OTC-32464-MS

Optimizing the Inspection Plans of Subsea Equipment Using Risk Analysis Methodologies and Simulations

Leonardo Oliveira Barros and Rene Thiago Capelari Orlowski, Research and Development Center – CENPES - Petrobras; Marcos Coelho Maturana, Adriana Miralles Schleder, and Marcelo Ramos Martins, Analysis, Evaluation and Risk Management Laboratory LabRisco, University of São Paulo

Copyright 2023, Offshore Technology Conference DOI 10.4043/32464-MS

This paper was prepared for presentation at the Offshore Technology Conference held in Houston, TX, USA, 1 – 4 May, 2023.

This paper was selected for presentation by an OTC program committee following review of information contained in an abstract submitted by the author(s). Contents of the paper have not been reviewed by the Offshore Technology Conference and are subject to correction by the author(s). The material does not necessarily reflect any position of the Offshore Technology Conference, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper without the written consent of the Offshore Technology Conference is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of OTC copyright.

Abstract

Cost reduction and risk management are well-know concerns in the offshore oil and gas industry and many approaches have been explored to deal with these issues. One way to reduce risk and costs associated with oil and gas exploration is performing the optimization of inspection plans, allowing monitoring the integrity of equipment while optimizing the use of inspection techniques, and tests and their respective frequencies based on the risk associated with the operation. This paper presents a methodology developed to perform this optimization and four case studies in which the methodology was applied.

Introduction

Since its origin, oil and gas offshore facilities deal with the challenge of guarantee the integrity of their equipment spending the least amount of resources as possible. Hence, the Risk-based inspection (RBI) was developed in the petroleum industry to help identify the riskiest equipment (by identifying the respective failure modes) and also to designing inspection programs that track the most relevant failure modes.

The inspection procedure aims mitigating the uncertainty related to the asset degradation state, enabling a better quantification of the actual damage, and, consequently, increases the accuracy of remaining life projections. However, underwater inspections have as outstanding characteristics the excessive cost and the limitation of inspection techniques available. Therefore, the costs involved in offshore subsea inspections are considerable and inspection plans optimization plays a crucial role in the balance of an asset management program.

In this context, this paper presents partial results of a major project focused on developing a program for monitoring the integrity, optimizing the use of inspection techniques and tests, and their respective frequencies based on the risk associated with the operation of subsea equipment. This project was focused specificaly on Christmas trees (XTs), Emergency Shutdown Valves (ESDV), Subsea Manifolds, Pipeline End Manifold (PLEM) and Pipeline End Termination (PLET) and carried out by PETROBRAS in partnership with the University of Sao Paulo (USP). The project was conducted by the Analysis, Evaluation and Risk Management Laboratory (LabRisco) from USP with the collaboration of Institute of Science

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

and Engineering of Sao Paulo State University – ICE/UNESP and the Nuclear Engineering Department – COPPE/UFRJ.

This paper presents the main steps developed to perform the optimization of the inspections plans of subsea equipment. The proposed methodology uses information from subsea equipment FMECAs, costs associated with inspection techniques and probabilities of detection of each failure mode when using each inspection technique considered as available; this information is used as input data for an optimization program based on genetic algorithm that seeks inspection plans that minimize both cost and risk. To present the application of the proposed methodology, four case studies are presented, i.e., optimized inspection plans are obtained considering four equipment: XT with direct hydraulic control system, XT with multiplexed electrohydraulic system, oil manifold and gas manifold.

Methods

As previous mentioned, the goal of the methodology presented in this paper is monitoring the integrity of subsea equipment and optimizing the use of inspection and testing techniques. To reduce the risk associated with the operation of the equipment, the possibility of using different methods at each inspection opportunity was considered. However, the cost of conducting inspections using several methods with high periodicity is impractical. Thus, the inspection plan optimization problem can be treated as a multi-objective problem, considering risk index and cost as conflicting objectives. Conducting the optimization process it is possible to define optimal solutions to inspection plans; each solution will provide a list of the inspections methods to be applied and the recommended time of their application, in a such way of obtaining a balance between acceptable levels of risk and cost associated with inspections.

There are many approaches to deal with multi-objective problems, one of the most well accepted is the use of Genetic Algorithms (GA), an optimization technique inspired in the concepts of evolutionary genetics. The optimization process considers a multicriteria objective function, consisting in the dimensions cost and risk. In the scope of the project here reported, the Non-Dominance Genetic Classification Algorithm (NSGA-II), developed by Deb et al. [1], was modified to perform the optimization. The genes are defined in terms of two variables: the type of inspection to be done and in which time it occurs, considering a finite window of opportunities for inspection occurrences.

The algorithm is fed by information obtained from the FMECAs of each equipment of interest and by additional information such as detection probabilities (for each falirue mode by each inspection technique) and costs associated with inspection techniques (raised in the inspection history) to create optimized inspection plans. These plans are characterized according to the associated costs and risk and can be presented in a cost vs. risk plot allowing, for example, the integrity manager to opt for a new inspection plan that has a lower cost while maintaining the risk level of the plan currently used.

The main steps of the proposed methodology are presented in Figure 1. First, the elaboration of the failures modes, effects and criticality analysis (FMECA) for each equipment within the scope of the analys; the FMECA can be elaborated following the recommendations of Modarres et al. [2]. It is worth noting that a computational tool called SisFMECA was developed to facilitate this step; the SisFMECA automates the process for collecting, validating, and analyzing data on failure modes of equipment and its components and promotes standardization of definitions and analysis methodologies, allowing analysts to have quick and accurate access to information common to the project under analysis.

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

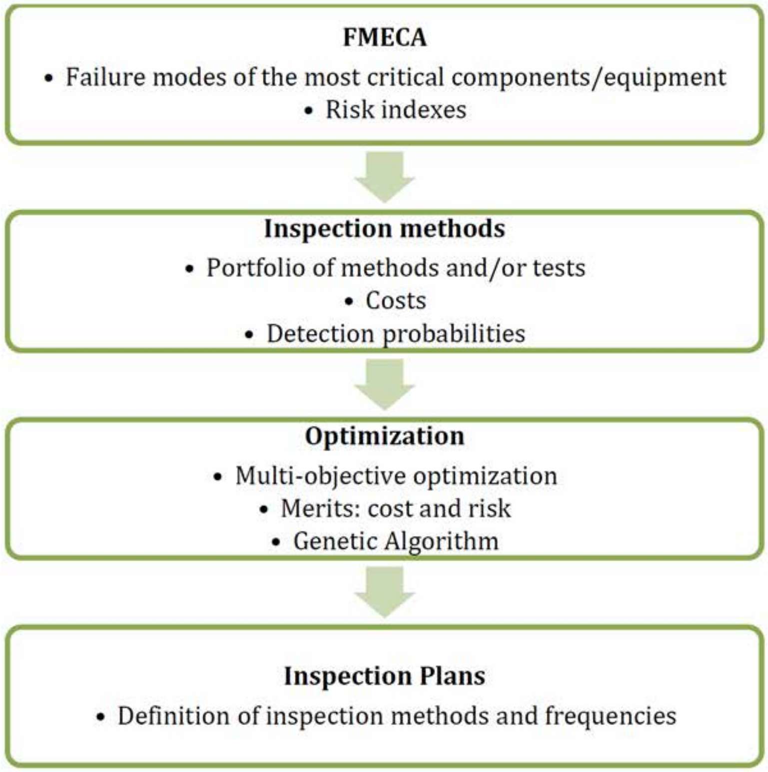

Figure 1—Main steps of the proposed methodology

The information provided by the FMECAs is used as input to the optimization process; however, the risk index, traditionally calculated in the FMECAs, composed of the probability of occurrence, the consequence and the probability of detection of the failure modes, is not ideal to be used in optimization process since it does not take into account the inspections executed during the lyfe time of the equipment. Therefore, a methodology to define risk index was also proposed in the scope of the project reported here and it was used to define the risk index considered during the optimization. The details of the risk index evaluation are presented by Maturana et al. [3].

Finally, the last information needed to perform the optimation concerns to the inspecton methods. For each equipment of interest, it is required to map the inspection techniques and tests available, defining its costs and its capacity to detect each failure mode of the equipment. The data about cost is obtained by historic data; however, information regarding the detection capacity is harder to find; then a methodology to define the probability of detection associated with each pair, failure mode and inspection method, was developed and it is presented in details by Cuba et al. [4].

The last step represented in Figure 1 focuses on the inspection plans obtained by the optimization. It considers different options for inspection plans, varying the types of inspection and their frequencies, calculating the Risk Indexes and the cost for each case; the risk varies depending on the probability of detection and the cost varies depending on the type and frequency of the inspection's applications. The optimization algorithm provides a set of optimal solutions (Pareto Frontier) as a function of the risk index and cost, defining for each plan what type of inspection to do and when. It is worth to note that a computational tool, called SOPI (Inspection Plan Optimization System), was created to allow the implementation of the optimization.

Study Cases

As previous stated, four equipment were chosen to the study cases aming describing the obtained results by the proposed methodology: XT with direct hydraulic control system, XT with multiplexed electrohydraulic

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

system, Oil Manifold and Gas Manifold. In this section, the main results of the optimization of inspection plans for these equipment are discussed.

In each case, firstly, the reference model of the equipment was defined, followed by the definition of its failure modes through the FMECA evaluation. Then, the risk index for each failure mode and component were calculated. Next, it were defined the costs and detection probability associated with each available inspection method or functional tests. And, finally, the GA was used to obtain the optimized inspection plans.

To facilitate the assessment of the inspection plans obtained from the optimization, a Risk Acceptance Criteria was defined. These limits were define based in international guidelines (such as the reference document R2P2 from HSE [5], [6]) and internal standards of the Petrobras. Additionally, a Standard inspection plan for each equipment was defined to allow the comparison between the risk and cost levels of the optimized plans with the levels of a plan considered typical to the equipment (the Standard plan).

Reference models definition

A reference model was defined for each equipment under analysis. The models were built based on the data provided by the Offshore and Onshore Reliability Data Handbook - OREDA [8] and refined by expert analysis.

The XT with multiplexed electrohydraulic system set consists of six main components, in addition to the XT itself: Tree Cap, hydraulic lines, production adaptor base, Tubing hanger, Vertical Connection Modules and the Control Module. The XT with direct hydraulic control system presents a similar set of subsystems; however, its Control System and other components are less complex. Both configurations are presented by Moura et al. [9].

Regarding the manifolds, they provide the link between the subsea field and the production facility. The Manifold consists of a network of pipes and valves for collecting and distributing the production flow. It also has Subsea Control Modules and chokes, equipment responsible for valves control and flow control, respectively. The configuration of the manifolds of the last two case studies were the same, the only difference between than is the operational condition, the first one is a manifold operating with oil while and the second one operates with gas (this diferrence causes impact on the consequences of possible undesired events). Details regarding the manifold configuration are presented by Nicolau et al. [10].

FMECA evaluation

The FMECAs were evaluated using the computational tool SysFMECA previously mentioned and following the main steps suggested by MIL-STD-1629A [11]:

- Bibliographic survey of failure modes and failure data;
- Identification of failure modes of each equipment, their causes, effects, and consequences, detection methods, failure effect probability, failure mode fraction, failure rate and operating time;
- Definition of severity class for failure modes;
- Establishment of a failure mode and equipment criticality rating.

Optimization of the study cases

The inspection plan optimaziation was performed using the GA presented in previous section and the information obtained from the FMECA evaluation. Addionally, it were used during the optimization: the the Risk indexes proposed by Maturana et al. [3], the cost associated with each inspection method obtained by historical data and the probability of detection associated with each inspection method defined according to the methodology proposed by Cuba et al. [4].

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

It was considered the equipment lifetime equals to 30 years and a window of opportunity for inspection at the end of each month (total of 360 inspection opportunities). At each opportunity it is possible to perform none, one or a combination of inspections and/or functional tests. Regarding the manifolds, five methods were considered (visual inspection, electrochemical potential measurement, eddy currents, ultrasound and radiography) while regarding the XTs seven different methods were considered (adding to the previous list the functional test of valves and the tightness test).

Several generations of solutions were generated, and by genetic operators, the best ones were selected; then, a set of optimal solutions based on risk index and cost (Pareto Frontier) was defined. The details of the optimization methodology are presented by Morais et al. [12].

Study cases main results

The main results of the study cases are presented in the next subsections. In each subsection, initially is presented the Standard plan of the equipment); aftereward, the result of the optimization is discussed.

XT with multiplexed electrohydraulic system. Concerning this XT reference model, the Standard plan considered consisted of functional tests every 6 months and visual inspections every 36 months during the entire useful life of the equipment (30 years), except during he first year, in which, six additional functional tests are performed.

The optimization considering monthly inspection opportunities, without interval limitations, obtained 137 optimal solutions (belonging to the Pareto frontier); that is, 137 different inspection plans. To carry out the analysis of the optimal solutions, the Standard Plan was used as a comparison, in relation to the maximum risk index and total cost. Therefore, among the 137 solutions, 14 showed a maximum risk index and total cost lower than the Standard Plan. Table 1 presents three of these solutions: the solutions, 104, 92 and 91 were chosen due to the first having lower cost keeping the same level of risk, the second for presenting an intermediate maximum risk index; and the third for presenting a significant reduction of the maximum risk index.

Table 1—Highlighted solutions of the Pareto frontier - XT with multiplexed electrohydraulic system

Solution	Δ% Cost	Δ% Risk
104	-61.99	-1.25
92	-19.03	-17.94
91	-13.09	-19.97

For this case, considering the opportunity of monthly inspections, without interval limitation, it was possible to generate a chart with the Pareto border of the risk index versus total cost, in which the mentioned solutions are highlighted, as can be seen in Figure 2. It is possible to note in the figure that all solutions are better than the Standard plan in terms of risk and cost.

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

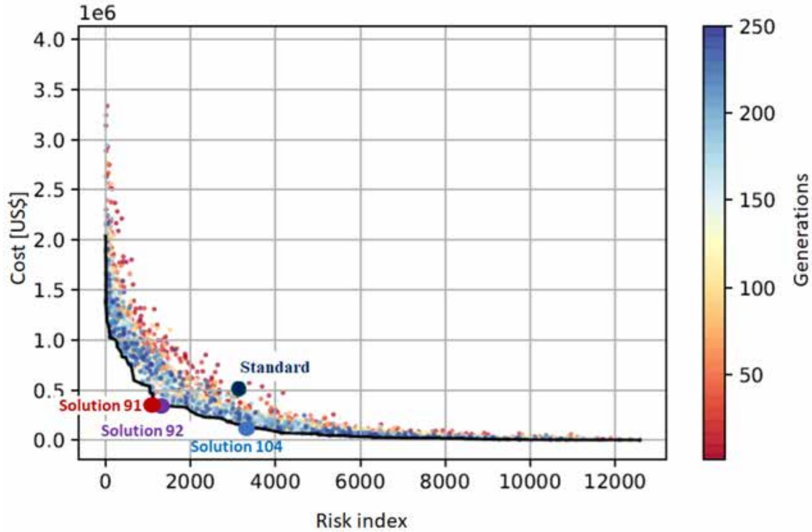

Figure 2—Pareto front XT with multiplexed electrohydraulic system

XT with direct hydraulic control system. The solutions obtained from the optimizations for this XT were also compared to the Standard plan, which is the same presented for XT with multiplexed electrohydraulic system. The optimization obtained 171 optimal solutions, in other words, 171 different inspection plans on the Pareto frontier. To conduct the analysis of these solutions, the Standard Plan was used as a comparison. Thus, among the solutions found, 33 showed a maximum risk index and total cost lower than those of the Plan.

Table 2 shows the highlighted solutions 143, 123 and 111. As in the multiplexed XT case, these were chosen because the former presenting lower cost keeping the same level of risk; the second for presenting an intermediate maximum risk index; and the third for presenting, among the selected solutions, a lower maximum risk index per period keeping the same level of cost.

Table 2—Highlighted solutions of the Pareto frontier - XT 600 m

Solution	Δ% Cost	Δ% Risk
143	-74.63	-0.64
123	-32.81	-14,26
111	-3,46	-19,23

For the case study of the XT with direct hydraulic control system, it was possible to generate a chart with the Pareto border of the risk index versus total cost, in which the mentioned solutions are highlighted, as can be seen in Figure 3.

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

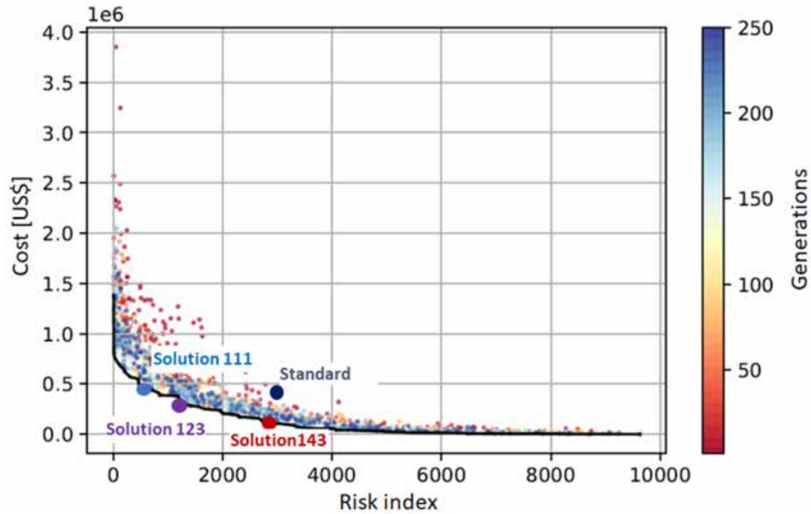

Figure 3—Pareto front XT 600 m

Manifold – Oil. To facilitate the analysis, the solutions resulting from the Manifold optimizations were also compared with a Standard plan. For the reference model of the Oil Manifold, it was considered as a Standard plan to conduct visual inspection, electrochemical potential, and ultrasound every 36 months throughout its useful life. It was considered a useful life of thirty years and an oppotunnity to inspection at the end of each month.

In this case, the optimization process provided 119 solutions, among which 19 presented maximum risk index or total cost lower than the Standard plan. As in previous cases, three solutions were highlighted. Solution 97 presents a small reduction in cost with a small increase in risk when compared with the Standard plan, while solution 95 presents a risk index reduction with moderate increase in cost; on the other hand, solutions 87 presents a very significant risk reduction at the expense of an important increase in cost. Unlike the previous cases, in which it was possible to present solutions with reduced risk and cost in relation to the Standard case, for this manifold, it is not possible to find solutions that present reductions in both variables, since the plan considered as Standard it is already on the Pareto frontier; thus, it is possible to reduce only the risk or only the cost, not both simultaneously. Table 3 presents these three solutions.

Table 3—Highlighted solutions of the Pareto frontier – Manifold oil

Solution	Δ% Cost	Δ% Risk
97	-9,02	+16,63
95	22,69	-12,13
87	115,18	-31,47

The Pareto border of the risk index versus total cost considering the manifold oil, in which the mentioned solutions are highlighted can be seen in Figure 4.

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

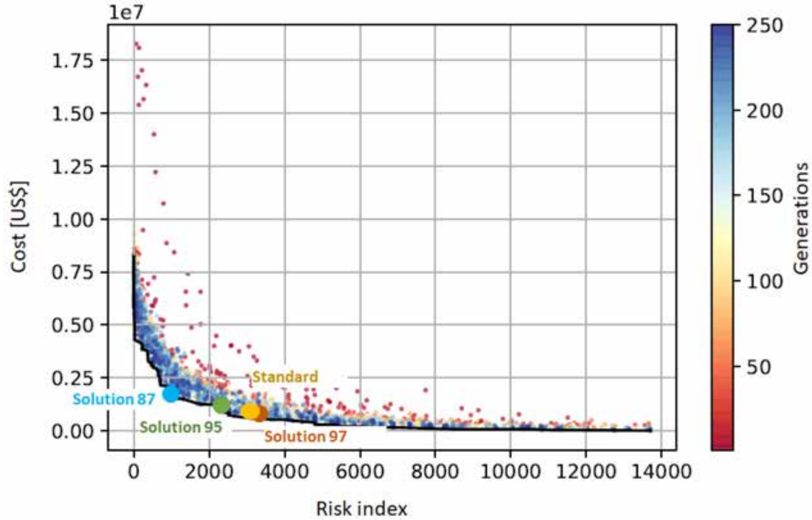

Figure 4—Pareto front Manifold Oil

Manifold - Gas. The solutions obtained during the optimizations of the inspection plans for the Gas Manifold were also compared to the Standard plan, which is the same presented for the Oil Manifold, although with different risk values since the failure modes and consequences determined for this model differ from the previous one.

Considering the Gas Manifold, 97 optimal solutions were obtained by the optimization, among the solutions, nine presented maximum risk index and total cost lower than the Standard Plan. Solutions 81, 76 and 73 stand out: solutions 81 was selected due to their much lower cost keeping the same risk level, solution 73, on the other hand, presented a lower risk index and a similar cost than the value of the Standard plan; and, solution 76 represents a intermediate solution presenting reductions in both risk and cost (see Table 4).

Table 4—Highlighted solutions of the Pareto frontier – Manifold Gas

Solution	Cost (US$)	Max Risk index	Δ% Cost	Δ% Risk
81	237,793	2.8670E+03	-58,8	-1,15
76	214,154	3,0891 E+03	-14,05	-10,64
73	567,947	1,6193 E+03	-1,6	-11,94

The Pareto border of the risk index versus total cost considering the Gas manifold, in which the mentioned solutions are highlighted is showed in Figure 5.

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

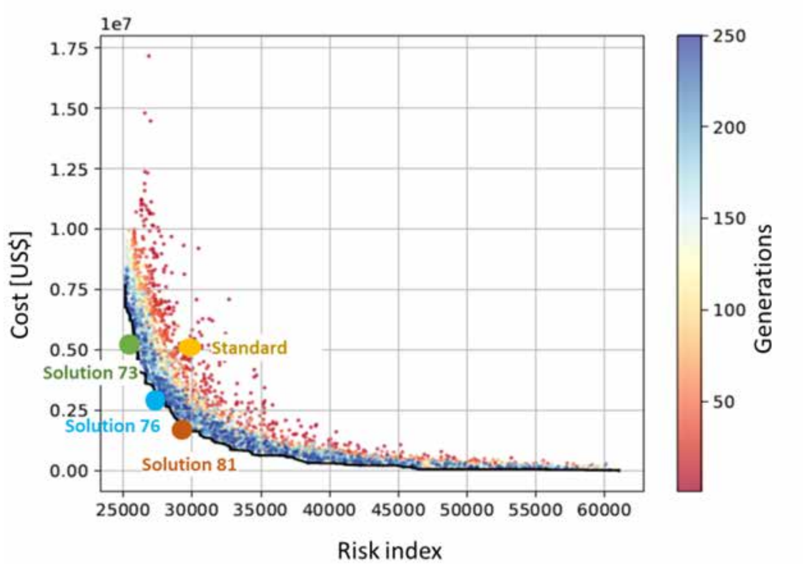

Figure 5—Pareto front Manifold Gas

Similar analyzes were performed considering, during the optimization, a minimum interval between inspection of six months. In a general way, the optimization provided inspection plans with lower costs and lower risk levels. Table 5 presents a summary of the results achieved considering half-yearly inspection windows.

Table 5—Result summary

Case 1 – XT with multiplexed electrohydraulic system	Case 2 – XT with direct hydraulic control system	Case 3 – Manifold (Oil)	Case 4 – Manifold (Gas)
• maintaining the same level of risk, it is possible to reduce the cost by more than 70%; • maintaining the cost level, it is possible to reduce the risk by about 25% • or reduce both by about 45% and 18%.	• maintaining the same level of risk, it is possible to reduce the cost by more than 84%; • maintaining the cost level, it is possible to reduce the risk by about 27%; • or reduce both by about 61% and 13%	• maintaining the same level of risk, it is possible to reduce the cost by more than 20%; • maintaining the cost level, it is possible to reduce the risk by about 29%; • or reduce both by about 11% and 18%.	• maintaining the same level of risk, it is possible to reduce the cost by more than 59%; • maintaining the cost level, it is possible to reduce the risk by about 17%; • or reduce both by about 46% and 8%.

Conclusions

This paper presented the main aspects of a methodology developed to optimize inspection plans for subsea equipment. The proposed methodology was incorporated into a customized computational tool for the multiobjective optimization of the subsea equipment inspection plan considering the risk associated with its operation and the costs for its realization.

The proposed approach explores the principle that inspections reduce uncertainties inherent in the prediction of failure rates, so that equipment can operate safely for an additional period. The risk resulting from failures is minimized and cost-effective inspection policies are achieved. As presented in the case studies, the developed methodology and tool allow the choice of inspection plans with lower costs and that meet the risk level accepted by the operator.

Additionally, aiming at the quality improvement of the information used as input in the optimization process, a computational tool for storing and creating subsea equipment FMECAs was also developed. Methodologies to perform the quantification of the risk associated with the equipment in operation and for quantifying the probability of detection for different combinations of failure modes and inspection techniques were also elaborated.

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025

Lastly, in future work, the proposed approach here also may allow the updating of the risk associated with the operation of subsea equipment using degradation simulation results associated with specific failure mechanisms, e.g., thickness loss by erosion and corrosion.

Acknowledgments

This paper reports part of the overall results obtained from Petrobras-sponsored research and development project entitled"Optimization of inspection, monitoring and testing processes for subsea oil and gas equipment", whose support the authors gratefully wish to acknowledge. Prof. Marcelo Martins also acknowledges his support from the Brazilian National Council for Scientific and Technological Development (CNPq) through grant 308712/2019-6.

References

1. K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Trans. Evol. Comput.*, vol. **6**, no. 2, pp. 182–197, Apr. 2002, doi: 10.1109/4235.996017.
2. M. Modarres, M. Kaminskiy, and V. Krivtsov, Reliability Engineering and Risk Analysis A Practical Guide, 2nd Edition. 2010.
3. M. C. Maturana, A. M. Schleder, P. F. F. M. Frutuoso, L. O. de Barros, and M. R. Martins, "Methodology for defining risk indices applicable to subsea equipment," in Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering - OMAE, 2022, pp. 1–8.
4. J. P. B. Cuba, M. R. Martins, A. M. Schleder, L. O. de Barros, and R. T. C. Orlowski, "Methodology to Define the Probability of Detection of Non-destructive Techniques in an Offshore Environment," in European Conference on Safety and Reliability (ESREL), 2022, pp. 1–8, doi: 10.3850/981-973-0000-00-0.
5. LabRisco, "Relatório Final - Projeto: Otimização de processos de inspeção, monitoramento e teste de equipamentos submarinos de petróleo e gás em operação.," *São Paulo*, 2022.
6. HSE, "Reducing risks, protecting people," 2001. doi: 10.1205/095758203762851994.
7. HSE, "Guidance on Risk Assessment for Offshore Installations," *HSE Inf. sheet*, no. **3**, pp. 7–31, 2006.
8. P. OREDA, T. SINTEF, Society, and G. L. DNV, *OREDA: Offshore and Onshore Reliability Data Handbook*, 6th ed., no. Volume 2-subsea equipment. OREDA Participants, 2015.
9. F. M. de Moura, M. R. Martins, and A. M. Schleder, "Application of Failure Mode, Effects and Criticality Analysis (FMECA) to Prioritize the Equipment And Components of the Subsea Christmas Tree System," in Proceedings of the 31st European Safety and Reliability Conference, 2021, pp. 3383–3390, doi: 10.3850/978-981-18-2016-8_632-cd.
10. A. S. Nicolau et al, "Component Criticality Rating of a Subsea Manifold using FMECA," in European Conference on Safety and Reliability (ESREL), 2022, pp. 1–8.
11. DoD-US, "Mil-Std-1629a: Procedures for Performing a Failure Mode, Effects and Criticality Analysis," Washington, DC, 1980.
12. C. H. B. Morais, E. Fernanda Marques de Moura, M. C. M. Abrahão, M. R. O. de B. Martins, R. T. C. L. D. R. Orlowski, and A. M. Schleder, "GENETIC ALGORITHMS APPLIED TO THE CONCEPT OF RISK BASED INSPECTION (RBI): OPTIMIZATION OF INSPECTION PLANS," 2022.

Downloaded from http://onepetro.org/OTCONF/proceedings-pdf/23OTC/23OTC/D031S037R004/3103427/otc-32464-ms.pdf/1 by Universidade De Sao Paulo user on 29 October 2025