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Inspection Optimization for Subsea Systems: A Risk and Cost Analysis of a Production Manifold

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To ensure continuity and safety in complex offshore operations, managing subsea equipment integrity is fundamental. Optimizing inspection plans is the key strategy for balancing risk control, costs, and integrity. The application of risk-based methodologies and reliability data allows for prioritizing resources on high-impact equipment, such as production manifolds, while avoiding both the over-inspection of low-priority items and the under-inspection of critical components. This paper presents the application of a methodology aimed at defining optimized inspection plans with a simultaneous focus on risk and cost. The methodology's development employed techniques, such as Preliminary Hazard Analysis (PHA), Event Tree Analysis (ETA), Fault Tree Analysis (FTA), and the Top Logical Model (TLM), as presented by Frutuoso and Melo et al. (2025). The information obtained in these stages formed the basis for the optimization phase, which was conducted using in-house software that combines Genetic Algorithms (GA) with the Risk-Based Inspection (RBI) approach. The application of the methodology generated optimized maintenance plans for a representative production manifold, simultaneously considering risk and cost criteria. For comparison, two reference inspection plans were analyzed: (i) a prescriptive plan derived from the recommendations for critical components from the NORSOK D-10 standard and (ii) a conservative plan, both used to establish risk thresholds. Furthermore, the results were benchmarked against a "typical plan" for this category of equipment, identifying alternatives capable of simultaneously reducing both risk and cost. The findings show that the proposed methodology outperforms the plan traditionally used, yielding significant efficiency gains without compromising established safety limits. Therefore, the study demonstrates the approach's potential as a decision-support tool for managing the integrity of subsea production systems, supporting the definition of more effective, economical, and sustainable maintenance strategies for the oil and gas sector.

Keywords: *Inspection Plan Optimization; Subsea Production Manifold; Risk Analysis; Integrity Management; Pareto Frontier.*

1. Introduction

The offshore industry operates in one of the harshest and most challenging environments on the planet. Subsea production systems, essential for extracting oil and gas in deep waters, comprise a vast range of complex equipment, such as Christmas Trees, Manifolds, Jumpers, Risers, and Umbilicals. These components are designed to operate continuously on the seabed, where increasing depths and technological complexities culminate in significant financial and operational pressures (Bai and Bai, 2018).

In this scenario, reliability is not just an objective but an absolute necessity. A failure in a subsea component can have catastrophic consequences, resulting in production downtime (Moreno-Trejo and Markeset, 2011), massive economic losses (Bai and Bai, 2018), and, in the worst cases, environmental accidents and fatalities, such as the Enchova Central Platform disaster that occurred in 1984 in the Campos Basin, near Rio de Janeiro, Brazil.

Although high reliability is not an inexpensive prospect, it is an indispensable investment when compared to the costs of an infield failure (Ikpe, 2019). Intervention for subsea repairs in the event of a failure is an extremely complex and costly operation, involving specialized vessels and extended periods of downtime that can cost millions of dollars. Therefore, it is imperative that systems are designed and maintained to operate for long periods, ideally (Kumar, 2016).

This is where asset integrity management becomes crucial, requiring a delicate balance between risk control and cost optimization. Maintenance, which can be corrective (after a failure) or preventive (to avoid failure), is the tool to ensure system availability (Calixto, 2016). However, the key to efficient and cost-effective maintenance, whose long-term effects can be modeled to determine the best strategy (Rausand and Høyland, 2004), lies in the quality of the information obtained through inspection.

Inspection is the data collection process that informs decision-making regarding the necessity, type, and urgency of maintenance, reducing uncertainties about a component's actual condition. An optimized inspection plan, grounded in methodologies like Risk-Based Inspection (RBI), does not mean "inspecting more," but rather "inspecting smarter." It focuses resources on the most critical equipment and the most probable failure modes — such as mechanical failures, cited as the most frequent in subsea production systems (Okaro, 2017), increasing the likelihood of detecting problems in their early stages.

The relationship is direct and impactful: an optimized inspection plan leads to a greater chance of early detection failure. Detecting an incipient defect allows maintenance to be planned and proactive, which is exponentially cheaper than emergency corrective maintenance. The repair of a small crack, for example, is vastly more economical than replacing a ruptured pipe section, in addition to avoiding secondary costs such as damage to adjacent equipment, production losses, and environmental and safety impacts.

Additionally, planning an intervention based on inspection data creates a window of opportunity to perform other inspections and preventive maintenance on nearby equipment. This synergy maximizes the return on the extremely high cost of mobilizing offshore resources, addressing multiple problems in a single operation and ensuring system reliability for an extended period. Thus, the optimization of inspection plans is the foundation of a predictive and risk-based maintenance strategy, proving fundamental to ensuring the safety, operational continuity, and economic viability of operations in the offshore industry.

1.1. *Objectives and Scope of the Study*

In this context, the objective of this study is to present the optimization results for inspection plans of a reference Subsea production Manifold, simultaneously weighing risk and cost factors. To this end, this article details the results obtained by applying an internal software that combines Genetic Algorithms (GA) with the Risk-Based Inspection (RBI) approach (LABRISCO, 2025), comparing the risk and cost indicators obtained with this new methodology against the approach traditionally adopted by operators in the oil extraction sector.

2. Background and Conceptual Framework

RBI analysis is a method applied to define the optimal maintenance strategy throughout the life cycle of subsea equipment (Calixto, 2016). Unlike risk and availability analysis, RBI not only identifies the main failure reliability and availability. These plans result in cost-effective inspection programs, considering both threats and opportunities, ensuring the integrity of subsea systems by preventing and minimizing failures (Ikpe, 2019).

2.1. *Reference Subsea Production Manifold*

The subsea equipment that originated this work was the manifold in production operation mode, referred to in this paper as the "Production Manifold." This system is considered a critical component within the offshore oil and gas extraction infrastructure, serving the primary function of collecting and consolidating production from multiple subsea wells. Through an integrated pipeline network, it directs the extracted flows to processing units such as fixed platforms or Floating Production, Storage and Offloading (FPSO) units.

Its operational performance is enabled by a sophisticated set of valves and control devices, which allow for the regulation of production flow, fluid separation, flow rate measurement, and chemical injection, ensuring the system's efficiency and safety (Bai and Bai, 2018).

Figure 1 graphically represents a typical arrangement of a Production Manifold, illustrating the operational flow indicated by arrows. The results presented herein were based on this reference model, through which failure modeling was carried out and, consequently, the risk-based inspection plan optimization process was applied — the outcomes of which are presented in this paper.

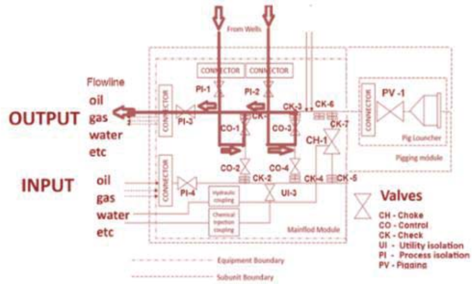

Fig. 1. Manifold Production Diagram in operating mode with representation of valve identification and classification flow.

2.2. *Overview of the Applied Methodology*

As a continuation of the methodology established and presented by Frutuoso and Melo et al. (2025), which sequentially and complementarily employed methodologies such as Preliminary Hazard Analysis (PHA), Event Tree Analysis (ETA), Fault Tree Analysis (FTA), and the Top Logical Model (TLM), the failure modeling results obtained through this approach served as the basis for the optimization process—and for the results derived from this process—presented in this paper within the context of the proposed objective. The risk quantification was performed following the approach proposed by Maturana et al. (2024) in which the risk is calculated based on the aggregation of damage frequencies and associated consequences. Subsequently, the optimization process was carried out in accordance with the methodology proposed by Rossi et al. (2023) enabling the systematic exploration of inspection plans under risk and resource constraints.

3. Application and Simulation Setup

The optimization process was carried out using input data derived from the failure modeling of the Production Manifold, reference inspection plans, and comparative plans in the GA.

3.1. *Input Data and Boundary Conditions*

The modeling presented in Frutuoso et al. (2025) generated initiating events that defined the risk priority analysis. Table 1 shows the main initiating events identified.

Table 1. Initiator events with identified barriers

AE	INITIATING EVENTS
MANO01	Loss of containment in the section between the connector and the flowline
MANO02	Loss of Containment in the section between Valve PI-3 and CO-1 and CO-3
MANO03	Loss of containment in the section between valves CO1 and PI-1
MANO04	Loss of containment in the section between valves CO-3 and PI-2
MANO05	Spurious closure of the PI-3 valve
MANO06	Spurious closure of valves (PI-1 and PI-2) or (CO-1 and CO-3) or (PI-1 and CO-3) or (PI-2 and CO-1)
MANO07	Clogging of the piping in the section between Valves PI-3 and CO-1 and CO-3
MANO08	Loss of containment in the pipelines before valves PI-1 and PI-2
MANO09	Loss of containment in at least one of the PI-1 and PI-2 valves
MANO10	Loss of insulation in the manifold inlet connectors
MANO11	Loss of containment in the pipes leading to the manifold inlet connectors
MANO12	Manifold Protective Structure Failure - Structural Deficiency

Once the TLM was developed, the next step consisted of the quantification and analysis of risk and the determination of point risk, with the generation of so-called minimal cut sets in the Probabilistic Safety Analysis (PSA), totaling 4,845 cut sets generated from the TLM.

The first processing step was then initiated with the possible consequence values represented in the cut sets. These values are considered indicators of the severity of the consequences associated with the sequences of events described in each cut set, providing a quantitative basis for evaluating the impact of failure scenarios. It is important to note that these consequence values are not universal and should not be interpreted as fixed or transferable between different applications. Instead, the definition of consequence categories and their corresponding values should follow applicable sector-specific standards, when available, or be established in accordance with the policies, risk acceptance criteria, and decision-making framework of the organization. In this study, the following severity values for consequences were adopted (Catastrophic; Critical; Average; Marginal; Despicable): Catastrophic (IV) = 30; Critical (IV) = 7; Average (III) = 1; Marginal (II) = 0.5; Despicable (I) = 0.

From these cut sets, data on inspection costs, inspection opportunity periods (in months), failure consequences, barriers and detection probabilities were considered. With this information, it was possible to begin the optimization process.

3.2. *Reference Inspection Plans*

For the analysis of results, two inspection plans were considered: one based on the NORSOK D-10 standard (NORSOK, 1998) and another adopting a conservative approach, both used to define the risk levels (Tolerable, Moderate, and Non-Tolerable), a plan considered typical for the equipment by the experts consulted (confidential company). It is important to emphasize that, in this case study, these risk tolerability limits were defined solely for illustrative purposes. In practical applications, tolerability thresholds should be established by the organization, taking into account its risk management policy, regulatory requirements, and decision-making criteria. In the reference plan based on NORSOK, applied to the Manifold, visual inspections were scheduled every 36 months throughout the entire service life of the equipment. In the Conservative plan, also applied to the Manifold, visual inspections were scheduled every 6 months throughout the equipment's service life, in addition to electrochemical potential measurements and ultrasonic testing every 6 months during the same period.

3.3. *Optimization Scenarios and Execution*

By applying the NORSOK plan to the reference model of the Manifold, a maximum risk index of 1.9591E-3 was obtained. This value was used as the upper limit of the Moderate range, establishing the "Moderate-Non-Tolerable" interface threshold for classifying the risk as "Non-Tolerable." The total cost associated with this plan was US$ 950,250.

For the Conservative Plan, the maximum observed risk index was 1.779E-3 and the minimum was 1.2093E-4. The latter was adopted as the lower limit of the Moderate risk range, establishing the "Tolerable–Moderate" interface threshold. The total accumulated cost associated with the implementation of this plan over 360 months was US$ 12,578,500.

The solutions obtained through the optimization process were compared with the "Typical Plan," as well as with the established risk limits described in the previous paragraphs. For the Manifold reference model, the Typical Plan also includes visual inspections, electrochemical potential measurements, and ultrasonic testing, scheduled every 36 months throughout the equipment's service life. The maximum risk index associated with this plan is 1.9472E-3, and the total accumulated cost is US$ 2,096,417. Figure 2 shows the variation of the risk index over 360 months for this plan.

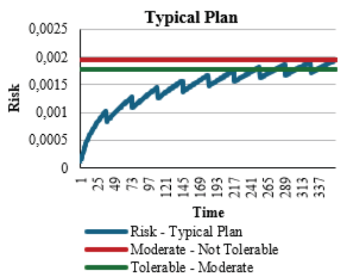

Fig. 2. Evolution of point risk over time for the Manifold under study by the Typical Plan.

In the graph, two reference lines can be observed: "Moderate-Non-Tolerable" and "Tolerable-Moderate," which visually delimit the risk ranges, defining the region corresponding to Moderate risk over a one-year period.

It can also be noted that, up to period 241, the risk remains within the range corresponding to Tolerable risk, below the "Tolerable-Moderate" threshold. The Typical Plan then reaches exactly the upper limit of the "Tolerable-Moderate" range, subsequently operating beyond the Tolerable limit and entering the Moderate risk range, where it remains until period 349, when it reaches the upper limit of the "Moderate-Non-Tolerable" range.

Finally, Table 2 presents a summary of the reference plans used for the analysis of the case studies involving the Production Manifold.

Table 2. Norsok Plan, Conservative Plan, and Typical Plan for the Production Manifold

NORSOK PLAN	CONSERVATIVE PLAN	TYPICAL PLAN
Visual inspections every 36 months throughout the equipment's useful life.	Visual inspections every 6 months throughout the equipment's useful life.	Visual inspections every 36 months throughout the equipment's useful life.
-	Electrochemical potential measurements every 6 months throughout the equipment's useful life.	Electrochemical potential measurements every 36 months throughout the equipment's service life.
-	Ultrasound testing every 6 months throughout the equipment's useful life.	Ultrasound testing every 36 months throughout the equipment's service life.

For analysis purposes, the inspection solutions whose costs and risks were lower than those of the Typical Plan are presented.

In the optimization scenario with monthly inspection opportunities and no restrictions on the interval between them, 71 optimal solutions belonging to the Pareto frontier were obtained; that is, 71 distinct inspection plans. For comparison purposes, the Typical Plan was adopted as a reference, considering the criteria of maximum risk and total cost. Among these 71 solutions, 26 showed both lower maximum risk and lower total cost compared to the Typical Plan. For example, 5 of these solutions are organized in Table 3, ordered from the lowest to the highest maximum risk value.

Table 3. Norsok and Conservative Plan Solutions with lower risk index and total cost than the Typical Plan

SOLUTION	COSTS (US$)	MAXIMUM RISK	Δ% RISK	Δ% COST
8066	2074027,027	1,77E-03	-9,21%	-1,07%
8774	1991310,526	1,77E-03	-8,91%	-5,01%
12139	1679638,86	1,78E-03	-8,73%	-19,88%
9836	1673139,833	1,78E-03	-8,65%	-20,19%
7143	1667424,792	1,78E-03	-8,64%	-20,46%

Based on these solutions, a graph representing the Pareto frontier was generated using the GA, plotting the risk index versus the total cost, as shown in Figure 3.

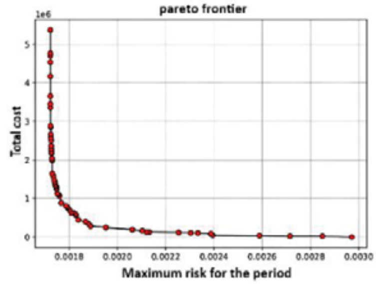

Fig. 3. Pareto frontier graph generated by GA as a result of the optimization process of inspection plans.

Figure 4 presents a comparison between the NORSOK, Conservative, and Typical plans and three optimal solutions generated by the GA, selected based on risk and cost criteria from among all the identified solutions.

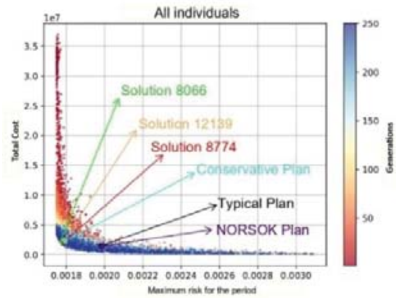

Fig. 4. Graph showing the convergence of genetic algorithm solutions across generations for Manifold.

4. Results and Discussion

In this section, three representative solutions obtained from the optimization process are compared with the typical inspection plan and discussed in detail in order to illustrate the potential and practical implications of the proposed methodology.

4.1. *Comparative Analysis of Plans*

Solution 8066 presented a maximum risk index of 1.77E-03, which is 9.21% lower than that of the Typical Plan, and a total cost of US$ 2,074,027.03; that is, 1.07% lower than the cost of the Typical Plan. Table 4 presents the inspection plan associated with this solution.

Table 4. Inspection Plan Solution 8066 - Manifold

Period	Description
12	Visual inspection
16	Visual inspection
100	Electrochemical potential measurement + Ultrasound
147	Electrochemical potential measurement + Ultrasound
160	Visual inspection
178	Visual inspection
179	Ultrasound
200	Visual inspection
225	Ultrasound
236	Visual Inspection + Electrochemical Potential Measurement
250	Visual inspection
269	Ultrasound
270	Electrochemical potential measurement + Ultrasound
282	Visual inspection
293	Electrochemical potential measurement + Ultrasound
303	Visual inspection
304	Visual inspection
309	Visual Inspection + Electrochemical Potential Measurement
320	Electrochemical potential measurement + Ultrasound
324	Ultrasound
325	Ultrasound
327	Visual inspection
332	Ultrasound
335	Electrochemical potential measurement + Ultrasound
339	Visual inspection
341	Visual Inspection + Electrochemical potential measurement
346	Visual inspection
349	Visual inspection + Electrochemical potential measurement + Ultrasound
353	Visual Inspection + Ultrasound
354	Electrochemical potential measurement + Ultrasound
355	Electrochemical potential measurement + Ultrasound
357	Electrochemical potential measurement + Ultrasound

Figure 5 presents the graph showing the evolution of the risk index over time for Solution 8066. It can be observed that this solution remains below the “Moderate-Non-Tolerable” and “Tolerable-Moderate” limits previously established (see section 3.3) approaching the “Tolerable-Moderate” limit in some periods but never exceeding it.

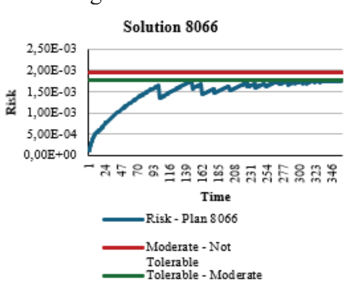

Fig. 5. Evolution of point-in-time risk over time for the solution 8066

Solution 8774 presented a maximum risk index also of 1.77E-03, which is 8.21% lower than that of the Typical Plan, and a total cost of US$ 1,991,310.53; a cost that is 5.01% lower than the Typical Plan. Table 5 presents the inspection plan associated with this solution.

Table 5. Inspection Plan Solution 8774

Period	Description
12	Visual inspection
16	Visual inspection
23	Visual inspection
47	Visual inspection
87	Visual inspection
100	Electrochemical potential measurement + Ultrasound
160	Visual inspection
177	Electrochemical potential measurement + Ultrasound
179	Ultrasound
200	Visual inspection
225	Ultrasound
236	Visual Inspection + Electrochemical Potential Measurement
250	Visual inspection
269	Ultrasound
270	Electrochemical potential measurement + Ultrasound
282	Visual inspection
293	Electrochemical potential measurement + Ultrasound
303	Visual inspection
304	Visual inspection
309	Visual Inspection + Electrochemical Potential Measurement
320	Electrochemical potential measurement + Ultrasound
327	Visual inspection
332	Ultrasound
339	Visual inspection
341	Visual Inspection + Electrochemical Potential Measurement
346	Visual inspection
349	Visual inspection + Electrochemical potential measurement + Ultrasound
354	Electrochemical potential measurement + Ultrasound
357	Electrochemical potential measurement + Ultrasound

Figure 6 presents the graph showing the evolution of the risk index over time for Solution 8774. It can be observed that this solution also remains below the “Moderate–Non-Tolerable” and “Tolerable-Moderate” limits. Similar to the previous solution, Solution 8774 approaches the “Tolerable-Moderate” limit in some periods but does not exceed it.

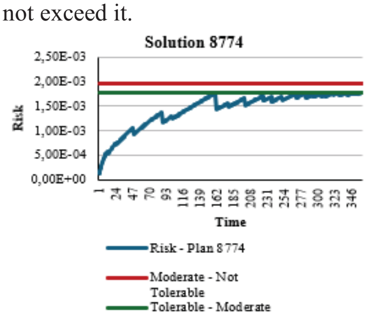

Fig. 6 - Evolution of point risk over time for solution 8774

Finally, Solution 12139 presented a maximum risk index of 1.78E-03, which is 8.73% lower than that of the Typical Plan, and a total cost of US$ 1,679,638.86, which is 19.9% lower than the cost of the Typical Plan. Table 6 presents the inspection plan associated with this solution.

Table 6. Inspection Plan Solution 12139

Period	Description
41	Visual Inspection + Ultrasound
100	Electrochemical potential measurement + Ultrasound
147	Electrochemical potential measurement + Ultrasound
155	Visual inspection
164	Visual inspection
200	Visual inspection
225	Ultrasound
236	Visual Inspection + Electrochemical Potential Measurement
250	Visual inspection
269	Ultrasound
282	Visual inspection
294	Visual inspection
309	Visual Inspection + Electrochemical Potential Measurement
315	Electrochemical potential measurement + Ultrasound
322	Visual inspection
325	Ultrasound
327	Visual inspection
332	Ultrasound
339	Visual inspection
341	Visual Inspection + Electrochemical Potential Measurement
348	Electrochemical potential measurement + Ultrasound
349	Visual inspection + Electrochemical potential measurement + Ultrasound
353	Visual Inspection + Ultrasound

Figure 7 presents the graph showing the evolution of the risk index over time for Solution 12139. As Solutions 8066 and 8774, this solution also remains below the 'Moderate–Non-Tolerable' and 'Tolerable–Moderate' limits, approaching the 'Tolerable–Moderate' limit in some periods but never exceeding it. It is worth noting that, for this study, no minimum interval between inspections was imposed in order to allow the genetic algorithm to more freely explore the solution space. Consequently, some inspection plans may be less practical from an operational standpoint. However, these plans can be subsequently adjusted by introducing practical constraints, and the associated risk can be recalculated to ensure that the resulting inspection strategies remain feasible while preserving acceptable risk levels.

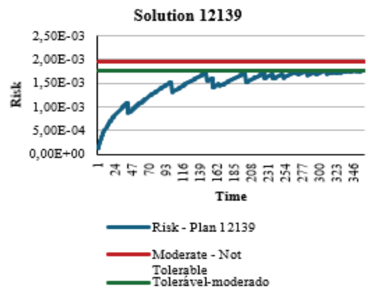

Fig. 7. Evolution of point risk over time for solution 12139

4.2. *Efficiency Gains and Sensitivity Analysis - Implications for Integrity Management*

The optimization results show significant gains in risk reduction and cost efficiency compared to the operator's Typical Plan. All three optimized solutions (8066, 8774, and 12139) maintained risk indices below the established safety thresholds, ensuring acceptable risk levels while achieving substantial cost savings.

Solution 8066 showed the lowest maximum risk index (1.77E–03), corresponding to a 9.21% reduction compared to the Typical Plan, with a total cost of USD 2,074,027.03; equivalent to 1.07% of the reference cost. Solution 8774 presented the same maximum risk index (1.77E–03), with a 5.01% cost reduction compared to the Typical Plan, totaling USD 1,991,310.53. Finally, Solution 12139, although exhibiting a slightly higher maximum risk index (1.78E–03), achieved the largest cost reduction of 19.9%, totaling USD 1,679,638.86.

The evolution of the point risk indices (Figures 5–7) indicates that all solutions maintain risk levels within acceptable limits throughout the analysis period. The graphical trends show that, although the risk curves of the optimized plans approach the "Tolerable-Moderate" limit at certain intervals, none of them exceed it, confirming that the safety constraints are effectively respected within the optimization process.

From a sensitivity perspective, the comparative analysis among the optimized solutions highlights the balance between cost efficiency and risk minimization. Solution 8066 stands out as the most conservative configuration, prioritizing risk reduction even with a slightly higher total cost. In contrast, Solution 12139 demonstrates that it is possible to achieve a significant cost reduction without exceeding the defined safety limits, making it a strategically attractive alternative for integrity managers seeking to balance economic performance with reliability assurance.

These results demonstrate that integrating Genetic Algorithms into the Risk-Based Inspection (RBI) framework enables the efficient identification of inspection strategies that maximize risk reduction per unit cost. This approach supports a shift toward data-driven, risk-based decision-making, enhancing the robustness, reliability, and cost efficiency of subsea integrity management in offshore production systems.

5. Conclusions

This study demonstrated the effectiveness of an integrated optimization methodology combining Risk-Based Inspection (RBI) principles and Genetic Algorithms for subsea integrity management. The proposed approach generated optimized inspection plans for a representative production manifold, achieving simultaneous reductions in risk and cost compared to traditional industry practices.

All optimized solutions maintained risk levels within acceptable safety limits, with the best-performing plan reducing maximum risk by up to 9.21% and total inspection cost by 19.9% relative to the operator's Typical Plan. These results confirm that significant efficiency gains can be achieved without compromising safety.

Overall, the integration of risk analysis, RBI, and optimization algorithms provides a flexible and robust decision-support tool, enabling the selection of inspection strategies aligned with operator risk tolerance and budget constraints, and supporting safer and more cost-effective subsea asset management in the oil and gas industry.

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