Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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Resilience-Based Maintenance: a new concept for subsea oil and gas industry

Master's thesis in Subsea Technology
Supervisor: Per Schjølberg
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Abstract

The Subsea oil and gas industry is one of the highly exposed industries to risks, disasters, and fluctuations in production.

Counting and limiting system failures and risks are not the best way to mitigate risks in light of the rapid development of systems, their high degree of complexity, and the interactions between them.

Resilience engineering makes the system proactive against threats through the ability to anticipate and adapt to the threat. Thus, a higher preparation and planning to absorb shocks and a smaller decrease in performance and productivity.

This thesis aims to demonstrate a new concept of maintenance called Resilience-Based Maintenance (RBM). RBM depends on preparation and planning to absorb the shock of events, adapt to them, and recover to the required performance.

RBM can predict and learn from events by analyzing the system's data in failure and success cases and setting leading indicators with specific characteristics and more accurately in monitoring performance and anticipating events.

RBM can be considered an important addition for subsea systems due to the complexity of these systems, which exposed them to unknown, and unexpected threats and failures.

The thesis aims to present the new concept with an explanation of its benefits, limitations, the sources from which it derives the resilience property, and how to evaluate its effectiveness.

This thesis is based on a literature review that included subsea production systems, an overview of types of maintenance and maintenance strategies, maintenance of subsea systems, a look at resilience engineering, methods of measuring resilience, and a discussion of RBM for subsea systems.

Keywords: Subsea, Resilience, Safety, Risk, Reliability, Maintenance

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I want to thank my family and friends, who showed me support, encouragement, and pride.

Table of Contents

List of Figures

List of Abbreviations:

1. BOP: Blow Out Preventer.
2. FMECA: Failure Mode Effects and Criticality Analysis.
3. VXT: Vertical Xmas Tree.
4. ASME: American Society of Mechanical Engineers.
5. NIAC: National Infrastructure Advisory Council.
6. ROV: Remotely Operated Vehicle.
7. RL: Resilience Loss.
8. PPM: Part-Per-Million.
9. MTBF: Mean Time Between Failures.
10. MEG: Mono Ethylene Glycol.
11. BFS: Barrier Fluid System.
12. TPM: Total Productive Maintenance.
13. RCM: Reliability Centred Maintenance.
14. TQM: Total Quality Management.
15. IoT: Internet Of Things.
16. CPS: Cyber-Physical Systems.
17. IMR: Inspection, Maintenance, and Repair.
18. NDE: Non-Destructive Evaluation.
19. NDT: Non-Destructive Testing.
20. DP: Dynamic Positioning.
21. ILI: In-Line Inspection.
22. RBM: Resilience-Based Maintenance.
23. SMART: Specific, Measurable, Achievable, Relevant, and Timed.
24. SIMS: Subsea Integrity Management System.

1. Introduction

1.1 Background and Motivation

1.1.1 History

In 1859, the first oil well was drilled in Pennsylvania, USA using cable tools. In 1897, in Summerland, California, USA, the first offshore well was drilled. Just 38 years after Pennsylvania's well. More than 150 offshore wells are producing in California Five years later, and they are now [66].

In time, Word trade has grown up, and the industry has taken various forms and developed rapidly, in total the whole humanity developing. Wealth and energy were central and vital to this development.

From the day humans started to drill oil wells, oil is the primary source of energy. According to Robert Rapier, 57% of energy consumption comes from oil and natural gas, up to 33% oil (on the top of energy sources), and natural gas comes in third place with a share up to 24% [67].

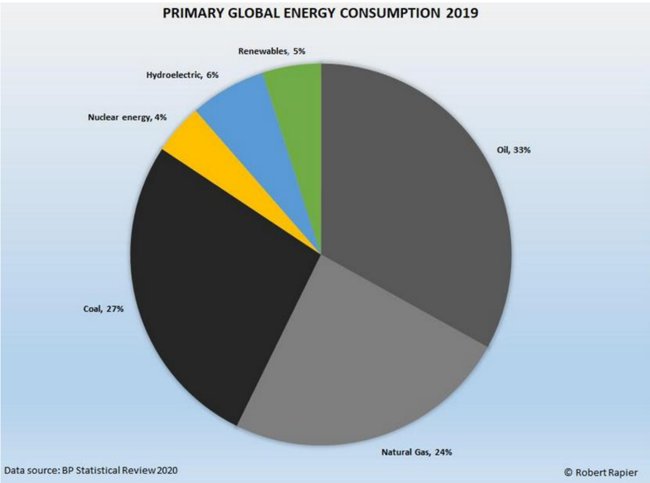

Figure 1: Primary Energy Consumption [67]

According to the official magazine of the international association of drilling contractors, in 2020 only, there is a need to drill 670000 wells to cover the global demand for energy [68].

Producing natural gas or oil onshore is always easier than offshore. As an outcome of the current developed level, producing hydrocarbons offshore from challenging environments is not as difficult as before.

According to Statista, hydrocarbons extraction in 2018 was 72% onshore and 28% offshore, and this ratio is expected to remain until 2025 [69].

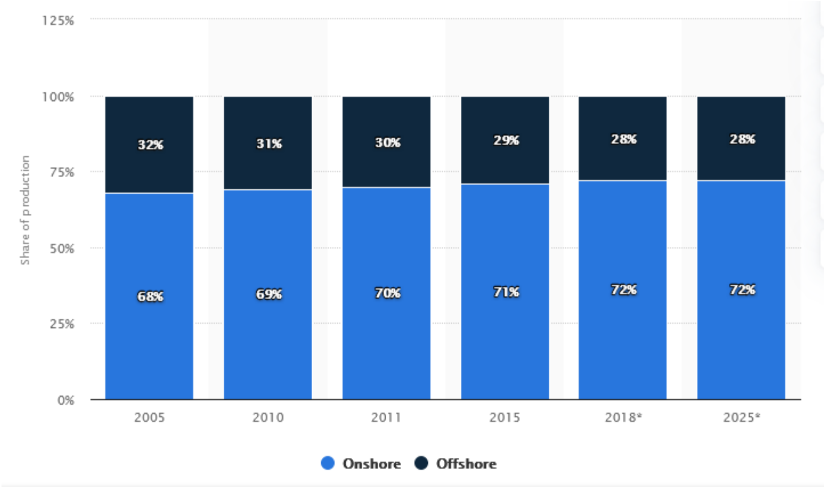

Figure 2: Hydrocarbons extractions between offshore and onshore through time [69]

1.1.2 The transition to subsea oil and gas industry

In the second half of 2014, the oil prices fell by 44%, which resulted in a massive drop in oil prices in recent history [61].

This event started thoughts about innovative solutions to support tightened budgets and increase production. Developing the subsea oil and gas industry was one of the options. This development of the subsea production systems can positively affect both, reducing the costs resulting from using new technologies and develop project's execution approaches [62].

The crisis of 2014 had another positive effect on the way of thinking toward the design of subsea equipment. This effect was a standardization of the equipment's creation, which could reduce the costs significantly for operators [62].

Companies started developing different subsea components that became more compact and lighter (e.g., compact manifolds, compact trees, etc.).

Figure 3: TechnipFMC’s trees: Subsea 1.0 (left), Subsea 1.5 (center), and Subsea 2.0 tree (right) [62]

The Subsea oil and gas industry involves high levels of digitalization. Where this trend can lead to many benefits as [62]:

- Optimize the concepts of design and selection.
- Improve risk.
- Reduce time and project execution.
- Enhanced safety.
- Optimize production.
- Optimize condition performance monitoring and production performance monitoring.

1.1.3 Challenges in the subsea oil and gas industry

To ensuring an efficient and effective flow of the produced hydrocarbons, producers must overcome a set of obstacles. These obstacles revolve mainly around the installation of equipment and especially the critical ones [63].

Each execution of a subsea project has challenges; it can be due to environmental conditions or the project's location, or other reasons. Risk assessment should carry on before the execution to assure safety and avoid other obstacles like excess stresses, overload, corrosion, fatigue, and cracking risks, which can cause failures. Many troubles are avoided by good planning and excellent design. During the installation, events can occur sequentially. It recommends having a perfect understanding of the seabed environment before project initiation [63].

1.1.4 Why risk assessment is vital in subsea production systems

Oil and gas offshore fields, as usual, are far away from shore. It can take hours for personnel to reach the oil and gas offshore platform by helicopter. In unexpected failures, maintenance operations can take days and maybe weeks to bring the damaged systems back to their average functional level. Therefore, maintenance management policies and risk assessment are necessary to avoid such scenarios.

By taking about hazards and failures, these offshore platforms and subsea systems are always equipped with safety systems and barriers to prevent and mitigate the consequences of hazardous events and mitigate the impacts on individuals, the environment, and the operating systems.

1.2 Objective

Risk assessment policies concern potential causes that lead to total failure and unwanted outcomes (e.g., disaster, accidents, incidents, etc.). Thus, there is no focus on things that do not go wrong. For example, let us say the probability of failure is 10^{-4}; this means 0.9999 is the probability of no failure. In other words, the risk is more concerned about safety issues, prevent damages from occurring, and mitigate their consequences, and it is not an indicator of system performance.

Resilience engineering can allow setting a scale of the performance and assess loosely onto process or system characteristics. Resilience is more related to the degradation of the process or the system. Thus, resilience can fill the gap between no failure and the occurrence of it.

Moreover, the nature of operations, installation processes, and maintenance in the subsea oil and gas industry require a system that deals with the unknown, unpredictable and unexpected.

In addition, subsea systems become more complex and challenging to track their failure causes, which demands a concept that adds flexibility to the operations and some adaptability to failures to ensure a grade of functionality and acceptable performance under stress.

Resilience can be an excellent addition to complex systems by equipping them with features like absorption of stresses, adaptability to failures, and maintaining acceptable performance until maintenance actions achieve the wanted performance.

This thesis aims to show a new concept that combines both resilience and maintenance called Resilience-Based Maintenance.

1.3 The scope

This report's scope focuses on the subsea industry's technical side, assuming that the environmental regulations are followed and there are no economic impacts.

The work done in this report is based on literary reviews of the latest findings in resilience engineering, taking into account other disciplines in which resilience engineering is involved to achieve a certain level of comprehensiveness of the principle.

The aim is not to make a quantitative analysis but to review methods and measures that can be used to assess the resilience of a technical system and combine the principles of resilience and maintenance in one concept.

1.4 Outline of the project

Chapter one presents background about the subsea industry's history and the transition to more subsea developments in the oil and gas industry. Moreover, it tells about the challenges facing this industry and how risk and safety assessment is vital. Additionally, chapter one provides insights into the objective and the scope of the project.

Chapter two shows the technical part of the subsea oil and gas industry and tells about typical components used in this industry. In addition, it tells about the maintenance and failures of the main subsea structures.

Chapter three defines maintenance and shows the types of maintenance. Moreover, chapter three introduces the concept of maintenance management and the two main approaches of maintenance; Reliability centered maintenance and Total productive maintenance. In addition, it tells about smart maintenance, its main components, and the state of the art of smart maintenance in the subsea industry.

Chapter four introduces the concept of IMR (Inspection, Maintenance, and Repair), Procedures of IMR, the tools of IMR. In addition, it shows the importance of IMR, challenges facing maintenance operations in the subsea industry, and the future of the subsea maintenance operations.

Chapter five introduce resilience science and define resilience. This chapter also shows the domains where resilience is used, and it tells about resilience’s properties.

Chapter six raises what methods are used to assess resilience and explains these methods.

Chapter seven presents the concept of Resilience-Based Maintenance and discusses what benefits and limitations this concept has. Moreover, it tells about the resources that support this concept and how to evaluate the effectiveness of the concept.

Chapter eight discusses how the concept of Resilience-Based Maintenance can be beneficial for the subsea oil and gas industry and conclude the findings of this thesis.

2. Subsea system

The Term subsea oil and gas industry includes operations where hydrocarbons extracted from reservoirs on great depths under the seabed pass through many components to reach the processing facilities.

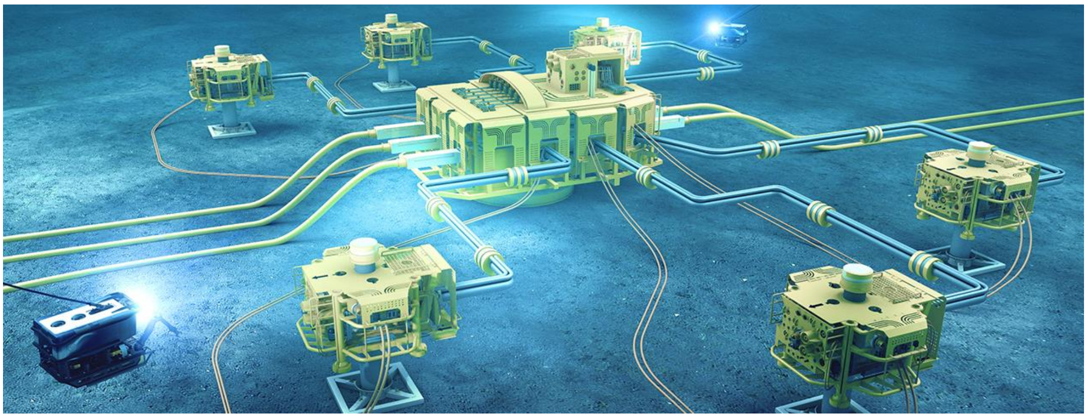

Figure 4: Subsea system [72]

The hydrocarbons flowing from the reservoir must flow to the wellhead, then Christmas tree, and through flowlines to manifold, then production facilities that can be offshore or onshore through pipelines and risers.

These production facilities include processing units as separators, valves, pumps, compressors, and pipes.

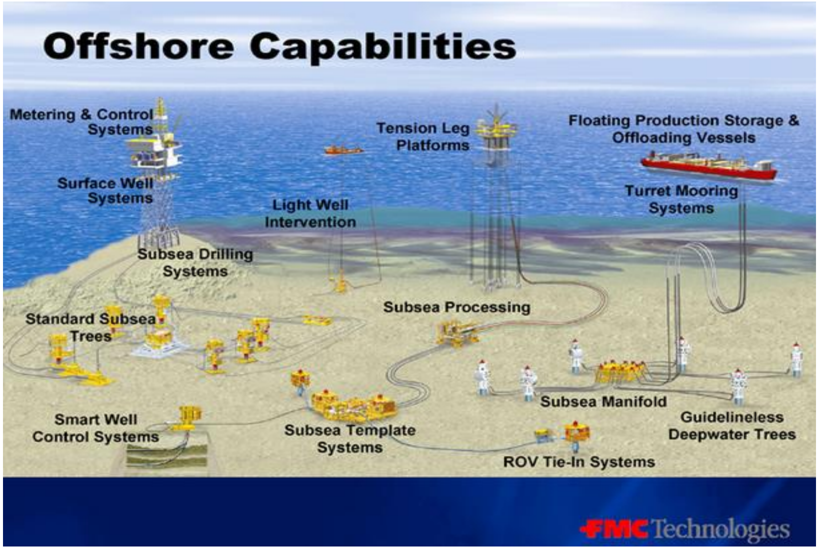

Figure 5: Different offshore platforms [73]

2.1 Subsea wellhead system

the wellhead is an interface and support with the Xmas tree and BOP. Besides, the Wellhead system withstands the loads during drilling completion and production operations. It ensures the right positioning of low-pressure conductor housing and high-pressure wellhead housing. Furthermore, the wellhead system designed with low sensitivity of water depth and sea conditions [70].

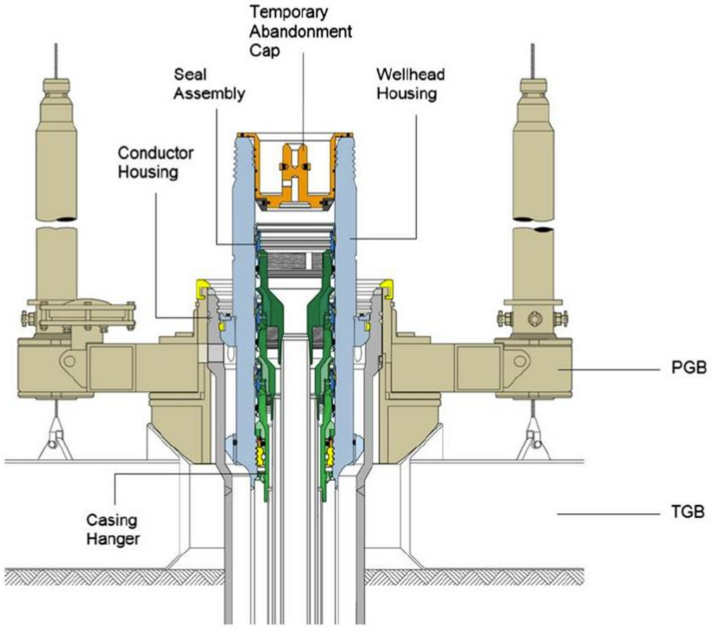

Figure 6: Subsea wellhead system [70]

2.1.1 Wellhead components

- Wellhead housing: the purpose of wellhead housing is to support intermediate and production casing strings. Two analyses should be performed while designing the wellhead housing: load stress analysis and thermal analysis [70].
- Intermediate casing hanger: it arrives in the first hanger position in the last part of the wellhead with dimensions of 16- or 13-5/8 inches. The main feature of this casing is to suspend the casing and BOP pressure end loads. While designing the intermediate casing hanger, reliability analysis and information should be listed in the FMECA [70].
- Production casing hanger: it settles in the second hanger position with dimensions 11-3/4 or 10-3/4 inches. It has the same feature as the last part, supporting casing and BOP pressure end loads.

- Lockdown Bushing: it protects the annulus seal from damaging while start-up or shut down operations by retaining the production casing hanger in its position. The lockdown capacity of this system is 3.2 million pounds. Component's perfect design demands the following work is done, finite element analysis, calculations, and reliability assessment using FMECA [70].
- Metal-to-metal annulus seal assembly: This part aims to seal the casing string annulus pressure from the bore pressure [70].
- Elastomeric annulus assembly: An emergency component works when the main metal seal fails [70].
- Casing hanger running tool: This tool's function is to run the casing hanger and set the annulus [70].

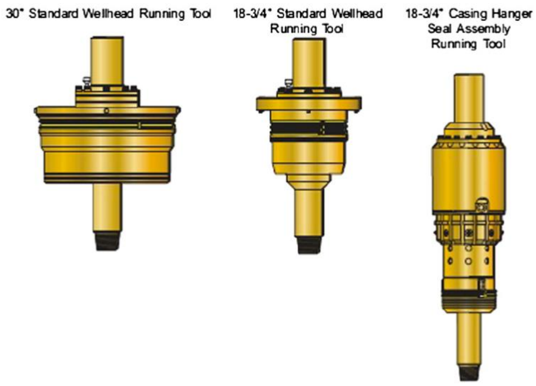

Figure 7: Casing hanger running tool [70]

- BOP test tool: This tool's function tests the BOP in case of unknown future pressure during drilling. Moreover, it is denoted to recover and run wear bushings [70].
- Isolation test tool: the tool is working as a test component of the Pack-off per mineral management service, which at the same time, it is sealing the BOP riser [70].
- OD wear bushing and OD BOP test tool: These components can test the BOP and expedite completions before installing the BOP [70].

2.2 Subsea Xmas Tree

When Xmas tree is used to let the well stream flow downstream, it is called production tree. If gas or water is injected through the tree into the formation, it is called an injection tree. Moreover, Xmas tree is sometimes used to adjust the flow through a choke. Xmas tree has a function of monitoring the well parameters such as pressure, annulus pressure, temperature and detects sand. Besides, Xmas tree has a safety function by its valves where it can stop the flow in a safe manner, either injected or produced. Xmas tree has a rule in flow assurance where it can be used to inject fluids such as corrosion inhibitors and hydrate preventors [70].

2.2.1 Xmas trees design structures

2.2.1.1 Vertical Xmas tree (VXT)

This type of Xmas trees is flexible during installation and widely used subsea. Master valve is placed above the tubing hanger in the tree. Installation of the tree occurs after well completion. Master and swab valves are stacked vertically. Placing the VXT on the top of the wellhead makes it easier to recover the VXT without recovering the downhole completion [70].

Figure 8: VXT made by FMC being lowered subsea [70]

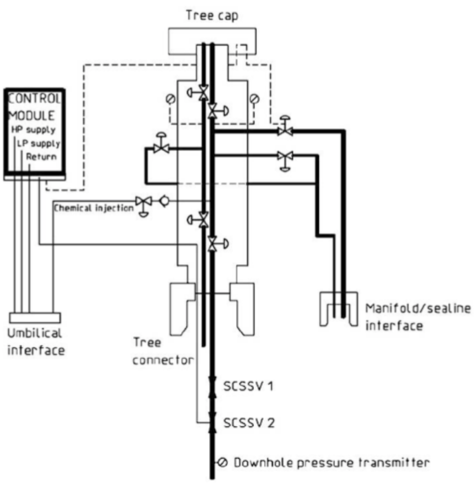

Figure 9: Schematic illustration of VXT [70]

2.2.1.2 Horizontal Xmas tree (HXT)

Valves in HXT are placed on the lateral side, which facilitates tubing recovery and well intervention. Tubing hanger is designed in the tree body, which demands to install the tree on the wellhead before the completion.

Figure 10: HXT made by FMC [70]

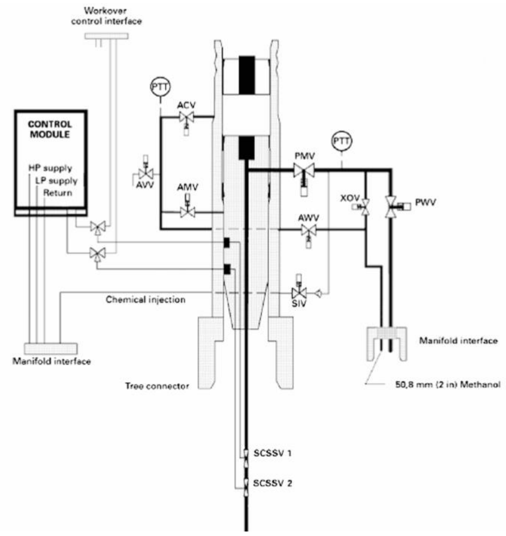

Figure 11: Schematic illustration of HXT [70]

2.3 Subsea manifolds

Manifolds are subsea structures installed on the seabed between wells. Several functions manifolds are intended to do, gathering, distributing, controlling, and monitoring the flow coming from wells. A subsea manifold is an arrangement of pipes and valves. The goal of using manifolds is to reduce the usage of pipes and risers, which optimize the fluid flow in the system. Jumpers connect the pipelines and wells with manifold [70].

A subsea manifold system is two parts. The first is the manifold, which includes piping, valves, control modules, pigging loop flow meters, etc. While the second part is the foundation, which secures support to the whole structure [70].

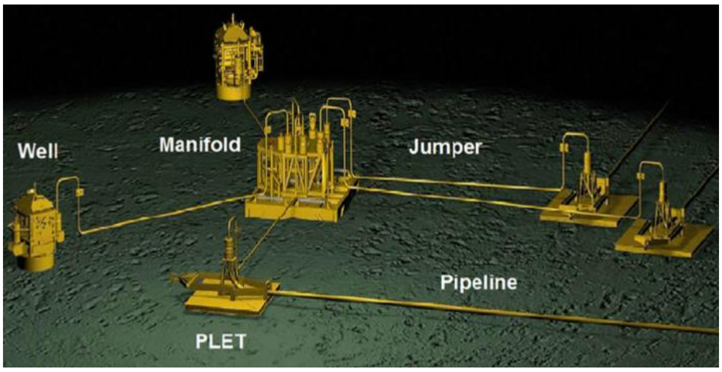

Figure 12: Subsea structure system [70]

2.3.1 Manifold foundation

- Mud mat with a skirt.
- Pile foundation

The choice of manifold foundation depends on two factors; the first is the soil condition; the second is the manifold size [70].

The manifold support structure is the interface between the manifold and its foundation. This support structure helps guide during the manifold's installation and measure the level relatively between the manifold and its foundation. Moreover, the support structure facilitates the manifold's replacement if a failure occurred and in the reinstallation process of a new manifold [70].

2.3.2 Manifold functions and purposes

Manifolds can be interpreted as a join point between the main parts of the subsea production system, where downstream there is the well system, and upstream the production pipeline system. Before sending the producing hydrocarbons to the production pipelines, manifolds collect fluids from different wells and mingling them in one line [70].

Manifolds receive fluids from the top-side and other subsea units and direct them into the wells or into other subsea units. These fluids can be, chemicals for flowing assurance, injection fluids like gas or water. Besides, manifolds are stations for ROVs.

2.3.3 Manifold components

Some components in a manifold intended to work during the project’s lifetime such as:

- headers
- Valves

- Chokes
- Hubs for pipeline connection
- Hubs for multiphase meter module
- Hydraulic and electric lines

Some other components are designed to be retrievable in case of failure like:

- Choke modules
- Subsea control module
- Multiphase meter modules

2.4 Subsea pipelines

The functions of pipelines and their usage are unlimited. They are the connection between all the subsea units, and they take different shapes according to their use. If the pipeline used between the wellhead, and the riser foot, carrying hydrocarbons, then it is called flowlines; otherwise, it is called export pipelines because the hydrocarbons are transported into it, from processing facilities to the shore [70]. There are different types of flowlines systems:

- Single-pipe pipeline system.
- Pipe-in-pipe system.
- Bundled system.

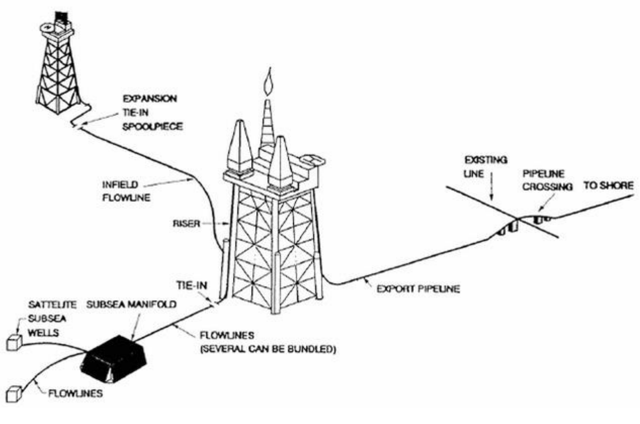

Figure 13: Subsea pipelines [70]

2.4.1 Design of subsea pipelines

The purpose of designing the pipelines is to find the pipeline dimensions' optimal parameters based on given data and information [70]. These parameters are:

- Internal parameter of the pipeline.
- Wall-thickness
- Pipeline material
- Type of protection, corrosion protection, coating, …, etc.

2.4.2 Other technologies of pipelines

2.4.2.1 Bundled pipe

This type serves different purposes because it includes various kinds of pipes (e.g., lines for power, signal, communication, and others)

Figure 14: Bundled pipe [57]

2.4.2.2 Pipe-in-pipe (PIP)

It is a kind of environmental barrier, where it conveys a heated medium in the annulus to melt possible hydrate plug along the pipe. It may also include a built-in “sheath” which allows for “heat tracing.”

Figure 15: Pipe-in-pipe [57]

2.4.2.3 Flexible flowlines

This type of pipelines has some particular specifications as:

- Smaller bending stiffness.
- Larger insallation tolerance.
- It can “curve” around obstructions.
- It is easy to be recovered and repaired.

And this type serves additional purposes due to multiple flowlines inside it. These additional flowlines can connect with control systems, production chemicals systems, power and signal systems.

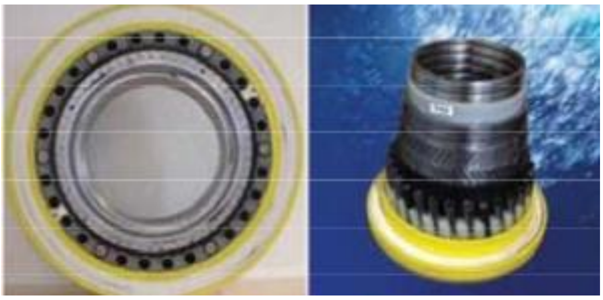

Figure 16: Flexible flowline [57]

2.5 Separators

After the hydrocarbons flow from the manifold structures, they enter separators. These/this separator(s) are/is located a short distance from the previous component in the process. It works according to gravity separations, where the three main components of hydrocarbons (Oil, Water, and Gas) split from each other [58].

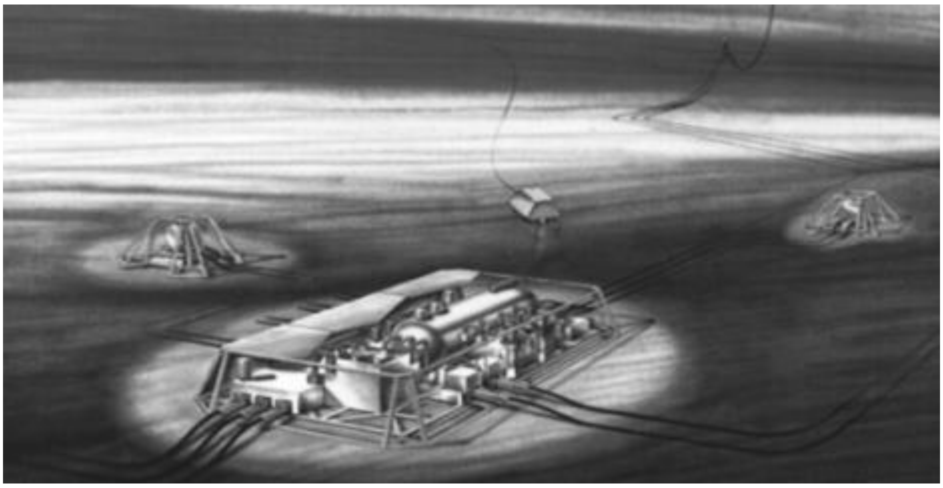

Figure 17: ABB subsea separation [58]

2.5.1 Types of separators

2.5.1.1 Two-phase separator

This type works on splitting two elements of the stream coming in (gas/liquid). It can be horizontal, vertical, or spherical.

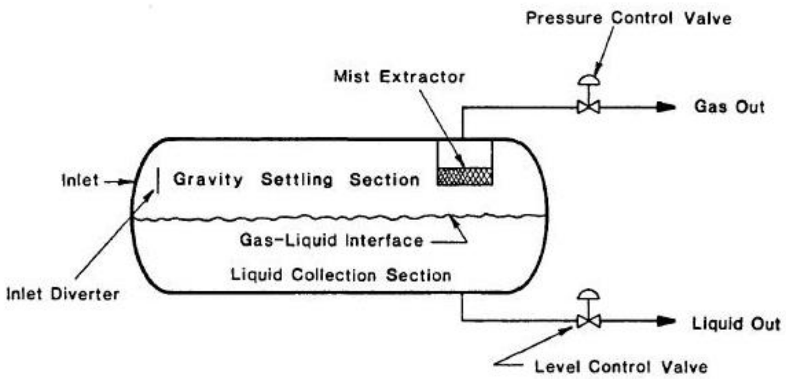

Figure 18: Horizontal two-phase separator [59]

2.5.1.2 Three-phase separator

This type splits the inlet stream into three elements (gas/liquid/liquid). Typically this type is designed as a horizontal separator, which gives an advantage of a large interface area between oil and water.

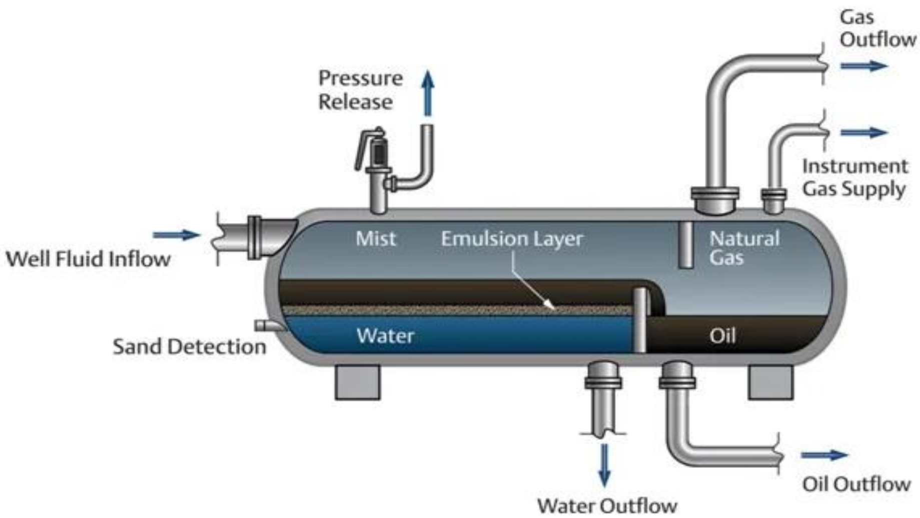

Figure 19: Horizontal three-phase separator [60]

2.6 Failures and maintenance of main subsea structures

2.6.1 Wellhead and Xmas Tree

NORSK D-010 defines a well's integrity as "*application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well.*"

In NORSK D-010, there are information and guides about the minimum requirements and solutions that should be followed in the well operations. The operating companies are responsible for compiling their operations and strategies with the instructions of NORSK D-010 [109]. The organizational solutions are as important as the technical and operational solutions; some of these solutions are :

- A qualified operational staff.
- Good communication between the responsible parties is required to operate the well correctly.
- Documentation.

The previous routine works as documentation and communication are significant as reports show that most accidents result from ignoring this type of work [109].

On the other side, hydrocarbons have properties of erosion and corrosion. The flowing of hydrocarbons will cause wear in the wellhead and Xmas Tree and degradation of the casing.

Preventive maintenance actions must be prepared and quickly take place to ensure the excellent and effective operation of the wellhead and Xmas Tree and to avoid catastrophic risks, sudden shut-ins, and significant financial losses [110].

The effect on wellhead and Xmas Tree structural integrity is dependant on the number of influences and the causes of degradation and failure. Unfortunately, these matters are not evident all the time, so inspection of structures and condition monitoring may reveal some failures that demand intervention [110].

2.6.1.1 Wellhead and Xmas Tree failures

Failures in the wellhead and Xmas Tree are two types:

- Failure caused by mechanical parts: Usually, valves and actuators are commonly faulty parts in the wellhead and Xmas Tree. The main valves are Master Valve and Offtake valves, and they are responsible for the flow control. Failures in the valves and actuators are mainly seizure and breakage [110].

- Failures caused by erosion and corrosion: wellhead and Xmas Tree are sitting on the seabed and surrounded by salt water and sand, in other words, corrosive and erosive environment. Corrosion and erosion also affect the internal parts of the wellhead and Xmas Tree, where the flow of hydrocarbons can damage the internals and the casing with time. The failure of corrosion and erosion appears initially as continuous thining of components, resulting in leakage that causes contamination to the environment and quicker degradation to other parts [110].

2.6.1.2 Wellhead and Xmas Tree maintenance

- Maintenance of mechanical parts: seizure is caused by loss of lubrication and if the component is not working for long periods. Fixing this failure requires flushing by lubricants, but this type of action does not sometimes work, which means that the component should be replaced. However, replacing is usually a costly process because it demands a shut-in of the well. It becomes more expensive if the component is stuck in place and requires special procedures to replace it [110].

  To avoid failures happen to mechanical parts like valves and actuators, these are some procedures that can help:

  - Condition monitoring and recording how many turns are required to open a valve and to do the opposite.
  - Regular inspection to search for marks of damage or leakage.
  - Quick intervention if damage in valves is found because these valves are necessary in case of emergency.
- Maintenance of erosion and corrosion: it is difficult to check if the casing string is intact, but monitoring pressure readings will help to know the flow characteristics inside the parts and reveal failures [110]. Changing flow characteristics inside the components is a good indicator of cracks or holes inside the casing strings. It is recommended to use corrosion inhibitors against corrosion and controlling the velocity of hydrocarbons inside the wellhead and Xmas Tree to avoid erosion caused by sand. Sometimes maintenance work can be very complicated, which requires a complete workover.

2.6.2 Pipelines

The marine environment is a challenging environment for subsea pipelines, which requires continuous following of pipeline's conditions. Moreover, fixing and repairing operations are costly, which makes preventive maintenance programs more financially feasible. Therefore, developments were made for this section of the subsea oil and gas industry in recent years. The staff that deals with pipelines become more trained, and they get training for emergency cases which is mandatory by regulators. The most significant cause of failure of pipelines is corrosion, externally or internally. When the gas pumped in the pipelines is reduced, these pipelines are used to transport liquids, enhancing corrosion. Corrosion protection has been developed in recent years, and some pipelines are operating beyond their expected lifetime. Checking for leakage has been developed recently, where boats and planes are used combined to make a visual inspection besides checking the pressure and the flow inside the pipelines. Even though corrosion is the main cause of failure, there are other reasons for failures, e.g., failure caused by vessels and their gear [111].

2.6.2.1 Corrosion control

Pipelines should be fabricated and designed according to industrial standards. These standards address the minimum operating design, post-construction, and testing standards. Corrosion occurs internally and externally, and the locations of its occurrence are mostly predictable.

The internal corrosion tends to occur in low spots and riser elbows, while the external corrosion tends to occur at splash zones at the sea surface [111].

2.6.2.2 Corrosion protection

- Externally: the coating is the commonly used protection against corrosion. Many standards provide testing intervals for the coating to verify its effectiveness. In some cases, cathodic protection is preferable where a low voltage is supplied to the pipelines using an external power source or an electrochemical reaction between two dissimilar metals. Another cathodic protection technique uses a sacrificial anode like zinc or aluminum to protect the pipelines. Cathodic protection requires monitoring; two ways are used, spot monitoring of the pipeline potential and close-interval potential surveys [111].
- Internally: Internal corrosion is more challenging than external corrosion because it is difficult to determine its location and amount. The inaccessibility of offshore pipelines makes it challenging to take intermediate sampling. Usually, monitoring internal

corrosion is done using three points, one on the platform, a middle point, and one at the end. Another way is immersing coupons in gas or liquid to decide if there is corrosion. When corrosion is found, the sample is analyzed to determine the amount of inhibitor to be pumped. However, inhibitors are used in gas pipelines, whereas in pipelines transporting liquids, operators rely on liquid flow to keep the water in suspension [111].

2.6.2.3 Maintenance of pipelines

Maintenance of pipelines on the seabed requires special developed equipment or well-trained divers. In addition, more care should be taken to the interface point between the pipeline and the platform because it can expose the platform and its personnel to a real danger. When performing an external inspection of corrosion, three things should be considered: cost, safety, and environmental impact. Divers and ROVs are used for visual inspection. ROVs are equipped with a magnetic tracking device to check the external physical condition of the pipeline. Other ways to perform visual inspection are sonars and magnetic devices. On the other side, two ways are used to perform maintenance and inspection for internal corrosion. The first one is pressure testing; this method is used to reveal leaks. The other is in-line inspection (ILI) or smart pigs, where a device is inserted into the pipeline to record data about metal loss and other characteristics [111].

3. Maintenance

"Maintenance is the combination of all technical, administrative, and managerial actions during the lifecycle of an item intended to retain it in or restore it to, a state in which it can perform the required function" (EN 13306:2001 Maintenance terminology).

The life cycle of functional components in production systems categorizes into three periods [74].

1. Nominal conditions.
2. It is working, but it is not as expected.
3. Stop working where it causes stoppage and initiation of followed maintenance work.

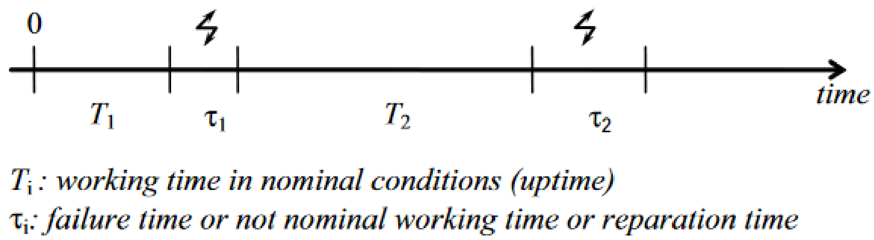

Figure 20: The life cycle of a component in a production system [74]

Generally, an item's life cycle in a production system will be subjected to failures and a time-dependent degradation process. However, the item can be repaired by restoration activity [74].

3.1 Defenition

Maintenance is the function that monitors and keeps plants, equipment, and facilities working. It must design, organize, carry out, and check the work to guarantee nominal functioning of the item during working times "Ti" (uptimes) and to minimize stop-ping intervals (downtimes) caused by breakdowns or by the resulting repairs [74].

In BS EN 13306:2010, maintenance is defined as "*combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.*" [116]

3.2 Maintenance types

Maintenance is divided into two main types corrective or preventive. Each of the previous kinds is also divided into different categories. The following figure shows the classification of the maintenance types.

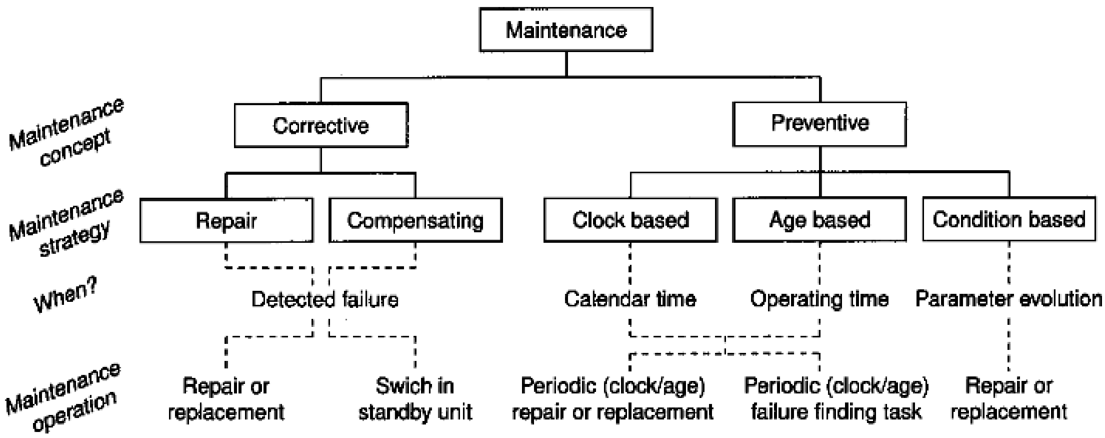

Figure 21: Classification of maintenance types [77]

3.2.1 Preventive maintenance (PM)

Preventive maintenance is planned maintenance and is performed when an item works appropriately, but a maintenance action occurs for the sake of avoiding future failures.

The main goal of preventive maintenance is reducing the probability of failure [77].

Som preventive maintenance actions can be [77]:

1. Inspection.
2. Adjustment.
3. Lubrication.
4. Replacement of parts.
5. Calibration.
6. Repairing.

Preventive maintenance divided into four categories:

1. Age-based maintenance.
2. Clock-baed maintenance.
3. Condition-based maintenance.

4. Opportunity maintenance.

3.2.1.1 Age-based maintenance

John Moubray, in his book Reliability-centered maintenance he calls this type of maintenance, Scheduled Restoration or Scheduled Discard tasks and defining it as:

"replacing or renewing an item to restore its reliability at a fixed time, interval or usage regardless of its condition" [76]

The purpose of this type of maintenance is the protection against failures that can occur to unknown wearing items that have a predictable mean time between failures "MTBF."

Clear service life can be determined for some items can be determined; therefore, the failure can be related to age. In some cases, the component is not worth the effort to be assessed because the process is not economically feasible, which can be a reason to choose age-based maintenance [76].

3.2.1.2 Clock-based maintenance

This type of maintenance is following a specified calendar time to perform preventive maintenance. Administrating this type of maintenance is much easier than age-based maintenance since it is performed at specified times [77].

Examples of clock-based maintenance [78]:

1. Inspect exterior sealant every three years.
2. Clean gutters every six months.
3. Lubricate pumps every 6,000 run hours.

3.2.1.3 Condition-based maintenance

Most of the failures give indications before they occur. However, monitoring the condition variables of an item can reveal some abnormalities in an early stage. This type of maintenance tends to start the maintenance work when a condition variable reaches a predetermined threshold.

One of the concepts of Condition-based maintenance is the P-F curve. This curve describes the evaluation of failure against time. The failure evolves until the point (P). It is possible to detect point (P), but the failure can be hidden, and the degradation can go faster until a functional failure occurs (F). The interval between (P) and (F) is called the window opportunity. The window opportunity is a time interval where the failure can be addressed, and maintenance work can be initiated [76].

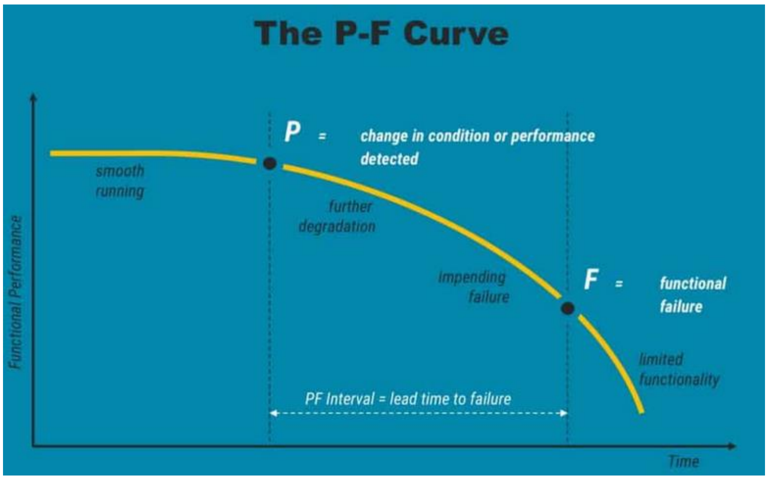

Figure 22: The P-F curve [76]

Condition-based maintenance intends to increase the possibility of intervention before the occurrence of a failure, not reducing its likelihood of occurrence.

In other words, Condition-based maintenance increases the probability of discovering a degradation process and avoiding sudden failures. Furthermore, it reduces the costs of failure and helps to achieve better planning and performing of maintenance.

3.2.1.4 Opportunity maintenance

This type of maintenance is more related to multi-item systems. When a planned or unplanned shutdown, the maintenance crew can take advantage of repairing or replacing items.

The main goal of opportunity maintenance is to increase availability and reduce production losses. A key element for this type of maintenance is to know when to replace a component during its useful life in a manner that makes the maintenance work economically feasible and effective.

3.2.1.5 Predictive maintenance

Utilizing Artificial intelligence, sensors, and machine learning, this type of maintenance can be highly effective and economically profitable. It can be seen as an advanced stage of condition-based maintenance. Monitoring a process parameters by online sensors draws a picture about its condition and makes it predictable if a failure will occur [76].

3.2.2 Corrective Maintenance (CM)

Corrective maintenance is also called breakdown maintenance or run-to-failure maintenance [77]. It is a reactive type of maintenance where the maintenance works initiate after the occurrence of failure that causes shutdown. The maintenance work involves identifying and repairing or replacing equipment. Safety-related failures and failures that cause production loss are on the top of the priority list of corrective maintenance tasks [80].

In the short term, corrective maintenance is not high-cost maintenance because it does not require many resources, expertise, infrastructures, technologies, and tools. However, it is inefficient and costly in the long term because the consequences of failure can be catastrophic, and the mean time between repair can be longer (MTTR). Additionally, Corrective maintenance does not search for the root causes, reflecting a longer mean time between failures (MTBF) [80].

3.2.3 Failure-finding maintenance

This type of maintenance is concerned the most about the protective system's hidden failures.

Hidden failure by definition is "*a failure which may occur and not be evident to the operating crew under normal circumstances if it occurs on its own"* [81]. Failure finding maintenance is a particular type of preventive maintenance.

Achieving the objectives of this maintenance (finding hidden failures) happens by inspection and testing.

3.3 Maintenance management

3.3.1 The need for maintenance management

Maintenance management can be interpreted as a restorative function of production management that ensures keeping production's assets services available and operating properly for a specific period. Minimizing the breakdowns and downtimes of the machines are objectives of maintenance while developing strategies that adopt the aims of maintenance actions and considering the technological and economic tough competitions in the industrial markets are done by maintenance management [95].

3.3.2 Importance of maintenance management

Maintenance management ensures smooth working of facilities and improves productivity. Besides, it helps to achieve optimum conditions for equipment. It can improve the operational efficiency of the plant facilities. Revenue and quality are essential factors of success in any industrial plant. For that, maintenance management increases this revenue by decreasing costs such as operating costs and improving the quality and quantity of products. As said, maintenance management adopts maintenance actions; it tends to enhance the costs of these actions by investing in the tools to perform maintenance and repairs [95].

3.3.3 Goals of maintenance management

Maintenance management exists to optimize the organization's performance and productivity and ensures effective and productive functioning. These goals can be achieved by applying proactive maintenance strategies that minimize breakdowns and lower the probability of failures [95].

3.4 Maintenance approaches

Maintenace approaches are sometimes referred to as maintenance strategies or philosophies. The focus from a maintenance approach to another is different; some focus on equipment reliability, while others focus on improving the quality of people and processes. Later and until now, maintaining physical assets is a need for people since we started building types of equipment and developing them. The need for maintenance approaches appeared by the increasing number, size, and complexity of assets and the increased specialization of maintenance tasks to be performed. All maintenance approaches use basic maintenance types for maintaining each asset of the total system [92].

The main types of maintenance approaches are:

- Total Productive Maintenance (TPM)
- Reliability centered maintenance (RCM)

Some facilities apply only one of these approaches in their maintenance plan, while studies show that using a combination of TPM and RCM can reduce downtime and increase productivity [93].

3.4.1 Total productive maintenance (TPM)

According to [94], TPM is defined as "*a method in which the focus is on elimination of main factors of production loss.*"

Japanese manufacturing industries started to use quality systems in 1960. When maintenance departments began to use total quality management (TQM) applications, a new maintenance approach developed. This approach is called "Total Productive Maintenance" (TBM). Total productive maintenance tends to achieve zero defect, zero loss, and zero failures and developing quality maintenance workers. TPM is seen as a people-centered approach to maintenance, making it suitable for all workers in business enterprises [92]. In short, (TPM) approach is based on people and process, transforms culture and the way we view our assets.

3.4.2 Reliability centered maintenance (RCM)

According to [94], RCM is defined as "*a structured, logical process for developing or optimizing the maintenance requirements of a physical resource in its operating context to realize its 'inherent reliability', where 'inherent reliability' is the level of reliability which can be achieved with an effective maintenance program*"

During and right after world war II, the need for reliable aircraft increased rapidly. Not only military airplanes but also manufacturers that produce passenger airplanes shared the same thoughts. The previous needs initiated the development of a new maintenance approach, which is later called "Reliability Centred Maintenance" (RCM). RCM tends to maximize the reliability of the physical assets by defining the failure modes of components or equipment of a system. Additionally, RCM ranks the consequences of each failure mode; if the consequences are safety-related or hidden to operators, preventive maintenance actions are preferred. RCM creates a life plane for each component in a system, and this life plane consists of preventive maintenance tasks that include replacement, maintenance, and condition monitoring. Some failures can be hidden, so RCM schedules preventive maintenance tasks of inspection and search for these types of failures [92]. RCM is daunting, but it establishes a strong foundation of maintenance strategies.

3.4.3 Comparison between TPM and RCM

- Total Productive Maintenance (TPM) [92]:

  Advantages :

  - Productivity improvement

    - Quality improvement
    - Cost reduction
    - Operator involvement

  Disadvantages:

    - Not a true maintenance concept
    - Lakes decision rules on maintenance policies
    - It does not focus on economic problems

- Reliability Centered Maintenance (RCM) [92]:

  Advantages:

    - Traceability
    - Cost-saving
    - Rationalization
    - Operator and Maintenance involvement
    - Plant reliability improvement

  Disadvantages:

    - Complexity
    - Extensive need for data
    - Reliability-Centered
    - It does not focus on economic problems

3.5 Smart maintenance

Smart maintenance is defined as “*an organizational design for managing maintenance of manufacturing plants in environments with pervasive digital technologies*” [96].

Smart maintenance represents a configural organizational design that includes the whole maintenance function of the plant to achieve effective and efficient decision-making and responsiveness to internal and external components [96].

3.5.1 Industry 4.0

It is also called “The next industrial revolution”. The idea came from Germany, where the government and working group formulated the new steps for the future of factory automation.

With industry 4.0, the industry will become more intelligent, and supply chains will be accessible through the internet. This access to the internet makes it possible to review readings from sensors connected to any machine on the network. The key to success for Industry 4.0 is that each industrial facility should adopt this step [97].

3.5.2 Internet of things (IoT)

IoT describes a network of physical assets equipped with sensors, software, or technology that enable data exchange with other devices [97].

Some technologies have helped to make objects smarter and able to be part of the network like [98]:

- Multiple technologies.
- Real-Time analytics.
- Machine learning.
- Commodity sensors.
- Embedded systems.

From a maintenance point of view, IoT can play an essential role in predictive maintenance. IoT can go over tasks like inspecting and searching for failures by using embedded sensors that provide real-time readings for equipment conditions. If these sensors capture abnormal functioning, they can initiate maintenance action to prevent consequential failures and improve productivity. With IoT, the machine will automatically calculate its MTTF and MTBF and report a need for maintenance. Sensors that drive this intelligence are driven by software that needs upgrades. When the machines are connected to the network, an upgrade can be pushed to the needy component [99].

The great value of IoT will be clear when a comprehensive look is taken at the entire system. Data are collected in clouds, processed, analyzed, and modeled; these data enable the prediction of breakdowns and limit availability loss [99].

3.5.3 Cyber-physical systems (CPS)

CPS is defined as "*a computer system in which a mechanism is controlled or monitored by computer-based algorithms*" [100].

Many machines and systems are equipped with technologies connected to the internet and communicate with databases and other systems. This automatic communication can increase performance and minimize human interference. Examples of these systems are many like smart houses where monitoring system is reading parameters about pressure, temperature, humidity, etc. It can give orders to the ventilation system or to the heating system to adjust to standard parameters. Another example where some posting firms started to have large stores equipped with robots that package things basing on orders that are ordered using the internet and send to the customer.

CPS can be a significant contribution because it enhances the efforts to make maintenance strategies more innovative and failure prediction and alarming processes more effective.

3.5.4 Big data

Big data is defined as "*a collection of data that is huge in volume, yet growing exponentially with time. It is a data with so large size and complexity that none of traditional data management tools can store it or process it efficiently.*" [114]

Big data stored from different fields have extensive statistical powers, but if it has high complexity, it can contribute to high false discovery rates [115]. Moreover, Big data is used in predictive analytics. Predictive analytics can help in many issues like business trends, fighting diseases, and maintenance; it can help know the trends of performance of a system or component, estimate mean time to failure, and measure a component's residual lifetime.

The characteristics of big data are the following [115]:

- Volume: the volume of big data is related to its value, and it should be in the size of terabytes or petabytes.
- Variety: type and nature of the gained data.
- Velocity: the speed of generating and gaining the data.
- Veracity: in addition to the size, the data should be reliable and have a quality value.
- Variability: format and structure of the data.
- Exhaustive: the data is gained from the whole system or some parts.

3.5.5 State of the art in subsea smart maintenance

Shell's smart maintenance program for Ormen Lange field is a subsea integrity management system (SIMS). This system depends on defining the personnel, processes, and systems that contribute to the field's safety and integrity. The purpose of SIMS is to increase availability and productivity With alertness to any emergency. It provides a kind of condition monitoring where Shell stores data gained from different systems in a database. The engineers use tools to analyze and gain information about any disruptions in operations and failures in equipment [113].

Inspection processes in SIMS follow the risk-based principle, where it takes into account three measures:

- The probability of failure.
- The consequensess of faiure.
- The faulty component’s ability to withstand the danger.

In diagnostics and inspection processes, the following details are significant:

- Acquired data.
- Condition monitoring analysis.
- Experts opinion.

In case of pending issues, an ROV inspection is needed to visualize the physical condition of the component [113].

4. Maintenance in subsea production systems

Subsea production systems are used to produce oil and gas in deep waters. These systems are tested and designed to operate in harsh environments, which can be risky. The risks can be in different forms, a collision with unknown objects, damage from fish-net, or equipment failure [101]. As the demand for oil and gas increases, the need for subsea production systems is increasing relatively, which increases the likelihood of recording failures in these systems [102]. For this reason, there is a demand for a combination of preventive and corrective maintenance. The preventive maintenance helps avoid future failures and mitigate their potential losses, where corrective maintenance restores the functionality of damaged components by replacing or fixing them, which helps keep operating and ensure the system's integrity. The combination of corrective and preventive maintenance actions is called Inspection, Maintenance, and Repair (IMR). The execution of IMR requires specialized vessels that are built for this purpose.

4.1 Subsea Inspection, Maintenance, and Repair Operations

Subsea IMR stands for the execution of three actions [103]:

- Inspection activities: These activities are used to check the conditions of subsea installations on the seabed, providing data to assess damages and prevent critical failures that can lead to losses in production or destructive events for the environment. On the other hand, it can draw a picture of the seabed conditions and geography preparing for new facilities installation. Methods that are used in inspection; non-destructive evaluation (NDE), and non-destructive testing (NDT) [104].
- Maintenance interventions: these actions tend to restore the functionality to faulty equipment on the seabed or beneath it; an example of such interventions is a routine replacement of a defective component. This part of IMR should have a good maintenance plan that considers cost, risk prevention, wanted outcomes, and investment benefits of maintenance. Applying preventive or corrective maintenance depends on the criticality of the system and the consequences of failures [104].
- Repair interventions: the act of replacing a defective component. This action is taken when the inspection activities indicate the compromised integrity of a system. Usually, repairs come with production losses, where these losses can vary between a production shutdown and reduced production. Executing a beneficial repair action demands an

appropriate repair plan. Some of the repair methods are refurbishment, retrofit, patch, and replacement [104].

4.2 Procedures of IMR's execution

According to [103], the following scenario happened in case of detection of failure:

1. The crew on the oil and gas platforms are usually the first who notice anomalies.
2. In case of anomalies, the crew in the control room records this as a Hazard notification.
3. Any hazard notification would go into three states in the log.
    - Ignore: this indicates that the failure can be tolerated.
    - Save: the failure will be grouped with other failures as action will be taken later.
    - Act: a repair action is urgent and should be taken immediately.
4. Usually, a production system has multiple redundancies, so the urgency of a repair act will be according to the number of redundant systems.
5. As the monitoring happens offshore, the onshore crew monitors the log, evaluates the execution of maintenance, and defines the risks.
6. If a maintenance action is urgent, a specialized maintenance vessel will be informed to mobilize to the location of failure.
7. The operator's IMR department decides the optimum usage of resources, and IMR service can be delivered to multiple fields.
8. The basis of an IMR plan is the analysis of the existing infrastructure's technical reliability, incoming reports from the installations, and long-term maintenance plans.

Usually, IMR operations are grouped into campaigns. A campaign can undergo delays and difficulties. Therefore, there is a database for logged failures that helps to do minor IMR operations. IMR's Operating companies have to optimize their operations in the long term, be ready for urgent demands, adapt to weather conditions.

4.3 Tools of IMR

4.3.1 The vessel

IMR's vessels are high-tech vessels that perform maintenance operations to subsea equipment using ROVs. When the vessel is at the maintenance location, it is fixed using DP technology (Dynamic positioning technology). Dp technology depends on the help of satellites to maintain an accurate position of the vessel using powerful thrusters which can move the vessels in all directions in a small area.

Figure 23: An IMR vessel [103]

It is worth mentioning that anchors are not used in the positioning process but only the powerful thrusters. Excluding anchors gives freedom to the ROVs in moving beneath the vessel with no obstacles. The body of the vessel has a hull that is used to lower or lift equipment. The vessel contains a bridge with a clear view in all directions; the crew can manage all the operations from the bridge [103].

There are two modes to operate the vessel:

- DP (Dynamic Positioning)
- Transit

Each mode has a separate console. Supplying the vessel with energy happens with the help of diesel engines. The number of engines varies from one vessel to another. Many factors are considered, e.g., size, the energy needed for the thrusters, energy required to the propellers engines, equipment, etc [103].

Usually, the vessels of IMR are equipped with side cranes and tower crane. These cranes are used for lowering and lifting ROVs and Equipment. The Tower crane is also called MHS (Module handling system); the most crucial function of MHS is stopping the pendulum motions in the horizontal plane with the help of wire guides. IMR vessels are equipped with protective equipment from the changing weather and a hanger to keep equipment protected. Besides, it has tanks and pumps that contain specific fluids for different operations; an example of these operations is cleaning wells [103].

4.3.2 ROV (Remotely Operated Vehicles)

ROV is mechanical equipment as closest to a mechanical lobster. The main parts of ROV are:

- Arms.
- Camera.
- Light.

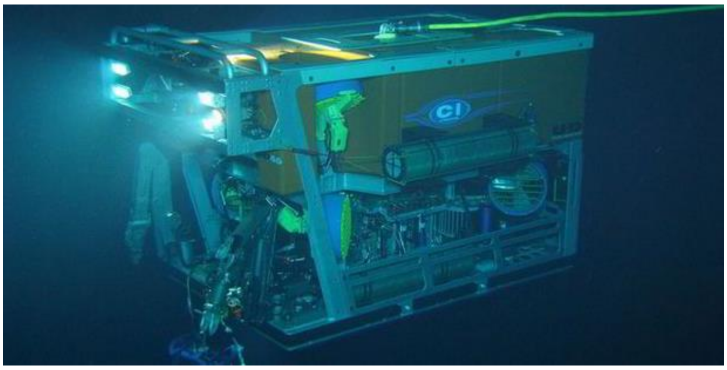

Figure 24: ROV [105]

When diving, the ROV is usually equipped with a toolbox and necessary components of the maintenance operation. The crew of the ROV is Two piolets on the vessel, and their tasks vary from simple tasks as installing a valve to complex tasks as scale squeezing. Controlling the ROV is done using two controllers, one with more power and the other is with more accuracy. Types of the ROVs carried on the vessel vary with size and functions. Some ROVs are Working ROVs used to perform complex maintenance tasks, others are smaller in size, and their tasks can be inspection and observation. The connection between the vessel and the ROV happens through a cable called Umbilical Cord. During the operation of the ROV, a supervisor is present with the two pilots.

4.4 Importance of IMR

Failures in oil and gas subsea equipment can bring catastrophic consequences on the oil and gas industry itself, the people working in this industry, and damage to the environment due to these failures. Due to the high risk of subsea equipment failures, investments in IMR are elevated to avoid the previously mentioned consequences and lower the associated risks and the high relative costs [106].

Using equipment condition data, process data, and data gained from the field allows operators to track equipment conditions, process deterioration to intervene when necessary [106].

4.5 Challenges of subsea maintenance

ABS showed in a report [104] some challenges facing the IMR at present:

- Technological limitations.
- Implementation of preventative monitoring and data usage.
- Selection of maintenance intervals.
- Maintenance strategy acceptance.

The lack of ability to give a comprehensive condition assessing of the permanent subsea structures shows the technological limitations facing IMR. As a result, there are difficulties in determining the equipment service life because of reliable data loss. Unreliable data has adverse effects on preventive maintenance or condition-based maintenance, making these data unusable and valueless and increasing the waste of time and costs [104].

The tendency to decrease the initial development costs can delay the initial incorporation plans of IMR, reflecting an increase in the costs of IMR later and the associated costs [104].

All these challenges should be discussed in the initial planning phases of future projects to decrease costs related to IMR and achieve maximum benefits of IMR operations [104].

4.6 Future of subsea maintenance

The future of subsea maintenance depends on the implementations of Subsea integrity management. Subsea integrity management is a concept that comes from the understanding of the structures that have been used underwater and integrity management [107].

From an industrial point of view, integrity management is understood as surveillance during operation, close to the concept of inspection management. Inspection management can be helpful for structures or components that are static and offer good accessibility by applying CP surveys (cathodic protection surveys) or UT testing (Ultrasonic testing). Other subsea structures as jacket structure, riser-caissons, conductors, templates, risers, and umbilicals are subjected to dynamic loads, so inspection operations will not be beneficial to avoid failures. Applying subsea integrity management provides the possibility to create simulations, monitoring, and testing, which helps increase the efficiency of maintenance operations, reduce the risks of failures, prolong the lifetime of equipment, and reduce costs [108].

Using the concept of subsea integrity management in the initial phases of project planning helps to understand the conditions affecting the remaining useful life of structures and systems. However, applying subsea integrity management decreases failure risks and helps assign intervals for inspections and maintenance and determining the expected repairs, costs and lowers the downtime. Besides, it helps to increase the confidence of operators, manufacturers, and investors [104].

5. Resilience

5.1 History of resilience

Resilience is an old word. This word is used to show a property of timber. It described the way that some types of wood react to sudden severe loads without breaking. Four decades from this term's usage, a reporter to the admiralty used the expression “modulus of resilience” to estimate the material’s ability to withstand loads. In 1973, professor Holling showed that an ecosystem's resilience could measure the capability of absorbing changes and keeping them existing. Holling defined resilience as: “the ability of a system to return to its equilibrium state after a temporary disturbance.” [2]

In 1970, the term resilience was used as a synonym for stress resistance in children's psychological studies. In the 21st century, the business community used the term resilience to dynamically describe the ability to reinvent business models and strategies as circumstances change. [2]

5.2 Definitions

The definition of resilience by Allenby and Fink was: “capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must.” [4].

Pregenzer said: “measure of a system's ability to absorb continuous and unpredictable change and still maintain its vital functions.” [5].

Haimes defined resilience as: “ability of system to withstand a major disruption within acceptable degradation parameters and to recover with a suitable time and reasonable costs and risks.” [6].

Vugrin defined system resilience as: “Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is that system's ability to reduce efficiently both the magnitude and duration of deviation from targeted system performance levels.” [7].

5.3 Resilience domains

According to Hosseini, Barker, and Jose E. Ramirez-Marquez the concept of resilience can be identified into four domains [3]:

- Organizational domain

- Social domain
- Economic domain
- Engineering domain

5.3.1 The organizational domain

Organizational resilience as a concept was invented to show a need for companies that can react to rapidly changing business environments. Sheffi defined the resilience of organization as: “the inherent ability to keep or recover a steady-state, thereby allowing it to continue normal operations after a disruptive event or in the presence of continuous stress” [8, 3].

Vogus and Sutcliffe defined organizational resilience as: “the ability of an organization to absorb strain and improve functioning despite the presence of adversity” [3, 21].

Another definition of this domain was by Sheffi; he said: “the company's ability to, and speed at which they can return to their normal performance level (e.g., inventory, capacity, service rate) following by disruptive event.” [3, 22]. McDonald said: “the properties of being able to adapt to the requirements of the environment and being able to manage the environments variability” [23].

5.3.2 Social domain

This domain's scope is to focus on the abilities of resilience from different perspectives, i.e., individual’s resilience, group’s resilience, community’s resilience, and environment’s resilience. Adger defined social resilience as: “ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change.” [3, 24]

The Community and Regional Resilience Institute defined resilience as the following: “the capability to predict risk, restrict adverse consequences, and return rapidly through survival, adaptability, and growth in the face of turbulent changes.*”*[3, 25].

Another definition of social resilience came by Cohen, where they defined it as: “ability of community to function properly during disruptions or crises.*”* [3, 26].

Pfefferbaum said: “the ability of community members to take meaningful, deliberate, collective action to remedy the effect of a problem, including the ability to interpret the environment, intervene, and move on” [3, 27]

5.3.3 Economic domain

Rose and Liao defined the economic resilience as: “the inherent ability and adaptive response that enables firms and regions to avoid maximum potential losses.” [3, 28]

A definition of Static economic resilience by Rose is: “the capability of an entity or system to continue its functionality like producing when faces with a severe shock”, And dynamic economic defined as “the speed at which a system recovers from a severe shock to achieve a steady state.*”* [3, 29]

Martin defined economic resilience as “the capacity to reconfigure, that is adapt, its structure (firms, industries, technologies, institutions) so as to maintain an acceptable growth path in output, employment and wealth overtime.”[3, 30]

5.3.4 Engineering domain

Youn defines the engineering resilience as: “the sum of the passive survival rate (reliability) and proactive survival rate (restoration) of a system” [3, 31]. While Hollanagel defined it as: “the intrinsic ability of a system to adjust its functionality in the presence of a disturbance and unpredicted changes” [3, 1].

Achieving resilience demands an understanding of the regular functioning, and at the same time, there should be understanding of the failure mechanisms [3, 32]. ASME said about resilience: “the ability of a system to sustain external and internal disruptions without discontinuity of performing the system's function or, if the function is disconnected, to fully recover the function rapidly” [3, 33].

Dinh came with six elements that can emphasize the effect of resilience in the industrial processes, which are: “minimization of failure, limitation of effects, administrative controls/procedures, flexibility, controllability, and early detection” [3, 34].

Some systems require engineering knowledge to be established and recovered from adversity, as the infrastructure systems, these systems require a special definition of resilience, as the definition of NICA: “the resilience of infrastructure systems as their ability to predict, absorb, adapt, and/or quickly recover from a disruptive event such as natural disasters” [3, 35].

5.4 Understanding resilience as a property

Resilience categorizes into four properties according to observers from different disciplines after researching specifics that influence the ability to create, manage, and sustain resilience.

5.4.1 Rebound

In this context, resilience means the system's ability to return to its standard functionality after suffering an event or abnormally from a stable state. The interest in resilience as a rebound is knowing the capabilities and resources before the period of rebound. The significant actions that help to recover from the disruption are the resources activated to deal with the event, not after the event.

Lagadec: “the ability to deal with a crisis situation is largely dependent on the structures that have been developed before chaos arrives. The event can in some ways be considered a brutal and abrupt audit: at a moment's notice, everything that was left unprepared becomes a complex problem, and every weakness comes rushing to the forefront” [18].

Resilience as rebound demands the event to be as a surprise such as it is beyond the events which the system is developed to deal with [9,19,20]. In this case, the scope of interest is how the disruption challenges the system’s base abilities, not the characteristics and consequences of the event [9].

5.4.2 Robustness

Increasing the system’s robustness can turn to a positive effect as the system can withstand a wider variety of disruptions. But a question was asked by David D. Woods: “what happens if the system is challenged by an event outside of the disruptions set?” [9]. Alderson and Doyle found that the form of robustness is: “system X has property Y that is robust in sense Z to perturbation W” [9, 36]. This means that the system should be well modeled to have the property of robust control [9].

This brings resilience to the front because if the system can not handle the occurred failures and kept working to a degree where some of the system’s goals are satisfied, it will collapse. This reveals that the system is brittle at its boundaries, which means that the system should be well modeled to deal with sudden perturbations.

Doyle and other safety researchers showed that an expansion in the robustness of a system would increase the ability that the system will be more vulnerable to other kinds of events than the modeled. [9, 37, 38, 39]

This is a kind of fundamental trade-off in complex adaptive systems, where becoming ready to deal with variation and constraints, but on the other side come other variations, constraints, and new disturbances. Studies initiated to understand how some system architecture succeed in solving this dilemma [9].

5.4.3 Graceful extensibility

Resilience can be understood as the contrary of brittleness or an extension of the adaptive capacity against unanticipated events [9, 20, 40, 10].

Usually, systems have some abilities to stand in the face of surprises that provoke their boundaries. Brittleness gives an understanding of how a system operates and reacts when the failure reaches the system’s boundaries. Defining these boundaries is a difficult matter; this definition can give an opportunity to understand the system performance within and beyond its boundaries [9].

Graceful extensibility as an important property of a system. This property should be integrated into the design because some adversities can challenge the system's boundaries or fall beyond it. These surprises that test the system at its boundaries can be tracked, and it can be used as indicators to activate the Graceful extensibility of the system [9, 11, 13].

Equipping the system’s performance with more competence helps change the system’s dynamics and some events that challenge the boundaries. Thus, this property, graceful extensibility, is a dynamic skill that helps the system to be adaptive to disturbances at its boundaries and success to withstand. Besides, graceful extensibility helps to anticipate the dangerous events, learn the formation process of disturbances, and invent a response that fits the challenge degree [9,13, 20, 41, 42].

Thinking of how a system should respond should lead to study the consequences of repeatedly starching system’s abilities in the face of challenges over time, which can result in weakness and problems of stress over time [9]. Studies have found pattern to realize how adaptive systems succeed and fail [9, 14]. The pattern is in two parts, the first one called decompensation, where the system suffers weakness to react against cascading disturbances. The second one is anticipation, where the system anticipate bottlenecks [9].

5.4.4 Sustained adaptability

In this context, resilience has the meaning of handling or adjusting systems' adaptive abilities with layers, and they can be a part of bigger systems [9, 36]. Even though some systems succeed for long periods to sustain adaptability, most do not, when facing new challenges [9].

In [9] David D. Woods mentions drivers that help the system to sustain adaptability over time. He claims that the system's architecture should be prepared with supporters that allow the system to "adopt" or be "adoptable" when faces "predictable challenges", and the drivers are:

- Over the life cycle, assumptions and boundary conditions will be challenged—surprises will continue to re-cur.
- Over the life cycle, conditions and contexts of use will change; therefore, boundaries will change, especially if the system provides valuable capability to stakeholders.
- Over the life cycle, adaptive shortfalls will occur, and some responsible people will have to step in to fill the breach.
- Over the life cycle, the need for graceful extensibility and the factors that produce or erode graceful extensibility will change more than once.
- Over life cycles, classes of changes will occur, and the system in question will have to adapt to seize opportunities and respond to challenges by readjusting itself and its relationships in the layered network.

After a period of challenge, the term "central resilience" can show the system structure's main factors that can withstand the disruptions and indicate the adaptability to keep adopting challenges over long periods [9, 50].

6. Resilience assessment approaches

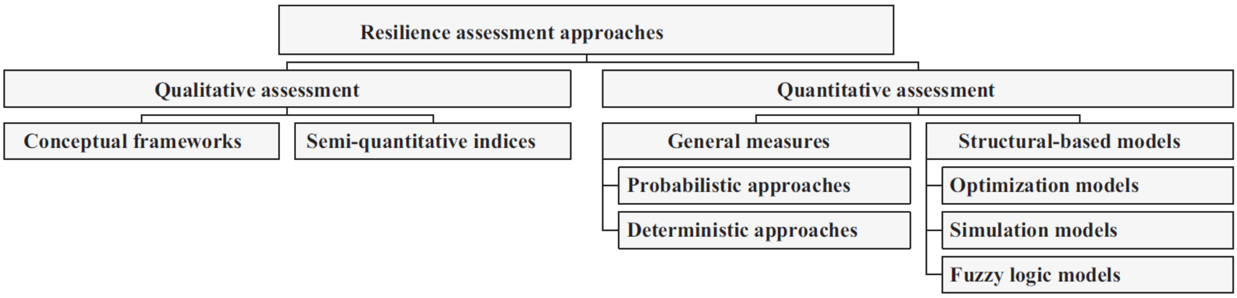

Figure 25: Classification of resilience assessment [3]

6.1 Qualitative approaches

6.1.1 Conceptual frameworks

Alliance in [43] suggested the following assessment structure of resilience in social-ecological systems:

- Defining and understanding the system under study.
- Identifying the appropriate scale to evaluate resilience.
- Identifying the system drivers and external and internal disturbance.
- Identifying the key players in the system, including people and governance.
- Developing conceptual models for identifying necessary recovery activities.
- Implementing the results of the fifth step to inform policymaker.
- Incorporating the findings of the previous step.

Vlacheas found some properties of resilience which Vlacheas considered as the most crucial in telecommunication networks, reliability, safety, availability, confidentiality, integrity, maintainability, and performance [3, 44].

Vugrin found in [45] that resilience can have relation with three capacities, absorptive, adaptive, and restorative. The first capacity is the amount where the system absorbing a distribution, while the second one (adaptive) the level where the system stabilizes its performance temporarily into new conditions after the distribution. The third property (restorative) is the level that shows how the system is able to restore its performance if the previous property was not effective [3].

Shirali in [46] have suggested the following limitations that make resilience in chemical plant, not achievable:

- A shortage of experience about resilience engineering.
- Intangibility of resilience engineering level.
- Choosing production over safety.
- Lack of reporting system.
- Religious beliefs, and economic problems.

Shirali, in another documentation [47] proposed indicators of resilience based on safety perspective:

- Schedule delays.
- Safety committees.
- Meeting effectiveness.
- Safety education.
- Worker’s involvement.
- Competence.
- Safety training.

6.1.2 Semi-quantitative indices

Using a semi-quantitative approach Shirali in [48] found six resilience factors in the process industry by surveying 11 unites in the process industry and gathering data related to the previous factors; it allowed setting scoring for resilience [3]:

- Top management.
- Commitment.
- Learning culture.
- Awareness.
- Preparedness.
- Flexibility.

Pettit in [49] studied an industrial supply chain. He used 152 questions divided between two groups, the first group contained six sub-groups of vulnerability, and the second group included 15 sub-groups of capabilities. Policymakers judged the importance of the factors by setting the weight to the factors. By using the weighted sum of the questions, approached two elements of resilience: “Level of the supply chain's vulnerability, and capability of the supply chain to withstand and recover from disruption.” [3].

6.2 Quantitative approaches

6.2.1 General measures

These measures assess the resilience quantitatively despite the structure of the system so that it can be used to different systems in the same context and logic. The general measures involve deterministic and stochastic approaches. [3].

6.2.1.1 Deterministic approaches

The deterministic method involves the following methods:

- Resilience triangle.
- Reinterpretation of resilience triangle
- Economic resilience metric
- Time-dependent resilience

6.2.1.1.1 Resilience triangle

Bruneau In [51] suggested the resilience triangle model measuring the resilience loss in a community after an earthquake by the following equation (1):

$$RL = \int_{t0}^{t1} [100 - Q(y)]\, dt \qquad (1)$$

Where:

- RL: resilience loss
- t_0: The time at which the disruption occurs
- t_1: The time at which the community returns to its normal state before the disruption
- Q(t): The quality of the community

Bruneau compares the community's degradation between its normal state (100) and the state when the disruption occurs [3]. The following figure shows the resilience loss between t_0, and t_1.

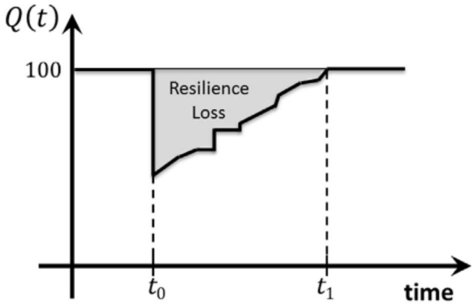

Figure 26: Resilience loss measurement [3, 51]

From the graph, we conclude that the bigger RL, the Smaller is the resilience. This method is generally applicable, and it can be used for different disruptions other than an earthquake in a community; it is helpful for systems where the concept Q(t) is a general concept[3].

Assuming the status of the system before the disruption is 100% is an unrealistic assumption. The resilience loss area can be challenging to calculate as a percentage because the triangle model assumes that the recovery starts immediately after the disruption and the disruption's impacts appear instantly after its occurrence [3].

6.2.1.1.2 Reinterpretation of resilience triangle

Zoble in [52] calculated what is known as: “the percentage of the total possible loss over some suitably long time interval” [3], which can be calculated from the following equation (2):

$$R(X,T) = \frac{T^* - XT/2}{T^*} = 1 - \frac{XT}{2T^*} \tag{2}$$

Where:

- T^*: Long Time interval to determine the lost functionality.
- X: Percent of functionality loss after the event, takes values between 0 and 1
- T: Time until full recovery, takes values between 0 and T^*
- R(X, T): percentage of the total possible loss

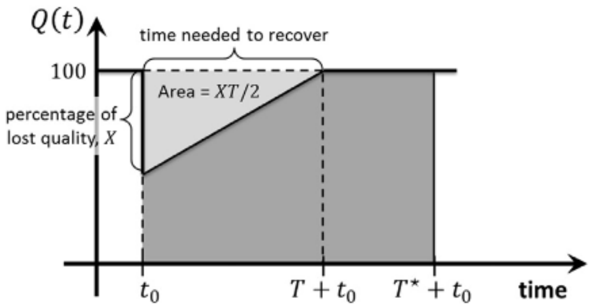

Figure 27: Reinterpretation of resilience triangle [3, 52]

The figure shows that the area XT/2 is the percentage of lost quality caused by one disruption. This method has an advantage, which is simplicity. On the other side, the assumption that the liner recovery of the system is unrealistic, and some systems may suffer more gradual degradation over time [3].

6.2.1.1.3 Economic resilience metric

The definition of economic resilience by rose [53] is: "the ability of an entity or system to maintain system functionally when a disruption occurs.". According to [3], this definition shows "the ratio of the avoided drop-in system output and the maximum possible drop in system output."

Eq. (3), estimated by Cox [54], evaluates London's transport system's resilience. The worst scenario is the drop in passengers if an attack happened to a kind of transportation mode.

$$R = \frac{\%\Delta \mathrm{Ymax} - \%\Delta D\mathrm{Y}}{\%\Delta D\mathrm{Ymax}} \tag{3}$$

Where:

- $\%\Delta D\mathrm{Y}$: Difference between no disruption and expected disruption.
- $\%\Delta D\mathrm{Ymax}$: Difference between no disruption, the worst scenario of performance after a disruption.

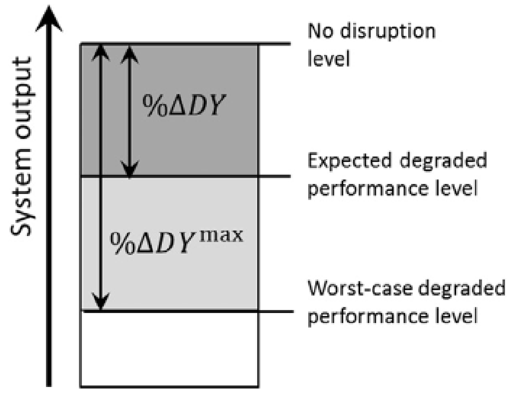

Figure 28: Illustration of economic resilience [3,53]

It might not be easy to estimate the dimensions of the expected degraded performance level "Width, depth, and intensity.", primarily if the event occurs is inestimable.

6.2.1.1.4 Time-dependent resilience

Rose [53] showed how resilience changes by hastening the recovery process through time. This process's main drivers are the quick restoration process and investment in the capital stock [3]. Eq.(4) calculates the dynamic resilience:

$$DR = \sum_{i=1}^{N} SO_{HR}(t_i) - SO_{WR}(t_i) \tag{4}$$

Where:

- t_i : Time step during recovery.
- N: Number of time steps.
- DR: Dynamic resilience.

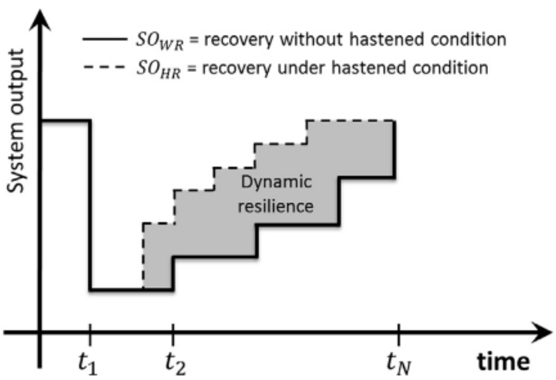

Figure 29: Dynamic resilience [3, 53]

Henry and Ramirez-Marquez [55] describe time-dependent resilience in the process of three states [3]:

- Normal functioning state from t_0 to t_e. At the normal state, some reliability in the system maintains a typical performance against disruptions.
- Disruption occurrence. At this state, the system is vulnerable and disrupted by an event e^jat time point t_e, while the effect of disruption varies until t_d. $\varphi(t_d)$ is the system's performance t_d.
- Recovery state starts at the time t_s until the performance stabilizes with value $\varphi(t_f)$at time t_f.

The following figure shows the described three states:

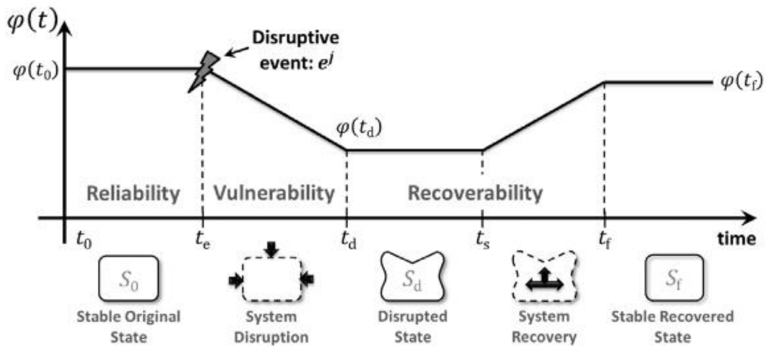

Figure 30: System performance and state transition [3, 55]

Eq. (5) shows resilience as a ratio of recovery to loss, where $\varphi(t)$ is an indicator of performance [3]:

$$Я_{\varphi}\left(\varphi\left(t|e^j\right)\right) = \frac{\varphi\left(t|e^j\right) - \varphi(t_d|e^j)}{\varphi(t_0) - \varphi(t_d|e^j)} \tag{5}$$

Я: this symbol is used to distinguish between Я for resilience and R for reliability.

6.2.1.2 Probabilistic approaches

To measure resilience, Chang and Shinozuka used two elements, loss of performance and length of recovery. They defined resilience as: “the probability of the initial system performance loss after a disruption being less than the maximum acceptable performance loss and the time to full recovery being less than the maximum acceptable disruption time.” [3, 64]

$$R = P(A|i) = P(r_0 < r^* \ and \ t_1 < \ t^*) \quad (6)$$

Where:

- A: represents the set of performance standards.
- r^*: maximum acceptable loss of system performance
- t^*: maximum acceptable recovery time.
- i: the magnitude of disruption.
- R: resilience.

The disadvantage of equation 6 is, it does not consider that performance loss and the recovery length can rise above their maximum acceptable values.

Ouyang came with the term “annual resilience” under multi-hazards, which is a stochastic time-dependent metric [3, 65]; Eq. (7) shows the annual resilience metric:

$$AR = E\left[\frac{\int_0^T P(t)dt}{\int_0^T TP(t)dt}\right] = E\left[\frac{\int_0^T TP(t)dt - \sum_{n=1}^{N(t)} Al\,A_n(t_n)}{\int_0^T TP(t)dt}\right] \quad (7)$$

Where:

- AR: stochastic metric.
- $P(t)$: Stochastic process.
- $TP(t)$: stochastic process.
- n: number of events.
- $N(t)$: total number of events that occurred during T.
- t_n: the time of the nth event.
- $Al\,A_n(t_n)$: the area between $P(t)$ and $TP(t)$.
- $\int_0^T P(t)dt$: the area between the actual performance curve and the time axis.

- $\int_0^T TP(t)dt$: the area between the target performance curve and the time axis over a length of time T
- $\sum_{n=1}^{N(t)} Al\, A_n(t_n)$: the term of multiple hazards.

7. Resilience Based Maintenance

7.1 Relationship between maintenance and resilience

Most companies focus on high performance, higher quality, lower cost, sustainability, etc. the reason for that is the global competition and the stakeholder's demands. As a result, maintenance and its requirements become more critical because they have a crucial rule in improvement.

Maintenance is an essential and supportive factor, especially for systems that have characteristics of limiting or preventing unexpected events. In addition, developing and improving the maintenance will reflect positively on the dependability of the assets [112].

Furthermore, engineered systems and their production processes are related to many factors as the human factor, environment, and cyber-systems. Thus, finding a new approach to maintenance is essential to ensure resilience for such complex systems. Furthermore, the new approach requires cooperation between people from different disciplines and applications of transdisciplinary perspectives [112].

When introducing resilience into a project, resilience properties (rebound, robustness, graceful extensibility, and sustained adaptability) will be inherent in that project. As a result, disruptions will decrease because the project's infrastructure will contain redundancy and flexibility in the processes, which will increase the project’s competitiveness in the market [112]. In addition, resilient projects demand integration and compliance between processes, systems, and the technology that is the infrastructure of these projects.

Achieving the idea of a resilient project requires a new approach to maintenance with conditions of uncertainty and unpredictability; it is not enough to apply previously know approaches, e.g., TPM (Total productive maintenance) [112].

The new approach should be based on potentials [112] :

- The potential to respond: by knowing what to do and doing it correctly when danger happens. This is done by using prepared planes, introducing new plans and activities, and modifying the functioning mode.
- The potential to monitor: monitoring all indicators from the internal and external environments that can show changes in performance in the short and long terms.
- The potential to learn: the ability to learn from the disruptions occurring to the system.
- The potential to anticipate: the ability to read the future and predict failures that can occur and making developments to the system and the operational conditions.

The success of this approach requires that the procedures are applied effectively and adequately. In addition, there should be a common sense of reading the future, where unexpected disruptions can not be faced only with prepared planes but with understanding the problem when it is occurring and taking quick and effective actions that significantly reduce relative costs [112].

7.2 Definition

Defining the concept of RBM requires taking into consideration three elements:

- Safety.
- Resilience.
- Maintenance.

Generally speaking, the idea of safety is based on keeping three elements in safe conditions:

- The public.
- The Environment.
- The system.

As a fact, threats are consistently present. The main concern is keeping threats at low levels as efforts continue to find possible threats, identify them, and create barriers to ensure safety now and in the future. While maintenance is concerned about keeping the system functioning to fulfill its required function using technical and administrative efforts.

In addition, the definitions of resilience do not support the idea of the total failure of the system. A resilient system will withstand the threat, absorb it, and rebound to do its functions. In case of severe failure, the system will degrade gradually, keep functioning at an acceptable grade and recover to proper performance.

Three factors should be taken into account in the failure and recovery process in resilient systems:

- Time.
- Cost.
- Risk.

Thus the recovery process should be at a desirable time, low cost, and safe.

Taking into account what was said above, the concept of Resilience-Based Maintenance is defined as:

Carrying out technical, administrative, and managerial efforts so that there is no complete system failure. When a failure occurs, it is gradually occurring, and the system is repaired until it returns to the required levels of reliability, performance, and safety—provided that the repair process is within a reasonable time, at an acceptable cost, and in a safe manner.

7.3 The concept of Resilience-Based Maintenance

The New concept of RBM should be based on the four potentials mentioned previously in 7.1.1, the potential of monitoring, responding, learning, and anticipating.

Monitoring is an essential element in indicating that an error has occurred in the system's performance or that an event is imminent. The idea of monitoring depends on leading indicators that can measure the system's safety and performance.

Baker in [119] has defined these leading indicators as "*Indicators that measure variables that are believed to be indicators or precursors of safety performance so that safety outcome is achieved.*"

Herrera and Hovden in [117] have defined the characteristics of these indicators as; Specific, Measurable, Achievable, Relevant, and Timed (SMART).

When something goes wrong, and after the system's recovery, the list of Leading indicators is updated to make the monitoring process more accurate and effective. As a result of the enhanced monitoring process, it will be easier for the decision-makers to activate the response when sufficient information about the system's conditions is provided. In addition, the provided information will decide the nature of the response and its amount.

This response also reflects the organization's readiness to deal with the system's setbacks. It is also a reaction that improves the phase of absorption, adaptation, and recovery from disruptions.

For the organization's preparations and plans to be successful, the following elements must be followed:

- The staff should be highly qualified and trained to deal with emergencies.
- Using the data collected through the monitoring process and the data that result from accidents in the learning and anticipation processes. The old data stored on the system can be exploited to know the trends of the system's performance in different circumstances. As for the information currently recorded, it helps to modify the system's

performance to the desired level. Collecting these two types of information provides the ability to predict and prepare against future dangers [112].

The following is a conceptual flowchart of RBM:

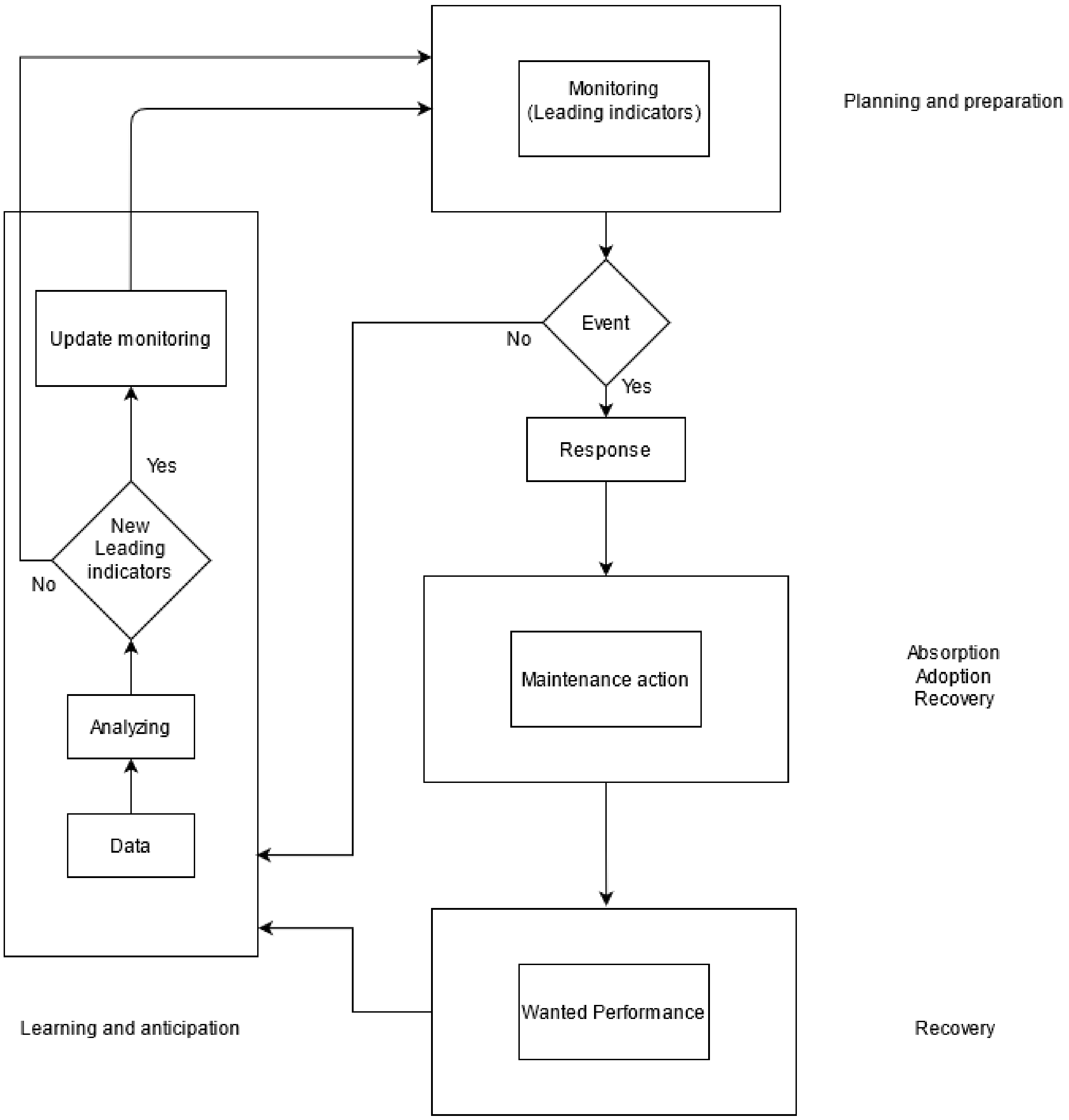

Figure 31: Conceptual flowchart of Resilience-Based Maintenance

7.4 Benefits of Resilience-Based Maintenance concept

A Resilience-Based Maintenance system provides adequate preparation and planning before and after the event occurs. The process of learning and anticipation ensures the possibility of predicting the occurrence of an event or finding indicators that may indicate that it is about to happen; these indicators were mentioned earlier as «leading indicators».

The data stored in the system after and before the events provide the ability to model the system's performance, and therefore a high capacity to predict possible future setbacks. This helps to determine barriers that prevent malfunctions and prepare for an appropriate response, thus effectively absorbing the event's impact, proper adaptation, and recovery at a good time and cost.

It is worth mentioning that the human factor is not entirely absent in this type of maintenance system. Still, the technological capabilities used and system data analysis help to reduce the resources usually used in traditional maintenance operations. As a result, systems that use Resilience-Based Maintenance will be reliable, highly efficient, and effective production capacities at the lowest costs and efforts.

7.5 Limitations of Resilience-Based Maintenance Concept

In systems where operational safety is a high priority issue, introducing resilience into this system is costly [120]. Resilience entails additional costs such as redundancy in components, training, developing the system's learning techniques, and increasing maintenance quality.

Processing the data stored in the system in success and failure states is time-consuming [121]. Therefore, improving the system's efficiency and reducing wasted time requires developing information analysis algorithms, which is another source of costs. Still, in general, the system productivity will increase, which compensates for these costs.

There is a necessary trade-off between accuracy and effectiveness in systems that use resilience [112]. Therefore it is vital to take into consideration the degree of uncertainty during monitoring operations.

7.6 Resources of Resilience-Based Maintenance concept

The primary strength resources of the Resilience-Based Maintenance system are the following:

- Resilient organization: Resilient organizations are characterized by solid leadership based on communication and interaction [122]. Communication and interaction between managers and employees create an atmosphere of trust within the organization and make them take responsibilities. As a result, it creates a solid creative environment within the organization that qualifies it to face changes in the work environment.

- Monitoring system: The ability of the RBM to anticipate events, absorb their effect, and adapt to them is due to the continuous monitoring of the leading indicators that represent critical indicators of the system's vulnerability and thus its overall performance.
- Redundancy: Redundancy enhances the resilience in RBM, where it reduces the possibility of a system failure. It is an essential supportive element of the phase of absorbing, adopting, and recovering.

7.7 Resilience-Based Maintenance effectiveness evaluation

In a report on disaster resilience in 2012, the National Academy of Sciences (NAS) showed a graph (Figure 32) for resilience in a system. The vertical axis expresses the system's performance, and the horizontal axis represents the time.

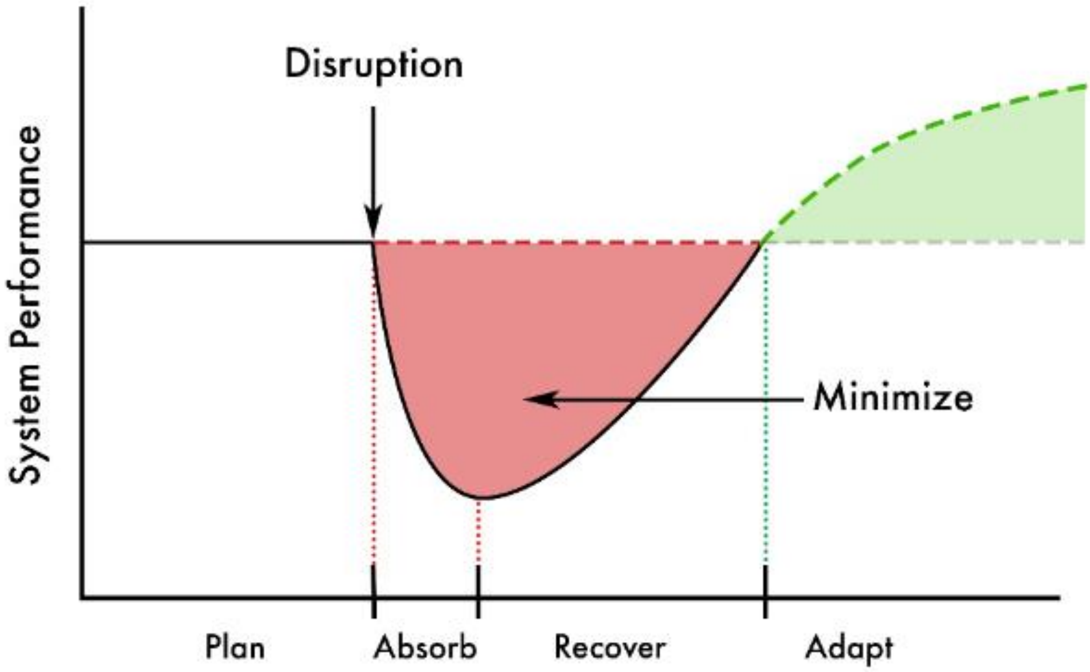

Figure 32: Disaster resilience in a System [123, 118]

A horizontal line for the system's performance level is shown in the figure. This level is the acceptable performance of the system in case of a disaster. The red area that appears below the horizontal line is the percentage of performance decline.

The effectiveness of systems based on resilience is achieved by decreasing the red area as small as possible. As a result, performance does not drop critically, and recovering to the required performance is done in a short time and smoothly. This is achieved through the following [118]:

- Vigorous efforts in the stage of preparation and absorption to prevent the occurrence of the threat in the first place.
- Suppose the threat prevention efforts do not succeed. Then, the system’s performance decline must be gradual and safe to maintain acceptable performance on the most critical operations.

The stages of recovery and adaptation are no less important than the other stages, as these stages must be characterized by speed, economic feasibility, and effectiveness.

8. Discussion and Conclusion

8.1 Discussion

The Subsea oil and gas industry is one industry where the possibility of disasters or failures causing harm to humans and the environment is high.

These dangers are multi-caused, as they may be caused by the human factor, the harsh environment, or unknown and unexpected causes, of course, due to the nature of the complex systems used in this industry.

In multi-dimensional and interacting systems, traditional strategies cannot increase the system's safety and reliability [124].

In fact, all maintenance strategies that are under development today depend on moving maintenance actions from the reactive phase to the proactive phase.

The transition from reactive to proactive represents a critical point for maintaining the subsea systems, as shown in chapter four the number of multi-dimensional preparations for the start of maintenance operations.

Thus, the most crucial part of the stage of avoiding malfunctions and disasters emerges by taking into account the possibility of occurrence and absorbing the shock through adequate planning and preparation and eliminating the causes of occurrence.

The concept of Resilience-Based Maintenance achieves this transition by relying on the stage of learning and prediction. As previously mentioned, monitoring of leading indicators helps and enhances the stage of planning and preparation for the event, which ensures less shock when it occurs and thus, maintains an acceptable level of productivity and performance.

Resilience-Based Maintenance adds to the subsea systems a feature of adaptability with threats based on anticipation. The anticipation process takes appropriate preparations and helps to maintain an acceptable level of performance until maintenance operations are completed and expected performance is restored.

In addition, redundancy is a primary source of Resisliecne-Based Maintenance. Adding redundancy for some systems or components helps absorb the shock of the event, adapt to it, and recover until an alternative is installed [125].

Resilience-Based Maintenance creates flexibility in operations, especially in critical production systems. In subsea systems, the surrounding environment is unhelpful, and caution is the most prominent feature during operations.

Since maintenance in this type of system (Subsea system) requires a long time and high costs, a system is needed to maintain productivity and performance under exceptional circumstances when a malfunction occurs.

Resilience-Based Maintenance can be supplemented with fault-tolerant systems, where these systems maintain a certain degree of performance despite the presence of a failure. As a result, adaptability is enhanced lack of performance is compensated.

In the end, Resilience-Based Maintenance provides flexibility to the system so that the system maintains acceptable performance and productivity under special circumstances while not neglecting the necessity of safety.

8.2 Conclusion

The thesis intended to overview the main subsea production systems, their failures, and the maintenance actions used for the most important of these systems.

Moreover, maintenance was reviewed in terms of types, strategies, how to carry out maintenance operations for subsea systems, and its high cost and long preparation.

In addition, resilience engineering has been reviewed from several domains with its properties and how to assess resilience in a system.

The main objective of the thesis is to integrate maintenance science with resilience engineering and present a new concept of maintenance that combines the most prominent properties of resilience (rebound, robustness, graceful extensibility, and sustained adaptability) so that it becomes the essential characteristic of the system against failures and threats.

The Resilience-Based Maintenance (RBM) concept was presented as a concept that ensures safety for humans, environment and system, and system's productivity and performance.

In other words, RBM expresses the risk by resilience, where a resilient system is a high-performance system that is capable of absorbing stresses, adapting to them, and recover to the wanted performance. Thus, moving from a state of functioning or not functioning (0 or 1) to a state where resilience expresses a performance ratio.

RBM can be an important addition to subsea systems, where malfunctions may lead to multi-dimensional disasters or shutdowns, which means multiple costs and loss of time.

8.3 Recommendations for further work

This thesis considered a theoretical principle in the research of subsea systems, maintenance science, resilience engineering, and the introduction of the RBM concept.

More researchers can be worked on it in the future to strengthen this principle or discuss its flaws:

- A mathematical model aims to measure resilience in subsea systems and expresses system performance and resilience properties.
- Research about the economic costs of applying the concept of RBM in the subsea oil and gas industry.
- Research data analysis in subsea systems to find leading indicators of risks and poor performance.

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