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Information structuring and risk-based inspection for the marine oil pipelines

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A B S T R A C T

The proposed work is incorporated into the research theme concerning the maintenance and inspection of sensitive facilities in production systems. It is essential to promote the methodological deployment of inspection techniques to ensure the good functioning of services provided by complex production systems as well as their different components. We use a risk-based inspection methodology offering an organized analysis with knowledge sharing for collaborative possibilities in a multidisciplinary context and it consists of the following steps: data acquisition and information collection, failure analysis (probability and consequences), risk assessment, inspection plan, mitigation and reevaluation. The application of this methodology can improve the maintenance management strategies of industrial companies. The inspection department is able to forecast its potential failure, root causes and impacts on the safe operation of the considered production system, based on a reliable inventory of existing situations and review options for continuous improvement in maintenance management. In particular, we addressed the application of a Risk-Based Inspection (RBI) methodology in the French petroleum company with operations on the west coast of central and southern Africa. The incorporation of expert knowledge into risk assessment is helping to find the best preventive plan for pipeline inspection in the case study.

Keywords:

Experience
Knowledge
Inspection
Maintenance
Risk assessment
Equipment failure
Intelligent pigging
Safety
Environment
Offshore production

1. Introduction

The current management frameworks of industrial enterprises must integrate engineering standards and recommended practices to reflect the increasing complexity of production systems. In addition, the legislation requires that enterprises comply with applicable normative rules by using industrial practices that are environmentally and logistically sustainable. In certain circumstances,

Abbreviations: Ath, Allowed minimum Thickness; CMIMS, Computerized Maintenance and Inspection Management System; Cof, Consequence of the failure; CL, Corrosion Likelihood; CR, Corrosion Rate; EFF, Effectiveness; ESD, Electrical Schematic Diagram; FPSO, Floating Production, Storage and Offloading; HSE, Health, Safety and Environment; HV, High-Voltage; HMI, Human-machine interface; LAY, Lay-out; Lof, Likelihood of failure; LV, Low-Voltage; MAOP, Maximum Allowable Operating Pressure; MOP, Maximum Operating Pressure; MOGA, Multi-Objective Genetic Algorithm; NCL, Natural Corrosion Likelihood; P&ID, Piping and Instrumentation Diagram; PCS, Process Control System; PFD, Process Flow Diagram; PSS, Process Safety System; PLC, Programmable Logic Controller; RBI, Risk-Based Inspection; RCM, Reliability Centred Maintenance; SLD, Single-Line Diagram; ST, State; SLD/C, Structural design or construction failure Likelihood; SLthird, Structural failure third party Likelihood; SLmec, Structural mechanical failure Likelihood; SLnat, Structural natural failure Likelihood; SL, Structure Likelihood; SAP, Systems, Applications & Products in Data Processing; UFD, Utility Flow Diagram.

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the law obliges companies to make risk information (threat cryptograms and the associated risk and safety descriptions) available on the industrial sites. The increasing complexity of oil and gas installations and operations, along with growing public awareness to ensure higher levels of safety, has put great pressure on the designers and operators to find innovative solutions to ensure safe as well as economically viable operation [1]. Reliability and Maintenance with tools such as RCM (Reliability Centred Maintenance) and RBI (Risk-Based Inspection) contribute to collaboratively working towards seeking reasonable and practical solutions in the industrial settings [2]. In scientific literature, there are different categories of risk analysis and risk-assessment methods and techniques (qualitative, quantitative and hybrid approaches) [3]. A varied range of methodologies presently in use for risk-based inspection includes marketable and internal software packages particular to explicit plants [4]. In the complex production systems, the work package of maintenance engineering is important to ensure continuity of services, optimize production capacity, improve safety and reduce the environmental impact. Risk Based Inspection (RBI) is an interesting maintenance perspective with an incremental stepwise procedure used to examine sensitive equipment such as pressure vessels, heat exchangers and piping in complex industrial plants [5]. RBI provides a modelling process for organizations to control its reliability, safety and health aspects, ensure maintenance compliance and to iteratively improve the technical performance

and cost of projects [6]. However, the implementation of the RBI requires structured and coherent information management in order to maximize its integration in the target computerized management information system for maintenance and inspection. The aim of this work is to propose a conceptual approach providing structured information for semantic modelling of the hierarchical organization of components that characterize all the sensitive areas of a complex system that must be inspected or verified by the RBI method. This semantic modelling will formalize the taxonomic organization of equipment and instruments of the considered system. These components are classified according to their nature through the study of essential documents and information provided by vendors and the manufacturer of the system. The obtained structured information can be transferred to the Computerized Maintenance and Inspection Management System (CMIMS) for the management issues (analysis and diagnosis) or engineering issues (task lists).

The paper is structured as followed. Section 2 exposes a background of the risk based inspection management. Section 3 presents the industrial challenge of the risk based inspection management. Section 4 presents the suggested methodology. Section 5.1 describes an illustrative case study for petroleum pipelines. Section 5.2 delivers an analysis of this study. Sections 6 and 7 presents the results and discussion based on research findings. Finally, Section 8 gives the conclusion and underlines both the related works and the challenges that lay ahead.

2. Background

2.1. Practices of risk-based inspection

Risk-based Inspection (RBI) offers practical ways for the implementation of an inspection process that provides to maintenance actors a method of assessing the probability and effect of failure, evaluating risk level and generating the kinds of relevant actions that can lead to development of required risk management policies [7]. There are different illustrations of RBI practices which increase cost effective actions and can be considered as promising developments to shift from a reactive to a proactive maintenance management in various domains. We mention as examples the implementation of risk assessment in civil engineering applications [8]. In the petrochemical and chemical industries, the deployment of online and offline inspection procedures to equipment such as pipelines has led to substantial improvements in operational reliability and the prevention of incidents (e.g. Management of Corrosion) [9,10]. In nuclear engineering and design, there are current practices and trends in the risk-based inspection and maintenance for safety evaluation [11]. The RBI method was used to assess the risk of large-scale crude oil tanks in order to determine the acceptable risk and internal inspection interval of tanks [12]. There are some examples of the application of risk-based methods in industrial coal-fired boilers with some interesting results [13]. RBI programmes are also established for reliability analysis purposes in heavy water plants with the assessment of failure pressure and estimation of the frontier state functional analysis [14]. The RBI methods are also adopted and useful in the offshore wind energy industry for the organization of maintenance logistics with significant influences on important cost parameters of energy production [15–17].

In general, the majority of industrial applications of RBI methodologies are used in the refinery systems and petrochemical sectors [18]. RBI addresses clearly the threats (personnel death and injury, damage to the environment and financial loss) to the integrity of the asset and it is performed for piping and vessels, including heat exchangers, tanks, pressure vessels, and filters [19]. Pipeline system inspections can be done either internally or externally as

continuous inspections over the complete pipeline length or as local inspections for particular sections or local zones in order [20]:

- *In-Line inspections (ILI)* of pipelines are generally accomplished using a pig. The pig moves through the pipeline guided by the flow or fluid or may be pulled by a vehicle or a cable. It gathers data as it turns through the pipeline. The technical resources may be automatic or self-contained or may be activated from outside the pipeline via a data and power connexion. Diverse technical resources can be combined in a pig train. The internal inspection techniques comprises Magnetic Flux Leakage, Ultrasound Technology (UT), Laser-optical inspection tool, Geopig and Calliper.
- *External inspections* are generally accomplished using a remotely operated transporter equipped with diverse inspection techniques and resources. This can for instance be techniques for visual inspections (video recording) and physical measurements (steel electrochemical voltage measurements). External inspection can also be accomplished by a diving team. The external inspection techniques comprises Visual/Video/photo, sidescan sonar (SOund NAVigation Ranging), Multibeam Echosounder (MBE), Cross profiler, Pipetracker, Sub bottom profiler, Stabbing, Eddy Current and External UT (Ultrasonic Testing).

The scope of these inspections methods encompasses all pressure systems in the industrial site, and they can be used to inspect pipes/other static equipment and take the geometric measurements (diameter, wall thickness, metal loss, crack and other defects). The selection of inspection method is based on optimizing a number of features that symbolize each technique: (i) Confidence in identifying the estimated damage state, (ii) Cost of technique/method, including human and technical resources, and (iii) Magnitude of maintenance support necessary to perform the work (scaffolding, process shutdown, opening of equipment).

2.2. Principles for risk evaluation

The RBI evaluation is used to engender an inspection plan at desired detail level of the considered system with adequate time allowing to not exceeded the risk limit, to keep track of degradation processes with the potential selection of the appropriate mitigation action. Risk acceptance limits for inspection planning resulting from main targets related to availability, profit and safety can imply pure maintenance engineering acceptance criteria such as acceptable wall thickness (requirement for pressure retaining purposes). The risk evaluation is based on consequences and probabilities of failures that are evaluated in a distinct way, under the following assumptions [21]:

- The consequences of system faults, loss of main functions and sub-functions, are independent of the equipment carrying out the functions.
- The actual equipment and the operational conditions affect the probability of failure.

The outcome of the RBI process is determination of [22]:

- location and extent of inspections and condition monitoring,
- inspection methods,
- inspection intervals.

The consequences of main function failures are evaluated according to the effect on the enterprise, activity sector, industrial site and system level regarding the production loss and direct cost measured in interruption and economic terms, while consequences of impairment of health and environmental degradation are

Table 1
General consequence classification [21].

Class	Health, Safety and Environment (HSE)	Production	Cost (exclusive production loss)
High	Potential for serious personnel injuries. Render safety critical systems inoperable. Potential for fire in classified areas. Potential for large pollution.	Stop in production/significant reduced rate of production exceeding X hours (specify duration) within a defined period of time.	Substantial cost – exceeding Y NOK (specify cost limit)
Medium	Potential for injuries requiring medical treatment. Limited effect on safety systems. No potential for fire in classified areas. Potential for moderate pollution.	Brief stop in production/reduced rate of production lasting less than X hours (specify duration) within a defined period of time.	Moderate cost between Z–Y NOK (specify cost limits)
Low	No potential for injuries. No potential for fire or effect on safety systems. No potential for pollution (specify limit)	No effect on production within a defined period of time.	Insignificant cost less than Z NOK (specify cost limit)

Table 2
The classification of equipment according their technological complexity.

Technological complexity	Low	Medium	High
Equipment	Static equipment without instruments Pipelines Storage tanks Incinerators ...	Low speed rotary equipment (speed ≤ 3000 rpm) Vertical pumps (power < 500 kW) Control and safety valves Electrical components (voltage < 400 V) Instrumentation	High speed rotary equipment (speed > 3000 rpm) All compressors Gas turbines Rotary hydraulic equipment Electrical components (voltage > 400 V)

classified with regard to predetermined consequence categories and approval criteria.

Concerning the evaluation of failure probabilities, this is indirectly expressed by the maintenance characteristics and operational experiences. Essentially, the equipment failure modes, operational conditions, location and external environmental factors are fundamental elements contributing to the calculation of the probabilities of failure according to the functions the equipment supports and applicable generic maintenance concepts. These generic concepts are issued from the collection of best practices of maintenance actions, strategies and maintenance details (e.g. structured analysis identifying failure modes and failure causes) for an enterprise.

The general consequence classification (defined in Table 1) is made in accordance with criteria for Health, safety and environment (HSE), Production and Cost (exclusive production loss)

The consequence classification methodology is applied for categorizing of static mechanical equipment with the purpose of selecting critical equipment for further analysis and prioritizes them for in-depth risk evaluations as the basis for preparation of inspection and maintenance programmes.

The technology of equipment is a factor influencing maintenance activities. Therefore it is possible to classify equipment according to the technological complexity needed to execute the maintenance engineering. Some examples of equipment classified according to their technological complexity are provided in Table 2.

3. Industrial challenge

In general, the maintenance and inspection activities are conducted in compliance with the considered enterprise policy with the following objectives:

- Safety and health of personnel and facilities
- Care for the environment
- Sustained operation and performance of the installations over time
- Maintain asset integrity
- Retained investment capital value of plant and structures
- Compliance with applicable local legislation

The purpose of inspection activities is to establish a basis for preparation and optimization of maintenance plans for industrial sites. The principles of risk analysis are essential for selection and prioritization of relevant types of site equipment and associated maintenance activities. For instance, the risk assessment and inspection process can be focused on static process equipment in industrial facilities, due technical or functional declines.

The process-based inspection requires knowledge of the following elements [22]:

- damage mechanism which depends on material properties, internal fluid compositions and the external operational environment – influential the probability of failure,
- consequence of leak failure with respect to personnel, environment damages and financial losses.

The combination of the above characterizes the risk of failure requiring the reduction or mitigation of associated consequences within the industrial system.

In particular, the work package of inspection provides the enterprise inspection team with the documents for the definition of the inspection strategy, programme and plan for each of the systems. For each document, some information is needed: TAG number (document number), supplier document number, title, kind of document (drawing, data sheet, supplier manual, etc.) and disciplines (mechanical, electrical, inspection, fabric maintenance, instrumentation, methods and maintenance engineering).

In order to make the description of an hierarchical arrangement of system components, the following documents are useful:

- Piping and Instrumentation Diagram (P&ID): a P&ID is a diagram that defines all the elements of a chemical process. The P&ID contains the instruments, equipment, valves and others with their designations.
- Process Flow Diagram (PFD): a PFD is a diagram used to describe the main components of a chemical process. Only equipment in direct contact with the chemical products and the transportation thereof (pumps, hoses, etc.) are represented.
- Utility Flow Diagram (UFD): the same principle as the PFD.
- Lay-out (LAY): the LAY is a drawing of the equipment.

- Single-Line Diagram (SLD): a SLD provides a basic understanding of the functions of the components of a system. Its vision is very simplified.
- Electrical Schematic Diagram (ESD): an ESD is a graphic representation of an electrical circuit. It shows the circuit components in the form of standardized symbols, as well as power and signals between these components.
- Equipment list. It identifies all the equipment that is present in the P&ID, PFD, UFD, LAY, SLD and ESD.

3.1. Hierarchical arrangement for the preparation of inspection and maintenance

The proper documentation and classification of the categories, characteristics, and interrelationships of the objects that actually or primarily exist for a specific application field is recognized as an important and fundamental activity in support of the implementation of the information modelling [23]. The hierarchical arrangement of different subset and elements of a target system can be useful in association with making selections as to how the inspection planning process is to be expressed and formalized. The level of detailing may be augmented for the high-risk functions and related subsystems and elements. It possible to establish the functional hierarchy and the technical hierarchy of system elements (e.g. part, component, pipe or equipment) that can be characterized by a unique identification (i.e. a tag number) allowing the traceability of inspection and maintenance processes.

3.1.1. Technical hierarchy

The technical hierarchy is the foundation on which an effective inspection programme and maintenance management should be built. It defines the technical structure of the industrial site by describing functional locations with unique identifiers. The technical hierarchy offers an outline of equipment units belonging to the same technical group, and indicates the physical relationship between main equipment, instruments, valves, etc. The goal of the technical hierarchy is as follows:

- display technical interdependencies of the installation;
- extraction of tags, equipment and spare parts;

- extraction of documents and drawings;
- extraction of historical inspection and maintenance data from Computerized Maintenance and Inspection Management System (CMIMS);
- scheduling of operations (e.g. relationships due to shutdown etc.);
- cost allocation and extraction;
- scheduling and organization of the inspection and maintenance programme;
- scheduling of corrective work.

Technical drawings (e.g. flow and one-line diagrams, P&IDs, etc.) can be used to classify packages and main equipment that can serve as a superior tag for the linked instruments, valves and other types of equipment. The level on which the inspection and maintenance objects are established is directed by practical considerations (e.g. traceability, consequence classification and costing analysis) and the different needs (preventive and corrective actions) to supervise and check the different inspection activities and maintenance programmes.

3.1.2. Functional hierarchy

The functional hierarchy is a logical diagram connecting all the industrial site functions characterized as functional units or main functions and sub functions. The level of detailing of the functional hierarchy may vary, but typically 4 to 5 levels are sufficient. Sub functions are connected to equipment/maintenance object in the technical hierarchy.

Each equipment within one sub function is given the equivalent classification because a fault, error or failure on any of these equipment (identified by the tag numbers) will cause the identical consequence on the main function.

The breakdown by activity sector shows that the components of systems in the industrial site are classified in the functional hierarchy organized in a tree with different levels (from level 1 system to various sub-Tag levels). We can see below the levels of the described hierarchy (Fig. 1).

The contents of various levels of the functional hierarchy are described in Table 3.

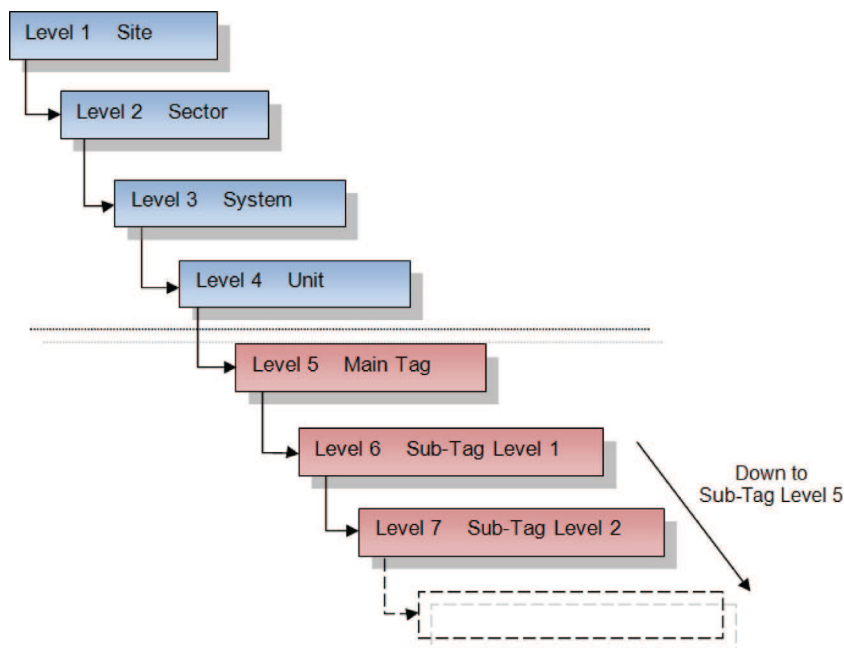


Fig. 1. An example of the functional hierarchy.

Table 3
The contents of various levels of the functional hierarchy.

Level 1 Site	The site is a geographical location of the equipment. For example, project facilities 'CLOV' are located in block 17 with the code 'CLO'.		
Level 2 Sector	The sector describes a set of the process system. This corresponds to a single installation section. For example for CLOV, we have the following description.		
	Code	Designation	Description
	FPSOT	Topside	All that is on the deck of the FPSO
	FPSOH	Hull	Inside the shell
	FPSOA	Accommodation	The living quarters
	BUOY	Buoy	Buoy of loading operations
	SUB	Subsea	Underwater workplaces
Level 3 System	A system is a set of interdependent equipment sharing common functional characteristics. For example, the treatment of water from the injection wells comprises all functional handling units contributing to the injection of water: filtration, treatment and injection.		
Level 4 Unit	A set of equipment dedicated to a specific process or a utility function (for example, water filtration within the water treatment system). A unit is a part of the installation which is operatively independent. It is also an entity which may be controlled. The unit is identified by a code of the subsystems.		
Level 5 Main Tag	The tag represents a unique functional identification of a device in a site. All equipment subject to maintenance, inspection or certification must be tag (e.g. pumps, boats, boilers and, vessels). Tags are defined mainly during the engineering phase and are listed on the following project documents: P&ID, PFD, UFD and Equipment List.		
Level 6 Sub-Tag	This concerns the creation of other sub-levels from the main-tag. The sub-tags can facilitate the description of instruments to identify. An instrument, such as a pressure transmitter, is always connected to an automated control and safety. The instruments belong to one of the following categories:		
	<ul style="list-style-type: none"> • Process Control System (PCS) (e.g. electronic modules, Programmable Logic Controller (PLC), Human-machine interface (HMI)). • Process Safety System (PSS) (e.g. valves and actuators). • Process Control Instrumentation (e.g. gauges, detectors, indicators, transmitters, switches). 		

The structural description of the organization of the functional hierarchy is further complemented by the functional descriptions about key features and capabilities of the equipment. This can help the manager to possibly set alternatives that could determine the characteristics and settings that are available [24–26]. Therefore, the user can consult this technical annotation on an organized source for any updated information regarding the functional descriptions, e.g. methanol storage drum control devices, methanol storage drum level transmitter or nitrogen supply shutdown valve of equipment and instruments are the components of the system under study in a petroleum project. These functional descriptions are really helpful in practical ways in working with repair and overhaul services, parts provisioning, support services and engineering services.

3.2. Maintenance packages and routes

In addition, using the list of equipment, the maintenance packages can be prepared by simply assigning groups to each of the input components based on factors such as functionality, ergonomics or criticality [27]. In the context of petroleum activities, a package is a set of equipment handling the same main fluid and/or dedicated to a specific process function. A package is a portion of an industrial facility that has a maximum of operational autonomy. It is also an entity that could be commissioned and dismantled to facilitate a reorganization or a safety issue.

Some typical packages identified are listed below:

- *Gas Compressor package*: Compressor/Motors (electric)/Electric heaters/Instrumentation/Valves (Manual and Actuated)/Control Panel.
- *Pump package*: Pump with sealing and cooling system/High-Voltage (HV) – Low-Voltage (LV) electric Motors/Electric heaters/Instrumentation/Valves (Manual and Actuated)/Control Panel.
- *Combustion Engine package*: Diesel Engine with air starting system, radiator (cooling)/Electrical Generator/Instrumentation/Valves (Manual and Actuated)/Control Panel.
- *Boiler package*: Boiler/Control and monitoring system/Instrumentation/Control and safety valves.
- *Vessels package*: Control and monitoring system/Instrumentation/Control and safety valves.

A route is a sequence of similar equipment, combined to simplify maintenance tasks. There are three different types of route:

- *Route type 1*: Applied on a unique area, unit or zone. This equipment often belongs to the same technical class which means that the work to perform would be the same.
- *Route Type 2*: Applied on multiple areas, units or zones.
- *Individual Equipment*: Applied on unique equipment, independently of the rest.

The next step is to use functional descriptions more effectively to improve criticality analyses and Risk-Based Inspection methods.

4. Methodology

In contrast to the systems in onshore production sites, systems in offshore production sites operate in extremely difficult conditions, e.g. water, air and other aspects of the natural and human environment. We apply the risk based inspection to all pipelines (onshore and offshore) and risers operated by subsidiaries of the French petroleum company with operations on the west coast of central and southern Africa. This covers the following categories of pipelines and risers:

- The offshore steel pipelines,
- The onshore steel pipelines,
- The static steel risers,
- The steel catenary risers.

In this context, the objectives of the application of the Risk based Inspection Methodology are the following:

- Listing of the facilities operated within a production centre to identify potential failure modes and high-risk areas.
- Estimation of the value of the risks associated with the operations of each device in a production cluster, based on a consistent methodology.
- Organization of appropriate inspection plans resulting from the identification of potential failure modes and risk assessment.
- Development of mechanical changes, both to the processes and operations that would reduce the risks.

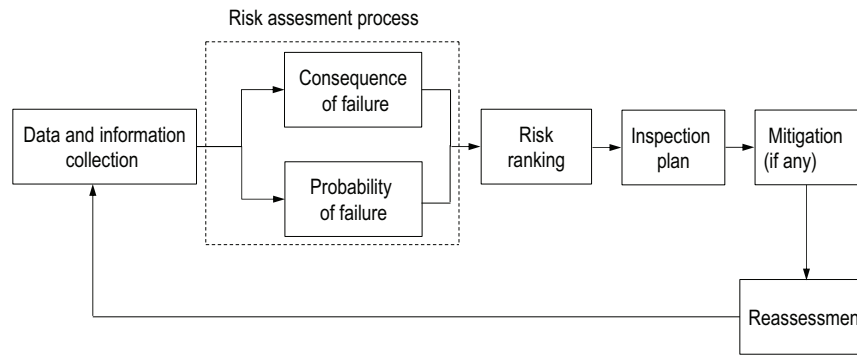


Fig. 2. The risk based inspection organization process [39].

Fig. 2 highlights the methodology for risk based inspection. This methodology requires achievement of seven main activities encompassing *data and information collection*, *risk assessment process* composed of *probability of failure rating* and *consequence of failure rating*, *risk ranking* in risk matrix, *inspection plan*, *mitigation* (in case of need) and *re-assessment* [28]. This methodology is normally used to define a risk based inspection plan iteratively.

The risk matrix is interesting for engagement in maintenance preparation, inspection programming and for ordering work orders. It is possible to use a variable number of classes for consequences as for probabilities. For example, the widely used risk scale (low, medium, high) or the colour scheme (red, yellow, green) of equipment provide means to visual identification of risk acceptance

criteria (e.g. unacceptable, undesirable, acceptable, negligible) with the emphasis placed on priority areas of intervention.

An example of a risk matrix (using probabilities of failures and consequences of failure) is shown in Fig. 3. This risk matrix displays three risk levels, indicated through colour coding:

- *Green – Low risk* – Risk is acceptable. Generally, action needs to be taken to guarantee that risk remains within this acceptable region; normally this involves operator round, cleaning, general visual inspections to check that there have been no alterations in equipment condition.
- *Yellow – Medium risk* – Risk is acceptable. Action (such as Non-Destructive Testing, functional tests and other condition monitoring processes) should be taken to measure extent of

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

Fig. 3. Example of the description of a coloured risk matrix [40].

Table 4
Relevant data concerning the internal part of pipelines.

Depth	Internal part of pipeline		External part of pipeline		Total
	In body of pipe	Weld area	In body of pipe	Weld area	
≥70%	–	–	–	–	–
60% to <70%	1	–	–	–	1
50% to <60%	1	–	–	–	1
40% to <50%	5	2	–	–	7
30% to <40%	20	21	–	–	41
20% to <30%	59	23	–	–	82
10% to <20%	357	7	–	–	364
Total	443	53	–	–	496

degradation so that action can be taken to guarantee risks do not rise into the red high-risk region.

- **Red – High risk** – Risk level is unacceptable. Action must be taken to reduce probability, consequence or both, so that risk remains in the acceptable region.

The implementation of the RBI therefore needs to collect all the data; type of equipment, the material used, the operating conditions, safety systems, the cost of failure etc., related to subsea pipeline production and injection of water and gas production centres on an Excel file to create a dynamic database. This is the first step and the most important part of the methodology as it will define the quality of inspection plans. Therefore, one has to understand the types of information required, thickness, length, operating pressure, maximum allowed pressure, etc., and their influence on the results. In addition a permanent judgement on values and information found is necessary in order to avoid possible errors. The collection of information for the development of RBI must ensure the access to industrial databases that contain all the information related to each defined business, production site or projects (production line drawings, technical documents, plans, alignment sheets with geographic coordinates and system specifications). For each RBI plan, two types of information, specific or generic, can be identified. On the one hand, some information is specific, for the pipeline identification, the following information is used: section identification, section function, coupling type, presence of thermal insulation, nominal thickness, shore approach, overpressure protection system, safety factor thickness, quality control (manufacturing), fabrication type, construction code status, pipeline crossing, elevation, rock dumping, diameter, Maximum Allowable Operating Pressure (MAOP) and Maximum Operating Pressure (MOP). On the other hand, certain information is generic e.g. for the detection system available, the following information is used: material grade, climate, shipping lane/traffic maritime area, anchorage zone, fishing trawling activities, presence of iceberg, cargo activity, seismic area, fault crossing, coastal or fragile system area and deep offshore. They are the same for all the poles? of production, because the pipelines are located in an area where there is no sea traffic, icebergs, or earthquakes, as all pipelines are in deep offshore. All information on the working environment of these subsea components have much more influence on inspection intervals.

The organization and verification of technical data are two necessary steps in any data collection activity for the sake of clarity, coherence and consistency of information sources [29]. In order to facilitate the exchange of information on maintenance and inspection management the Excel form is widely used to enter information into the data collection system and such information may be exported to various other programmes such as Systems, Applications & Products in Data Processing (SAP), among others.

5. Analysis

5.1. Situation of internal part of petroleum pipelines

We are interested here only in the internal portion of the pipelines. There are two points of corrosion by more than 50% deep. The nominal wall thickness is 17.5 [mm] which can be reduced up to 50 [%] as a result of corrosion.

The corrosion rate is calculated from thickness data available from equipment inspections. In total there are 492 points of corrosion with varying depths below 70% (as described in Table 4).

The equivalent allowed maximum depth is 80%. Table 4 shows certain relevant data concerning the internal part of pipelines. The data presented in this table are real and they are collected by intelligent pigging that is a highly sophisticated instrument measuring pipeline wall thickness and metal loss by direct measurement of the thickness of the pipeline wall.

After the first inspection of the internal part of pipelines, corrosion is found with a dense and regular distribution of the deterioration at the base and along the internal parts. The inspection of pipelines can detect metal loss and corrosion through electromagnetic waves.

The corrosion rate is calculated from thickness data available from equipment inspections. However, if corrosion rates cannot be determined from thickness inspection data, conservative estimates may be established using expert opinions from knowledgeable materials. The maximum corrosion depth in body of pipe is based on Table 4 for the presence of one occurrence in the interval 60% to <70% ($0.64 * 17.5 = 11.2$ mm). The result is a conservative value for the estimated corrosion rate, but it is not always the case. There is a clear distinction between corrosion rates in body and weld area. The maximum corrosion depth in weld area is based on Table 4 for the presence of two occurrences in the interval 40% to <50% ($0.50 * 17.5 = 8.75$ mm).

5.2. The realization of the implementation plan

Step 1: the identification of the probability of failure to establish a risk matrix. In the general, the probability of failure can be determined as a linear combination of corrosion (i.e. environment) and structural induced failure. The weights used in the linear combination depend on the contextual assumptions and inspection techniques that are used in the risk based inspection methodology. In the considered context, it is assumed that corrosion (i.e. environment) and structural induced failure have an equitable contribution to pipeline failure. In addition, CL and SL are levels of probability which are in between the numbers 1 and 5, $1 \leq CL \leq 5$ and $1 \leq SL \leq 5$ then $1 \leq 0.5 * CL + 0.5 * SL \leq 5$.

The level of probability is given by the following formula:

Likelihood of failure (Lof) = 50% CL + 50% SL.

- Corrosion Likelihood (CL) is used to estimate the corrosion and Structure Likelihood (SL) is used to estimate the structural failure (construction, design, mechanical and others). The severity of events is specified with probability levels describing five levels of probability which are in between the numbers 1 and 5, with 1 being the lowest and 5 being the highest: 1-Very Low, 2-Low, 3-Moderate, 4-High and 5-Very High.
- CL = NCL – EFF – ST
 - Natural Corrosion Likelihood (NCL): the probability level of natural corrosion (without mitigation).
 - Effectiveness (EFF): the level of effectiveness of mitigations or maintenance if there were.
 - State (ST): the internal state of the pipeline due to the corrosion.
- In order to find the NCL, one must calculate the ratio of the Corrosion Rate (CR) and the Allowed minimum Thickness (Ath), with:
 - CR = maximum depth of corrosion/age of the pipeline = 11.2/8 = 1.4 mm/year.
 - Ath = it is calculated by multiplying the allowed maximum depth by the nominal value (allowed maximum depth × nominal value). In the case study Ath is 80% of the nominal value. Ath = 0.8 * 17.5 = 14 mm.
 - So, Ath/CR = 10 mm/mm/year.
 - This ratio of 10 mm/mm/year corresponds to a NCL = 4.
- For the EFF, the value is zero (=0), because there was no mitigation, maintenance, nor inspection.
- The ST is the maximum percentage of metal lost so far, 64%.
- So to conclude CL = 4.0 – 0.64 = 3.36. During the calculations of the probability level of failure and risk level, the results are generally rounded upwards, so we will take a rounding value with **CL = 4**.
- SL = (SL_{mec} + SL_{D/C}) + SL_{third} + SL_{nat}
 - Structural mechanical failure Likelihood (SL_{mec}) = it corresponds to the probability level of a mechanical failure.
 - Structural design or construction failure Likelihood (SL_{D/C}) = it corresponds to the probability level of a failure in the design or construction.
 - Structural failure third party Likelihood (SL_{third}) = it is the probability level of a failure due to an external event.
 - Structural natural failure Likelihood (SL_{nat}) = it is the probability level of a failure caused by the natural environment.
 - SL_{nat} and SL_{third} are zero values because there has never been a failure caused by the environment or by an external event. Also no failure in the design nor construction have been identified and no mechanical failure has been observed since the putting into operation of this production site.
 - The assessment of the facility's management system evaluation consists of a series of interviews with plant management, operations, inspection, maintenance, engineering, training, and safety personnel [30]. As regards the process safety information, one should address the question regarding the quality control procedures in place and practiced to ensure that all identified materials meet specifications when received and used.
 - However, none of these failures are indicated because there was nothing observed, and in the absence of any other information to the contrary, it was assumed that the value of the variable SL is the lowest possible value i.e. SL = 1.

Finally, we have **Lof** = 50%CL + 50%SL = 2 + 0.5 = 2.5. This result is rounded upwards, so we will take a rounding value with **Lof = 3**.

Step 2: the calculation of the consequence of failure is classified on a scale ranging from 1 to 5. There are three types of consequences: the staff safety, environmental impact and pollution, with the financial and economic impact. The scale of the consequence is

Table 5
Relations between production loss and financial consequence.

Production loss	Financial consequence
Production loss >5 days of affiliates average production	5
Loss between 1 and 5 days of affiliates average production	4
Loss less than 1 day of affiliates average production	3
Limited loss	2
Negligible production loss	1

given by the following formula:

Consequence of the failure (Cof)

$$= \text{MAX}[\text{pollution}; \text{financial consequences}; \text{personnel safety}]$$

For the Cof, we take the highest value among the three consequences. In order to determine the severity of the consequences and therefore the level of risk, we made some assumptions about the possible failure modes and we took the one with the highest probability level and criticality. The assumptions are:

- The pressure of the water is approximately 140 bars and the pressure of the operations (inside) is about 60 bars in the presence of a hole, this means therefore that the sea water enters the flow-line due to the pressure difference. So there is no pollution, no impact environmental, no financial loss and no danger to personnel safety.
- When production is shut down on the right section, one can switch the entire production on the left line thus avoiding financial consequences. But however many operations occur. To switch the production on the left line, one must know its capacity to receive the entire production of the right line. All these parameters can decrease oil production capacity significantly, so there will be significant financial consequences.
- The considered section of the production site is in subsea and away from the Floating Production, Storage and Offloading (FPSO), therefore the consequences for direct personnel safety is zero.

In our context, we will always take the most unfavourable case for the calculation of different consequences, this means that we must stop the production activities in this particular petroleum site. So in this case, there are financial consequences. In practice it includes the losses generated by the production loss that is less than 1 day of affiliates average production. As it can be inferred from

		Consequence				
		Moderate 1	Serious 2	Major 3	Catastrophic 4	Disastrous 5
Likelihood	5					
	4			✘		
	3					
	2					
	1					

Fig. 4. Example of risk matrix used for the case study.

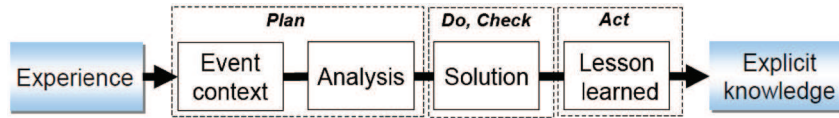


Fig. 5. Experience model incorporating problem-solving technique [23].

Table 5, with respect to the financial consequence, the criticality coefficient has the value $Cof = 3$.

The overall level of risk of the studied pipeline (including probability level of corrosion and the probability level of a structure failure) in the considered production site is calculated by the following formula:

$$\text{Global Risk} = \text{Likelihood (Global Probability)} \\ \times \text{Consequence (Severity)} = Lof * Cof = 3 * 3 = 9$$

6. Results

The definition of inspection intervals by using relevant devices to perform various inspection operations on a pipeline. Particularly, intelligent devices are very smart instrument devices that contain electronics and sensors that gather several forms of data during their inspection tour through the pipeline. One must calculate the level of risk, taking into account the likelihood of corrosion and the criticality of the consequences:

$$\text{Corrosion Risk} = \text{Likelihood (Probability of corrosion)} \\ \times \text{Consequence (Severity)} = CL * Cof = 4 * 3 = 12$$

The coloured risk matrix (as shown in Fig. 4) is intended to display that as Probability of Failure (PoF) and Consequence of Failure (CoF) increase, the risk becomes significant.

Then we compare this result on a risk matrix to determine the type of risk level (low with green colour, medium with yellow colour and high with red colour). With a likelihood having the value 4 and a consequence having the value 3 and according to this coloured risk matrix, a medium level of risk is shown.

The indicative information on the inspection plan is provided in Table 6. It can be seen from this table that we can determine the interval of the next inspection by smart instruments using electromagnetic acoustic transducers to check for general condition, potential failures and normal operation of the pipelines. In our case the level of risk is average and value of CL is 4, so the next inspection by smart instruments will be in 4 years.

Domain experts also believed, in these cases based on personal experience, that they would have to choose a CL with value 5 and a consequence with value 5, because they took into account the fact that there is no injection of a corrosion inhibitor (catalyst) in wells. So with a CL having the value 5 and a Cof having the value 5 they find an interval of 2 years, but other parameters (such as the status of other interconnected systems for example) are involved with their associated impacts on inspection activities. Based on these circumstances, a specific intervention by the maintenance engineering is

Table 6
Indicative information on the inspection plan.

Corrosion risk = High		Corrosion risk = Medium		Corrosion risk = Low	
CL	Interval	CL	Interval	CL	Interval
1	Max (15, $T_i - T_0$)	1	Max (20, $T_i - T_0$)	1	No inspection
2	10	2	12	2	15
3	5	3	8	3	10
4	3	4	4	4	5
5	2	5	3	5	Not applicable

at this moment not being planned; therefore the interval of the inspection plan is reduced.

As a result it is considered that an interval of one year is the best preventive plan for pipeline inspection in the case study.

7. Discussion

As a complement to the explicit knowledge extracted from available data and information that are regularly used in the RBI processes, it is indispensable to identify the implicit knowledge applied by domain experts, and moreover the stepwise principles of problem-solving methods. In petroleum industry, as in many other complex domains, the part of implicit knowledge in the expert problem-solving process has an important impact on the results attained. Hence, the modelled experience feedback processes integrate the description of more detailed explanation in knowledge acquisition and interpretation problem-solving methods. In order to acquire knowledge from experience feedback processes, a conceptual model (context, analysis, solution and lesson learned) incorporating problem-solving methods to generate explicit knowledge from practical experiences is presented in Fig. 5.

The principal categories of knowledge acquisition techniques includes these five elements [31]: (i) Interviews with observations and protocol analyses, (ii) Classification techniques for identification of conceptual domain vocabulary, (iii) Exploitation of recorded cases, (iv) Extraction of associations rules, (v) Identification of patterns of reasoning. These recognized knowledge acquisition techniques are operative in revealing the rules and constraints underpinning the expert reasoning, so it is possible to give explicit outline and a formal background to knowledge components deployed by domain experts. In fact, the explicit specification of conceptual vocabularies of the experiences with the associated problem solving methods meaningfully impacts the way in which the RBI takes place, as supported by their influence in the formalization of information and knowledge acquisition.

8. Conclusion

Maintenance and inspection engineering is a complex task that requires experienced knowledge to allow the good management of the requirements analysis, planning and inspection operations, maintenance, repair or overhaul of the considered system. Particularly, in the petroleum domain, the main target for the inspection process is the management of reliable system integrity so that performance in compliance with environmental and technical standards is efficiently retained through the system's lifecycle.

In this document, we describe a research approach using a risk based inspection methodology to improve the capability and associated maintenance services concerning the effective functioning of the technical systems in offshore production sites. The achieved results with the proposed approach are tangible since they allow the determination of thorough inspection of the pipelines and what the optimum interval cycles are for the necessary inspection plan. The proposed approach is applicable to the company discussed in this paper and it is also a generic method which can be applied in any petroleum or O&G companies. It may be applied to other systems or sectors of activities with sensitive components in order to inform them about the risk analysis that requires knowledge-intensive tasks in the engineering field.

Knowledge acquisition and interpretation problem-solving methods from experience feedback processes (e.g. valuable case studies of expertise in sedimentary petrography [32]) can be included in risk assessment of inspection planning. The use of previous information from similar contexts would improve the anticipation of future developments in complex systems in time. The generated lessons learnt could make a useful contribution to the understanding of failure prediction, and the time scales to reach these failures and possibly including the study of the potential consequences. This is to provide domain experts with a database of historical data on the considered system with its properties and environmental constraints, taking into account the damage it has sustained during ageing. Helped by such an information base, the expert has a tool for risk analysis in which reference can be made to determine the expected developments and mechanisms causing damage and their sequence leading to the system failure (failure scenarios). The criticality assessment of these scenarios in terms of occurrence, severity and detectability and the root cause analyses allow to identify the most critical scenarios and predict the circumstances of their occurrence. For instance, there are some established procedures for safety assessment probabilities based on the evaluation of German operational experience for piping systems with different diameters [33].

Nevertheless, due to the complexity and uncertainty of the refining and petrochemical units and risks, operational analyses are difficult to achieve by using risk techniques with classical logic [34]. Likewise, a fuzzy logic framework can be engaged in the establishment of an RBI programme for systems of the petroleum industry. The advantage of this approach lies in its ability to include contextual experiences along with acceptable deterministic models in the information processing [35]. Also the inspection management department can order risk reduction decision makings using risk prioritization of the asset failures [36]. Therefore the use of appropriate methods and approaches, careful investigation during the risk analysis phase, and its comprehensive and organized results are essential to make proper risk-based inspection decisions [37].

Alternatively, a RBI methodology might be combined with Multi-Objective Genetic Algorithm (MOGA) for defining efficient inspection programmes in terms of inspection costs and risk level [38]. Finally, RBI could be included in a larger framework; for example, an approach giving multi-attribute decision-making with aggregated risk analysis [4] or experience feedback strategies [41–44].

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