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MASTER'S THESIS

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ABSTRACT

Today there are three commonly used methods in the management of the integrity of a process plant: Reliability Centred Maintenance (RCM), Risk Based Inspection (RBI) and criticality analysis for maintenance purposes described in NORSOK Z-008. All three methodologies work on the same underlying philosophy by combining probability of failure and consequence of failure with the intention to classify the equipment with regards to maintenance or inspection activities.

This thesis explores the possibilities of combining these existing maintenance and inspection methods into one unified approach. The thesis makes a comparison study between key elements of the three methods. These key elements are: grouping and classification of equipment, the use of acceptance criteria, consequence of failure assessment, probability of failure assessment, risk evaluation and updating and evergreening of existing plans.

The result of the comparison study shows that the similarities between the methods were many, both in configurations of the strategies and in how the results are used to govern further actions. The differences found were, in many cases, due to the fact that these methods deal with different equipment; some discrimination between equipment types may also need to be done in a unified approach.

So, in light of the results, we can assume that a unified approach towards maintenance and inspection is feasible without losing vital aspects of any of the methods.

ACKNOWLEDGMENT

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TABLE OF CONTENTS

FIGURE LIST

CHAPTER 1

INTRODUCTION

Chapter 1

Introduction

1.1 Introduction

In the management of the integrity of a process plant the three commonly used methods are Reliability Centred Maintenance (RCM), Risk Based Inspection (RBI) and critical analysis based on NORSOK Z-008. Historically, RCM has come from the civil aviation industry. It helps to rationalize design, maintenance and inspection activities based on operational, economic and safety/environmental criteria. It does this by planning the maintenance tasks and frequencies for performing them based on the failure frequencies and consequences. On the other hand, RBI was developed by the joint efforts of DNV and API and launched in 1995 specifically for use by the oil and gas industry. It is a decision-making technique for inspection planning based on risk – comprising the probability of failure (PoF) and consequence of failure (CoF). NORSOK Z-008 has been developed for the preparation and optimisation of maintenance programmes for oil and gas installations. It is based on risk analysis and cost-benefit principles.

The major difference between the three is that while RCM and NORSOK Z-008 are applied to rotating machineries or mechanical functional systems, the RBI is applied to static or stationary mechanical equipment. Secondly, RCM and NORSOK Z-008 use historical data (failure statistics) to calculate the probability of failure; on the other hand, RBI uses degradation models to calculate the probability of failure. Thirdly, while RCM and Z-008 use Failure Modes and Effects Analysis (FMEA), RBI tends to use Quantitative Risk Assessment (QRA) methodology.

A deeper analysis of the three shows that they work on the same underlying philosophy of calculating the risk by combining the probability of failure and consequence of failure. While the purists may argue about the finer distinctions between the three, it would be interesting to study whether it is possible to combine the three approaches into an integrated approach. The integrated approach would endeavour to optimise inspection, maintenance and availability of plant equipment by introducing a structured means of reliability and risk management techniques.

1.2 Aim of the thesis

The aim of the study is to integrate the three related methodologies (RCM, RBI and criticality analysis) into a single integrated tool. This is done to develop a concept that can be used on both static equipment and rotating machineries. By developing this concept it would be possible to take on larger inspection and maintenance tasks.

This thesis shall focus on how to develop a strategy that can be used in spite of the different equipment characteristics, so as to benefit from the strengths of the three methodologies.

1.3 The scope of work

This work shall contain a detailed comparative study between RCM, RBI and criticality analysis. Based on the comparative study, a platform for an integrated approach shall be developed. The work shall be based upon NORSOK standards and best practice guidance from the industry.

1.4 Limitations

Considering that there are a number of variations of the same methodology, this work is limited to the following:

- The RCM methodology: Based on the book *Reliability-Centred Maintenance* by John Moubray.
- The RBI methodology: Based on DNV's Recommended Practice DNV-RP-G101 *Risk Based Inspection of Offshore Topsides Static Mechanical Equipment*.
- NORSOK Z-008 (Criticality Analysis for Maintenance Purpose), NORSOK Z-013 (Risk and Emergency Preparedness Analysis) and NORSOK Z-016 (Regularity Management & Reliability Technology).

For these methodologies, only topside equipment of offshore oil and gas installations located on the Norwegian shelf have been considered.

1.5 The approach

The approach can be divided into three phases:

1. Literature study.
2. Comparison of the different methodologies.
3. Report writing.

The literature study was conducted to enhance the understanding and knowledge about Reliability Centred Maintenance (RCM), Risk Based Inspection (RBI) and the NORSOK approach to maintenance through the standards Z-008, Z-013 and Z-016. In connection with the literature study dialogues and meetings were carried out with employees and inspection specialists working at DNV. These discussions dealt with the general understanding of the thesis and specifically about aspects around the RBI methodology.

The comparison of different methodologies was done based on the literature study but also involved discussions with experts in the area. Considering the time available and the amount of work, it was decided that this thesis should only compare some of the vital aspects of the methodologies. The following parts were compared:

1. Grouping and classification.
2. Acceptance criteria.
3. Consequence of failure.
4. Probability of failure.
5. Risk evaluation.
6. Updating and evergreening.

1.6 Structure of the thesis

This thesis is built up of four chapters with several different sub-chapters. The theory behind the different maintenance and inspection strategies that have been considered has been presented in Chapter 2. Chapter 3 describes the results and discussion. Chapter 4 gives the major conclusions of the work. The references used for the study are presented at the end; most of the references are information that has been used as background knowledge, and are not directly present in the text.

CHAPTER 2

INTRODUCTION TO RCM, RBI AND NORSOK Z-008

Chapter 2

Introduction to RCM, RBI and NORSOK Z-008

2.1 Introduction to maintenance

"Maintenance is a combination of all technical, administrative and managerial actions, including supervision actions, during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function." (Norwegian Technology Centre, 2001, taken from prEN 13306)
Or:

"Maintenance: Ensuring that physical assets continue to do what their users want them to do." (Moubray, 1997, p. 6)

Today maintenance is an important part of almost any industry in the world and holds a relatively large share of the operational budget. But maintenance is not a new phenomenon; for example, when people in former times were keeping up their tools they were basically doing maintenance. But maintenance was really first introduced alongside the industrial revolution. The first factories were not specially mechanized; a result of this was that downtime was not a big concern for the plant owners. Equipment was also to a large extent both over-designed and not particularly complicated; this caused the equipment to be both reliable and easy to repair (Moubray, 1997). So there was little need for frequent preventive maintenance, and most of the equipment would be run to failure.

This would change drastically during and after the Second World War. The arms race between the Axis and the Allies had required more mechanized and effective factories, planes, vehicles and ships. After the war ended, these plants and machinery were widespread and both society and industry were depending upon them.

When the complexity of the equipment rose, the reliability of the equipment fell; downtime became a serious challenge. This led to a demand for better ways of ensuring that the assets would work as intended and, instead of letting assets run to failure, preventive maintenance was introduced. In the 1960s preventive maintenance consisted of fixed maintenance intervals (Moubray, 1997). Not only did maintenance become a more vital part of most industries, the maintenance costs also went up. As a result, the plant owner had to begin to manage these costs, and maintenance planning and control systems became more common (Moubray, 1997). More mechanized equipment meant higher purchase prices for the assets. To expand the profit, people began searching for ways to expand the lifetime of the equipment (Moubray, 1997).

From mid 1970 and forward to today, the need for maintenance has risen further. Industries such as the petroleum industry, the nuclear industry, the space industry and the airplane industry, to mention some, have brought forward the need for expansion and development of maintenance in the last decades. Higher plant availability and reliability, greater safety, better production quality, no damage to the environment, longer equipment life and greater cost effectiveness were needed (Moubray, 1997). As a product of these demands, the costs of maintenance increase, and today the cost of maintenance is one of the largest expense**s** regarding operational costs.

Today there may be new challenges that have to be solved. For example, on the Norwegian coastal shelf some of the oil drilling platforms is at the end of their indented lifetime; at the same time, their oil reservoir is shrinking alongside with profitability. To be able to keep these platforms in operation, new strategies may be required that make maintenance more cost-efficient.

Another challenge is the area of Lofoten, the Barents Sea and the Arctic areas. To be allowed to operate in these areas, it may be essential to conduct operations without any consequences to the environment. This could require an improvement in the already existing maintenance methods.

2.2 Reliability Centred Maintenance

2.2.1Introduction

The RCM methodology first saw light in the late 1960s as a result of the introduction of the jump jet aircraft. Every aircraft has to have a preventive maintenance programme approved by the Federal Aviation Administration to get a licence. When the first jumbo jet, the 747, was developed, the cost of the existing preventive maintenance programmes would have been too expensive to operate the jumbo jet in a profitable fashion. On that basis, the commercial aviation industry began to re-evaluate its maintenance strategies and the product of this evaluation became the MSG-1 (maintenance steering group-1) for the 747. The new strategy made use of decision trees to rank the different preventive maintenance tasks along with a plan for preserving critical components during flight. By conducting the MSG-1 plan, the maintenance cost went down and the 747 became a reality. During 1975 the programme was adopted by the department of defence under the new name Reliability Centred Maintenance (RCM) (Smith, 1993).

RCM has been described in a number of ways, for example:

*Reliability is the probability that a device will satisfactorily perform a specified function for a specified period of time under given operating conditions (*Smith & Hinchcliffe, 2003).

Reliability centred maintenance: a process used to determine what must be done to ensure that any physical asset continues to do what its users wants it to do in its present operating context (Moubray, 1997, p. 7).

A systematic consideration of system functions, the way functions can fail, and a priority-based consideration of safety and economics that identifies applicable and effective PM tasks (Electric Power Research Institute (EPRI) cited in Rausand, 1998 page 121).

Since then the RCM methodology has spread to several industries worldwide and a number of articles and book have been written on the subject. RCM has become an SAE standard (JA1011-12).

As mentioned, a lot has been written on this subject. In an attempt to be true to one description of the methodology, the rest of the relibability centred maintenance chapter is based on the textbook ***Reliability Centred Maintenance (RCM 2)*** written by John Moubray.

The goal of RCM on the one hand is to reduce the cost of a maintenance programme, and on the other to focus on the reliability of the system; this in general means the plant's capacity to maintain uptime. Through a RCM approach, the resources are distributed to the area of the plant where they could most improve the reliability of the system.

2.2.2 The work process

RCM analysis is carried out by asking seven key questions about the asset or the system that is looked into. These questions are as follows:

1. What are the functions and associated performance standards of the asset in its present operation context?
2. In what ways does it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?

The first question is clarifying what functions the different equipment shall possess. John Moubray states in the book *RCM 2* that: *"A function statement should consist of a verb, an object and a desired standard of performance"* (Moubray, 1997, p. 22).
For example, a pump should pump at least 400m^3/hour crude oil from x to y.

When determining the desired performance level, it is important to take into consideration that the desired performance level cannot exceed the performance standard the equipment is built for. For example, a pump cannot meet a desired performance of 800m^3/hour if the pump is only constructed to manage 600m^3/hour. Therefore, when defining the performance of the assets, the built-in capacity of the asset should be found before the desired standard of performance is determined.

One mistake that may be made is to look only at the pump, and treat different pumps of the same type alike. Different operational contexts could have a large impact on the frequency and severity of the failure mode. For example, both the frequency and severity of failure will change if the pump mentioned above is used to pump water instead of crude oil. Different geographical areas with various working environments would also have an impact, for example the difference between the dry and sandy environment in the oil field in Texas compared to the wet and cold environment on the oil and gas field in the Arctic Zone.

The primary function of equipment or systems is often easy to set, but most equipment also has one or more secondary functions. In most cases it is not enough to look only at the primary function of equipment or a system. A failure on a secondary function may be unacceptable as well. For example, in some scenarios it is not enough that a pump delivers an acceptable flow rate, it is also required that the pump should indicate the flow rate. The indication of the flow rate will then be a secondary function of the pump.

The second question, in what ways does it fail to fulfil its functions, deals with which way the component or system might fail. A functional failure is defined as "*the inability of any asset to fulfil a function to a standard of performance which is acceptable for the user"* (Moubray, 1997).
It is important to record all the functional failures belonging to each function. But what is a functional failure and who should decide whether or not it is a failure? For instance, if the previously mentioned pump can not deliver the desirable amount per time unit, some may say it is failing. Let us say it should have delivered 600m^3/hour, would it then be a failure if it only delivered 595m^3/hour? What about if it delivers more, let us say it delivered 700m^3/hour, is this a failure? Different people in different working positions may have different points of view. It is, therefore, important that a dialogue is created between different work positions to establish the performance standards and define functional failure. For example, it can be decided that a pump has a functional failure if the flow rate deviates more than ±20m^3/hour.

The third question is finding out what causes each functional. *"A failure mode is any event which causes a functional failure"* (Moubray, 1997 p. 22).
The RCM methodology uses Failure Modes and Effects Analysis (FMEA) to identify and record all the failure modes which are reasonably likely to cause functional failure. So that this process is not too time-consuming, it is necessary to rule out failures modes that are so unlikely

that they can be ignored. But if the consequences of these failure modes are likely to be severe, more caution should be taken before they are ruled out.

The RCM categorizes failure mode into three groups. The first group concerns failures that cause the capacity of the equipment or system to drop below the desirable performance level after the asset is put in use. Further, the *RCM 2* gives five main causes for this:

- *Deterioration.*
- *Lubrication failures.*
- *Dirt.*
- *Disassembly.*
- *"Capability reducing" human errors.*

(Moubray, 1997 p. 58.)

The next group concerns failures that cause the performance to rise above the desirable performance level. When the asset performs over the specified level, the deterioration may increase due to the extent of working load. Higher performance of some equipment could also bring the system out of balance. For example, if a pump starts to deliver $800m^3$/hour instead of $600m^3$/hour, the flow into the pump may not be sufficient or the component after the pump may not be able to deal with the increased amount of gas or fluid. *RCM 2* mentions four reasons for increase in performance level:

- *Sustained, deliberate overloading.*
- *Sustained, unintentional overloading.*
- *Sudden, unintentional overloading.*
- *Incorrect process material.*

(Moubray, 1997, p. 61.)

The last group comprises failures that are caused by assets that cannot meet the desirable level of performance because of lack of initial capability. This could be, for example, a pump that the manufacturer states could manage $800m^3$/hour and the user sets the desirable performance level to $700m^3$/hour. But because of faults, this specific pump has just an initial capability of $500m^3$/hour.

The fourth question is trying to state what happens if a functional failure occurs. It is important to note that this question does not deal with the consequence of a failure. For example, if a pump is delivering less than it should, then the answer could be loss of flow rate. Or perhaps the pump has a leak, and then the answer to question four would be loss of containment. In other words, a failure's effects describe what happens when a failure mode occurs.

Question five will categorize the different outcome when a functional failure occurs. In a maintenance point of view, the negative outcome of an event is a consequence of failure. The severity of the consequences of failure can vary a lot. Some may affect the production quality or customer service. Others may threaten safety levels or the environment. Some may also have an impact on several areas and some may not have an impact at all.

This question will describe how and how much it matters when a failure occurs. The RCM methodology begins by looking at the effects of each failure mode, and thereafter classifies them into three broad categories of consequences. Three of the categories - safety and environmental consequences, operating consequences and non-operating consequences - are evident failures. It is important to take into consideration failures that are not detected under normal circumstances; these are what the RCM methodology calls hidden functions. A hidden function would typically concern protective devices; for example, it is hard to find out if smoke detectors are working without testing them, or to know whether a system that should alert operators of dangerous conditions works without the dangerous conditions being present or without testing.

The criteria used to determine whether or not a proactive task is technically feasible are looked more deeply into in question six. RCM makes it clear that a proactive task should be performed if the combination of reduction of the consequence and the cost can be justified. But before a proactive task can be carried out the proactive task needs to be technical feasible. John Moubray claims that a proactive task is feasible if *"……it is physically possible for the task to reduce, or enable action to be taken to reduce, the consequences of the associated failure mode to an extent that might be acceptable to the owner or user of the asset"* (Moubray, 1997).

In order to carry out and to choose proactive tasks, there are two matters that are important. The first is the relationship between the age and the probability of failure. The second is how the failure progresses when it starts to occur.

The seventh question deals with cases where a proactive task cannot be found. A default action is chosen if a proactive task is not beneficial. Default actions could be redesign, failure findings or run to failure.

2.2.3 Grouping and classification

To conduct the RCM methodology the way it should be done, it is important to get a systematic overview of all the equipment that is relevant for the analysis. RCM uses hierarchic levels to group and classify the equipment, functions and failures at different levels. These levels go from plant level to system level, sub-system levels and all the way down to single components. Based on this, the decision on which equipment hierarchy level the analysis should be done is taken. How the asset is grouped and classified in a RCM analysis depends on the level the analysis is performed on. It is possible to break down a system into single components, but this would make the analysis very time-consuming and expensive. John Moubray explains in *RCM 2* that one of the more common mistakes regarding RCM is that the analysis is often carried out at too low a level in the equipment hierarchy. The RCM process should start at a high level in the equipment hierarchy, and if necessary break the asset down into sub-systems. The functions of the equipment and the level of desirable performance have to be settled. Assets usually have both primary and secondary functions; these need to be specified.

RCM uses FMEA worksheets to classify equipment or systems.

2.2.4 Acceptance criteria

Risk acceptance criteria with respect to safety and environmental protections are used as a boundary for the RCM process. If the risk level exceeds the acceptance criteria, some action has to be taken to reduce either the consequence of failure or the probability of failure. The handbook *RCM 2* suggests that:

"For failure modes which have safety or environmental consequences, a proactive task is only worth doing if it reduces the probability of the failure to a tolerably low level" (Moubray, 1997).

This means that if the probability of failure can not be reduced sufficiently by proactive actions, the consequence has to be minimized by redesign or by changing the settings in such a way that the failure no longer has a consequence for safety or the environment.

In the RCM methodology there is an acceptance criteria of few or no risks regarding operational and non-operational losses. Instead it is more of a cost-benefits analysis that determines what should be accepted. The *RCM 2* handbook states that:

"For a failure mode with operational consequences, a proactive task is worth doing if, over a period of time, it costs less than the cost of the operational consequences plus the cost of repairing the failure which it is meant to prevent" (Moubray, 1997, p. 106)
and:
"For failure modes with non-operational consequences, a proactive task is worth doing if over a period of time, it costs less than the cost of repairing the failure it is meant to prevent (Moubray, 1997, p. 109).

2.2.5 Consequence of failure

The RCM methodology divides consequence first into two: evident failure and hidden failure. Evident failure is then divided into three categories. If a failure has the potential to kill or injure someone, or if the failure can result in damage to the environment, these failure would then be classified under safety and environmental consequences. Failures that can have an unwanted impact on the operations or the productions would be classified under operational consequences. Consequences that affect neither safety nor operation are gathered under non-operational consequences, this would typically be cost regarding repair.

Hidden failure is failure that would not be detected under normal circumstances. These failures would often not have a direct effect on their own, but they can contribute to the severity of an evident failure.

2.2.6 Probability of failure

To be able to decide the criticality of the different assets in a RCM analysis, the RCM methodology uses probability of failure values or failure rates multiplied with the severity of the consequence of failure; the answer is called the PRN (probability/risk number). The asset with the highest PRN is the asset that is analyzed first.

2.2.7 Risk evaluation

Risk is a combination of consequence of failure and probability of failure. RCM uses three questions to determine the degree of risk that is tolerable. The first question is to determine the consequences by asking: *"what could happen if the event under consideration did occur?"* Next the probability is discussed by asking: *"How likely it is for the event to occur at all?"* These two questions give an estimation of the risk belonging to a specific process. The last question is: *"Is this risk tolerable",* which is based upon risk acceptance criteria.

The risk level in the specific industry is also a factor that has to be included. For example, there is a bigger risk involved in working on an offshore installation compared with working in a grocery store. This means that sometimes a bigger risk has to be taken in some industries than in others.

RCM is of the opinion that the evaluation of the risk should be done by a group. The group should represent people who have a clear understanding of the failure mechanisms and knowledge of both the likelihood of failure and possible measures to reduce the risk. (Moubray, 1997).

RCM uses various factors in the task of deciding what is tolerable. Firstly - and perhaps most importantly - is how the risk can be controlled or to what degree the people affected by the risk can control it.

Another factor is what kind of employees may be affected; for example, a soldier would possibly have a different view of tolerable risk in a war zone than a civilian working in an oilfield. Or a person with diving training would perhaps have different and fewer concerns regarding an overturn of a helicopter than a person with hydrophobia or claustrophobia.

2.2.8 Updating and evergreening

When the RCM analysis is finished the process does not end. Through an RCM analysis, many decisions have been taken based on incomplete, inaccurate or non-existent data. Decisions have also been taken about the consequences and likelihood of failure modes which have not happened yet or perhaps will never happen. Another factor challenging the RCM process is that the assets and the process will change over time, meaning that the present analysis will be old and perhaps useless after a given time.

This means that the RCM analysis should be updated regularly to supplement the analysis and to make sure that the analysis is still valid.

2.3 Risk Based Inspection

2.3.1 Introduction

Risk based inspection (RBI) is a methodology which aims at establishing an inspection programme based on the aspects of probability and consequence of a failure. RBI focuses on avoiding loss of containment of pressurized equipment, due to material deterioration. RBI normally addresses the deterioration of static process equipment such as piping and vessels, including heat exchangers, tanks, pressure vessels, and filters (DNV, 2009).

Inspection is one of the many dedicated activities within offshore management that contribute to controlling and minimizing offshore risks. Inspection is carried out to reveal and confirm whether the process of degradation in a component is occurring. Inspection of the equipment will also give vital information on how the real process is developing compared to the expected scenario. This information can be used to define new measures to improve both the design of the equipment and the actions that are taken to preserve the risk level of the component. This will also provide assurance that the asset integrity is maintained in accordance with the intention of the design. Chapter 2.3 is based on the DNV's recommended practice DNV RP-G101.

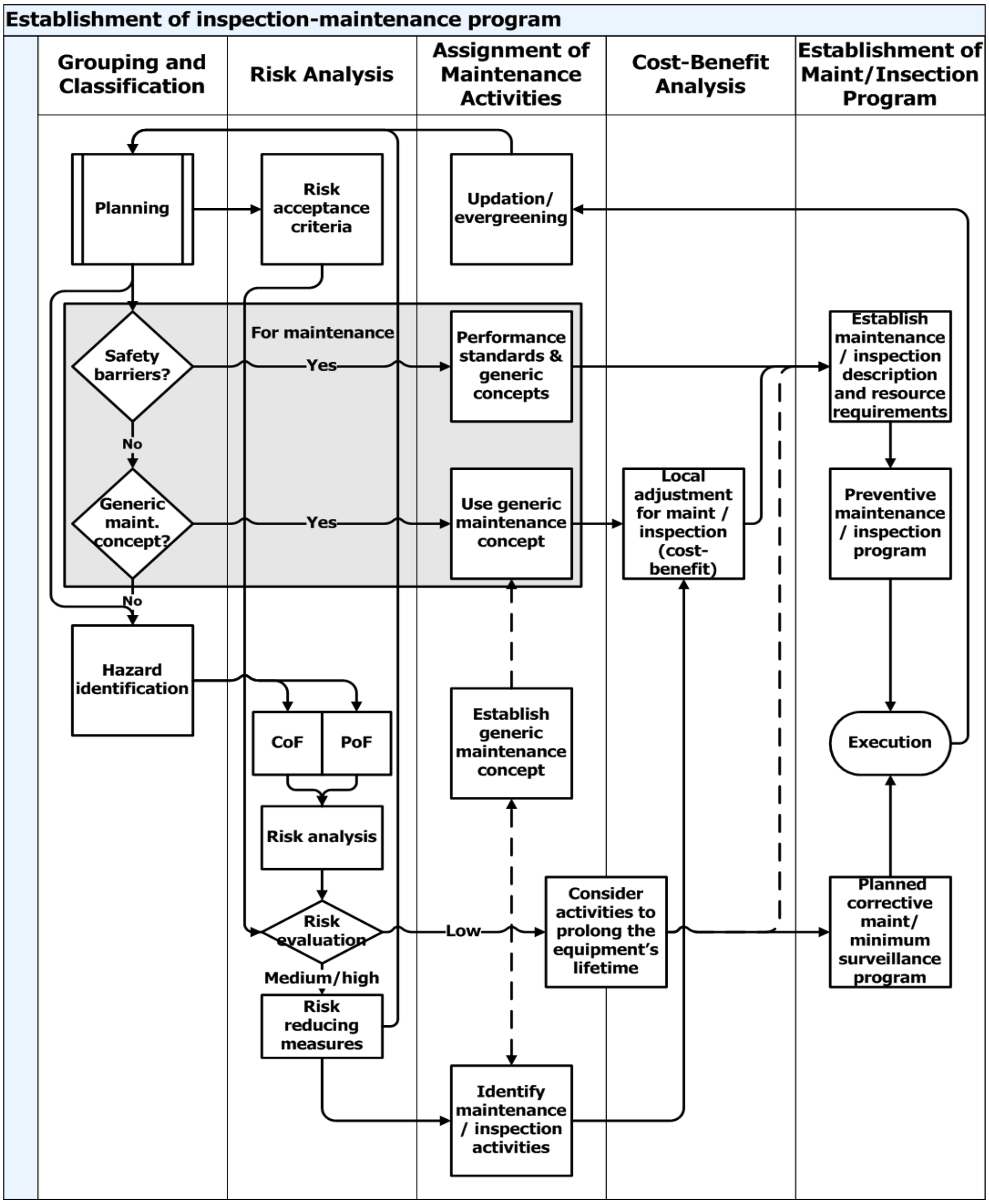


FIGURE 2.1 Establishment of inspection-maintenance program (DNV, 2009)

2.3.2 Process

RBI is a management tool to optimise inspection, and to make recommendations for monitoring and testing plans for production systems (DNV, 2009). By conducting a RBI analysis the final results should answer what to inspect, when to inspect, where to inspect, how to inspect and what to report.

To determine what part of a system or which components to inspect, RBI uses, as mentioned, risk as a prioritisation criterion.

The results of a risk based inspection programme can be summed up in Figure 1.2

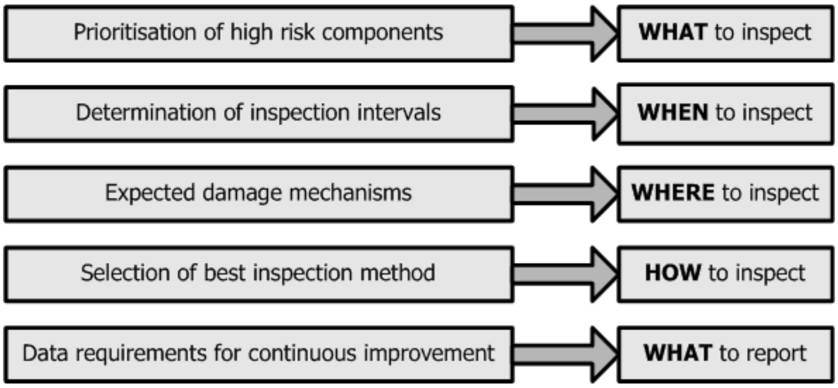


FIGURE 2.2 Deliverables of an RBI assessment to the inspection program (DNV, 2009)

Before the RBI assessment can be carried out, information needs to be collected. The more information that is available the more accurate and more easy the RBI assessment will be to complete. Because of the assessment of risk in the RBI process, there is a need of a minimal information level to ensure that the risk picture gives a correct view of the situation. When there is a lack of vital information, the risk assessment may be too inaccurate, and instead of describing the real risk it may give a description of the risk that is misleading. In such cases RBI should not be chosen. Here are some typical input sources, taken from DNV RP-G 101 page 25, which are needed in the RBI evaluations:

- *Line list*
- *Equipment list*
- *System descriptions manual*
- *Engineering numbering system*
- *Equipment data and vessel sheets*
- *Piping data sheets*
- *Inspection/failure/replacement details*
- *Inspection/failure/replacement history knowledge*
- *Corrosion protection philosophy*
- *Coating specifications*
- *Insulation specifications*
- *Quantitative Risk Analysis (QRA)*
- *Design accidental load analysis*
- *Production data (past and future)*
- *Key operation and maintenance personnel*

(DNV, 2009)

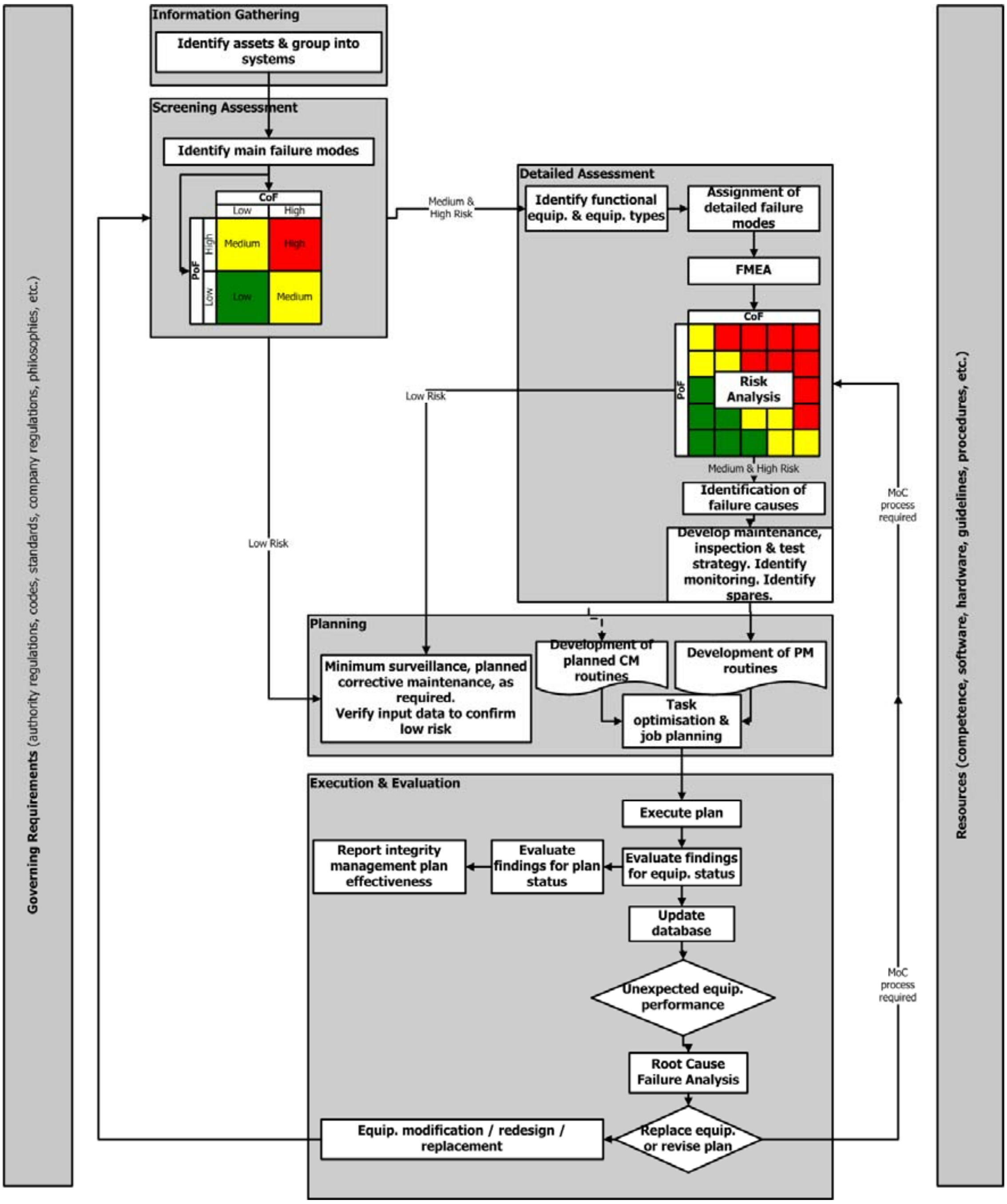


FIGURE 2.3 RBI generic inspection programme (DNV, 2009).

After the information is gathered the next step is a screening assessment, where equipment with low consequences and low probability of failure is separated from further assessment. Equipment with either high or medium consequence or probability of failure is brought forward for a more thorough evaluation.

The task of the detailed assessment is, according to DNV RP-G101, to: "...*identify the relevant degradation mechanisms, estimate the extent of damage, estimate when inspection should be carried out, and propose what inspection technique should be used to ensure acceptable risk levels*" (DNV, page 20, 2009).

The results of the screening assessment and the detailed assessment are used as an input in the planning process. The planning process is not carried out by the same team that worked out the screening and the detailed assessment. The planning team work at the inspection point level, also taking into consideration other factors that have not been covered in the previous work. These factors can be logistic, a need for interaction with maintenance activity and permission for inspection by operations personnel.

The final plan is executed and any new information is used to update the plan. In the following chapters the thesis will go more closely into some of the main parts in the RBI process.

2.3.3 Grouping and classification

On a plant there are different equipment levels. Before an RBI analysis can be carried out the equipment needs to be grouped into specific hierarchic levels. The RBI methodology makes use of five equipment levels.

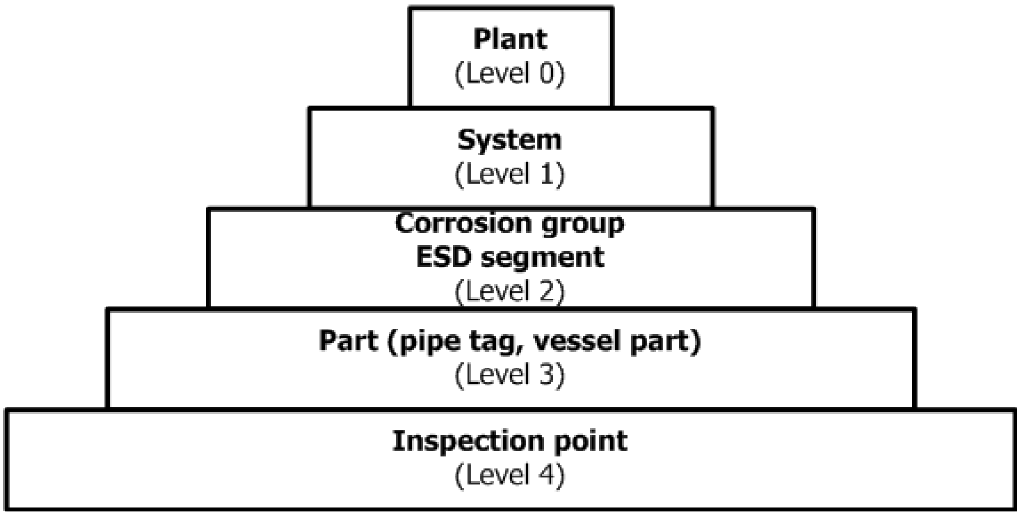


FIGURE 2.4 RBI hierarchical system

The highest level in the hierarchy refers to the plant level. An assessment at this level is used to prioritise between different plant and installations when it comes to budgets or distributions.

The next level is the system level. This level consists of all the main system that together runs the plant. DNV RP-G101 mentions the separation and stabilization system, the open drain system, the closed drain system and flare system among others as examples of systems (DNV, 2009). Assessment at the system level is, in most cases, used to identify systems that are significantly contributing to the risk level for the plant.

The system level is broken down into corrosion group and/or ESD segment levels. At this level the groups of components should be defined such that assessment for one component can be applied to the rest of the group. A corrosion group should contain components with similar failure mechanisms in order to ease the probability of failure assessment. Since a segment is a pressurized system which can be automatically closed-in by emergency shutdown valves, the maximum volume released from a leak is defined by the volume in the segment. ESD segment is therefore defined to ease the consequence of failure assessment.

The ESD segment level or the corrosion group is broken down into either pipe tag or vessel part. This level is used to look more closely into specific parts that may have a certain relevancy for the risk assessment. To assess all components at this level takes too many resources, and is therefore not practicable. Based on the assessment on this level the inspection plan is developed.

The bottom level is the inspection point level. Assessment at this level is only carried out for inspection points of special concern.

2.3.4 Acceptance criteria

Inspection is carried out to maximize the availability and profitability without having a negative influence on the safety of humans and the environment. DNV RP-G 101 recommends that authority and corporate/management targets for safety, profit and availability should be used as acceptance limits when planning the inspection. The risk acceptance criteria can be expressed qualitatively, quantitatively, semi quantitatively or technically.

When a quantitative approach is chosen, risk acceptance criteria should be established for each type of risk. These criteria are used to prioritise components for inspections and used as a foundation to make sure that inspection is carried out before risk breaches the acceptance criteria.

Risk limits for personnel safety are often governed by the authorities. One way for an organization to develop risk acceptance criteria based on the limits given by the authorities, is to first carry out a risk analysis to determine whether the risk on the installation meets the requirement given by the authorities. If the risk level is acceptable, it is possible to use the following technique given by DNV RP-G101:

- *"The quantitative risk analyses usually present how process accidents are estimated to contribute to the total risk (typically 30-50% contribution).*
- *Statistics regarding contribution of process accidents from different types of equipment (about 30% of process accidents occur in piping).*
- *Statistics regarding 'inspectable' events. Historic data shows that corrosion causes about 30% of piping failures in the process system."*

  (DNV, 2009, p. 52)

Based on this information it is possible to derive a risk acceptance criteria that represents static process equipment.

Environmental consequences are measured in volume or mass release, or in monetary cost based on volume or mass that are released and the clean-up cost. If clean-up cost and fines are included in the economical assessment, then the environmental assessment is ruled by the economical assessment. DNV RP-G101 recommends this approach if a quantitative method is chosen. If the economical and the environmental risk assessment are kept separate a qualitative method is recommended.

Acceptance for economical risk can be based on either availability or on inspection costs. Acceptance criteria based on availability derives from availability targets that are broken down similarly to the method used for safety acceptance limits. The other option is to base the acceptance criteria on cost benefit. According to this method, inspection is only carried out when it is "worth spending the money". If the inspection cost is of a higher magnitude than the economical consequences, inspection is not carried out.

2.3.5 Consequence of failure

The failure mode in an RBI assessment is loss of containment. The consequence is then evaluated as "*the outcome of a leak given that such a failure will occur*" (DNV, 2009, page 15).

The RBI methodology divides consequence into three main groups: safety consequences, environmental consequences and economical consequences. The safety consequences deal with injuries and deaths due to occurrence of failure. Failure modes that could have an unwanted effect on the environment are classified under environmental consequences. Financial loss due to downtime, production quality, repair etc. is gathered under economical consequences.

Since RBI mainly looks at the containment function of a system, the failure mode is loss of containment. When a leak occurs there can be two scenarios, the leak is ignited or not. In DNV RP-G 101, some factors that are considered when a leak occurs are listed:

TABLE 2.1 Factors to consider in consequence assessment (DNV, 2009).

Ignited leak		
Safety Consequence	**Economic Consequence**	**Environmental Consequence**
Consider loss of life due to: ⇒ Burns to personnel ⇒ Direct blast effects to personnel ⇒ Indirect blast effects to personnel (missiles, falling objects) ⇒ Injuries sustained during escape and evacuation	Consider the costs of: ⇒ Repair of damage to equipment and structure ⇒ Replacement of equipment and structural items ⇒ Deferred production ⇒ Damage to reputation	Consider the effects of: ⇒ Toxic gas release ⇒ Smoke
Unignited leak		
Safety Consequence	**Economic Consequence**	**Environmental Consequence**
Consider loss of life due to: ⇒ Toxic gas release ⇒ Asphyxiating gas release ⇒ Impingement of high pressure fluids on personnel	Consider the costs of: ⇒ Deferred production ⇒ Repairs	Consider the effects of: ⇒ Hydrocarbon liquids spilled into the sea

Except for the repair cost, the consequence is not dependent on the equipment that fails. The severity of the consequence is determined based on the conditions the failure creates and the circumstances in which the failure occurs. For example, if the containment function of a pump fails, the consequence is dependent on the volume released, whether the release is toxic or whether the leak gets ignited and not the fact that the failure happened in a pump. Based on this, the consequence assessment should be carried out at either the system level or at the ESD segment level. Consequence for failure can be described quantitatively, qualitatively or by using a mix between those two.

RBI does not take redundancy into account in the consequence assessment.

2.3.6 Probability of failure

The analysis object for the RBI is, in general, pressurized pipes and vessels, and the failure mode is loss of containment caused by degradation of the equipment. The probability of loss of containment is related to the extent of the degradation and the uncertainty regarding the component's ability to resist its loading (DNV, 2009).

RBI makes use of three different degradation models which show the expected failure rates.

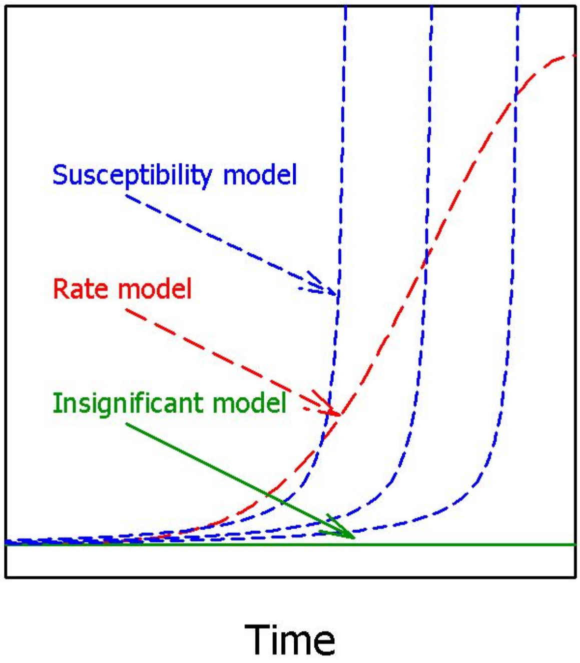


Figure 2.5 RBI degradation rates (DNV, 2009)

The insignificant rate model deals with components where degradation is unexpected. When degradation is not expected, components gets assigned a fixed probability of failure value of 10^-5. Based on the assumption that there is no degradation mechanism present, the risk value will be the same regardless of time. In this case the only reason for inspection of such components would be to determine that the premises have remained valid.

The rate model is applied when the result of degradation is wall thinning of the components. When wall thinning occurs, the probability of failure will increase with time. The DNV RP-G 101 lists four factors that the rate models depend on; these are:

- *Material properties.*
- *Wall thickness.*
- *Fluid properties.*
- *Operating conditions.*

(DNV, 2009)

Since the probability of failure increases with time, inspection can be a tool to measure the development of degradation. If inspection is chosen, the inspection results can and should be used to update and adjust the rate model to fit to the actual situation.

The susceptibility model describes the contribution made by external events to probability of failure. The probability value is set, based on the environmental and operational conditions. When such an event occurs, the damage happens very quickly. Therefore, it is difficult to discover and actuate countermeasures in time, by the use of inspection. But DNV RP-G 101 states that it can be beneficial to monitor key process parameters *"such as excursions or change of conditions that can trigger degradation"* (DNV, 2009).

The unknown model deals with components that have inadequate information. In such cases the components are assigned a PoF value that equals 1 and further investigation is needed.

In the RBI assessment the likelihood of a failure occurring is composed of four probability shares. The first one, PoF technical, expresses the uncertainty around the design loads and load bearing capacities. These are typically normal random variable and man-made uncertainty (DNV, 2009).

PoF accidental uses historical data to determine the probability of failure caused by accidental events. Such events can, for example, be a blow from a hanging load or a dropped object.

PoF gross error focuses on failure caused by human mistakes. These mistakes can be found in all phases in the lifetime of an installation, e.g. fabrication, installation, operation etc.

PoF unknown are probabilities of failure on the basis of unknown or very rare or unexpected phenomena. These are often very unlikely to occur but they may represent a very high consequence if they do occur, and therefore they can influence the overall risk picture.

When the assessment is done quantitatively, it is usually only the PoF technical that is used, but PoF technical can also be done quantitatively.

2.3.7 Risk evaluation

Risk is the combination between consequence of failure and probability of failure and, in an RBI assessment, can be done quantitatively, qualitatively or by using a combination of the two. One way to present the risk is by using a risk matrix; DNV RP-G 101 recommends the use of 5x5 matrixes to achieve adequate resolution of detail. It can be beneficial to use separate matrixes for the different consequence classes.

PoF Ranking	PoF Description	Time to Inspect (years)				
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	Corrective Maintenance	4	2	1	1
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	Corrective Maintenance	4	2	1	1
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	Corrective Maintenance	Corrective Maintenance	4	2	2
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	Corrective Maintenance	Corrective Maintenance	8	4	4
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	Corrective Maintenance	Corrective Maintenance	8	8	8
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirnonment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	Business	No downtime or asset damage	< € 10.000 damage or downtime < one shift	< € 100.000 damage or downtime < 4 shifts	< € 1.000.000 damage or downtime < one month	< € 10.000.000 damage or downtime one year
CoF Ranking		A	B	C	D	E

FIGURE 2.6. Example of decision risk matrix (DNV, 2009)

Risk that lies in the green area is seen as acceptable; this means that action only needs to be taken to insure that the risk would not increase with time. The yellow area represents medium risk; the risk is acceptable but actions have to be implemented to prevent the risk from rising further. Typical actions that are implemented are, for example NDT, functional tests and other condition monitoring.

The red area represents risk that exceeds the risk acceptance criteria, and therefore the risk is not acceptable. Action must be taken to lower the consequence, probability or both sufficiently that the risk lies within the acceptable region.

DNV RP-G 101 mentions two ways the risk assessment can be implemented. One is to use risk to prioritise among the equipment and system. Rank the most critical items based on the risk levels, and address the item with the highest risk level first. The second way is to use risk acceptance criteria and, based on the degradation rates, address first equipment where risk will soon cross the risk acceptance limit.

2.3.8 Updating and evergreening

The results and knowledge that are gained through the inspections process shall be used to update the plans for future inspections. The RBI process works in a loop; when new relevant information is discovered the plan should be revised in order to be up-to-date.

2.4 NORSOK Z-008

2.4.1 Introduction to Z-008

The NORSOK standards have been developed by the Norwegian petroleum industry to assure that the safety, value-adding and cost-effectiveness for existing and future activity is at an acceptable level. This thesis will mainly be focusing at the NORSOK standard Z-008 since this especially concerns maintenance.

The NORSOK Z-008 is the standard for the optimisation and preparation of maintenance programmes for new and in-service installations offshore and onshore. This standard manage the integrity of equipment and plant systems including sub-sea production systems, offshore topside systems and oil and gas terminals. NORSOK Z-008 covers equipment like mechanical equipment, instrumentation and electrical equipment. The standard does not concern load bearing structures, floating structure, risers and pipelines.

The Z-008 leans upon the RCM methodology for the analysis work; the standard recommends that when a generic maintenance programme is not established, a more detailed RCM analysis should be carried out.

The NORSOK Z-008 does not stand alone, as the figure below shows; the Z-008 is in interaction with both NORSOK Z- 013 (risk and emergency preparedness analysis) and NORSOK Z-016 (regularity management and reliability technology).

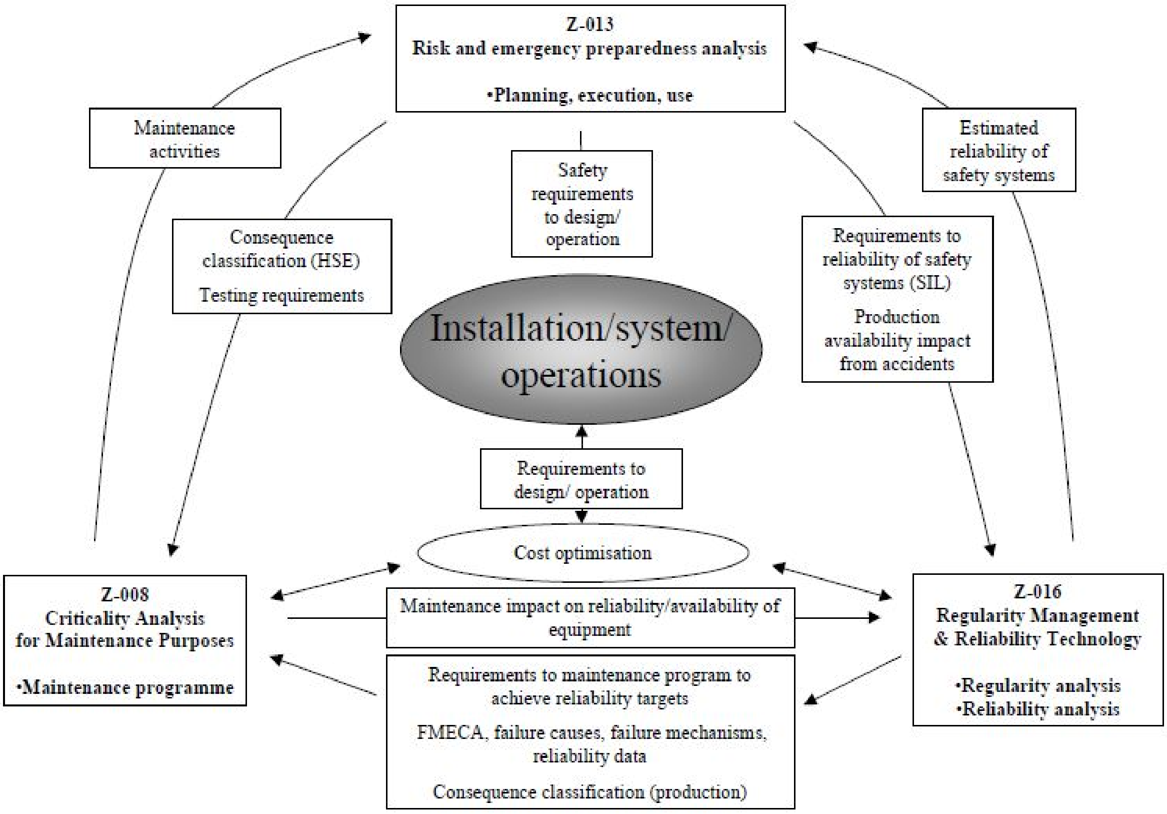


FIGURE 2.7 Relations to other NORSOK standards (NORSOK Z-008, 2001)

The next chapter is, to a large extent, based upon Z-008.

2.4.2 Process

Based on risk assessment and a cost-benefits mentality, the NORSOK Z-008 is establishing a foundation for the preparation and optimisation of maintenance programmes. Z-008 recommends that historical data and experience from both operations and maintenance should be used as a basis for the maintenance programme; this method is called the generic maintenance concept. If there is lack of information or experience, Z-008 recommends that an RCM analysis should be carried out.

2.4.3 Grouping and classification

The Z-008 is of the opinion that the equipment must be arranged into a hierarchical system. The Z-008 operates with five different levels, beginning at the top with plant, then system, main function, maintenance object and finally tag number.

Pieces of equipment, identified by their tag number, that are carrying out the sub-functions shall be assigned to only one sub-function. Some may be involved in more than one sub-function; in this case the equipment should be assigned to the most critical sub-function. All equipment shall have the same descriptions, the same consequence classification and redundancy as the sub-function they are grouped under.

2.4.4 Acceptance criteria

Z-008 only briefly refers to risk acceptance criteria; it states that: *"requirements should be made with respect to availability, capacity and performance of safety critical functions…".* These requirements should be based upon OLF 066 recommended guidelines for the application of IEC 61508 and IEC 61511 in the petroleum activities on the Norwegian shelf, NORSOK standard Z-013 and NORSOK standard Z-016. (Z-008., 2001, rev.2)

According to the NORSOK standard Z-013 the basis for the risk acceptance criteria should include;"

1. *The regulations that control safety within the activities.*
2. *Recognized norms for the activities.*
3. *Requirement for risk reducing measures.*
4. *Knowledge about accidents, incidents and consequences of these.*
5. *Experience from own similar activity."*

(Z-013, 2001, page 34 , rev. 2)

Z-013 states that risk acceptance criteria seldom applies for regular maintenance, but risk criteria can be used in maintenance planning to achieve a cost-effective programme and the risk acceptance criteria can be used to rank and prioritise equipment (Z-013, 2001, rev. 2).

2.4.5 Consequence of failure

Z-008 classifies consequence into three groups: HSE (health, safety and environment), production and cost. According to Z-008, HSE consequences can jeopardize the safety of humans and the environment. Consequences regarding loss of income caused by downtime, reduced production or loss of production quality are classified as production consequences. Cost consequences are loss of funds excluding production loss.

Main functions and sub-systems can contain redundancy. This means that if a failure occurs, the consequence will be reduced since there are other parallel units doing the same job. Sub-functions with redundancy should be identified and the degree of redundancy should be calculated. Z-008 classifies main functions and sub-systems into three levels of redundancy, as the figure below is an example of.

Red.	Redundancy degree definition
A	No redundancy i.e. the entire MF is required to avoid any loss of function.
B	One parallel unit can suffer a fault without influencing the function.
C	Two or more parallel units can suffer a fault at the same time without influencing the function.

FIGURE 2.8 Classification of redundancy for main function (NORSOK Z-008, 2001)

2.4.6 Probability of failure

Probability of failure should be based on documented operational experience and failure characteristics, in other words, failure history and expert opinion. When there is an existing generic maintenance programme that fits, this should be used. But situations occur where the actual equipment has significant differences compared with the equipment that has formed the basis for the generic maintenance programme. The new equipment shall then be treated separately as a separate generic class. Another factor is that operational conditions can change from area to area. When adopting a generic maintenance programme, an assessment should be done to discover the effect the operational conditions, location and external environmental impacts may have on the probability of failure. This should be done before the assignment of generic maintenance programmes.

In cases where a generic maintenance concept has not been developed, the probability of failure should be accessed through an RCM analysis by doing an FMECA. An FMECA is a quantitative method to analyse failure mode, effect and the probability of failure. When estimating the probability of failure, the data used should be based on operational experience of the actual equipment, and by using failure data from existing or similar operations.

2.4.7 Risk evaluation

According to the Z-008, the assessment of consequence and probability should be done separately. This is based on the fact that the consequence of system faults such as the loss of main and sub-functions **is** independent of the equipment carrying out the function. For example, if a sub-system experiences a fault, the severity of the consequence will depend upon the result of the failure, not the source of the failure. This changes when assessing probability of failure, because the probability of a failure depends on the reliability of the equipment and the influence of operational conditions on the equipment.

Since the consequence of failure is independent of the equipment, the consequence evaluation is done for each system by the same principles regardless of whether a generic maintenance concept or an RCM analysis is used. Consequences for production loss or direct costs are measured by the effect the failure has on the installation; the consequence value is then in downtime or monetary terms. Consequences regarding personal injury and environmental damage are classified in accordance with pre-defined consequence classes and acceptance criteria. The figure below shows how a consequence of failure can be expressed.

Consequence	S- Safety & environment	P- Production availability	C - Cost
3 - High	• Potential for serious personnel injuries • May render safety systems inoperable • Potential for fire in classified areas	• Stop in production / significant reduced rate of production exceeding X hours (specify duration) within a defined	• Substantial cost • exceeding Y NOK (specify cost limit)
2 – Medium	• Potential for injuries requiring medical treatment • Limited effect on safety systems controlling hydrocarbons	• Brief stop in production / reduced rate of production lasting less than X hours (specify duration) within a defined period of time	• Moderate cost between Z – Y NOK. (Specify cost limits)
1 – Low	• No potential for: Injuries, fire or effect on safety systems.	• No effect on production within a defined period of time	• Insignificant cost less than Z NOK. (Specify cost limit)

FIGURE 2.9 Consequence of failure NORSOK Z-008 (NORSOK Z-008, 2001)

The assessment of probability of failure is dependent on the reliability of the equipment; this means that the data shall be based on operational experience and failure characteristics.

2.4.8 Updating and evergreening

The NORSOK Z-008 does not suggest a clear practice when it comes to updating the maintenance programme. But it recommends that the assessment should be documented and made available for updates and improvements, when more information and facts from operation become available. Z-008 states that at least decision criteria, definition of consequence classes, main function description, sub-function description, assignment of equipment to sub-function and the assessment of the consequences of loss of main functions and sub-functions for all consequence categories, including necessary arguments for assignment of consequences classes, should be documented and made available for updates.

CHAPTER 3
SUGGESTION FOR A UNIFIED APPROACH

CHAPTER 3

SUGGESTION FOR A UNIFIED APPROACH

3.1 Introduction

As mentioned, different inspections and maintenance methods are used on different equipment. Different groups can be working alongside each other to avoid failure of mid or high risk systems or equipment. The question is: is it necessary to deal with inspection and maintenance with more than one methodology, or is it possible to develop a new method that can be used on both static and dynamic equipment?

There are several advantages if a unified approach can be developed. One of them is that it makes it possible to establish an overall risk picture of all the process systems on a plant, based on the maintenance and inspection results. Based on regular inspection or maintenance intervals, this risk picture can be kept up-to-date at all times. As a result of this, the management has the opportunity to act in accordance with a complete and up-to-date risk assessment of the process systems.

At the moment, maintenance and inspection activities are planned separately; a combined plan for maintenance and inspection activity could be beneficial. For example, if a maintenance activity required a halt in production or scaffolding, inspection could also make use of the conditions that are settled by the maintenance and vice versa.

Systems or sub-systems often contain a number of different components, both static and dynamic equipment that has to interact to perform the intended system function. At present inspection only deals with static equipment and maintenance only takes responsibility for the dynamic equipment. This type of practice depends on exchanging information between the maintenance and inspection management; if this dialogue is poor or non-existent, vital information may be lost. For example, if sand is detected in one of the pumps and this information is not handed over to the inspection group, the deterioration rate may increase without the inspection noticing it. With a combined inspection and maintenance strategy, this exchange of information would be easier, since the information flow between inspection and maintenance would happen within one group.

One joint maintenance and inspection group may also make it easier to control overlap between static and dynamic equipment. The risk based inspection and the generic maintenance and the reliability centred maintenance make use of the same principles; this means that a unified inspection and maintenance group can save resources since personnel can be used at both fields.

The advantages can be many, but is it possible to unify an existing maintenance and inspection programme into a new approach?

3.2 Relation between RCM, RBI and Z008

A revision of the seven questions:

1. What are the functions and associated performance standards of the asset in its present operation context?
2. In what ways does it fail to fulfil its functions?
3. What causes each functional failure?

4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?

In Figure 3.1 a comparison between the three methodologies has been done, in which all three methodologies are following the same seven questions of RCM in an assessment of a pipe.

The seven questions of RCM	RCM of Pipe	RBI of Pipe	Z008 of Pipe	RBM of Pipe
What are the functions and associated performance standards of the asset in its present operating context?	Transport fluid or gas	Contain fluid or gas	Transport fluid or gas	Contain and transport fluid or gas
In what ways does it fail to fulfil its functions?	Loss of containment and loss of flow.	Loss of containment.	Loss of containment and loss of flow.	Loss of containment and loss of flow.
What causes each function failure?	Corrosion, erosion and obstruction	Corrosion, erosion	Corrosion, erosion and obstruction	Corrosion, erosion and obstruction
What happens when each failure occurs?	Leakage: Fire, explosion, toxic release, loss of flow	Leakage: Fire, explosion, toxic release.	Leakage: Fire, explosion, toxic release, loss of flow	Leakage: Fire, explosion, toxic release, loss of flow
In what way does each failure matter?	Loss of life,environmental damage. Loss of production, repair costs	Loss of life,environmental damage. Loss of production, repair costs	Loss of life,environmental damage. Loss of production, repair costs	Loss of life,environmental damage. Loss of production, repair costs
What can be done to predict or prevent each failure?	Monitoring and inspection of the degradation rate MTTF, MTTR or failure rate	Monitoring and inspection of the degradation rate PoF	Monitoring and inspection of the degradation rate MTTF, MTTR or failure rate	Monitoring and inspection of the degradation rate PoF, MTTF, MTTR or failure rate
What if a suitable proactive task cannot be found?	Failure finding, redesign, run to failure.	Redesign, run to failure.	Failure finding, redesign, run to failure.	Failure finding, redesign, run to failure.

FIGURE 3.1 RCM, RBI, NORSOK Z-008 and RBM assessment of pipe.

Question 1:

There are some differences; for example, the RCM and the Z-008 are focusing more on how the equipment functions in interaction with the system, and therefore the function of a pipe will be described as transporting fluid or gas. RBI, on the other hand, is focusing more on the specific task of the pipe itself, which is containment.

Question 2:

The occurrence of functional failure can also vary slightly. There are two possible events that can create functional failure in the RCM and the Z-008 assessment: both obstruction and loss of containment can obstruct the transport of gas or fluid. Since RBI only defines the function of a pipe to contain gas or fluid, the only functional failure would then be loss of containment.

Question 3:

What causes functional failure would also not be identical; in addition to corrosion and erosion, the RCM and Z-008 also take obstacles into consideration.

Question 4:

If a failure does happen, RBI only considers possible events that arise caused by leakage; RCM and Z-008 also take into consideration loss of flow.

Question 5:

The possible consequence of failure is the same for all three methodologies; the only difference is that RCM and Z-008 also evaluate production consequences regarding obstruction of flow.

Question 6:

RCM and Z-008 use often expressions like mean time to failure (MTTF) to predict failures and RBI uses degradation rates. In reality, all three are using failure rates to predict time to next failure. RCM and Z-008 use historical data to predict failure rates, RBI uses different parameters to calculate failure rates.

Question 7:

If a proactive task cannot be found all three methodologies, recommend redesign or corrective maintenance based on whether or not the risk is acceptable. RCM and Z-008 can also use failure finding tasks by checking hidden functions for whether they have failed or not.

The examples in this chapter show that in spite of some differences between them, there are also several similarities. The author means that an inspection or maintenance method should not be limited before the assessment, and all relevant equipment functions, failure modes and so on should be taken into consideration before they are ruled out.

As this chapter has shown, the RBI assessment is not that different from RCM when using the same seven questions. This example is hypothetical, but the next chapter focuses on how RBI deals in reality with the same key topics as RCM.

3.2 Identification of 7 Questions in RBI flowchart

Both risk based inspection and reliability centred maintenance are management decision tools to determine when, where, what and how much maintenance or inspection should be done. As mentioned, the RCM proceeds by asking seven questions; the answers to these questions give the information that is needed in the assessment. But these questions are not really unique to RCM. The figure below shows that almost all the questions the RCM methodology uses as a framework are indeed answered through an RBI assessment.

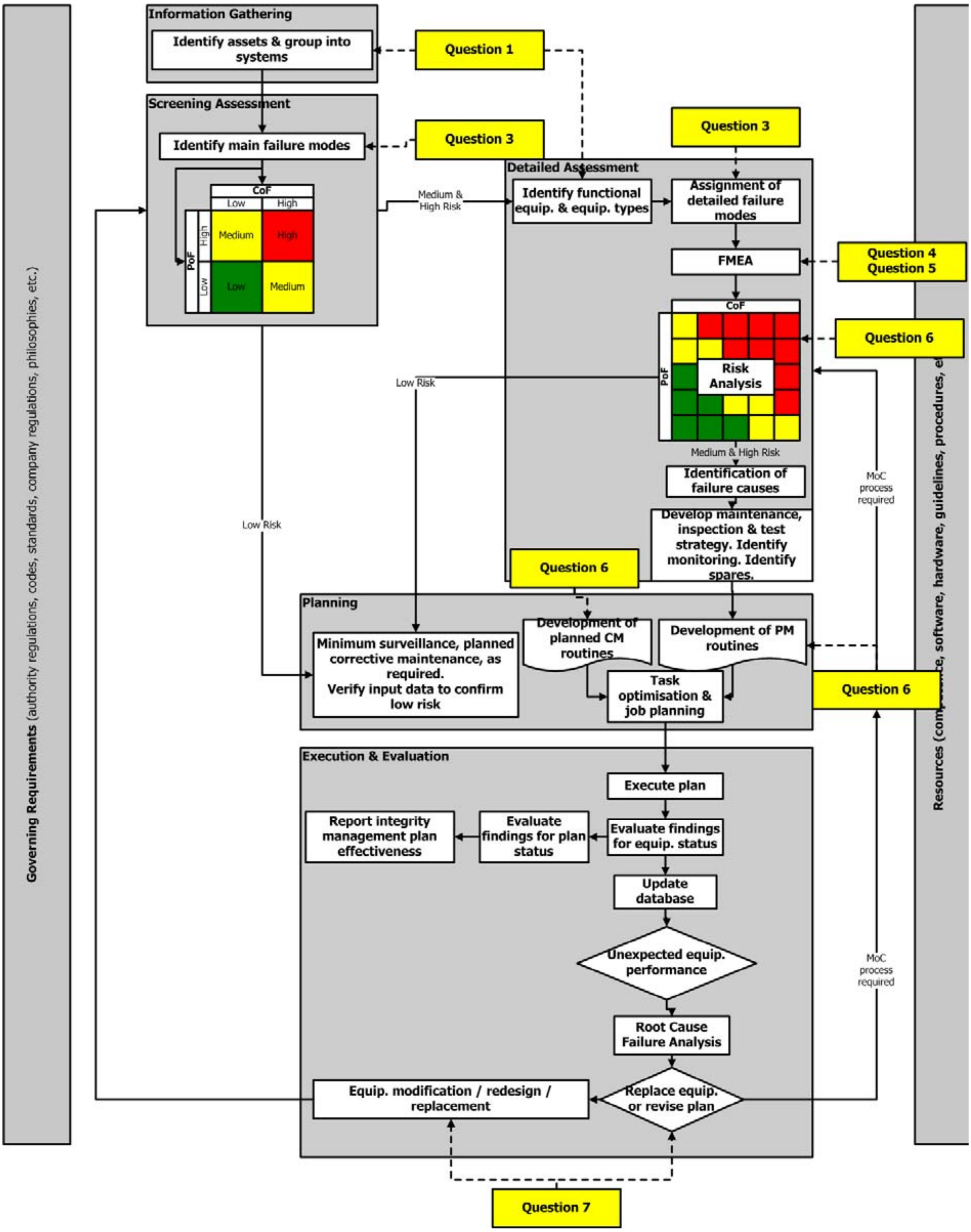


FIGURE 3.2 The seven questions in the RBI working diagram (DNV, 2009)

As Figure 3.2 shows, the RBI assessment makes a decision on almost all the same questions as RCM; however, question two is not answered. This question is about the ways in which equipment fails to fulfil its functions. And when choosing an RBI assessment, this question is in reality already answered, because RBI only concerns loss of containment.

Based on this, the processes of RCM, NORSOK Z-008 and RBI are built up around the same principle and they concern the same topics through the process. The next sub-chapter will look more closely into similarity and difference in some key topics and try to give some recommendations on how an integrated approach can be obtained.

3.3 Grouping and classification

Grouping and classifiaction.

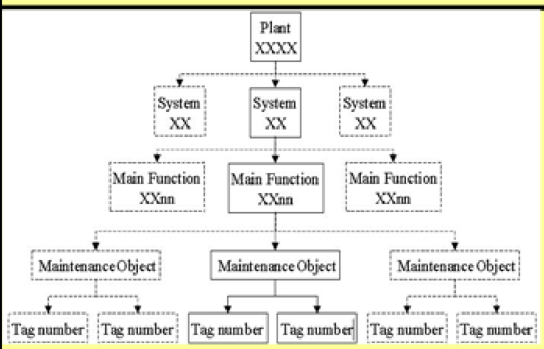
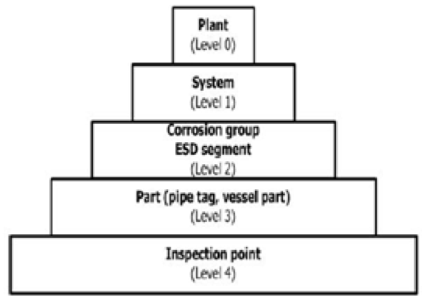
	RCM and NORSOK Z-008	RBI
Equipment Levels	**Five levels.** - Plant. - System. - Main function. - Maintenance object. - Tag number.	**Five leves.** - Plant (level 0) - System (level 1) - Corrosion group ESD segment (level 2) - Part(pipe tag, vessels part) (level 3) - Inspections point (level 4)
Equipment hierarchy	 ***(NORSOK Z-008, 2001)***	 **(DNV RP-G 101, 2009)**

FIGURE 3.3 Comparison RCM, NORSOK Z-008 AND RBI: Grouping and classification

All three methodologies begin the planning with grouping and classification of the equipment. This is done in a hierarchical system, starting at the plant level before breaking the installation into different systems. RCM and NORSOK Z-008 break down the system into main functions based on which purpose they have, for example pumping, heating etc.

RBI in general, however, only concerns loss of containment for static mechanical equipment, such as pipes and vessels. So in an RBI assessment, the failure function is the same throughout the hierarchical system. This means there is no point in arranging the system after functions. Instead RBI arranges the system after the failure mechanism that affects the probability of failure, such as corrosion groups, or the ESD segments that describe the amount of gas or fluid that can leak out and therefore affect the consequence of failure.

This shows that all the three methodologies try to arrange the systems in a systematic manner. The RCM and the Z-008 divide the system based on specific tasks that the system needs to fulfil to do its required duty. The RBI methodology divides the system into groups with similar corrosion mechanisms or into ESD segments.

To be able to develop an integrated maintenance and inspection strategy, some adjustment has to be made in how the different strategies group and classify the equipment. The RBI methodology, expressed trough the DNV RP-G101, mainly concerns the containment function and the Z-008 disregards the containment function and the inspection. This means that, in a way, these different methodologies complement each other.

The NORSOK standard Z-008 recommends that all main functions should be divided into sub-functions. Containment is mentioned as one of the sub-functions but the standard does not deal with the subject of inspection, and instead it refers to DNV RP-G101 for more supplementary information regarding inspection. This means that Z-008 in reality groups and classifies static equipment under sub-functions but disregards a further study. One solution for RBM can be to base the grouping and classification on the Z-008 framework, and classify static equipment under maintenance objects or sub-functions. To make the inspection assessment effective, the sub-function, containment, should be classified further down into ESD segment levels or into corrosion groups.

The figure below shows one suggestion for a hierarchal system for an RMB approach.

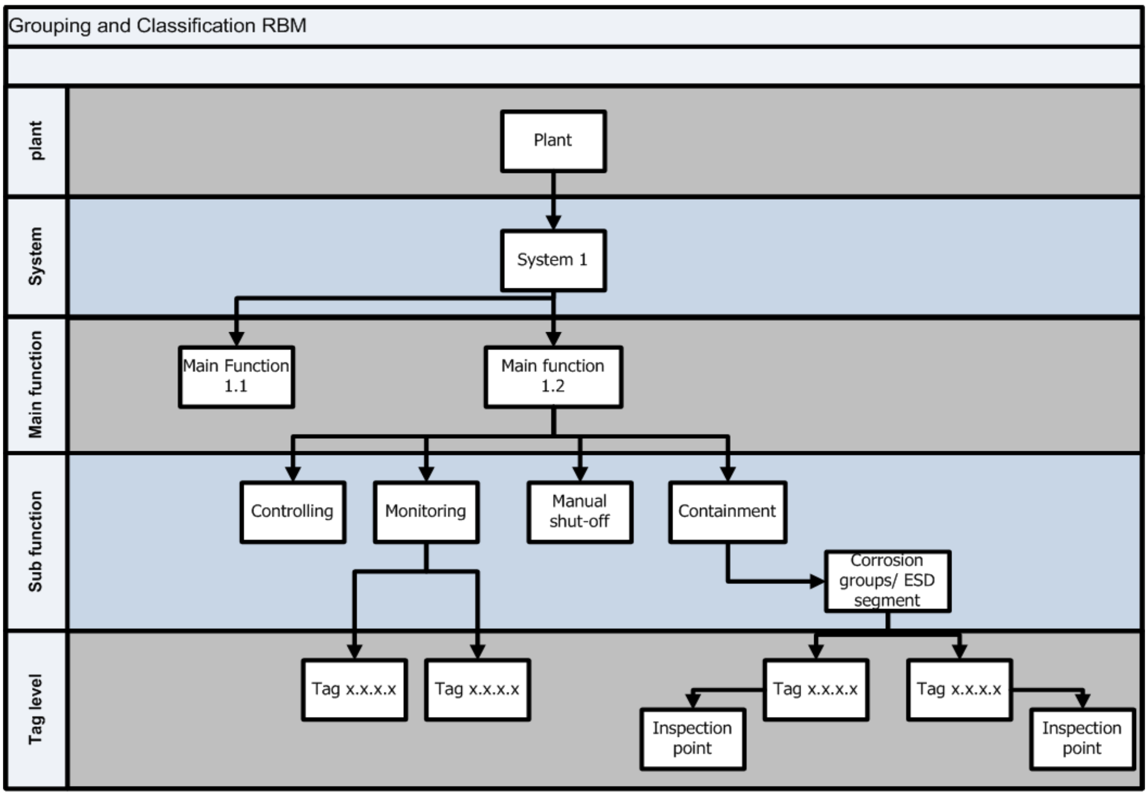


FIGURE 3.4 Grouping and classification in a unified approach.

By employing this classification model, the dynamic equipment will be treated as the Z-008 suggests. The static equipment that is normally treated by RG-G 101 will - in the two first steps - follow the same practice as described in the RP-G 101. The main function, however, is not described in the DNV RP-G 101, but then it does not interact with dynamic equipment in the same manner that a unified approach needs to. All systems have main functions that together create the system. And main functions have sub-functions that again create the main functions. Containment is seldom a main function; in most cases, containment is a function that is needed to operate the main function. For example, a pipeline may need some sort of monitoring, manual shut-off or controlling and so forth. But pressurised static equipment needs to be grouped and classified differently regarding consequences and especially when it comes to probability of failures; this will be explained later on in the consequence and the probability chapter. Static equipment should, therefore, according to the DNV RP-G 101, be grouped into ESD segments and/or corrosion groups.

3.3 Acceptance criteria

Acceptance Criteria			
	RCM	**RBI**	**Z008**
Safety	**Risk acceptance criteria**	**Risk acceptance criteria**	**Risk acceptance criteria**
Environment	**Risk acceptance criteria**	**Risk acceptance criteria**	**Risk acceptance criteria**
Operational	**Cost-bentfit analysis**	**Risk acceptance criteria** **If degradation rates is known, cost-benefit analysis can be used**	**Cost-bentfit analysis**
Non-Operational	**Cost-bentfit analysis**	**Risk acceptance criteria** **If degradation rates is known, cost-benefit analysis can be used**	**Cost-bentfit analysis**

FIGURE 3.5 Comparison RCM, NORSOK Z-008 AND RBI: Acceptance criteria

There is a small difference in how RBI, RCM and Z-008 use acceptance criteria to determine how maintenance and inspection should be carried out. When evaluating the safety level, all three methodologies use risk acceptance criteria, either given by the legislative authority and/or the company management.

But risk acceptance criteria given by the authorities are just a minimum limit that the risk must be under to be tolerable. Since these are minimum requirements, they should not be used to determine that the risk is "low enough". Companies can of course set their own risk acceptance limits. But if these risk limits are set at too ambitious a level, it can be very expensive - and in some cases impossible - to meet the requirement. If these limits are set too loosely, the risk limits are too easy to meet, and the risk is not sufficiently reduced. This means that setting good risk acceptance criteria is difficult.

Today the ALARP principle has become more common in the industry. This principle is based on the premise that a task should be carried out as long as it can not be proven that there is a gross disproportion between the cost of the measure and the actual risk reduction. As opposed to a real human life, the value of a statistical saved life can be determined; the U.K Health and Safety Executive operates with a value of about £1 000 000. There is no given answer for when a measure is in gross disproportion to the risk reduction. A value six times the value of a statistical saved life is often used, but if the risk in the first place is high, the proportion may be larger before an action is rejected.

An example of an acceptance criterion derived from the ALARP principle can be that a statistical human life is valued at 10 000 000 NOK, and to achieve a gross disproportion the cost for the inspection or maintenance activity needs to exceed that amount, for example, six times. So a maintenance activity is planned with a cost of 500 000 NOK; the expected risk reduction is estimated to reduce potential loss of life (PLL) from 10^-2 to 10^-5 over a two-year period before the same maintenance activity has to be done again. Over this period it is then expected to save 0.01998 statistical human lives. The cost per saved statistical life is then 500 000 NOK/0.01998 which equals about 25 000 000 NOK per statistical life. Based on this, the maintenance activity should be carried out since the cost is not grossly disproportionate in comparison with the value of a statistical saved life.

But in a maintenance and inspection context, the use of ALARP can involve some difficulties or at least some challenges. The result of a maintenance task is not permanent and this has to be taken into consideration when estimating the increased safety level. Mechanical equipment can be complex and it can be difficult to estimate how much the reliability has increased as a result of maintenance action. This does make it hard to calculate the potential risk profit, and it would be difficult to see whether the cost of maintenance action is in gross disproportion to the risk profit or not. And since the ALARP principle practices reversed burden of proof , the action has to be done just because it can not be proven that there is a gross disproportion.

Some failure rates for mechanical equipment show that likelihood for failure does not increase with time and more rapid maintenance will, in some cases, make bad matters worse because human failure is added. This means that the only way to achieve a higher reliability is to redesign the equipment. In such a context the ALARP principle may work fine, but to redesign and change equipment to achieve a risk level as low as is reasonably practicable is not really a maintenance task.

The ALARP principle may not be suitable for inspection. It is hard to quantify how an inspection gives a risk profit, since inspection alone is just a verification tool. Therefore, inspection may need strict limits to act in accordance with.

Despite these concerns, ALARP may be introduced with success to some areas of maintenance. But the author is of the opinion that if this is to work, the company management and the maintenance management have to collaborate closely.

Acceptance criteria for governing of the environmental risk is given either by legislating authorities or by the companies themselves. In this case the ALARP principle is not suitable or it can at least be an expensive approach to governing the risk since the environmental consequences are often expressed in monetary terms, and because a risk reduction can only be rejected if it is proven that there is a gross disproportion between cost and reduction. In this case companies can be forced to carry out action that costs six times the expected money saved. And this would not be very cost-effective management.

It can be argued that it is too cynical to only think of cost regarding environmental risk. The environmental legislation on the Norwegian costal shelf is often seen as strict in comparison with other geographical areas and therefore the authority acceptance criteria can be used, but the author is of the opinion that the environmental risk should not be accepted just because it is below the acceptance criteria. There should also be an assessment to determine whether the risk can be further lowered by means of, for example, a cost-benefits analysis.

The risk reviews of economic or production consequences are almost treated identically by the three methodologies. Both RCM and Z-008 use a cost-benefit analysis to determine whether the economic risk can be justified based on cost. RBI, on the other hand, uses risk acceptance criteria to value the economical consequences, but when the degradation mechanism is well known RBI can also make use of a cost-benefit analysis, and only inspect when it is worth spending the money. When considering the economic risk, people do not want to pay two dollars for something that only generates one dollar. So economic risk is - and probably should be - governed by a cost-benefit way of thinking, as long as it does not affect the risk for safety or the environment.

The author is of the opinion that a unified approach should make use of a cost-benefit analysis to govern the economical consequences. The environmental risk level should be governed by risk acceptance criteria; when equipment falls within this limit a cost-benefit analysis should be done to see if it is beneficial to reduce the risk further. Acceptance criteria for safety should be handled similarly to the environmental risk, but instead of a cost-benefit analysis the ALARP principle should be used where it is possible. Since inspection needs stricter limits to act in accordance with, risk acceptance criteria should be shaped for inspection purposes.

Even though the author recommends different acceptance criteria for maintenance and inspection, it does not mean that that inspection and maintenance can be treated in the same methodology. It is not necessary that what should be inspected and what should be maintained should be governed by the same limits.

3.4 Consequence of failure

Consequence of failure			
	RCM	RBI	Z008
Categories of CoF	Safety and environmental consequences. Operational consequences. Non-operational consequences.	Safety Consequences Environmental Consequences Economical Consequences	Safety and environmental consequences. Production consequences. Cost (exclusice production cost) consequences.
Detect the CoF	FMEA: Inspect the failure effect. Hidden failure	Estimate the leak volum. Evaluated as the outcome of a failure given that such a failure will occur.	FMEA: Inspect the failure effect. Equipment redundancy

FIGURE 3.6 Comparison RCM, NORSOK Z-008 AND RBI: Consequence of failure

RCM, NORSOK Z-008 and RBI use the same consequence types; they are only dividing them into different groups. RCM and the NORSOK Z-008 classify safety and environmental consequences into the same group, RBI divides them into two separate groups.

RBI has traditionally focused on static equipment like pipes and vessels, and RCM and NORSOK Z-008 inspired maintenance has focused on dynamic equipment like motors, pumps and so on. But the consequence of a failure is not dependent on the equipment the failure derives from; the consequence is a result of the condition a failure brings about. For example, if a leak occurs the consequence would depend upon the volume that can leak out, the pressure, temperature, ignition source and so on. Whether the leak came from a pipe or pump is indifferent for the consequence assessment. However, consequences derived from repair costs are dependent on the equipment. But these consequences are just based on the repair cost of the damaged equipment, and there is no need to treat static equipment in a different way from dynamic equipment with regards to repair cost. Based on this, a unified consequence assessment can be applied to all equipment regardless of its functionality.

But there are some issues that have to be sorted out. For instance, the NORSOK Z-008 takes into account redundancy between equipment; this subject is not dealt with particularly in either RCM or RBI. In reality, redundancy could ease the economic consequences of a failure. Take, for example, two parallel pipelines that are supplying hydrocarbon into a separating tank. If one of the pipes gets ruptured, the equipment redundancy would not affect safety and the environment consequence, but if the other pipeline can supply enough hydrocarbon to the tank, the economic consequences would be reduced. The author is of the opinion that redundancy should be taken into consideration both in the consequence assessment and in the maintenance and inspection planning. When planning maintenance work, documented redundancy can be very useful since redundancy can make it possible to do maintenance without shutting down the whole system and thus make the maintenance work cheaper. If the redundancy is not taken into consideration in a consequence assessment, the results may be too conservative and inaccurate, making them useless.

There is not a big difference among the three strategies in the consequence assessment. So it does not need too much innovation to develop a consequence assessment that can be applied in an integrated tool for static and mechanical equipment.

One suggestion could be to divide the consequence into at least four classes: safety consequences, environmental consequences, production consequences and cost and repair consequences. The consequence assessment can be done at system level since the consequence would be independent of which piece of equipment failed.

3.5 Probability of failure

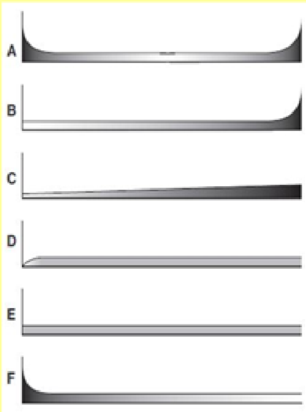
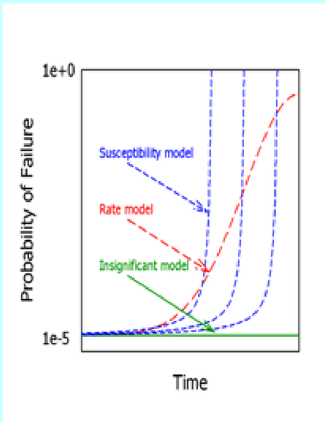
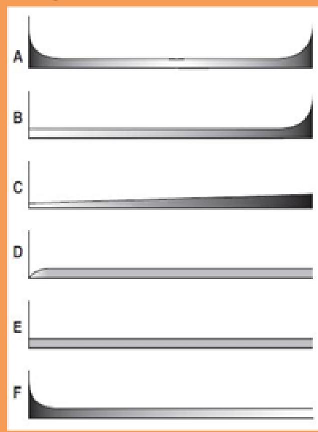
Probability of failure.			
	RCM	**RBI**	**Z008**
Degradation models	**Six degradation models** 	**Four degradation Models.** 	**Six degradation models** 
Quantitative	**Probability of failure based upon historical data.**	**Probability of failure calculated on the basis of the component degradation.**	**Probability of failure based upon historical data.**
Qualitative	**Probability of failure based upon historical data and experts` opinions.**	**Probability of failure based on experts' opinions.**	**Probability of failure based upon historical data and experts' opinions.**

FIGURE 3.7 Comparison RCM, NORSOK Z-008 AND RBI: Probability of failure

All three methodologies estimate the probability of failure, but the estimations are based on different sources. RCM and NORSOK Z-008 rely on historical data from earlier experience and RBI, on the other hand, makes use of present operational conditions in a probabilistic assessment. This difference may arise from the fact that mechanical equipment in general has several failure modes;

so to calculate the probability of failure of each one would require an enormous number of resources. This - and the fact that there is an amount of historical data that gives a good pointer on the probability of failure for most of the mechanical equipment - makes use of historical data best suited for mechanical equipment.

When dealing with static process equipment like pipes or vessels, the most dominant failure mechanisms are corrosion and erosion. And in this case historical data may not be suitable, since the corrosion rate and erosion are dependent on the actual operational conditions at the site. The corrosion depends on temperature, the CO_2 content of liquid or gas, the pressure and so on, and these are factors that could be unique for each site.

The probability of failure depends on the equipment; this might makes it necessary to treat mechanical and static equipment different. The probability assessment for mechanical equipment should mainly be based on operational experience and for static equipment should mainly be derived from the actual operational environment. But if the corrosion or erosion rates from the probability assessment of static equipment can give new information and knowledge about failure rates in mechanical equipment, then this information should be used. And, of course, if historical data can give new information regarding probability of failure for static equipment, this should also be taken into consideration.

So, to develop a unified approach for inspection and maintenance, the probability assessment cannot be carried out in the same way for static equipment and mechanical equipment. But this might not be a problem since the probability assessment already depends on the equipment. So the main difference is that different techniques need to be applied to assess the probability for a pipe than those that are applied to assess a pump or a motor. The result of the assessments can still be used together.

3.6 Risk evaluation

Risk evaluation			
	RCM	RBI	Z008
Evaluation methods.	Failure Mode, Effects, and Criticality Analysis. (FMECA) Risk priority numbers (RPN)	Quantitative Risk Assessment (QRA)	Failure Mode, Effects, and Criticality Analysis. (FMECA) Risk priority numbers (RPN

FIGURE 3.8 Comparison RCM, NORSOK Z-008 AND RBI: Risk evaluation.

Risk evaluation is conducted to determine what the level of risk is, and whether any action is needed. The risk analysis and the risk evaluation together form the risk assessment.

All three methodologies use risk assessment to classify the components or systems after where they are likely to fail and which consequences a failure would involve. RCM and the NORSOK Z-008 use a Failure Mode and Criticality Analysis (FMECA) to determine the criticality of the equipment. RBI combines consequences and probability of failure and presents the result in the form of a risk matrix. When using a risk matrix to communicate, it is important to bear in mind that a risk matrix is just a tool to present the risk and not a risk analysis (Terje Aven, Willy Røed, Hermann S. Wiencke, 2008).

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

FIGURE 3.9 Example of risk matrix from (ISO, 2000, cited DNV, 2009)

All three methodologies use a risk assessment as a basis for the selection of maintenance or inspection objects. If the risk is low or the equipment is not seen as critical, i.e. low probability and low consequence, the equipment or system is disregarded from further processing. If the risk or criticality is medium or high, the equipment or system needs to go through a more extensive investigation, and based on the probability of failure, the consequence of failure and the failure mechanism, a plan for mitigating the risk is created.

The RCM and the NORSOK Z-008 make use of model-based risk analysis and RBI uses a more standard risk analysis. The reason for this could be that mechanical equipment can often be vulnerable for several different failure modes and FMECA is a suitable tool to handle and detect these failure modes. Pipes and vessels, on the other hand, are not exposed to that many failure modes; in general it is only loss of flow, or loss of containment. The method to derive the risk is not the same but the results from the risk analysis and the risk evaluation are used in the same manner.

3.7 Updating and evergreening

A risk assessment can never be more accurate than the quality of the inputs in the analysis or the knowledge in the evaluation; this means that the quality of the maintenance or inspection plans is limited by the information quality and quantity. Therefore, updating is vital and inspection and maintenance planning should work in circles. If new information is revealed, the information should be included in the existing plans.

The author is of the opinion that one of the biggest weaknesses that all three methodologies possess is that there is no clear procedure or plan for how and when the maintenance or inspection plan should be updated. In a unified approach it should be clearly stated how the updating process should be conducted.

CHAPTER 4

CONCLUSION

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4.1 Conclusion

The purpose of this assignment was to take a starting point in today’s maintenance and inspection practice, and see whether or not it was possible to unify them into one integrated tool for maintenance and inspection purposes. Today maintenance and inspection are two separate activities, governed by separate plans and separate equipment assessment. On the Norwegian coastal shelf there are three methods used to govern the integrity of a process plant: Reliability Centred Maintenance (RCM), Risk Based Inspection (RBI) and criticality analysis for maintenance purposes described in the NORSOK Z-008.

This thesis has shown that there is great similarity between RBI, RCM and NORSOK Z-008, both in configuration of the strategies and in how the result is used to govern further actions. All three methodologies group and classify the equipment in a similar manner and they make use of consequence and probability of failure to assess the criticality or the risk of the equipment. And RBI does in fact answer the same questions that RCM assessment is built up around. There are also some differences, for example the estimation of probability of failure. However, it is not necessary to treat all equipment types alike during all stages of an assessment before it can be called an integrated approach; the important thing is that the results can be used together.

So, in light of this thesis, it is likely that we can assume that a unified approach towards today’s maintenance and inspection strategies is feasible without losing important aspects of any of the strategies. But work has to be done on this subject before a unified approach can be achieved.

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