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MASTER'S THESIS

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Acknowledgment

This thesis work is the final part of my studies at the University of Stavanger (UIS), and it concludes my Master's of Science degree in Offshore technology, specialization Risk management. The study of this thesis has been executed at UIS, in cooperation with Apply Sørco in Norway.

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Alireza Moharramzadeh Gelyani

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1 Introduction

1.1 Background

In 1998, the petroleum Safety Authorities Norway (PSAN) gave instructions to the oil and gas companies for testing of safety critical valves. This regulation follows the widely accepted standard IEC 61508 for functional safety systems. In order to simplify the use of IEC 6150 the PSAN recommends OLF guideline. According to PSAN the emergency safety critical valves as a part of safety function system should be tested annually.

1.2 Objectives and research context

In projects that affect safety there are risk and uncertainty due to different issues such as future income, costs, loss of lives, damage to the environment and etc. The testing, as a tool for increasing the reliability, is an activity which can affect the safety. The testing interval has a direct influence on reliability and relatively on safety. The aim of this project is to discuss the rationale for the PSAN requirement, as annual testing by the operators is considered as too strict. The expected utility theory which is the backbone for all economic thinking is used as basis for the discussion. This thesis also discusses that the requirement on annual testing likely will be too strict also from a societal point of view, if the effects of annual testing are seen only as improvements in reliability of the valves. One is then disregarding the fact that testing of safety critical valves also has negative effects on safety for those who perform the tests, as well as negative effects for the environment. This thesis work should be seen in relation to the researches carried out by Associate Professor Abrahamsen E.B. and risk management group at university of Stavanger regarding to addressing issues related to the problem of balancing the different concerns safety and economy. The paper at the end of this thesis work addresses one of these problems.

1.3 Structure of thesis

This project consists of two parts. Part I is an introduction for the part II, which consists of my paper and constitutes the main content of the thesis. The rest of part one consists of; Section 2 terminologies which provide a basic definition about the terms which are used in this thesis, including relation between safety and reliability and some basic maintenance definitions. Section 3 introduces rules and regulations regarding safety critical valves, also, the definition of such valves. Section 4 contains a brief introduction to IEC 6150 standard and OLF guideline, in addition, this section includes maintenance/testing important steps. Section 5 introduces impacts of testing and describes simple testing procedure for Emergency Shot down Valve (ESVs). Section 6 provides a review and discussion of basic decision analysis, including expected utility theory, cost-benefit analysis and cost-effectiveness analysis. In addition, it gives some information about consumer theory which is a part of expected utility theory. Figure 1.1 gives a clearer view on the structure of this master thesis and the reason of including the part one in present work.

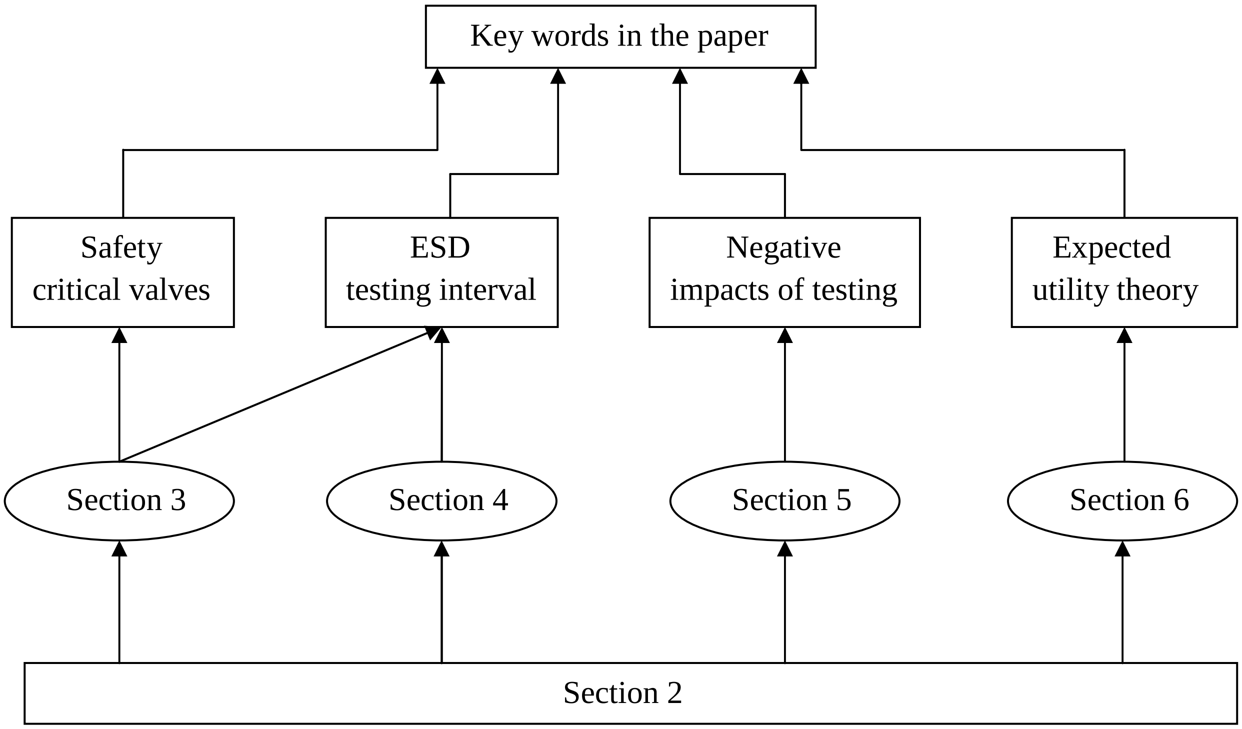

Figure 1.1 Frame work of this master thesis

2 Terminologies

2.1 Historical perspective

Reliability evaluation introduced to the industries after World War I for the first time. On that time, the using of two engines instead of one engine in airplanes was compared with respect to the past accidents rates per hours flying time. [1]

The first formal reliability analysis was conducted by Lusser R. after World War II in Germany. The Werner Von Braun Company had problem with V-1 missile. The first series of ten missiles were so week they all blew up on the launching pads or fell into the English Channel. Lusser suggested that maybe it is better to use many week lines instead of one week line. Based on this idea, Lusser produced the low of reliability. This low stated that for a system which works only if its components work, reliability is equal to the reliability which is produced by its elements. This low was a based for applying a better design, use stronger materials, harder and smoother wearing surfaces and est. in different systems. The result of using such systems had grate economical improvements in USA industries. [1]

The relation between safety and reliability introduced during the COLD War. Americans and Russians had a competition for sending a man to moon. The big concern was how to make the space craft safe and reliable. So, large amount of money invested on education and research in the reliability and the risk. [1]

Nowadays, with public interests in risk and safety, many industrialized countries are concerned about reliability and risk analysis. In Norway the parliament stated that we want to be a world leader in offshore safety. Thus, the oil and gas industry in Norway faces many regulations, standards and guidelines which are concerned about risk and reliability.

2.2 Objectives of reliability and risk analysis

The primary purpose of risk and reliability analysis is to provide a foundation for decision makers to decide which solution and or action is needed for different situations. Some of the main objectives of reliability and risk analysis are as fallows. [1]

- To provide bases for comparing reliability and risk with acceptance criteria
- To prepare foundation for evaluating the project profitability
- To prepare a more effective and safer procedures regarding operations and or monitoring the plant
- To provide systematic view for understanding the events and consequences due to these events
- To have a better view on the system and interaction between components of the system based on the analysis
- To increase the motivation and competence for following up the systematic safety

The benefit of analysis depends on how we plan the analysis, how we fallow up this plan and how efficient is our safety management.

Several subject areas involve with execution of risk/reliability analysis. Such areas can be;

- Knowledge about the system operational and technical aspects as well as factors that lead to failure
- Knowledge about the analysis methods and techniques and also in many cases basic economical knowledge
- Data (accident data) regarding reliability/risk should exist for estimating these issues

2.3 Definitions

2.3.1 Model

Models are use in different areas such as reliability/risk analysis and economy to simplify the realistic world. These models can be graphical or mathematical. "The important point is that models are idealized and simplified the real life, so, the results from models are valid in the model and they can be correct only to the extent that the model is realistic". The characteristic of such model is; simplicity and accuracy. [1]

2.3.2 Probability and frequency

"Probabilities are referring to the future event that has more than one possible of outcomes. In a specify satiation (stochastic) only one of these outcomes will happen, however, we can not say which. The probability of an event is measure as a chance of occurrence of an event in the interval [0, 1]. The probability is usually can be estimated (assessed) based on the historical data such as; accident statistic and the operating statistics of components and systems". [1]

"Frequency; can be defined as an average number of events per unit of time or per operation". [1]

2.3.3 Accident

Accident is defined as "undesirable event that can lead to Loss of human life, personal injuries, significant damage to the environment or significant economic loss". [1] Such an undesirable event called accident in this project.

2.3.4 Reliability

"Reliability is defined as a characteristic of the ability of a component or system to perform a specific function". [1]

The measure for reliability level can be varying in different situations. Such measure can be;

- Average lifetime
- Average number of failures per unit of time (frequency of failure)
- Probability of system or components functioning in the specific point of time such as Probability of Failure on Demand (PFD).

2.3.5 Reliability analysis

“The systematic way to analyze reliability can be defined as a reliability analysis”. The result of this kind of analysis can be used as; [1]

- Foundation for making decision on alternatives and actions regarding optimizing reliability and cost
- Recording the reliability
- Bases for determining requirements on reliability of equipment and system
- Foundation for Quantitative Risk Analysis (QRA) and qualitative risk analysis”

2.3.6 Reliability management

“By using reliability management, one can understand all systematic measurers used in order to reach the specific reliability level that requested by predefined policies, goals and acceptance criteria. One of the important parts of reliability management is reliability analysis. Acknowledge that one part of safety management is reliability management”. [1]

2.3.7 Risk

In this project maybe the everyday speech meaning of risk can be useful. Every day speech is defined risk as a danger that the accidents exposes to human life, the environment and economic values. One way to express risk quantitatively is to use the equation

$$\text{Risk} = \text{frequency (probability)} \times \text{consequences (of the accident)} \qquad (1.1)$$

Although, the general and more complete definition of risk is; Risk can be described by (A,C,U,P,K),where A is the initiating event ,C the consequence of this event and the prediction of it, U is uncertainty about what value C can take, P is probability of this event and K is the background knowledge. [2]

2.3.8 Risk analysis

Systematic way of analyzing risk is risk analysis. [2]

2.3.9 Safety

One of the meanings is which used in this project is that the safety is “the characteristic of ability to prevent damages and losses due to consequences of accidents whether these accidents are occurred randomly or as results of actions”. The damages and loses can be either monetary such as economical values or non monetary values such as life and health of human beings or biological and physical environment. With this definition we can say that there is a strong relation between risk and safety. When the risk is high, safety is low and vice versa. [1]

2.3.10 Safety management

“By using safety management, one can understand all systematic measurers used in order to reach the specific safety level that requested by predefined policies, goals and acceptance criteria.” [1]

2.3.11 Acceptance criteria

Acceptance criteria can be defined as the desirable or acceptable level of risk or reliability. Acceptance criteria can be stated by verbal or numerical statement/quantity. Such statement or quantity can be stated by governments or company requirements. Acceptance criteria can be for example the criteria for; Quality, A certain number of accidents per year and or a certain number for the probability of failure on demand (PFD). [1]

Our understanding and attitude to the risk level of activities are two key factors that can affect the acceptance criteria. Some important factors that can help us to achieve these understanding and attitudes are;

- Benefits associated with the activity
- The probability of having a significant accident
- Whether the technology is old or new
- Whether the risk is voluntary or not

2.3.12 Failure

“A failure is an unsatisfactory condition”. [3] Failures can be divided in to two groups;

1. Functional failures

These are the failures that unable the system or subsystem to obtain the standard level of performance. These failures can be categorized to functional failures. These inabilities of the item can be either inability to perform a specific function or perform lower than the required level of performance. However, there are possible situations that the combination of these inabilities be existed for the item. For Emergency Shutdown Valves (ESV’s) inability to be closed in emergency situation is an example of functional failures.

2. Potential failures

These are identifiable physical conditions which can assure the functional failure(s). Such failures in many situations are hard to find. Fortunately, Reliability Centered Maintenance (RCM) which is defined as a process for maintenance strategy setting, bring the definition of potential failure as a specific group of failure to the maintenance theory. Due to this, concepts such as inspection (testing) and condition monitoring find their application in the maintenance world. Thus, one can find the potential failure(s) by doing inspection for example pressure tests on the valves. [3]

2.3.13 Definition of system failure

One can find this meaning by using the definition for system and failures. We can divide failures in systematic failure such as leakage in shutdown valves or non systematic failure such as human error during testing of the valves.

2.4 Relation between Safety and reliability

Safer activities in the company can be achieved by the more reliable systems and equipments. Having a non reliable shutdown system or valve can cause the undesirable process shutdown that can be lead to lose of the revenue in the company. Also, reliability of equipment has a direct effect on the safety of staffs and environment. In addition, it has indirect effect on the reputation of the company since the failures in such systems and maintain them can delay the production or making a big disaster. [1]

Reliability management is the systematic way that can reveal how much reliability is needed regarding the goals, policies and acceptance criteria. However, this is acknowledged that the optimized level of reliability should be seen by cost-benefits analysis. Thus, optimized reliability level of the system should produce as a result of the economic optimization process as a part of reliability management.

Safety/reliability management should be involved within the whole life cycle of plant which is planning phase, the construction phase, the operational phase and decommissioning and removal phase. So, it is continues task that should be developed in line with other tasks and activities. In line with the aim of this project I just go into the safety task and development in operational phase. Reliability management tasks can be considered in line with other area of management such as economic management. Flowchart in figure 1.1 shows the essential reliability management procedures and task. [1]

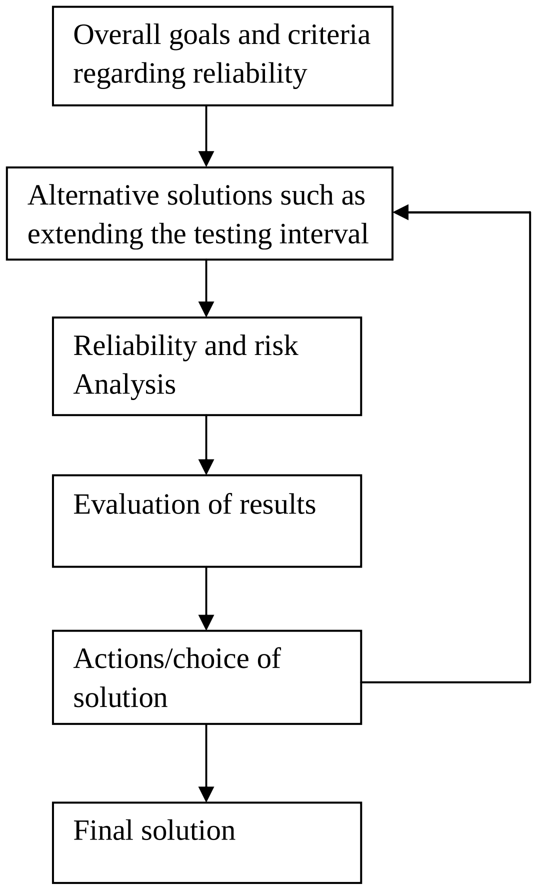

Figure 1.1: The reliability management flowchart in operation phase

The acceptance criteria and indirectly the goals in operation phase for reliability can be found in the standards and guidelines see for example section 3 of present thesis. One of the important parts in operation phase is maintenance. With doing maintenance desirable level of reliability with respect to the acceptance criteria and company goals can be obtained. This is the key to reach desirable level of safety.

2.5 Maintenance

For many years the subject of maintenance was known for humans. Maintenance traditionally was seen as a costly point where the company wealth reduced due to its costs. Recently this view to maintenance had been changed. Nowadays, maintenance is not only seen as an opportunity to increase the company profit but also the opportunity to increase the safety level. These achievements can be gained due to this fact that maintenance maintains the desirable level of availability, reliability and operability. [3]

2.5.1 Maintenance definition

As all devices can be impaired, maintenance defined as a function is which necessary to be done for the devices to restore the production process. [3]

2.5.2 The objectives of maintenance

It is important to know the fundamental maintenance objects due to growing the modern industries that need more complex equipment and relatively complex maintenance function(s). This maintenance objects can be understood from the below explanation

"It is the task of the maintenance function to support the production process with adequate levels of availability, reliability and operability at an acceptable cost."[3]

From the above sub-objectives (availability, reliability, operability) the reliability definition was explained in pervious pages. To avoid repeating here the rest of sub-objects are explained.

- Availability-The proportion of time that component or system is functioning in non-failed state, is called availability. It is a maintenance job to provide acceptable level of availability. This desirable point should be seen by optimizing availability with respect to cost. [3]
- Operability- It is the ability of the system to provide desirable level of production with respect to design limit(s). [3]
- Cost- All the maintenance activities optimization and/or execution should be done in the light of economical analysis process. [3]

2.5.3 Maintenance strategy

Each time the failure happens company will lose wealth. Failure should repair and this is costly. Often failures can cause bigger failures or even catastrophic accident which is not only exposed cost to company but also reduces their reputation.

On the other hand, failure prevention is costly, so, always there is a trade-off between prevention of failure and the costs of failure. One should decide to prevent the failure occurrence or let it occurs and then handle it. The way that we treat with failures is called maintenance strategy. [3]

2.5.4 Maintenance Plan

The first essential element for executing maintenance, like other activities, is to have a maintenance plan. The foundation designing maintenance plan can be found from many different approaches (methodologies). One of the best options for plan design foundation is Reliability Centered Maintenance (RCM) (as it is accepted by many experts, see e.g. ref. [3]). RCM can be defined as a process for maintenance strategy setting. RCM can reveal what maintenance to do, when and how often.

RCM object is to give a maintenance plane. Such plan is a combination of maintenance strategy for handling different failure in different equipments. The chart in Figure 1.2 shows strategy structure of maintenance. This figure can give a better understanding on maintenance strategy.

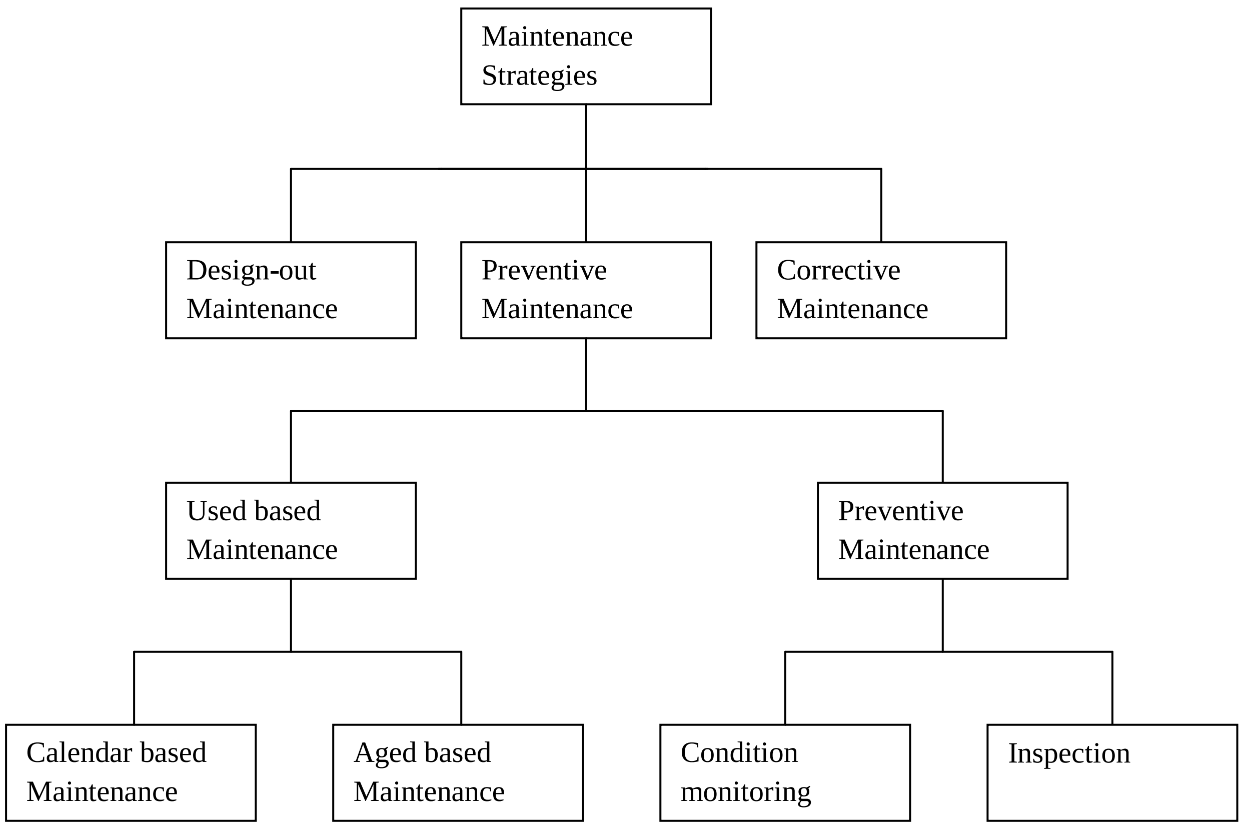

Figure 1.2: Maintenance strategies [3]

From the above chart the Inspection will be explained due to aim of this project. Interested readers are encouraged to read literature, such as reference [3], in this subject for further information.

2.5.5 Inspection

It's a kind of maintenance strategy which indicates that the equipment or system should be tested or inspected as often as the desirable reliability level can be guaranteed.

There are lots of standards and guidelines for doing such maintenance strategy. In this thesis OLF guideline and IEC6150 are used as an example for doing inspection on the Emergency Shutdown Valves (ESV).

3 Rules and regulations

In 1998, based on the one rational sentence which states that “Probability reducing measures shall, to the extent possible, be given priority over consequence reducing measures” [1], the Petroleum Safety Authorities Norway (PSAN) gave instructions to the oil and gas companies for testing of safety critical valves. The new instructions was based on the inter alia Section 42 old existed regulation where there were instructions for establish a test program for safety critical valves, functionality tests and leakage test.

In this new regulation emphasize is on minimizing the internal leakage through a closed sectionalizing valve. This regulation was published at the Activities Regulations, Chapter IX (Maintenance).In this Section PSAN stated that the emergency shutdown system verification should satisfy the Safety Integrity Level (SIL).This requirements and numbers can be defined and calculated based on IEC 61508 standard and OLF’s Guideline 070. The OLF guideline notices the general requirement is to verified safety critical valves with full-scale function test at least once a year. Such test not only should cover the all parts of the safety function but also it must take into consideration the leakage rate through close valve. [4], [5]

Regarding the above requirements PSAN expects the operators to:

- Identify and perform criticality classification of safety critical valves
- Establish limit values for evaluation of each safety critical valve’s functionality
- Prepare test program for testing of safety critical valves
- Establish routines for evaluation of test results compared to predefined limit values

3.1 Safety critical valves

The safety critical valves in this project are defined as “the valves that should close and sectionalize the main process in order to secure platform in an emergency situation” [4]. Emergency Shutdown valves (ESV) can be included to this kind of valves. In this project, ESV is used as an example of safety critical valves. Other safety critical valves like Sub Sea Isolation Valves (SSIV), Blow Down Valves (BDV) and etc, are not addressed in present work. [4]

4 The concept of Functional safety and IEC 61508

IEC 61508 provides requirement to minimize the failure and hazards of the systems that are safety critical. This standard is concern about the functional safety as a part of the overall safety. Functional safety depends on a system or equipment operating correctly in response to its inputs.

Functional safety is defined as a method of dealing with elimination or reduction the hazards in the safety-related systems. In general, the hazards analysis should be conducted to find the significant hazards for equipment or any associated control system in its intended environment. Then, this analysis will reveal that the functional safety is necessary to ensure adequate protection against each significant hazard or not.

“In this standard term safety-related is given to the systems that are required to perform a specific function or functions to ensure risks are kept at an accepted level”. [6] Such functions are defined as safety function. The requirements to achieve functional safety are;

1) Safety function requirements (What the function does), That can be found from hazard analysis
2) Safety integrity requirements (the likelihood of a safety function being performed satisfactorily), which can be found from risk assessment

These two elements are the foundation of functional safety. “One simple rule in this standard is the higher the level of safety integrity, the lower the likelihood of dangerous failure”. [5]

4.1 E/E/PE safety related systems

Nowadays, most safety function duty is being carried out with electronic, electrical or programmable electronic system (E/E/PE). Thus, the present standard focuses on this kind of systems. The IEC 6150 contains requirements to minimize failure such as random hardware failure mechanisms and common cause failures in the E/E/PE systems and control them when they arise.

In this standard some requirements such as concept, scope definition, hazard analysis and risk assessment are needed for the areas that are still not fully decided to use the E/E/PE safety-related systems. If there is any possibility of using E/E/PE technology, then, the standard should apply for finding the safety requirements for such system. The standard can help firms to do this job in a methodical, risk-based manner.

The other requirements such as documentation, management of functional safety, Functional safety assessment and competent can be used in not only, E/E/PE safety-related systems but also, in other safety related systems.

The examples of E/E/PE that are named in IEC 61508 are;

- Emergency shut-down systems in a hazardous chemical process
- Railway signaling system
- Automobile indicator lights, anti-lock braking and engine-management systems
- Est.

Such safety-related system includes all parts of the system that are essential for doing the safety function.

4.2 Objectives of IEC 61508

The aims of IEC 61508 are as fallows;

- Show the potential of using E/E/PE system for improving the safety and economic performance
- Protect the safety framework being replace by technological developments
- Provide a technically sound, system based approach, with sufficient flexibility for the future
- Support the safety-related systems requirements of performance identification with risk-based approach
- To generalize the standard that can directly apply in various industries such as machinery, process chemical plants and rail or product standard (e.g. power drive system)
- Provides a means for users and regulators to gain confidence when using computer-based technology
- Provide requirements based on common underlying principles

4.3 Technical approach

IEC 61508;

- Uses a risk based approach to identify the safety integrity requirements of E/E/PE safety related systems, and includes a number of examples of how this can be done.
- Uses an overall safety lifecycle model as the technical framework for the activities necessary for ensuring functional safety is achieved by the E/E/PE safety-related systems
- Covers all safety lifecycle activities from initial concept, through hazard analysis and risk assessment, development of the safety requirements, specification, design and implementation, operation and maintenance, and modification, to final decommissioning and/or disposal
- Encompasses system aspects (comprising all the subsystems carrying out the safety function, including hardware and software) and failure mechanisms (random hardware and systematic).

- Contains both requirements for preventing failures (avoiding the introduction of faults) and requirements for controlling failures (ensuring safety even when faults are presents)
- Specifies the techniques and measures that are necessary to achieve the required safety integrity

4.4 Safety integrity levels

The present standard introduces 4 different level of safety performance for safety function such as table 3.1. They called safety integrity level (SIL), each of these levels needs some requirements. The requirements are more restricts in (SIL 4) which is the highest safety integrity level, compare to for example (SIL 3). The lowest level is (SIL 1). Thus, for the system that has more critical safety duty in plant, one should apply higher SIL level is which has more rigorous requirements.

Safety Integrity Level (SIL)	Probability of Failure on Demand (PFD)
4	$10^{-5} \leq$ PFD $< 10^{-4}$
3	$10^{-4} \leq$ PED $< 10^{-3}$
2	$10^{-3} \leq$ PFD $< 10^{-2}$
1	$10^{-2} \leq$ PFD $< 10^{-1}$

Table 4.1 PFD requirements regarding SIL

One important note here is that in systems with more than one safety function which requires different SIL level, the strictest SIL level should apply for the entire E/E/PE safety-related system.

4.5 IEC 61508 base for other standards

The authors of this standard say that this standard can be used directly by industries. Also, they mentioned it can be a basic foundation for other standards related to the E/E/PE safety-related systems or sub systems. Some application areas of IEC 61508 for example are as fallows;

- Facilitate the maintenance of the ‘as design’ safety integrity of E/E/PE safety-related systems
- As a basis for carrying out assessments of safety lifecycle activities

Although, IEC 61508 is a general standard for different industries, the process industries has developed their own standard for Safety Instrumented Systems (SIS), which is called IEC 61511. The OLF Guideline combined these two standards.

4.6 OLF Guideline

IEC 61508 is a widely accepted international standard that provides risk-based approach to determine SIL for systems performing safety functions. The application of this standard is also recommended by PSAN regulations. To meet the IEC 61508 requirements, lots of calculations and QRA analysis need to be done which create difficulties for the users. OLF guideline try to provide documents for simplify the use of standard IEC 61508.

OLF provides a guideline for application of IEC 61508 and IEC 61511 in the Norwegian petroleum industry. Present guideline is resulted from cooperation between different operators and the various suppliers. In this document one can find the minimum SIL requirements for the most common instrumented safety functions on a petroleum production installation in line with the requirements in IEC 61508.

Also, this document gives some reliability data based on SIL requirements for different safety functions based on assumption such as concerning diagnostic coverage, fail-safe design, etc.

OLF guideline illustrated three important elements for Safety Instrument System (SIS) design. These elements are

- Relation between SIL and failure probability
- Restriction on design based on the safety failure function, Hardware fault tolerance and the complexity of the component
- Avoidance and control of systematic failures

This guideline can be applied in all instrumented safety functions. Some of such systems can be found in PSAN and NORSOK and some are not. In order to be in line with the purpose of this project, requirements for Emergency Shut Down valves are mentioned here. These requirements are in the appendix A.4 in this guideline.

Component	No. of components	Total PFD
ESV	1	8.8×10^{-3}

Table 4.2: PFD requirement for ESV

According to this guideline risk should reduce by using safety-related systems which are safety instrumented systems (SIS) such as ESD, safety system based on other technology such as PSV and additional risk reduction facilities such as procedures. Based on the above sentence and figure A.1 in IEC 61508-5 diagram 4.1 is created as a Framework of risk reduction.

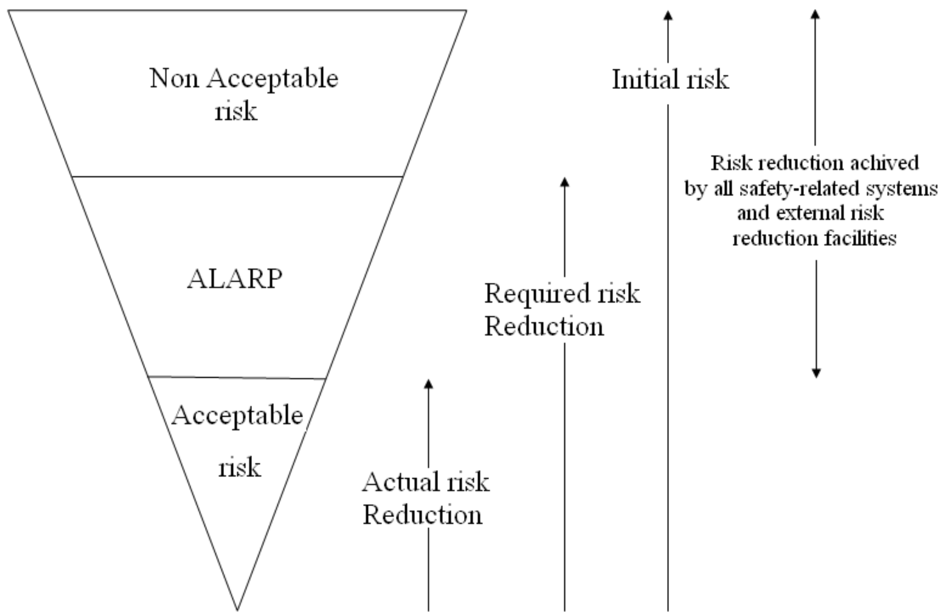

Figure 4.1 Frame work for risk reduction

OLF used the safety lifecycle as both IEC 61508 and IEC 61511 illustrated to provide the framework in order to determine the requirements relating to specification, design, integration, operation, maintenance, modification and decommissioning of a safety instrumented system (SIS).

4.6.1 SIS maintenance

According to this guideline the aim of maintenance of Safety Instrument Systems (SIS) is to keep such systems functions in accordance with the safety requirements specification. Maintenance/testing regarding to this requirement are essential steps which can ensure the SIS does not deteriorate below the predefined safety integrity level. In order to do this the firm should fallow the chart below;

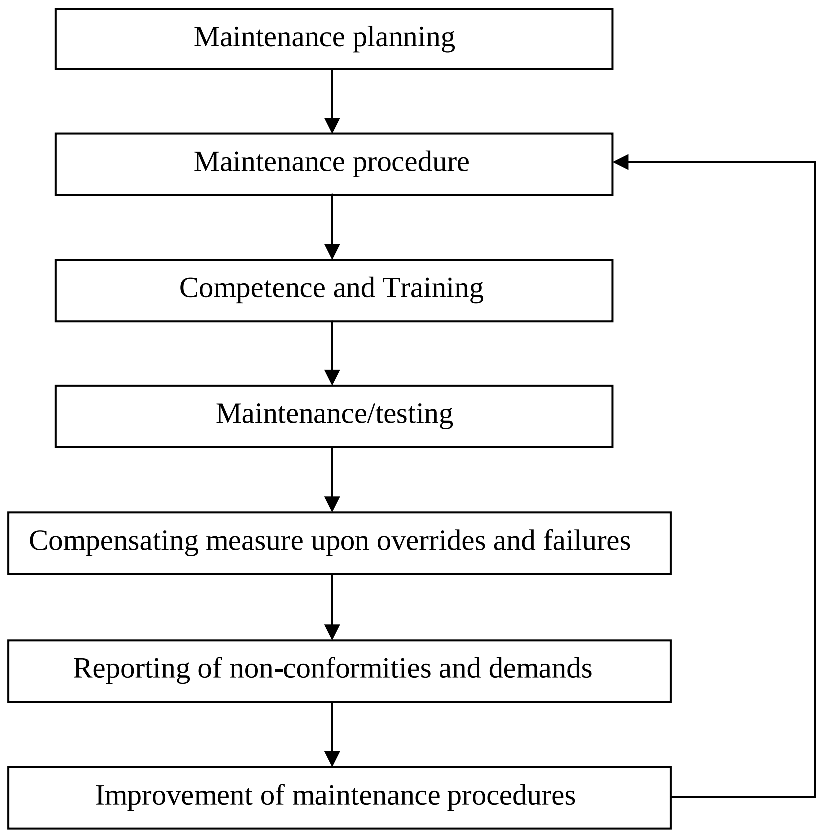

Figure 4.1 Frame work for maintenance [7]

4.6.2 Maintenance planning

As every other activity, testing/maintenance planning should be conducted prior use of the SIS. In this section in addition to standard routine for planning, expertise should define the category of SIL level for the SIS. [7]

4.6.3 Maintenance procedures

All the procedures should follow the aim of maintenance which keeps the SIS deterioration blow the SIL level. OLF guideline illustrates different elements that should be addressed in the procedures such as tracking maintenance performance.

4.6.4 Competence and training

The Norwegian low of activity says that the maintenance should be done by expert and trained staffs. Firms should have a program for training the maintenance crew to gain full functional performance of the SIS. This program should give the staffs of maintenance good understanding of several issues such as general principles of safety integrity levels and use of compensating measures.

Operators should be aware of the competence on the function and operation of the SIS. Such competence can be achieved by understanding the issues like; the general principles of safety integrity levels, how the SIS functions and etc. [7]

4.6.5 Maintenance/testing

The maintenance description and testing the SIS, compensating measure and all maintenance routine should be included by the maintenance program. Also, the SIS maintenance should include many elements for example determine the periods for inspection. This periodic testing can help the firm to find the potential failures. Such failures can only find by regularly testing the SIS function(s). This functional testing includes not only the entire SIS (if it's possible regarding safety and operation limits) but also each sub-system should be tested one by one. These sub systems are; sensing element(s), logic solver and the actuating devices. [7]

Although, this sub systems check reduce the need of integral test of SIS such as valves, according to the OLF guideline and lows still firm should test the entire SIS. The integral test of SIS such as valves requires process shot down. The process shut down can be a good opportunity for integral tests if it has characteristics such as;

- The shut down should fulfilled the requirement of functional testing
- All the equipments that are in the scope of functional testing should be covered by the shut down zone. Equipments that are not covered by shutdown zone should be tested separately.
- occurring in the last half of the current test interval

If such a shutdown be executed by the firm, then, according to the OLF guideline the next planned functional test maybe can be skipped.

As a routine for the maintenance the reports for all steps should be prepared. Based on these reported data one should be able to calculate required reliability parameters such as failure rates (λ).

4.6.6 Compensating measures upon overrides and failures

According to the PSA regulations operation with impaired SIS is not allowed. Thus, planning for the maintenance should cover the compensation measures in the fallowing operation situations;

- dangerous detected failures
- overriding of the Safety Instrumented Function (SIF) or part of the SIF for functional proof testing or maintenance activities

Such planning is essential to ensure that the risk level is, blow the defined acceptance criteria for the entire life of installation. [7]

4.6.7 Override/Inhibit/Disable

If one or some subsystems in the SIS are affected by overriding, inhibiting or disabling then the safety barrier can not do its job properly. Thus, compensating measures or manual action should be per determined in such circumstances. Such activities can be as fallows; [7]

- functional proof testing
- preventive maintenance activities
- field equipment malfunction
- field equipment replacement

4.6.8 Reporting of non-conformities and demand

In order to obtain the aim of maintenance which is keep the SIS below the SIL requirements, it is essential to assess the difference (non-conformities) between the predefined behavior and actual behavior and if it is needed do the modifications. [7]

4.6.9 Improvement of maintenance

The important point that needs to be mentioned here, according to the aim of this thesis, is that planners should be able to adjust the interval of the maintenance/testing. In order to estimate the optimum interval for maintenance/testing, planners should use the data and importations to recalculate the parameters such as failure rate (λ). [7]

5 Impacts of testing

The functional test of the safety critical valves involves generating a pressure at a controlled steady pace into the safety valves until its open. In real world this kind of test can not be down unless the operator shut down the production. In fact the procedure for leakage test is;

- shot down the production and close the valve
- pressure downstream the valve is bled off
- pressure build-up is measured

In some platforms operators do this test during their annual turnarounds, then, the cost of the test is less than the platforms that they are not willing to have turnaround every year. However, second group of the platforms should shot down their production for hours to do this test. On the other hand, these forced shot down production can affect other installation. This manual test is an expensive procedure due to the loss of income. Also, it has negative effect on the safety level in itself (PSAN 2004) due to production shut down and manual intervention into the hydrocarbon system. Thus, companies are willing to find the optimized interval between verifications. [4]

The pros and cons of preventive maintenance should be seen in the light of cost-benefit theory. We should do preventive maintenance (testing) as long as the improvement in the reliability is larger than the negative effect of shut down. Table 1 shows the main negative and positive effect of this kind of maintenance.

Positive effects of yearly testing	Negative effect of yearly testing
Improved functionality/reliability in an ESV situation	Increased probability of test induced failures and test independent failures (e.g. operator error) Increased number of process shut downs of the process can generate leakages Increased amount of work on the hydrocarbon system

Table 5.1 impact of safety critical valves testing [4]

Also, suppliers complains that nearly half of the valves sent to onshore for maintenance and work over are found to be tight and functioning upon initial tests before maintenance is carried out. This means that the today’s testing procedures are not so appropriate. [4] Thus, we should optimize test intervals to minimize manual intervention into the hydrocarbon system.

6 Rational decision-making theory review and discussion

This section gives a brief introduction to decision analysis theory, emphasising expected utility theory, cost-benefit analysis, the use of expected values to support decision making. In addition, some axioms and consumer theory which are the foundation of the expected utility theory are represented in present section. The purpose of this section is to highlight some aspects such as practical applicability of the expected utility theory, cost-benefit analysis and the ability of cost-effectiveness analysis to reveal value of statistical life, rather than giving the comprehensive review on these subjects due to the aim of this thesis. Also, the comparison of these two methods; cost-benefit and expected utility theory, is given.

6.1 Expected utility theory

Consider a decision situation involve uncertainty among possible outcomes. The problem is to make a “good” decision in this kind of situation. For example think about situation where a firm wants to choose between investment alternatives. In such circumstances, the optimization of the expected utility in theory is a ruling paradigm among economics and decision analysis which can reveal how to make decision strictly in a mathematical way, see e.g. [8] and [9]. In mathematical term, expected utility is introduced by Eu(X), where u represents the utility function and X represents the outcome is which can be different attributes, such as costs and the non-economical variables. The expected utility is an interesting tool, normative theory which can provides recommendation for decision-makers based on a rational basis. It can be proved that for our assumed firm with coherent preferences among consequences and assessments about uncertain quantities, the only sensible way to proceed is by maximizing expected utility. Coherency in assessment of uncertainties of events for the firm means it should follow the rules of probability. Coherency in consequences for the firm means it adherences to a set of axioms (ref. Section 6.4). [10]

In practice it is hard to work out with expected utility theory. In literature such as [8] and [11], the specification of the utility function is explained by the lottery process which is not straightforward and easy to explain. One way to deal with the lottery process is to define the parametric function for utility function, which is defined up to the certain parameters, and the value specification is reduced to assigning a number to this parameters. For example assume utility function u=u(X), where X is the vector of all X_is. In the way to determine the utility value first step is to assign utility value to the best and worse outcome (consequence). Assume best outcome which represents by x, has utility value equal to 1, and the worse outcome which represents by y, has the utility value equal to 0. The problem now is to assign utility value to the rest of possible outcomes. [12]

Consider an urn of standard balls with different colours. The desirable outcome can results by picking up let us say black colour. The proportion of black balls represents by u. Let a ball be drawn at random; if the ball is black the outcome x results, otherwise, the outcome is y. We refer to this lottery as “x with a chance of u”. Now, gambler should see the outcome (z) to how extend is better than y or worse than *x* due to “x with a chance of u”, with certainty? If u=1 means that gambler is in a better trade off than z; if u=0 it is worse. If u decreases, the gambler earns less and vice versa. Hence there must be a value of u such that you are indifference between “x with a chance of u” and a certain z, call this number u_0. In this way the gambler is better than z if $u > u_0$ and relatively he/she is worse than z if $u < u_0$. Then, the u_0 value is the utility value of the outcome z. The other utility values can be assigned in the same way as above. [12]

There is uncertainty regarding outcomes. These uncertainties can be assessed by probabilities. Expected utility can be raised by combining the probabilities and the utility values for the different outcomes. The alternative with highest expected utility is optimal within the given framework. [12]

The above example from ref. [12] can show that the specification of the utility function following this procedure is extremely difficult to implement, and in most cases not feasible. There are some methods that can be used for simplifying this procedure such as using the linear utility function and categories of parametric utility function. Such simplification can ease the elicitation of the utility functions, but it can create new problems as the specification utility function is to varying degree reflecting the decision maker’s preferences. [12]

Despite from such difficulties the author of this thesis thinks we need some references, even if it is to some extend theoretical, for the development of and for the measurement of the goodness of decision. Such references can be provided by expected utility. [11]

There are also different practical analysing methods which can address the balance between costs and benefits such as cost-benefit analysis.

6.2 Cost-benefit analysis and cost-effectiveness analysis

Cost-benefit analysis can be seen as an approach for balancing the benefits and cost of a project. The country currency is the common scale used to measure benefits and costs. The idea is to give the monetary value to the list of burdens and benefits. Transformation of goods to the monetary value should be done in the way that reflects the maximum amount the society is willing to pay for the project. Assigning monetary value to the market bundles is easy, as the prices on the market bundle reveal the willingness to pay. The problem arise as one wants to assign the willingness to pay for non-market (non-economical) goods, such transformation is difficult to assess. Different methods exist for doing such job such as contingent valuation and hedonic price techniques. Here Hanley and Spash [13] approach is referred. [3], [4]

After assigning monetary value to all attributes, the total performance can be calculated by the expected net present value, the E[NPV], see ref. e.g. [14]. To measure the NPV of the project, the cash flows (the movement of money into out of the business) related to project are determined, and the time value of money is taken to consideration by discounting future cash flows by the appropriate rate of return. [7] The NPV formula can be as fallows;

$$\mathrm{NPV}=\sum_{t=0}^{n} \frac{a_t}{(1+\mathrm{i})^{\mathrm{t}}} \qquad (6.1)$$

Where a_t is equal to the cash flow at the time t, i represents the required rate of return, or discount rate. The terms capital cost and alternative cost are also used for i. As these terms imply, r represents the investor's costs related to not employing the capital in alternative investments. In the projects with known cash flows in advance, the other rate of return related to risk-free investments, such as bank deposit, can be used as the basis for the discount rate in NPV formula. In order to outweigh the possibilities of unfavourable outcomes when the cash flows are uncertain, which is the common case, the cash flows are normally represents by their expected values $E[a_t]$ and rate of return is then increased based on their Capital Asset Pricing Model (CAPM). This is not representing all the risk adjustments, only the systematic risk will be addressed by such approach and it will ignore the unsystematic risk. The unsystematic risk is related to the specific project uncertainty, such as accident risk, hence, the systematic risk refers to the general market movements, such as movement cased by political events. [14]

Cost-benefit analysis can be distinguished by the cost-effectiveness analysis. The cost-effectiveness analysis can calculate the form expected cost per expected saved lives (statistical life) indices. Although, such analysis can not explicitly assign value to the benefits, such as statistical life, as is essential in the cost-benefit analysis. [10]

6.3 Comparisons of approaches and some concluding remarks

The main obstacle between these analyses is to what extent one is willing to make the factors in the problem clearly comparable. Different views are exist between expertise regarding to which of these analysis can be used in problems. Usually, safety experts like to adopt cost-effectiveness analyses, while, economists and decision analysts prefers to adopt cost-benefit analyses and expected utility theory in their problems. [10] In many literatures, see e.g [15] and [16], comparisons and the frame work for using such analyses can be found. The main point here as ref. [10] and [14] illustrated one should see these methods as a tools are which can not replace the management review and judgment. These tools can provide a useful basis for measuring and development of the goodness of decisions, but not in the traditional way of providing hard recommendations.

6.4 axioms

Consumer behaviour's fundamental axiom is summed up in one statement saying: "people choose the best thing they can afford". In the way of understanding consumer behaviour, three different steps need to be explained;

Consumer preference, Budget constraints and Consumer choices

To explain the concept of consumer preference economists try to answer one question on how consumers preferences one good to another. They answered this question by describing these preferences graphically. Before introducing these graphs some assumptions should be explained;

- Completeness: preferences are assumed to be complete. In other words, market baskets (bundle) are comparable and rank able. Thus, for two imaginary market baskets A and B, the consumer can prefer A to B, B to A, or be indifferent (each bundle satisfied the consumer equally). [17]
- Reflexive: Any bundle is at least as good as itself. In mathematical language for each combination of two goods such as x_1 and x_2 we can write: $(x_1,x_2)\geq(x_1,x_2)$.[18]
- Transitivity: preferences are transitive. Transitivity can be best explained mathematically. Let's say the consumer have three bundles such as $A(x_1,x_2)$, $B(y_1,y_2)$ and $C(z_1,z_2)$. If he or she prefers A to B: $(x_1,x_2)\geq(y_1,y_2)$ and B to C: $(y_1,y_2)\geq(z_1,z_2)$, Then this consumer will prefer A to C: $(x_1,x_2)\geq(z_1,z_2)$. [17]
- Monotonicity: More is better than less. Consumers are never satisfied or satiated, more is always better, even if just a little (as long as we don't have undesirable goods such as air pollution).[17]

6.5 Indifference curves

The consumer's preference can be shown in different curve which is called indifference curve. An indifference curve represents all combinations of bundles that provide the person with the same level of satisfaction. As an example, assume Tina has a bundle with two services, x_1 internet and x_2 telephone. She will be satisfied if she uses 10 hour telephone and 50 hours internet per month. She will also be as satisfied if 20 hours telephone and 30 hours of internet are given to here. Figure 1 shows all the combinations of consuming x_1 and x_2 which satisfy her.

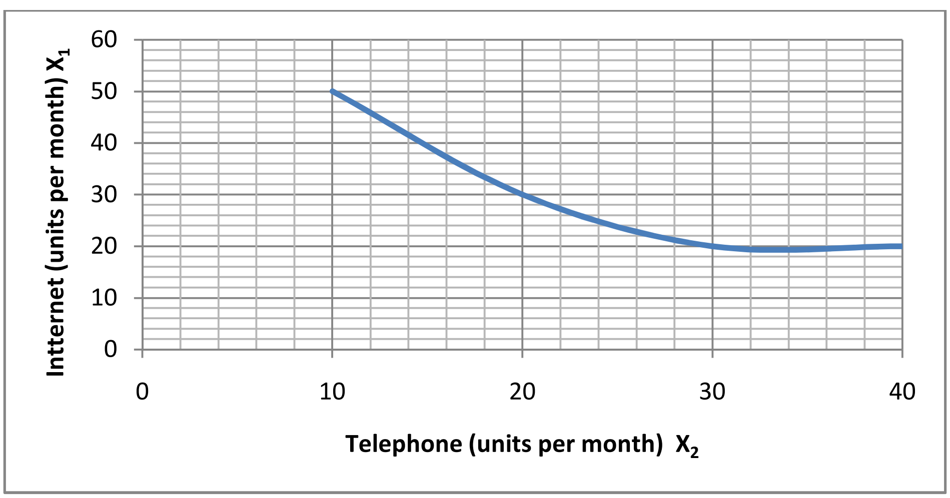

Figure 6.1 An Indifference curve

This graph illustrates the internet consumed hours per month on the horizontal axis and the monthly telephone consumption on the vertical axis. The curve illustrates the bundles for which the consumer is indifferent to (x_1,x_2). [17]

6.6 Indifference maps

Consider the above example again, all the combinations of persons preference can be shown by a set of indifference curves called an indifference map. Figure 2, shows an example of an indifference map v_1, v_2, v_3.

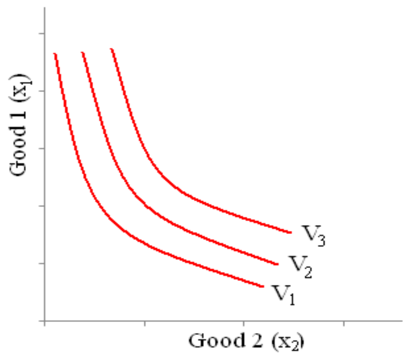

Figure 6.2 An indifference map

As more is better, v_3 has the highest level of satisfaction and v_1 the lowest level. Note that indifference curves can't cross each other. If like in figure 3 they cross each other then points A and B locate in the same indifference curve that means, hence, the consumer is indifferent between them (they locate in different indifference curves). Person is indifferent between A and D. Consequently, he or she should be indifferent between B and D. Thus, they should be on the same indifference curves. However, as figure 6.3 shows these two points are in the different indifference curve v_1 and v_2 respectively. So, indifference curves can't intersect each other. [17]

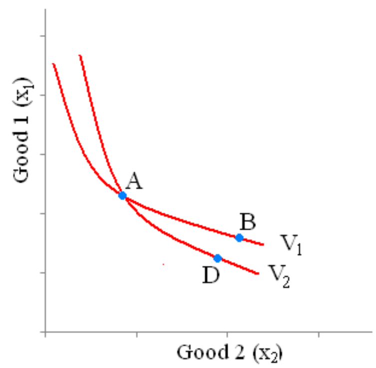

Figure 6.3 indifference curve can't cross

6.7 The shape of indifference curve

"The shape of an indifference curve describes how a consumer is willing to substitute one good for another" [17]. It's reasonable due to the fact that real life is full of trade-offs. Tina consumption example illustrated that she is willing to give up 20 hours of internet to gain 10 more hours of telephone service.

Many different kinds of indifference curve established in economical world; such as perfect substitutes, perfect complements, well-behaved and so on.[17] Due to the aim of this thesis, only the well-behaved indifference curve is explained here. Interested readers are encouraged to read literature in the field of microeconomics, see references [10] and [11].

6.8 Well-behaved indifference curve

Recall the assumption in the indifference curve: more is better (Monotonicity).It is obvious that by applying this assumption resulted curve has negative slope. If one move from the right to the left of the curve then he/she will see a worse position, and if one move from down left to the right up he/she will has the best position. [17]

The other assumption here is: an average is better than extremes. So, if two bundle such as (x_1,x_2) and (y_1,y_2) are selected from one indifference curve the assumption says that

$$\left(\frac{1}{2}x_1+\frac{1}{2}y_1, \frac{1}{2}x_2+\frac{1}{2}y_2\right) \qquad (6.2)$$

Actually, the above assumption is a special case of the below assumption when t=12

$$(tx_1+ (1- t)y_1 , tx_2 + (1- t)y_2) \text{ when } 0\leq t \leq 1 \qquad (6.3)$$

The assumption above can reveal the convex shape of a well-behaved indifference curve such as figure 6.4, because a convex set has the property that if you take any two points in the set and draw the line segment connecting those two points, such line segment can be laid entirely in the set. [2]

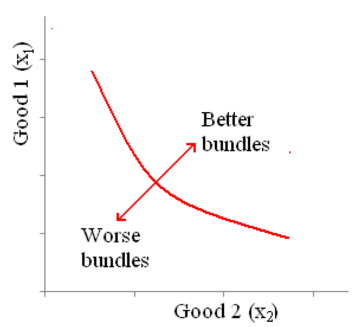

Figure 6.4 Monotonic preferences

6.9 The marginal rate of substitution

It's useful to know the amount of the consumer is willing to give up from one good to obtain more from the other good (s).This amount is called the marginal rate of substitution (MRS).As a matter of fact, it's the same as the slope of indifference curve, also, recall that the slope of indifference curve is negative, so MRS is a negative number in every point on indifference curve for two goods (x_1,x_2). Equation (6.4) shows the relation between MRS and slope of indifference curve in a mathematical way. Figure 6.5 shows it graphically.

$$\text{Slope}=\frac{\Delta x1}{\Delta x2} = \text{marginal rate of substitution} \quad (6.4)$$

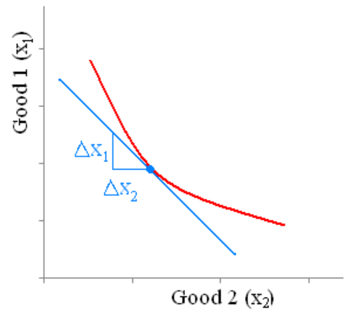

Figure 6.5 The marginal rate of substitution (MRS)

The well-behave indifference curve above shows MRS will decrease by going down on carve. This means that the consumer's willingness of using one good decrease if we give him or her more from one good. It can be also seen as just another justification for the convex shape of the well-behaved indifference curve. [17]

6.10 Utility

"People obtain utility by getting things that gives them pleasure and by avoiding things that give them pain". [17] In economy it refers to the "giving number to the satisfaction that a consumer gets from a bundle".

6.11 Utility Function

Utility function is a formula that assigns number to every combination of bundles (indifference curves)in the way that the more-preferred bundle (indifferent curves which is located on the right side of the graph) has a higher number than the bundle which is less-preferred (indifference curves which is located in the left side of graph). For example consider the bundle of v(x_1,x_2) with utility function equal to $v(x_1,x_2)=x_1^2x_2^2$. Related curves are depicted in figure 6.6 for v=1,2,3.

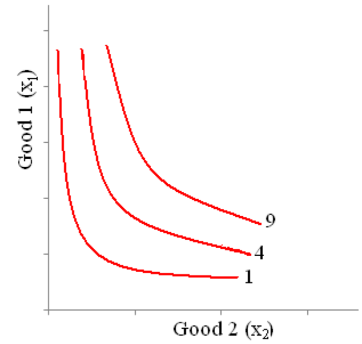

Figure 6.6 indifference curves for different v values

6.12 Budget Constraints

In real life consumer have various limitation for using the goods such as budget. Remember the Tina example she has a limited income per month. Let's say she has S income monthly and assume she just want to spend all her money on two services (Internet and telephone).The price of telephone is P_T and the amount that she use it is T, also price of internet service is P_I and the amount of she use it is I. The amount of money she will spend in telephone and internet services are $P_T T$ and $P_I I$ respectively. As a result, the combination of two services that she can buy will all lie on this line: $TP_T+IP_I=S$, which is plotted in the figure 6.7.

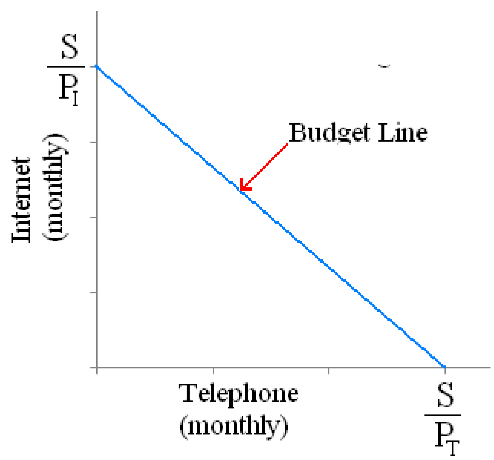

Figure 6.7 The budget line

In economical terms, budget line indicates all the combinations of T and I for which the total amount of money spent is equal to income. It's obvious that by changing the amount of income the budget line location will shift to the right, also, a change in the prices of services or goods can change the slope of the budget line.

6.13 Consumer Choice

The fundamental logic in consumer choice is one clear and logical sentence:”consumers choose the bundle that maximises their satisfaction from their set budget”. [17] So, maximizing the bundle must satisfy two conditions:

- It must be located on the budget line: As budget line includes the maximum amount of money that the consumer has.
- It must give the consumer the most preferred combination of goods and services.

Meeting this condition will force us to one point on the indifference curve which is the point where the slope of the indifference curve is equal to the slope of the budget line. Figure 6.8 shows this situation.

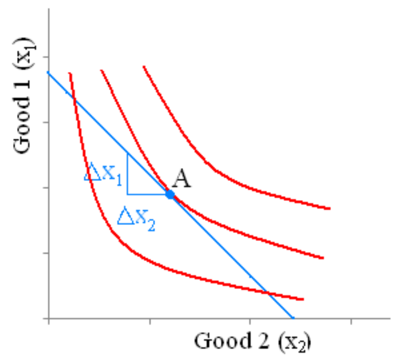

Figure 6.8 The optimal point

As figure 6.8 illustrated, point A is the point of tangency between the indifference curve v_2 and the budget line. Such point is called optimal choice. At this point MRS is equal to budget line slope. [17]

7 Further work

In projects that affect safety there are risks and uncertainties related to different attributes, such as future income, costs, loss of lives, damage to the environment and so on. Risk management is all activities used to manage these risks and uncertainties. The author of this thesis wants to work on the development of new knowledge, principles and methods to improve the risk management, especially addressing issues related to the problem of balancing the different concerns safety and economy.

The purpose for the near future is to improve the paper in the part II of this thesis with some numerical simulation (comparative statistic) and publish it on the journal.

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Part II

SOME CONSIDERATION ON HOW OFTEN SAFETY CRITICAL VALVES SHOULD BE TESTED BASED ON EXPECTED UTILITY THEORY[1]

ABSTRACT

The regulation given by the Petroleum Safety Authority Norway (PSAN) requires annual testing of safety critical valves. In the present paper we discuss the rationale for this requirement, as annual testing by the operators is considered as too strict. The expected utility theory which is the backbone for all economic thinking is used as basis for the discussion. We show that requirements formulated by the authorities on how often safety critical valves should be tested, usually will be stricter than what the operators prefer. We also show that the requirement on annual testing likely will be too strict also from a societal point of view, if the effects of annual testing are seen only as improvements in reliability of the valves. One is then disregarding the fact that testing of safety critical valves also has negative effects on safety for those who perform the tests, as well as negative effects for the environment.

1. INTRODUCTION

In 1998, the Petroleum Safety Authorities Norway (PSAN) gave instructions to the oil and gas companies for testing of safety critical valves. The new instructions was based on the inter alia Section 42 old existing regulation where there were instructions for establishing a test program for safety critical valves, functionality tests and leakage tests.

In this paper we will use safety critical valves such as Emergency shutdown Valve (ESV) as an example from the oil and gas industry. However, our arguments and results can be used in any industry which safety of testing is a critical issue in their field of work.

According to PSAN the Emergency Shutdown Valves (ESVs) should be tested at least once a year. This kind of testing should not only cover the all parts of the safety function, including closing of the valve but also, it must take into consideration the leakage rate through the close valve. [1], [2] The traditional way to ensure that there is no leakage through a valve in closed position is to arrange a differential pressure over the valve, and to detect a possible pressure change in the inventories upstream/downstream the valve, due to a leakage through the valve in closed position [9]. Some of the valves in the gas support network are however located upstream/downstream large gas inventories on the seabed. In such cases it can be very costly to introduce a differential pressure, and also technically challenging to carry out a test as described above.

[1] In this paper some texts are inspired from [4] and [7] due to publish the extended version of present paper under the name of both authors Moharramzadeh A. and Abrahamsen E.B.

Doing such test requires that the production be shutdown. More preferably, these tests are planned to be carried out in the turnarounds. However, often some facility managers do not like to have a yearly turnaround. In such a situation they are forced to shut down the production for several hours to do valve testing by law. Such shutdown is not desirable for manager(s), not just because of lost the production time and money, but the fact that they are aware of the negative shutdown impacts on their safety level due to manual intervention in to the hydrocarbon system.

Firms complain that cons of annual testing are much higher than its pros for them on their safety level. We can see testing in relation with safety. This relation can be described by three elements; first the testing of the component normally reduces the probability of failure and increase the safety level relatively. Then, one can say regarding to safety and this element perform testing in a very short period to increase the reliability and relatively safety. Second element is that often doing testing (or shortly after tests) is involved with some probability of accidental events. The third element is that failures are often introduced during execution of testing. The last two elements are negative impact of testing. Due to such negative impacts firm says that the annual testing is too strict. [3]

But does it mean that annual testing of ESVs is inappropriate? Or can we say that annual testing is appropriate even if it is inappropriate for the company?

To answer these questions we use the expected utility as a foundation for our argumentation. The expected utility theory, as a backbone for all economic thinking, states that the best decision alternative is the alternative with the highest expected utility. We will not repeat the rationality of this principle, but it has validity under very reasonable conditions for logical and consistent behavior; see for example [4].

The purposes of this paper are twofold. First-we show that requirements formulated by the authorities on how often safety critical valves should be tested, usually will be stricter than what the operators prefer. The reason maybe is that the authorities are not taking into account the negative cost of testing and operator's activity usually causes negative externalities to society. Second-we show that the requirement on annual testing likely will be too strict also from a societal point of view, if the effects of annual testing are seen only as improvements in reliability and relatively safety. The above statements are in line with the fact that the investment on the testing as a reliability increasing tool for an expected utility maximizer will normally be higher in circumstances where one omits the negative impacts of testing.

This paper is organized as fallows; in section 2 an expected utility model is developed to analyze the appropriateness of annual testing of safety critical valves first in the view of firm then regarding society point of view, when they consider the negative impact of testing. Then in section 3 regarding finding optimal interval for testing, a short discussion about the value of a statistical life is given. Finally, in section 4 we draw some conclusions.

2. AN EXPECTED UTILITY MODEL FOR ANALYSING THE APPROPRIATENESS OF ANNUAL TESTING OF SAFETY CRITICAL VALVES

In this section an economical model is developed to study the appropriateness of annual testing of safety critical valves in decision-making. Attention is given to both firm and society view. First we will see the appropriateness of using annual testing for an expected utility maximizing firm.

2.1 On the appropriateness of annual testing of safety critical valves for an expected utility maximizing firm

Consider an assumed firm that has interest in one oil and gas field. This company has preference over wealth x and non-economic variable h. In the following, h is referred to an expected fatality, but it can be also any kind of non-economic values such as injuries. The preferences can be represented by the utility function

$$U(x,h) \tag{1}$$

We follow the standard in the literature and assume that the utility function has a concave form and it is increasing with x. The relevant marginal utility can define with ($\partial U/\partial x$) that illustrate the wealth increases. The firm then considers the utility of an extra dollar of wealth to be higher when it is relatively poorer than the utility of an extra dollar when it is relatively richer. We also assume that the utility function is decreasing and convex on h. The firm then considers that the disutility of one extra fatality is reduced by the number of fatalities. This indicates that the disutility for the first fatality is higher than the disutility of going from 10 to 11 fatalities. We assume in the simple model for this firm there are just two states of the world: one where there is no accident and one where an accidental event occurs. If an accidental event not occurs the firms wealth and the number of fatality are respectively x_1 and h_1 ($h_1 = 0$). Also, we can assume the firm's wealth reduce to a level x_2 ($x_2 < x_1$) and the number of fatalities increase to a level h_2 ($h_2 > 0$) if an accidental event occurs. We assume also the firm's wealth reduce with a constant level A if an accidental event happens. Such assumption seems reasonable in many cases such as emergency shutdown valve (ESV) failure which can lead to the platform lost. The initial number of fatalities given an accidental event and the initial wealth are h_0 and x_0, respectively. The probability of an accidental event (being in state 2) is denoted p.

Suppose that the firm's probability of an accidental event is depending on the period of testing the safety critical equipment in the field, such as critical safety valves for example ESVs. We suppose that the period length of doing tests depends on the investment r in tests. Thus, the probability of accidental events depends on r, P(r).It is logical to assume that the probability of failure P is the concave decreasing function of r; $\partial p/_{\partial r} < 0$ and $\partial^2 p/_{\partial^2 r} < 0$. This means that the probability of failure will be reduced by decreasing the testing interval (increasing the investment on testing). In practice it is sometimes not really true because of testing failure occurrence.

The magnitude of increasing number of expected fatalities (v) depends on the investment r. If we consider the (v) as an expected value of fatalities, then it depends on probability P of accident which depends on r. Thus, we can assume that v is a convex increasing function of r, $\partial v/_{\partial r} > 0$ and$\partial^2 v/_{\partial^2 r} < 0$. We can say that the expectation of fatalities will increase if the accidental event occurs during testing the ESV.

Collecting the above, under these assumptions the firm's problem is to choose r in order to maximize;

$$EU_{Max} = [1-P(r)]\, U(x_1,h_1) + P(r)U(x_2,h_2) \quad (2)$$

Where

$$x_1=x_0-r; \qquad x_2=x_0-r-A \quad (3)$$

and

$$h_1=0; \qquad h_2= h_0+v(r) \quad (4)$$

The derivative of the expected utility with respect to r is;

$$\partial EU/_{\partial r} = \left[\left(-\partial P/_{\partial r}\right)U(x_1,h_1)\right] + \left[\partial U/_{\partial x_1}(-1)(1-P(r))\right] + [\partial P/_{\partial r}\,U(x_2,h_2)] + [P(r)\,\partial U/_{\partial x_2}(-1)] + [\partial U/_{\partial h_2}(v_r)P(r)] = 0$$

$$-P_rU(x_1,h_1)-U_{x1}(1-P(r))+P_rU(x_2,h_2)-P(r)U_{x2}+U_{h2}V_rP(r)=0$$

$$P_r[U(x_2)-U(x_1)]=U_{x1}(1-P(r)) + P(r)U_{x2} - P(r)V_r\, U_{h2} \quad (5)$$

$$P_r = \frac{[1-P(r)]U_{x1}+P(r)U_{x2}-P(r)U_{h2}V_r}{U(x_2,h_2)-U(x_1,h_1)} \quad (6)$$

Where U_{xi} denotes partial derivatives of U_x with respect to i, U_{hi} denotes partial derivatives of U_h with respect to i, V_r is the derivative of V with respect to r and P_r is the derivative of P with respect to r. Note that P_r which can be calculated here is a negative value due to the nature of expected utility theory which states that U is a concave reducing function so, $U(x_2,h_2)<U(x_1,h_1)$. Thus, the denominator of equation 4 is negative.

From the equation (6), the essential condition to maximize the utility function is that a marginal decrease in the probability of failure due to an increase of the investments in testing be equal to the expected utility of consumption in wealth, $[1-P(r)]U_{x1}+P(r)U_{x2}$, minus disutility of expected fatalities due to increasing the investment on tests, $P(r)U_{h2}V_r$, divided by two states of utility, $U(x_2,h_2)-U(x_1,h_1)$. [10] This means that the firm's optimal investment in testing is at the point where the marginal utility of the last dollar spent on reduction in probability of accidental event is equal to the reduction in probability in losses, caused by the last dollar spent on testing. The marginal utility spent on increasing in reliability consists of two parts; (I) marginal utility from a decrease in the wealth, $(1-P(r))\ U_{x1}+ P(r)\ U_{x2}$, and (II) marginal disutility from an increase in the number of expected fatalities, $U_{h2}\ V_r\ P(r)$. Hence, even though the fatalities regarding tests can not decrease or increase the reliability, it will influence the firm's decision as long as the firm considers about avoiding accidents. If firm omits this term in the problem, which means that firm is not take into account the expected fatalities during tests (or shortly after that), then the firm will increase the investment of tests and relatively shorten the test period without considering about the whole safety level. This seems to support the notion that analysis focus only on testing as a tool for increasing reliability in absents of seeing tests as potential activity that can affect the expected fatalities, will lead to underestimating the safety measures and it will if the effect of negative impacts of tests are not taken into account.

As we see from the condition (6) firm's can find the optimal point for P_r and relative investment on testing or similarly the test intervals. Now assume that in the case of testing ESV the firm optimal point of investment, which is calculated by equation (6),is at the point P_r* which denotes investment r* and the relatively test period τ*.

To graphically show the results of firm's decision problem, we follow the literature standard and introducing x_1 axis as the investment on testing of safety critical valves. We introduce the x_2 axis as investment on other activities in figure 1. We assume also that the firm has the constant income (budget line). The budget line for the firm is shown in figure 1.

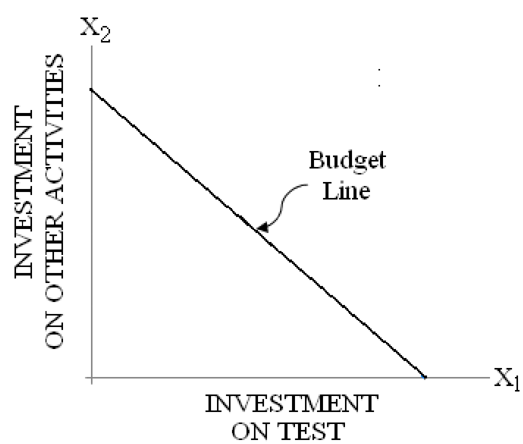

Figure 1. Firm's budget line

By putting all the non-economical terms (V_r) into monetary value (e.g. by the equation 18 in section 3 of present paper or [5]), we can find which combination between x_1 and x_2 that will be optimal for the firm. The firm optimal investment on testing of the safety critical valves depends on the firm's preferences. To graphically illustrate the firm's preferences for all combinations of x_1 and x_2, we can draw a set of curves that each provide the firm with the same level of satisfaction. These curves are known as preference curves. There are an infinite number of indifference curves, one for every possible level of satisfaction. In fact, every possible combination between x_1 and x_2 has an indifference curve passing through it. In figure.2 there such curves are depicted.

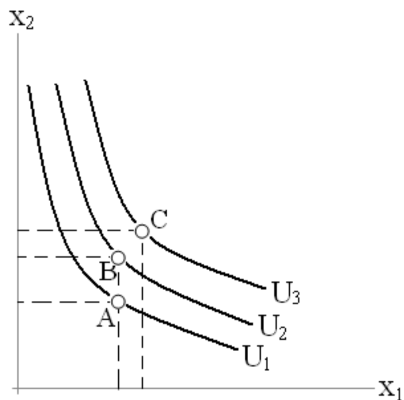

Figure 2. Indifference curve map for x_1 and x_2

Combination between x_1 and x_2 on U_3 are preferred to those on U_2, which in turn are preferred to those on U_1. This is simply a reflection of an assumption that more is proffered to less, as maybe seen by comparing A, B and C.

Given the indifference curves (preferences) and the budget line, we can determine how much money the firm will invest in the testing. Assume that the firm invests in testing to maximize satisfaction (normally profit) they can achieve, given the possible choice available. Figure 3 shows how the problem is solved.

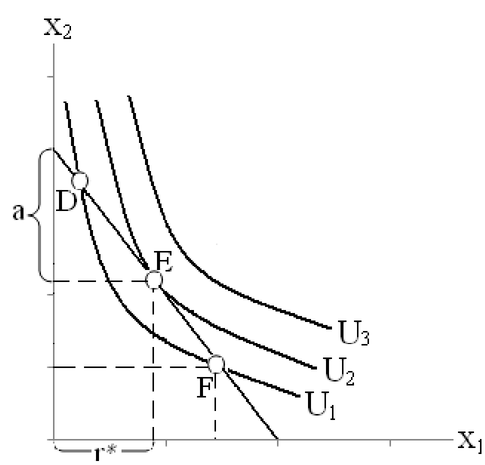

Figure 3. Optimal investment on testing in the firm's view

Point D on indifference curve U_1 is not the most preferred choice, because the firm can move to a higher utility level by spending more money in the testing. Similarly, the firm can do better than point F. The firm can then move to a higher utility level by choosing to invest less money in the tests. Thus, point E maximizes the firm's satisfaction. At this point the slope of the budget line is equal to the slope of the indifference curve. In the economical literature, the tangent to the budget line and the tangent to the indifference curve are referred to as the Marginal Rate of Transformation (MRT) and the Marginal Rate of Substitution (MRS), respectively. We can see that at the point E, MRT is equal to MRS, MRS_{Firm}= MRT. At this point the firm invest an amount of r* on testing, which will reduce the investment on other activities to the point a. The r* represents the amount of money the firm willing to spend on test which can denote the test interval τ*.

2.2 On the appropriateness of annual testing of safety critical valves from a social point of view

An optimal point of investment on testing, and relatively testing interval, for society is equal to the optimal investment on testing for the firm if no market failures exist. A market failure exists when the production or use of goods and services by the market is not efficient. One important instance in which market failure can occur is externalities. An externality is an economically significant effect due to the activities of an agent/firm that is not influencing the agent's/firm's production, but which influences other agents' decision [6]. Externalities can be positive and negative. The standard example of negative externality is pollution from one firm that reduces productivity or well-being for other firm/individuals. However, it can just as well be the effect of accidents caused by a firm's activity if the firm does not take these into account when managing its activity. An example of a positive externality is the effect of a bee farmer's activity on surrounding fruit farms. If the firm is in some way made to take the externality into account, we say that the externality is internalized, and it is not an externality anymore. [7]

The analysis regarding the appropriateness of annual testing of safety critical valves from a societal point of view in a situation with no market failures is equal to the analysis from section 2.1, as an optimal investment in testing for the society is equal to the optimal investment in testing for the firm if no market failures exist. Certainly, the annual testing of the valve, which requested by regulations, cannot be appropriate for society when no market failure exist. But can we draw the same conclusion in situations if market failures exist?

To answer this question we have to expand our model from section 2.1 by including the externality, z, as a new factor. You may look at the externality as a cost of an accidental event for society which is not a cost for the firm. The externality cost depends on the non economical term h_2 which depends on investment on testing r. Thus, z depends on r. We assume that the externality cost z(r) is an increasing and concave function in r, ${\partial z}/{\partial r} > 0$ and ${\partial^2 z}/{\partial^2 r} < 0$.

As the externality is not a part of firm's decision problem, the optimal investment in testing for the firm is r* in the same way as mentioned in section 2.1. However, the investment in testing is too low from societal point of view. The firm takes account of the private costs of an accidental event (the costs that it imposes on it-self), but it ignores the societal costs (the private costs plus costs that it imposes on society).

In order to determine the optimal amount of money spent on testing from a societal point of view, we ask what would happen regarding the investment on testing if costs imposed by the firm on society are borne by the firm itself. In this case the firm would choose r to

$$EU_{Max} = [1-P(r)]\,U(x_1,h_1) + P(r)U(x_2,h_2) \tag{7}$$

Where

$$x_1=x_0-r; \qquad x_2=x_0-r-A-Z(r) \tag{8}$$

and

$$h_1=0; \qquad h_2= h_0+V(r) \tag{9}$$

The first order derivative is;

$$\partial EU/_{\partial r} = \left[\left(-\partial P/_{\partial r}\right)U(x_1,h_1)\right] + \left[\partial U/_{\partial x_1}(-1)(1-P(r))\right] + [\partial P/_{\partial r}\,U(x_2,h_2)] + [P(r)\,\partial U/_{\partial x_2}(-1)] + [\partial U/_{\partial h_2}(v_r)P(r)] + [\partial U/_{\partial x_2}(-z_r)P(r)] = 0$$

$$-P_rU(x_1,h_1)-U_{x1}(1-P(r))+P_rU(x_2,h_2)-P(r)U_{x2}+U_{h2}V_rP(r)-U_{x2}Z_rP(r) =0$$

$$P_r[U(x_2,h_2)-U(x_1,h_1)]=U_{x1}(1-P(r)) + P(r)U_{x2} - P(r)V_r\,U_{h2}+P(r)Z_rU_{x2} \tag{10}$$

$$P_r = \frac{[1-P(r)]U_{x1}+P(r)U_{x2}-P(r)U_{h2}V_r+P(r)U_{x2}Z_r}{U(x_2,h_2)-U(x_1,h_1)} \tag{11}$$

From the equation (11), the essential condition to maximize the utility function is that a marginal decrease in the probability of failure due to increasing of the investment on testing be equal to the expected utility of consumption in wealth, $[1-P(r)]U_{x1}+P(r)U_{x2}+P(r)U_{x2}Z_r$, minus expected disutility of expected fatalities due to increasing the investment on tests, $P(r)U_{h2}V_r$, divided by two states of utility, $U(x_2,h_2)-U(x_1,h_1)$. As we mentioned before, This means that the firm's optimal investment on testing is at the point where the marginal utility of the last dollar spent on reduction in probability of accidental event is equal to the reduction in probability in losses, caused by the last dollar spent on testing. Now assume that the investment on testing which can satisfy the equation (11) is r** and the relevant testing interval of such investment is τ**. By comparing the equation (11) and (6) we can see that in the equation (11) we have a positive term $P(r)Z_rU_{x2}$, is which reduce our P_r (recall that P_r is a negative value) and relatively increase investment on testing. Thus, the investment regarding new probability of failure would be r** which is larger than the previous optimal investment r*, r**>r*, and relatively τ** is shorter than the τ*, τ**<τ*. This means that the marginal utility benefits of a given investment in testing increase if all the costs are taken by the firm compared to the situation where some costs are taken by society and not by the firm itself.

We can say that the marginal rate of substitution (MRS) in the society point of view is higher than the marginal rate of substitution for the firm; $MRS_{Society} > MRS_{Firm}$. To graphically show such a situation we can say that the optimal investment in the testing for the firm implies that the marginal rate of substitution for society is at the point which is greater than the marginal rate of transformation; $MRS_{Society} > MRT$. Recall that the optimal point of investment on testing is at the point E for the expected utility maximizing firm in figure 3 where the marginal rate of transformation (MRT) is equal to marginal rate of substitution (MRS), $MRT = MRS_{Firm}$. The requirement $MRS_{Society} > MRT$ dictates that the optimal solution from a society point of view (point F) is to the right of point E. Figure 4 shows this situation.

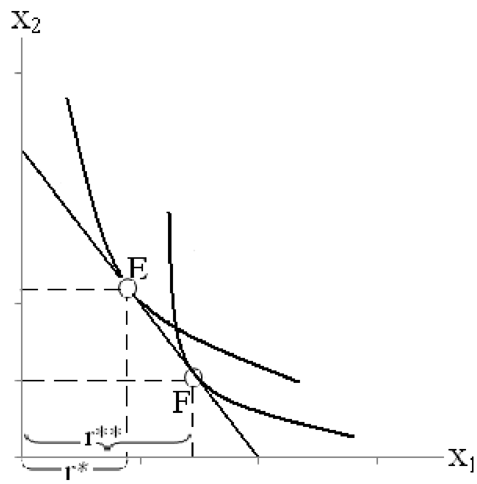

Figure 4. Investment on tests in the view of society

From figure 4 we can see that point F is not optimal for the firm as MRT at this point is higher than MRS_{Firm}. The firm could be better off if the investments on the testing are reduced. However, at point F the MRT is equal to the $MRS_{Society}$. This means that society can be better off if more money is invested on the testing of safety critical valves.

This can be a support for the society emphasizing on strict regulation of annual testing of safety critical valves. We can see from the above graph that the society should force the firm to take in to account the society costs and invest more on tests. Such forces can be done by regulations which are in line with the Jones-lee [8]. Jones-lee stated that the use of acceptance criteria from a societal point of view can be appropriate, even if such criteria violate the axiomatic basis of the expected utility theory. However, in practice it is not possible for the government to pay attention to individual situations. The same requirement has to be adopted for all possible situations; otherwise the inefficiency in the allocation of scarce resources is then very likely. This is in line with [7] where it was shown that the use of acceptance criteria can be appropriate for society if government adopted such a requirement for each possible situation.

Now, we want to see the firm's problem of finding the optimal point of investment on testing with the standards (regulation) requirements. In the standards the authority requests the safety critical valves such as ESV's to be tested annually. If this regulation takes to account the negative impact costs of testing such as expected fatalities (the term (V(r)) then the optimal point for the probability of failure in the society eye is equal with the standard. On the other hand, what will be the firm decision problem if the standards do not take in to account the negative impacts of tests? To see the influence of such ignorance in the firm's problem, we will show the expected utility maximize without considering negative impacts of tests. Such expected utility could be;

$$EU_{Max} = [1-P(r)]\, U(x_1,h_1) + P(r)U(x_2,h_2) \tag{12}$$

Where

$$x_1=x_0-r \qquad x_2=x_0-r-A-Z(r) \tag{13}$$

and

$$h_1=0 \qquad h_2=h_1 \tag{14}$$

The first order conditional is

$$\partial EU/_{\partial r} = \left[\left(-\partial P/_{\partial r}\right)U(x_1,h_1)\right] + \left[\partial U/_{\partial x_1}(-1)(1-P(r))\right] + [\partial P/_{\partial r}U(x_2,h_2)] + [P(r)\,\partial U/_{\partial x_2}(-1)] + [\partial U/_{\partial x_2}(-z_r)P(r)] = 0$$

$$P_r[U(x_2,h_2)-U(x_1,h_1)]=U_{x1}[1-P(r)]+P(r)U_{x2}+P(r)Z_rU_{x2} \tag{15}$$

$$P_r = \frac{[1-P(r)]U_{x1}+P(r)U_{x2}+P(r)U_{x2}Z_r}{U(x_2,h_2)-U(x_1,h_1)} \tag{16}$$

Condition (16) says that a marginal decreasing of the probability of failure due to increasing of the investment on testing is equal to the expected utility of consumption in wealth, $[1-P(r)]U_{x1}+P(r)U_{x2}+P(r)Z_rU_{x2}$, divided by two states of utility, $U(x_2,h_2)-U(x_1,h_1)$. This means that the firm's optimal investment on testing is at the point where the utility of the last dollar spent on reduction in probability of accidental event is equal to the utility of the reduction in losses. The marginal utility spent on reduction in probability only consists of the marginal utility from a decrease in the wealth, $(1-P(r))\, U_{x1}+ P(r)\, U_{x2}+P(r)Z_rU_{x2}$. This result can explain the state that the testing is a tool for reducing the probability of failure and the only thing that can stop the investment on testing from going to infinite is the cost of testing. Assume that P_r*** can satisfy condition (16) which is equal to annual testing of the valve (τ***) and investing on testing (r***). By comparing the two conditions (11) and (16), we can see that the positive term of $(U_{h1}V_rP(r))$ omits in equation (16). It means that the new P_r*** is less than the previous one (P_r**), recall that P_r is the negative value. Regarding to our first assumption which is probability is a concave reducing function of (r), the company should invest much more on tests(r***>r**). Thus, the test period in the view of standards for the firm is less than calculated period with respect to condition (11),(τ***<τ**). This means that the request for the annual test of safety critical valve is too strict in the society view. This means that the requirement of annual testing of safety critical valves underestimate the safety measures. Such requirement can not increase the safety level, but also increase the probability of an accident such as fatalities during testing.

From the analysis above, we can see that the use of an annual testing interval for the safety critical valves can not be appropriate for society, but can only be inappropriate.

Collecting the above arguments, the calculated P_r in the view of society, P_r^{**} should be somewhere between P_r* and P_r***, $P_r^* < P_r^{**} < P_r^{***}$. The investment on testing should be between the standard view and firm view. Thus, the interval between test should be between τ* and τ***, τ***<τ**<τ*. This indicates that the marginal utility benefits of a given investment in testing increase if we ignore negative impacts of testing. To graphically show this results we can say that the marginal rate of substitution in the standards view is higher than both firm and society point of view, $MRS_{standard} > MRS_{Society} > MRS_{Firm}$. This circumstances denotes that the marginal rate of investment on testing for the regulation (standards) is at the point which is greater than the marginal rate of transformation in the firm and society view, $MRS_{Standard} > MRS_{Society} > MRS_{Firm} = MRT$. According to this requirement the optimal solution from a standard point of view (G) is to the right of point E and F. Figure 5 shows this situation.

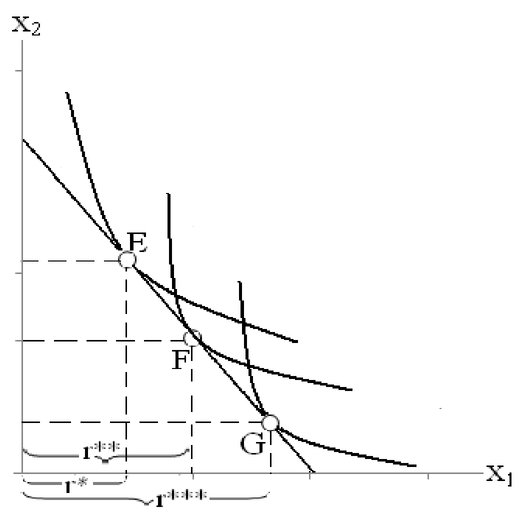

Figure 5. Optimal investment on test in standard, society, Firm

Figure 5 illustrates that point G is not optimal for the firm as MRT at this point is higher than MRS_{Firm}, in addition, this point is not optimal for society as MRT at this point is also greater than $MRS_{Society}$. Both firm and society could be better off if the investments on testing are reduced. This means that the annual testing intervals of safety critical valves are too strict for the society and the firm.

Hence, we can not omit the term $P(r)U_{h2}V_r$ as we argued in section 2.1. Also, we have to note that an increase in fatalities will increase the society's cost of accidents. Thus, society can not omit the term that includes the expected fatalities during testing.

Until now attention has been given to not neglecting the negative impact of test, also, we show that annual testing of safety critical valves is too strict for society and firm. One can also ask then "what is the optimal period between tests?"

3. THE VALUE OF A STATISTICAL LIFE

Up to know we present model in line with the principle of many researchers in safety in which there is no explicit trade-off between wealth and fatalities. However, from the above analysis we can conclude the fact that when the expected fatalities included in the model, it influenced the magnitude of the investment on testing. Most economists will regard this trade-off as being present independently of whether it is explicitly made, as the decision made in each case will reveal how many resources one is willing to invest to reduce fatalities, and thereby the value of a statistical life (VSL).

That any decision that includes the fatalities during tests and value of a statistical life can be seen by finding condition below from equation (6).

$$V_r = \frac{[1-P(r)]U_{x1} + P(r)U_{x2} - P_r[U(x_2,h_2) - U(x_1,h_1)]}{P(r)U_{h2}} \qquad (18)$$

From the condition (18) we can see that changing in the number of fatalities due to increase in the investment on testing, relatively decrease the interval between tests, is expressed as a function of the other values. One can calculate the VSL just by getting integral from V_r. Use of such values at least can avoid more resources being spent on testing to increase reliability without considering the negative impacts of testing.

4. CONCLUSIONS

We have shown that the annual testing of the safety critical valves such as ESV's is not appropriate, but inappropriate for both firm and society. In fact we have shown that such interval is too strict for firm if they take into account the negative impact of testing. Such negative impact, as we use in this paper, can be increasing the expected fatalities for the testing crew. By ignoring the negative impact of testing one may then in the safety point of view say that invest on testing to the infinite to increase the reliability, however, this is acknowledge that testing it self can be a potential activity that can reduce the whole safety level of firm, in addition, tests have negative impacts for the one who perform it as well as the environment. Moreover, by not taking this into account when making decisions, one is likely to allocate resources inefficiently when managing risk, thereby underestimating the safety level. We have shown that the requirement on annual testing usually is stricter than what the firms prefer. The main reason is that firm's activity usually causes negative externalities to society. Also, we have shown that yearly testing of safety critical valves is too strict for society point of view due to considering the negative impacts of testing as long as they consider about avoiding accident.

At the end, we have shown that for finding the optimal investment in testing, it will fruitful if we calculate the VSL in every situation. Although, we have to note that giving just one value to all situation can be a recipe for disaster. Thus, in every circumstance we have to calculate the probability and consequences of testing failure.

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