendations will also be provided.

4.3.1.1 IOM STRATEGY

Inspection: the inspection plan is shown on Figure 4-11.This planning is based on the experience from analysis made during the detailed engineering phase and the fabrication phase.

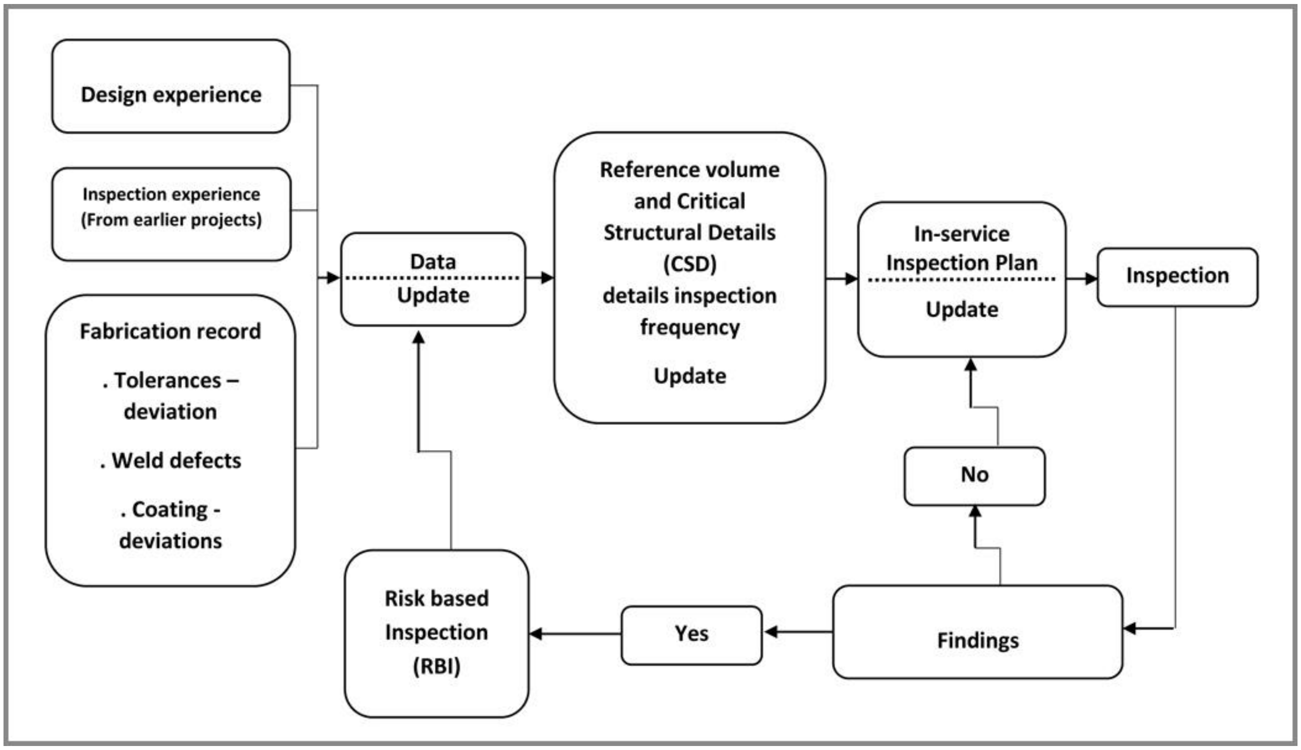

Figure 4-11: Scheme for development of inspection plan (Ludescher and Pederesen).

According to (Ludescher and Pederesen), the in-service inspection plan shall describe:

- ✓ Where to inspect (critical area)
- ✓ What to inspect (how much)
- ✓ Method and accessibility for inspection
- ✓ When to inspect (frequency of inspection)
- ✓ Identification and reporting

It has been shown that inspection planning will eventually converge to the following process (Ludescher and Pederesen):

- If no damage require more detailed observation, inspection frequency is set to 3 – 4 years for North Sea platforms. "Bjørnafjorden SFTB" is not exposed to the same rough North Sea conditions and an interval of 5 years is possible (Ludescher and Pederesen).

- Inspection is made in 2 steps for limiting costs and still getting detailed information.

<u>Step 1:</u> First, rough screening of large parts of the structure for damages, Second, verification of findings by detailed inspection of identified points / damages (Ludescher and Pederesen).

<u>Step 2:</u> Detailed inspection of a selected region considered as representative for the condition / degradation, visual inspection of damages complemented by simple testing for checking quality of corrosion protection. Especially in the case of concrete, damages may be hidden under the concrete cover and techniques for non-destructive testing are important for damage detection in an early state (Ludescher and Pederesen).

Operation: Based on (Ludescher and Pederesen), the main objectives for operation are to assure:

- ✓ High availability (min. periods with reduced capacity and no complete shutdown)
- ✓ High reliability (disruption only after announcement)
- ✓ High safety (traffic safety and technical installations)

In order to achieve these objectives, some requirements are provided regarding to concepts below in the reference (Ludescher and Pederesen):

- Requirement for availability
- Requirement for safety
- Optimized tunnel cross section
- Restricted operation due to maintenance
- Two-way traffic in one tube
- Cross connection
- Traffic safety
- Emergency exits

Maintenance: There are four maintenance activities that has been proposed for this design (Ludescher and Pederesen). Special inspection, planned maintenance, unforeseen maintenance and planned major rehabilitation Table 4-7 shows the duration and description about these maintenance activities.

Table 4-7: Main categories of maintenance activities (Ludescher and Pederesen).

Maintenance activity	Duration	Description
Inspection	1 hour to 8 hours	Limited / main / special inspection with access afoot, using slowly moving vehicle or lift / working platform
Planned maintenance	hour to 8 hours	Periodical maintenance and repair that can be planned in ahead for suitable periods
Unforeseen maintenance	10 minutes to 8 hours	Work triggered by failure in critical technical systems or by traffic accidents
Planned major rehabilitation	Several weeks or months	Extensive repair / replacement after expired service life of items like communication system, drainage system, wearing surface, illumination etc.

Monitoring: Preliminary monitoring strategy includes 2 phases:

- First phase: with intense monitoring of various design parameters in order to verify design assumptions and to gain knowledge for new projects.
- Second phase: with a long term monitoring of key properties for safety and durability determined on the basis of findings in phase 1.

According to (Ludescher and Pederesen), Monitoring are required to be uses in four main area below:

- Traffic related monitoring
- Monitoring of actions on structure e.g. actions like wave and water
- Monitoring of concrete structure
- Monitoring of tether

The required devices and tools for this purpose are quite clearly mentioned in (Ludescher and Pederesen).

4.3.1.2 EVALUATION OF THE PROPOSED IOM STRATEGY

Design of the stabilizing elements (tethers and anchors or pontoons and their connection to the concrete tubes) has been evolving, making a detailed evaluation of required maintenance difficult. However it is shown at the end of (Ludescher and Pederesen) that no particular challenge needs to be expected (Ludescher and Pederesen), the evaluation of this proposed maintenance can still be discussed more.

4.3.1.3 OPTIMIZATION RECOMMENDATIONS

No optimization point has been mentioned in the reference.

4.3.2 DISCUSSIONS

1. However, a general model is proposed for this concept, the precise detail about the inspection plan are not explained in the document.
2. There are not accurate evaluations done for this strategy. However, for the FB concept, there are evaluation from two perspectives (cost and traffic disturbance) are done. For TLP concept, no evaluation is included in the related document.
3. There is no optimization recommendations are provided for this concept, same as TLP. Although, for FB concept, optimization recommendations for concrete, mooring and steel parts are provided.

CHAPTER-5 MAINTENANCE MODELS FOR NEW BRIDGE CONCEPTS

5.1 QUALITATIVE COMPARISON METHOD

Hai Canh Vu (postdoctoral fellow in NTNU) suggested SVV, a qualitative maintenance comparison in collaboration with NTNU. The objectives of this method is to assess the maintenance process in three concepts introduced by SVV for the Ferry Free E39 project.

The methodology relies on two main criteria to assess and to predict the maintenance performance for the project objectives. The two proposed criteria are Maintainability and Maintenance-related risks (Canh Vu). They are described in the following subsections 5.1.1 and 5.2.1. It is assumed that the costs and economic issues have been considered already in the life cycle cost analysis. So these perspectives are overlooked in the proposed methodology (Canh Vu).

5.1.1 MAINTAINABILITY

Maintainability is defined as the “Measure of ease and rapidity with which a system or equipment can be successfully inspected and maintained” (Canh Vu). In this project, maintainability is characterized by three different levels, named Good Maintainability, Moderate Maintainability and Difficult Maintainability (Canh Vu). By discussing the three sub-criteria of maintainability, it would be possible to judge about the final maintainability level in the specific system (Canh Vu). The three sub-criteria are explained below.

1. **Accessibility of critical components:** Accessibility of critical components concerns their maintenance frequency and their access difficulties during the required maintenance process (Canh Vu). Maintenance frequencies of the critical components are mostly clear. To determine the access difficulty for these components, three questions are proposed. The answers to these questions can help to clarify the access difficulties of the critical components (Canh Vu). The proposed questions are:
    - *Can critical components be assessed at any time, and independently with the weather, or operation conditions?*
    - *Does the access to maintained components require special skills or tools?*

- *Does the access to maintained components have negative impacts on the safety of repairman?*

2. **Complexity of maintenance tasks:** There are two questions suggested and the answer to them can explain the complexity level of maintenance tasks (Canh Vu):

   - *Do we have enough experiences to maintain the components?*
   - *Does the maintenance of components require special or new maintenance skills, new maintenance management system?*

Logistic supports: Logistic supports are outlined based on the repair team availability and availability of spare parts and necessary maintenance tools (Canh Vu). This information are mostly included in the Inspection, Operation and Maintenance (IOM) plans. Examples are such as, required personnel, required special, maintenance tools and in stock stored equipment.

5.1.2 MAINTENANCE-RELATED RISKS

Maintenance-related risks, as the second criteria proposed, is defined as the "*Criterion measuring all the negative impacts of maintenance activities on three concepts, Traffic, Environment and people*" (Canh Vu). (It is worth explaining the people mentioned in the definition, it refers the people who perform the maintenance process.)

Maintenance-related risks can be analyzed as one of the risk analysis of the project (Canh Vu). This criteria evaluates the adverse effects of maintenance activities in the three risk areas listed below:

- Traffic disturbances: closures of the bridge, speed reduction.
- Environment pollution because of the maintenance actions
- People safety

Based on the methodology proposed, there is a connection between the two main proposed criteria of maintainability and maintenance-related risks (Canh Vu). The connection considers all the three intended risks areas, explained earlier, in relation to maintainability (Canh Vu). Figure 5-1 shows this connection more clearly.

The methodology relies on the analysis of the maintainability and maintenance-related risks. It is then compared based on the three concepts proposed by SVV, 1) Floating bridge (FB), 2) Suspension Bridge Supported by Tension Leg Platform (TLP), and 3) Submerged Floating Tunnel Bridge (STLP). This can enable us to discuss and judge regarding the three concepts from the maintenance point of view (Canh Vu).

Figure 5-1: Correlation between Three Maintenance-Related Risks, Traffic Disturbances, Environment Pollution and People Safety (Canh Vu).

One of the advantages of this method, as a qualitative model, can be that it is a methodology used to compare and to assess the maintenance strategies even when there is lack of data. Also, as the concept of maintainability and maintenance-related risks are very general, the most important aspects of design can be taken into consideration. Furthermore, in the initial stages of the design, typically, there are some difficulties to obtain data.

However, the accuracy of the method is still under consideration. As there is no quantitative measure to compare the strategies together, it can be sometimes difficult to exactly present the criteria. Additionally, the cost and economic issues, which is considered to be important, are not discussed by this method.

5.2 SUSTAINABILITY-BASED METHOD

Sustainability-based method is one of the methods proposed for the maintenance assessment of this project. Sustainability is one of the significant concerns during the design process of an infrastructure (Walter). Sustainability addresses some issues that improve the architectural quality and financial benefits. These issues can be environmental, social or economic. Sustainability can have the best effects on building performance not only in the design process, but also the early design process of the structure (Walter) (ECDGE). An integrated design process is required for a sustainable design (Alwaer and Clements-Croome). A sustainable design can assure the comfy and high quality structures which contribute to higher economic savings and less impacts on the environment (Bragança, Vieira and Andrade). It is worth to discuss about the three concepts, “Green” “intelligent” and “sustainable” buildings in this part.

Sustainable buildings is defined as “a subset of sustainable development with continuous process of balancing all the three systems environmental, social and economic sustainability” (Plessis).

Green buildings is explained as “a part on sustainability building’s concept which mostly focus on using the environmentally friendly approaches” (Plessis).

Intelligent building is defined as “sustainable, healthy and technologically aware. It meets the needs of all the stakeholders” (Alwaer and Clements-Croome).

As a combination of these three concepts, “Sustainable intelligent buildings” can, therefore, be described as “a complex system of inter-related basic issues: People (owners; occupants, users, etc.); Products (materials; fabric; structure; facilities; equipment; automation and controls; services); and Processes (maintenance; performance evaluation; facilities management) and the inter-relationships between these issues” (Alwaer and Clements-Croome). These issues include all the phases of a building’s life span. All the concepts can lead to achieve a building that has the best combination of environmental, social and economic values, mentioned earlier. In other words, it provides us structures that is environmentally-friendly considering their life cycle cost (Alwaer H) (Alwaer H) (Alwaer).

From maintenance point of view, sustainability, as an integrated methodology, can guarantee the efficiency and effectiveness in the operation and maintenance activities (Alwaer and Clements-Croome). Sustainability can also drive operations and maintenance in a way which improves the health care and public health not only in the site and work environment, but also in the community (Alwaer and Clements-Croome). Operations and maintenance considering sustainability can lead to lower costs, energy assumption and waste. In other words, sustainability can make greener long-term or optimal operations and maintenance with minimum impacts on well-being and natural resources and environment (Alwaer and Clements-Croome). Therefore, sustainability assessment is proposed as one of the possible methods to apply for the objectives of this project.

Classically, sustainability principles are applied for the designed and existing systems. However, researchers show that it can lead to higher and longstanding effects if it starts from the opposite direction (Walter). Sustainability standards would lead to better results if they are applied from the initial steps including design and manufacture stages. The reason is that the possibility of optimization in primary stage is significantly higher (Bragança, Vieira and Andrade). Also, in case of applying any changes to the project, the cost would be lower compared to the sustainability assessment after-design phase (Bragança, Vieira and Andrade). As it can be seen in Figure 5-2, the possibility to influence the impacts and costs in the planning stage is quite higher than construction costs and costs on further phases. When the project reaches the construction and use phases, this possibility become lower and lower compared to the previous phase.

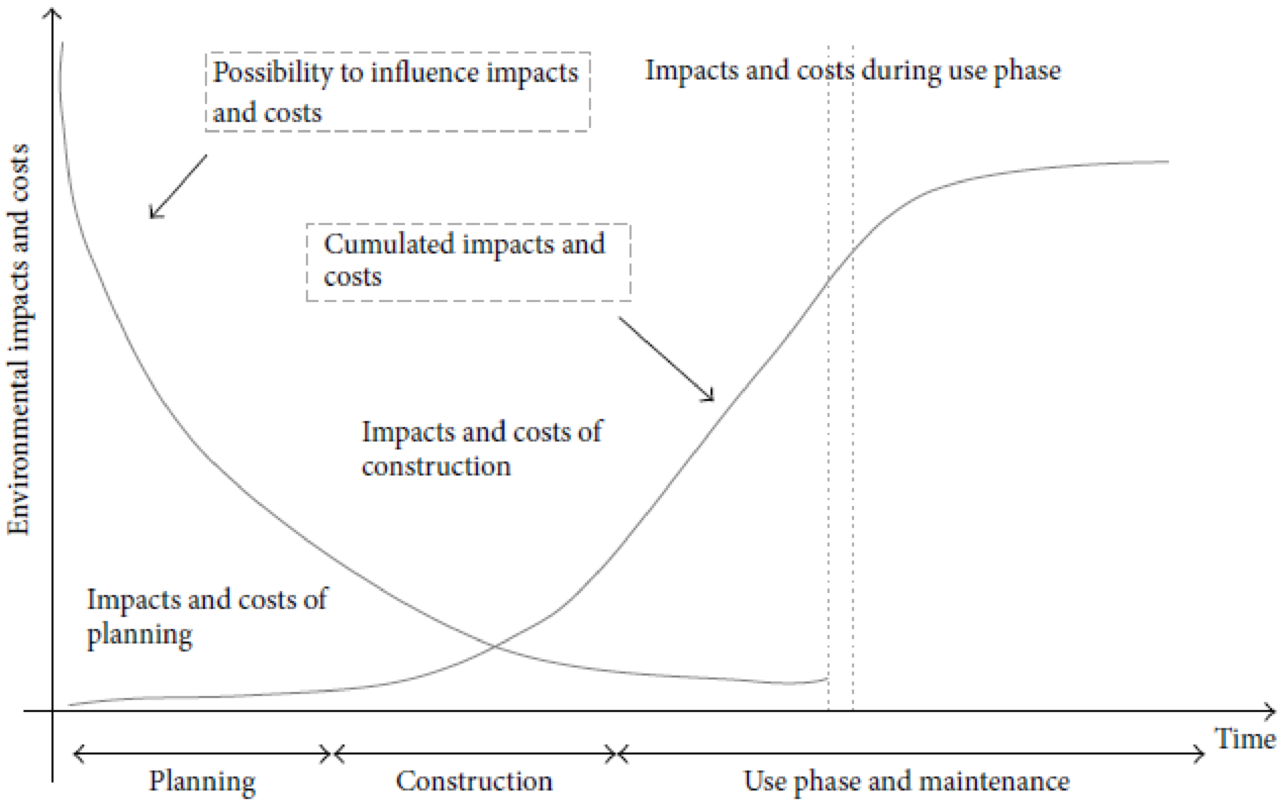

Figure 5-2: Influence of Design Decisions on Life Cycle Impacts and Costs (Kohler and Moffatt).

Now, it is required to know the detailed project phases and to understand what means by the early phase of a project. Figure 5-3 explains the whole design stages of the building.

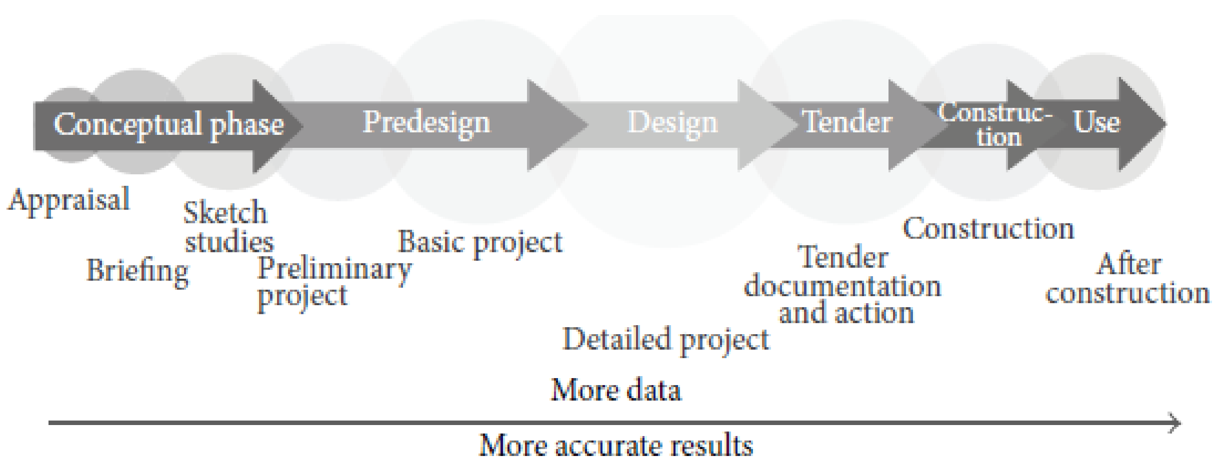

Figure 5-3: Design Stages of a Building (Andrade, Vieira and Bragança).

As it can be seen in Figure 5-3, there are two phases as initial phases of a project, the first of which is conceptual phase and the second phase is called predesign phase. In these two initial phases, it is possible to highly affect the performance and costs by sustainability principles (Bragança, Vieira and Andrade).

In order to assess sustainability performance in these two phases, two general types of indicators are introduced for each phase (Bragança, Vieira and Andrade). Core indicators are introduced as the solution in conceptual phase. Core indicators concern the environmental, energy and life cycle cost impacts on the buildings. There are the indicators, shown in Table- 5-1, 5-2 and 5-3, which are introduced based on the reference databases and catalogues from this type (Bragança, Vieira and Andrade). Additional indicators, on the other hand, can only be used in the next phase which is pre-design stage (Bragança, Vieira and Andrade). Figure 5-4 shows the impact of the core and additional indicators clearly (Bragança, Vieira and Andrade). These indicators have been introduced in order that they would be identified and predicted. Also, finally to achieve the ultimate objectives of sustainability-based methodology, which is to assess the sustainability performance by finding and analyzing the most important indicators. The methodology is explained in more detail later.

Table 5-1: Sub-indicators describing environmental impact indicator (Bragança, Vieira and Andrade).

Indicator	**Unit**
Global warming potential, GWP	kg CO2 equiv
Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11 equiv
Acidification potential of land and water; AP	kg SO^{2-} equiv
Eutrophication potential, EP	kg $(PO4)^{3-}$equiv
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethene equiv
Abiotic resource depletion potential for elements; ADP elements	kg Sb equiv
Abiotic resource depletion potential of fossil fuels ADP fossil fuels	MJ

Table 5-2: Indicators describing energy impacts (Bragança, Vieira and Andrade).

Indicator	Unit
Total primary energy demands and share of renewable and non-renewable primary energy resources (in operation phase)	kWh/m2·year

Table 5-3: Indicators describing life cycle costs (Bragança, Vieira and Andrade).

Indicator	Unit
Construction costs	€/m^2
Operation costs	€/m^2
End-of-life cost	€/m^2

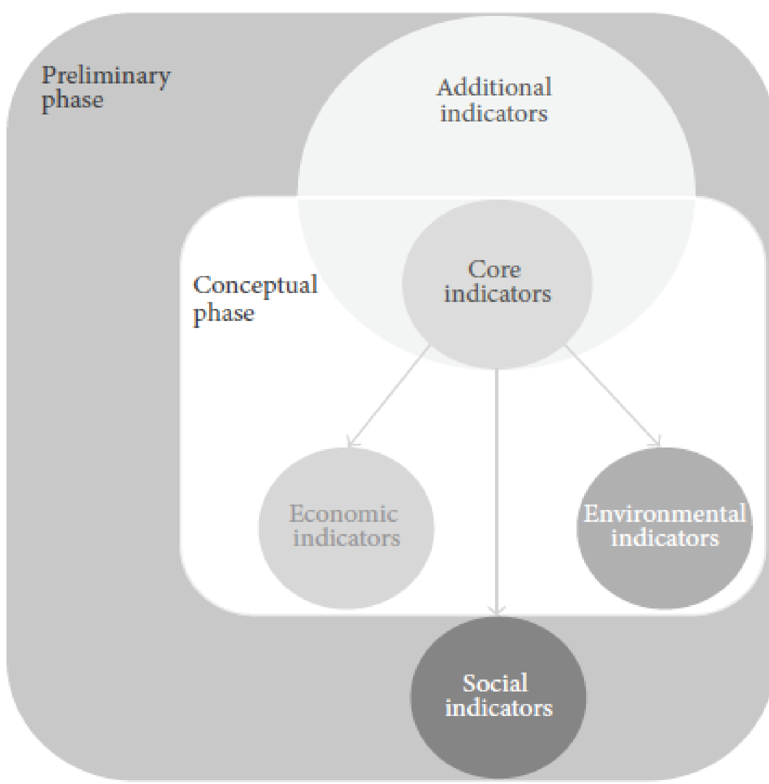

Figure 5-4: Core indicators and additional indicators (Bragança, Vieira and Andrade).

The sustainability-based methodology consists of three main phases which are explained shortly in the following (Alwaer and Clements-Croome).

Phase1: To develop general conceptual models that highlight the critical selection factors and indicators (Alwaer and Clements-Croome)

In this phase, there are specific number of experts and key persons from different areas related to the project. They are invited to review the indicators by literature and surveys (Alwaer and Clements-Croome). An initial set of indicators has already been made based on the explained indicators, local environment, needs, time, interests, culture, data, economy and the business objectives. The experts select their intended indicators (S. Roaf). Then, they determine the importance for each selected indicator. The selections are done based on their knowledge, preference and expertise (Alwaer and Clements-Croome).

Phase 2: To test and refine the general conceptual models, developed in phase 1 by testing the level of importance of the selection criteria and indicators (Alwaer and Clements-Croome).

In this phase, it is also discussed by the invited experts about the priority levels compared to other indicators. This process can be called pairwise comparison (Alwaer and Clements-Croome). Priority levels are categorized as shown in Table 5-4.

Table 5-4: The Correlation between the Priority Levels and Value Criteria (Alwaer and Clements-Croome).

Priority Levels (PLs)	Values interval
Low priority	**1-3**
Medium priority	**4-6**
High priority	**7-10**

Phase 3: To develop a practical model for sustainable intelligent building systems assessment and performance (Alwaer and Clements-Croome)

In this phase, the tool called the Sustainable Built Environment Tool (SuBETool) is used. This tool can help to achieve more intelligent, efficient and comfortable building (Alwaer and Clements-Croome). The tool analyses the multi-criteria decision making using Analytical Hierarchical Process (AHP). It helps to get an overview to the selected indicators and the selected values in order to analyze and calibrate them for sustainable intelligent buildings (Alwaer and Clements-Croome).

Furthermore, the Sustainable Building Score would be found based on the Equation 5-1 (Larsson), shown below, using SuBETool.

$$\text{Sustainability Score} = [\,(\text{L}) * (\text{PL})] \tag{5-1}$$

- L: Level of Performance
- PL: Priority Level (which is judged by the experts)

Level of Performance (L) values are selected as a number between -2 to +5. Priority levels (PL) are judged as a number smaller than 10. The maximum priority that can be selected is 10 (Alwaer and Clements-Croome). As a result, Sustainability Score can be calculated. It enables us to measure the performance of sustainability in the system (Alwaer and Clements-Croome). These values are interpreted as shown in Table 5-5.

The final result based on this assessment expected is to have a sustainable building which consists of less cost, more reliability, more integration regarding the stakeholders, planners, urban policy makers and so on (Alwaer and Clements-Croome).

Table 5-5: Sustainability values interpretations (Alwaer and Clements-Croome).

Sustainability Values intervals		**Sustainability Performance**	**Descriptions**
Min.	**Max.**		
+4	**+5**	**Excellent performance**	• Best sustainability condition
+3	**+4**	**Very good performance**	• Stable sustainability condition
1.5	**+3**	**Good performance**	-
0	**1.5**	**Standard performance**	• Minimum acceptable practices • Difficulty in find data
-2	**-1**	**Unsatisfactory performance**	• Unlikely to meet accepted regulations and criteria. • The impact is negative on environment, social and economic issues.

This can be one of the proposals to choose between the three concepts presented by SVV for "Bjørnafjorden" bridge project. This approach can show the sustainability analyses for each of the three concepts. The concept with better sustainability performance can be selected as the best solution for "Bjørnafjorden".

On the other hand, as it can be seen this model is considered as a subjective assessment. Therefore, there are some difficulties regarding the definitions and practices in the intelligent buildings (Alwaer H) (Alwaer H). One of the other disadvantages of this method, which makes this model a bit hard, is the differentiations between the expert's and stakeholders' ideas (Alwaer and Clements-Croome). Take an economy group, as an example, one economist can value one specific indicators more than others. However, the other one selects this indicator as the lowers importance. So, the diversities between the perspectives can sometimes be seen clearly in the process.

CHAPTER-6 DISCUSSION AND CONCLUSION

As mentioned in the introduction, the main objectives of this report are to be able to answer the following questions. Therefore, the following discussion is written with the purpose of answering the three questions.

- **Question 1:** What are the classical maintenance strategies in civil engineering?

In civil engineering, the classical maintenance strategies are presented based on the preventive policies. Therefore, these types of maintenance are so-called preventive maintenance. Preventive maintenance can be performed on-demand or periodical.

There are some factors that impact the maintenance intervals. Environmental circumstance, bridge structure, bridge location, bridge age and the used components can be mentioned as the influencing factors. In order to find the most proper maintenance interval, structural reliability method is presented. This method, which relies on the structural reliability theory, provides us with appropriate maintenance intervals.

Further, Risk-Based Maintenance (RBM) method are explained as another maintenance strategy used in civil engineering. RBM method enables to increase or decrease the maintenance interval based in the risk level of the structure. Risk level of the structures can be assessed by their Occurrence Factors (OFs) and Consequence Factors (CFs) in the structure. OF and CF values can be claimed by using the data from condition assessment in the structure, and elicitations of experts who are from the Reliability Assessment Panel (RAP).

- **Question 2:** What are the future maintenance strategies in civil engineering?

As future maintenance strategies can be used in civil engineering, qualitative comparison and sustainability-based methods are presented. This is done in order to assess the maintenance performance in the structures. These two methods are adapted to the design phase of the project and can be helpful to analyze the maintenance performance while the structure is still in pre-design phase.

In qualitative comparison method, maintainability and maintenance-related risks are presented as the main criteria to assess the maintenance performance in the design phase. However, cost and economic issues can be also considered as one of the criteria. It is overlooked in the method due to the fact that it is already considered in the Life Cycle Cost (LCC) of the structure. By assessment of the maintainability level and its correlation with the related risks, it can be possible to judge about the maintenance performance in the structure.

Further, researchers believe that sustainability can assure the effective and efficient maintenance performance in the structure. They believe that sustainability can be more useful when it considers for the pre-design phase. In sustainability-based method, it can be possible to judge the maintenance performance by finding the sustainability score. Sustainability score is the multiplication of the level of performance and priority levels which are claimed by experts' judgments.

❖ **Question 3:** What type of inputs can be provided from this report for SVV regarding the "Ferry Free E39" project?

"Ferry Free E39", which is a unique highway bridge project, presented as the used case in this report. This project is still in pre-design phase and the uniqueness of this project is about the crossing over the "Bjørnafjorden". "Bjørnafjorden" has an extraordinary characteristics because of its depth and length. So, these characteristics make this project exceptional and huge-scale in comparison with the other highway bridge projects.

Qualitative comparison and sustainability-based methods are proposed as the possible approaches to find the proper solution to this project. In pre-design phase, there is not enough accurate information about the concepts. Therefore, they can be performed best in the pre-design phase of structure projects and assess the maintenance performance in that phases.

Qualitative comparison and sustainability-based methods can be taken as inputs for SVV to be considered. Qualitative comparison can enable SVV to have a better overview through the maintainability and the related risks regarding traffic disturbance, people safety and also environment. Sustainability can assure the effective and efficient maintenance performance of the structure. Further, sustainability-based method can provide the sustainability performance score. Based on the sustainability score, it can be possible to analyze and discuss the performance of the structure in terms of sustainability.

Based on this report, it can be recommended to perform more evaluations from different perspectives on the three proposed concepts, Floating bridge (FB), suspension bridge supported by tension leg platform (TLP) and submerged floating tunnel bridge (SFTB). For instance, in addition to qualitative comparisons, quantitative evaluation can also be useful to assess the maintenance performance of each concept. Probabilistic methods are already suggested in (Pederese, Innebern and Andersen) to achieve more precision about the maintenance strategy proposed.

Furthermore, qualitative comparison and sustainability-based methods can also be performed as future researches regarding the three proposed concepts. As it has been mentioned earlier, these two methods also adapt to the pre-design phase in the projects. Therefore, they can be performed usefully for the objectives of “Ferry Free project” focusing on the part crossing over the “Bjørnafjorden”.

REFERENCES

Aker Solution. "Proposal Regarding " Operation And Maintenance Strategy" For a TLP in BJØRNAFJORDEN." 2015.

Aktan, A. Emin, et al. "CONDITION ASSESSMENT FOR BRIDGE MANAGEMENT." *JOURNAL OF INFRASTRUCTURE SYSTEMS* (1996): 10.

Alwaer H, Sibley M, Lewis J. "Different stakeholder perceptions of sustainability assessment." *Architectural Science Review (ASR)*. 2008.

—. "Factors and Priorities for assessing sustainability of regional shopping centres in the UK." *Architectural Science Review (ASR)*. 2008.

Alwaer, H. and D.J. Clements-Croome. *Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings*. Dundee: ScienceDirect, 2010. <www.elsevier.com/locate/buildenv>.

Alwaer, H. "Regional shopping centres in the UK: sustainability indicators and application of an assessment model." *Unpublished PhD thesis*. Liverpool: The University of Liverpool, School of Architecture, 2006.

Andrade, J., S. Vieira and L. Bragança. "Selection of key sustainable indicators to steel buildings in early design phases, in Heli Koukkari, Lu´ıs Braganc¸a, Samir Boudjabeur." *in Proceesings of the International Workshop on Concepts and Methods for Steel Intensive Building Projects*. Munich: ECCS, May 2012.

Ashrae. "Ashrae green guide: the design, construction, and operation of sustainable buildings." Atlanta: GA: American Society of Heating, Refrigerating and Air-conditioning Engineers, 2006.

Bragança, Luís, Susana M. Vieira and Joana B. Andrade. "Early Stage Design Decisions: The Way to Achieve Sustainable Buildings at Lower Costs." *The Scientific World Journal* (2014): 8.

Canh Vu, Hai. *Qualitative Comparison Relating to the Maintenance Aspects of the Three Concepts: Comparison Criteria Suggestions*. Trondheim: Norwegian University of Science and Technology (NTNU), 2016.

Chen, Wai-Fah and Lian Duan. *Bridge Engineering Handbook, Second Edition: Construction and Maintenance*. 2nd. Florida: CRC Press, 2014. <https://books.google.no/books?id=kavMBQAAQBAJ&source=gbs_navlinks_s>.

Civil Engineering and Engineering Mechanics. 2012. Department of Civil Engineering & Engineering Mechanics. 04 05 2016.

Coastal Highway Route (Ferjefri)E39, [http://www.vegvesen.no/vegprosjekter/ferjefriE39/English]. 19 November 2012. The Norwegian Public Roads Administration. 5 December 2015.

ECDGE. *A Green Vitruvius: Principles and Practise of Sustainable Architectural Design*. European Commission Directorate General XVII for Energy. London: James & James Science Publishers, 1999.

“EN 1990.” 2002.

ES ISO 2394: 2012. Ethiopian Standards Agency, 2012.

"Eurocode 8 - Section 6." (n.d.). <http://www.rcsolver.com/en/Eurocode-8-ductility-class>.

Ghosn, Michel. "Application Of Probabilistic Methods In Bridge Engineering." New York: Department Of Civil Engineering , The City College Of New York, 2006.

Google Map. n.d. 09 06 2016. <https://www.google.no/maps?espv=2&biw=1242&bih=585&q=bj%C3%B8rnafjorden&bav=on.2,or.r_cp.&bvm=bv.124088155,d.bGg&ion=1&sns=1&um=1&ie=UTF-8&sa=X&sqi=2&ved=0ahUKEwjf87ShoJ3NAhUBiiwKHdlPDywQ_AUIBygC>.

Kohler, N. and S. Moffatt. "Life-Cycle Analysis of the Built Environment." United Nations Environment Programme Division of Technology, 2003.

Larsson, Nils. *About SBTool 07*. 2007. 20 05 2016. <http://www.iisbe.org/iisbe/sbc2k8/sbc2k8-download_f.htm>.

Lepore, Dr. Domenico. "How Can You Optimize Resources and Processes?" *Resource Optimization* (2015).

Ludescher, Hannes and Rune Pederesen. "OPERATION AND MAINTENNACE IN BJØRNAFJORDEN SUBMERGED FLOATING TUNNEL BRIDGE." 2015.

Maintenance in History, [http://www.leanexpertise.com/TPMONLINE/articles_on_total_productive_maintenance/tpm/tpmprocess/maintenanceinhistory.htm]. 25 August 2011.

MIL-HDBK-338B. MILITARY HANDBOOK, ELECTRONIC RELIABILITY DESIGN HANDBOOK. UNITED STATES OF AMERICA: Department of Defense (DoD), 1998. <http://www.sre.org/pubs/Mil-Hdbk-338B.pdf>.

"NCHRP Report 782." *Proposed Guideline For Reliability-Based Bridge Inspection Practices* (2014).

"NORSOK N-005." n.d.

Pederese, Henning, Poul Innebern and Jacob Egede Andersen. *Operated And Maintennace - Steel Structure*. Oslo: COWI AS, 2015.

—. *Operation And Maintenance - Mooring*. Oslo: COWI AS, 2015.

—. *Operation And Maintenance-Concrete Elements*. Oslo: COWI AS, 2015.

Plessis, Du C. "Sustainable development demands dialogue between developed and developing worlds." Building Research & Information, 1999.

Preventative maintenance (PM). 2015. Maintenance Assistant Inc. 13 12 2015. <https://www.maintenanceassistant.com/preventative-maintenance/>.

"Proposal Regarding " Operation And Maintenance Strategy" For a TLP in BJØRNAFJORDEN." 2015.

Rausand, Marvin and Arnljot Høyland. *System Reliability Theory: Models, Statistical Methods, and Applications*. 2nd. 2004.

Rausand, Marvin. *Risk Assessment: Theory, Methods, and Applications*. New Jersey: John Wiley & Sons, 2011.

S. Roaf. "Benchmarking the ‘sustainability’ of a building project." *Assessing building performance.* Ed. Vischer JC Preiser WFE. Oxford: Elsevier, 2005.

The European Commission. *ENV.2007.3.1.5.2. - Performance indicators for health, comfort and safety of the indoor built environment*. Belgium: CORDIS (Community Research and Development Information Service), 2011.

Walter, S. "Sustainable by Design—Explorations in Theory and Practice." *Earthscan*. London, 2006.