Safety Science 177 (2024) 106570



Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety





A decision support system to assess the operational safety and economic benefits of risk-based inspection implementation strategies

Eugenio Oropallo [a,*], Paolo Piscopo [b], Piera Centobelli [c], Roberto Cerchione [d], Eduardo Nuevo [e], Alvaro Rodríguez-Prieto [f]

[a] Department of Computer, Control and Management Engineering, Sapienza University of Rome, Via Ariosto, 25 – 00185 Rome, Italy
[b] MBDA ITALIA, Via Monte Flavio, 45, 00131 Roma, Italy
[c] Department of Industrial Engineering, University of Naples Federico II, P.le Tecchio 80, 80125 Naples, Italy
[d] Department of Engineering, University of Naples Parthenope, Centro Direzionale di Napoli Isola C4, 80143 Naples, taly
[e] Department of Industrial Inspection and Technical Assistance, SGS Tecnos, 28042 Madrid, Spain
[f] Department of Manufacturing Engineering, Universidad Nacional de Educación a Distancia (UNED), 28040 Madrid, Spain

A B S T R A C T

The modern industrial landscape is defined by increased competition, shorter response times, lower costs, and more reliable processing to meet customer demands. As a result, it has gained traction worldwide, and the necessity to undergo radical digital transformations in how they deal with processes. Specifically, it is receiving great relevance to the construction of specific decision support systems (DSSs) to help monitor industrial systems with a data-driven analytic approach, aiming to maximise reliability and efficiency. Maintenance is one of the most investigated processes based on risk-driven inspection.

The Risk-Based Inspection (RBI) procedure, widely consolidated in the scientific field thanks to the publication of the API RP 581 manual of the American Petroleum Institute, is one of the most used procedures in the oil and gas sector to carry out risk assessments of the integrity of industrial components. It forms the basis for developing inspection plans within which the components to be inspected are prioritised based on the associated risk of failure.

The use of non-intrusive inspection methodologies, based on non-destructive testing techniques, is incorporated into the assessment as an alternative to other traditional inspection strategies based on direct inspection. These techniques may help to reduce the number of scheduled plant shutdowns and the associated cost due to production loss.

This research aims to develop a decision support system (DSS) based on the guidelines of the RBI procedure that is easy to use and open to access to support decisions in a cost-benefit analysis of the maintenance process.

The system was developed focusing on a real plant, assessing the operational and financial risk of the shell and tube heat exchanger. The data used to implement the procedure in the system were provided by the company SGS specialised in industrial components' certification and inspection.

The current assessment has been performed for the damage mechanisms that affect the considered equipment: thinning, external corrosion, and CUI. All of the referred damage mechanisms are corrosion-based. None of the other multiple damage mechanisms that could affect the industrial equipment has been considered in this work.

1. Introduction

Nowadays, many industries face complex challenges in order to optimise the operations and functionalities of their plants in a highly dynamic supply chain and market demand environment (Arena et al., 2022). Consequently, even maintenance functions must find a new dimension driven by the continuous growth of global competitiveness (Di Nardo et al., 2021; Velmurugan & Dhingra, 2015). The importance of plant assets maintenance is inextricably linked to the concern of the organisation's overall quality and resulting profitability, which are vital to the organisation's operations (Lee et al., 2023).

The oil and gas sector is one of the most sensitive to maintenance, since it leads the world-wide energy supply (Yang et al., 2009). Besides, this industry is a highly competitive sector where the world's leading companies compete against each other by focusing on technological innovation and process optimisation (Antomarioni et al., 2022; Sharma et al., 2015). A complex risk framework needs to be appropriately managed to ensure the success of an oil and gas project. Currently, there is a greater awareness of the need to assess the risk related to the safety of personnel (including company employees and community), the

* Corresponding author.
E-mail addresses: eugenio.oropallo@uniroma1.it (E. Oropallo), piscopo.paolo.97@gmail.com (P. Piscopo), piera.centobelli@unina.it (P. Centobelli), roberto.cerchione@uniparthenope.it (R. Cerchione), eduardo.nuevocalle@sgs.com (E. Nuevo), alvaro.rodriguez@ind.uned.es (A. Rodríguez-Prieto).

https://doi.org/10.1016/j.ssci.2024.106570
Received 5 October 2023; Received in revised form 10 January 2024; Accepted 29 May 2024
Available online 9 June 2024
0925-7535/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

business interruption and the environmental damage; however, industries focus mainly on risk assessment limited to on-site plant safety, since it is there where the hazard starts (Rawat et al., 2022). Managers can consider risks when deciding when, where, and how to inspect and assess equipment used for business (Adedipe et al., 2020; Keers & van Fenema, 2018). Hence, this industrial reality pays great attention to the plants' maintainability, reliability, and safety principles.

To reduce the amount and frequency of maintenance costs and improve maintenance practices, various analysis techniques are used to assess the risk and damage to equipment (ISO 14224, 1999). The reliability of equipment and systems is currently one of the main business strategies to improve an organisation's market position and achieve and maintain a competitive advantage (Mohammed, 2023). On the other hand, failure of equipment and systems can be highly costly for companies (Lees, 1996).

Selection of an appropriate approach is crucial in maintenance, and the connected outputs are difficult to assess (Chris & Wang, 2001). Traditionally, a maintenance strategy must be balanced to maximise equipment uptime and facility performance, while requiring the least resources and costs. In short, the maintenance strategy should be selected appropriately to improve the competitiveness of the production (Velmurugan & Dhingra, 2015). Three leading maintenance strategies are failure maintenance, preventive maintenance, and predictive maintenance.

Failure maintenance is the most straightforward maintenance strategy to implement, where the equipment can operate until it fails and, consequently, is repaired or replaced. Preventive maintenance is widely used in manufacturing, where equipment is checked, properly repaired, and renewed regularly to avoid unplanned downtime. Predictive maintenance uses sensors to monitor the condition of manufacturing assets. (Ramotsoela et al., 2018; Tamilselvan & Wang, 2013). Such data are often used to establish an alarm system to detect any abnormal behaviour and ensure regular and continuous operation (Joung et al., 2020). Other maintenance strategies, such as opportunistic and corrective maintenance, can be adopted to maximise the availability of manufacturing systems (Sellitto, 2020).

Time or risk can be assumed as reference variables for the strategy to verify the condition of the assets. A time-based inspection (TBI) strategy establishes the inspection frequency in fixed time intervals, depending on the characteristics, for instance, of the equipment, the process fluid. Instead, a risk-based inspection (RBI) strategy defines an inspection plan in such a way that the maximum risk is always kept below a threshold level (risk target). RBI evaluation is based on the examination of the equipment and associated damage mechanisms. As a result, RBI connects the mechanisms that cause equipment failure to the inspection strategy that effectively reduces the associated risks.

The classic TBI strategy has been generally overcome, and through a more robust comprehension of the causes of degradation, the focus has moved to the conditions of the items, reinforcing a RBI approach (API RP 581, 2016). In contrast to the TBI strategy, which considers parameters mainly related to the consequence of failure, RBI allows scoring inspection and maintenance activities by evaluating both the likelihood of failures and their consequences, and identifying high-risk items (Arena et al., 2022).

Furthermore, according to API RP(2016), the RBI methodology takes into account the type of inspection is designed considering the specifically identified damage mechanisms and the level of inspection effectiveness is adjusted based on the calculated probability. Therefore, it significantly improves the condition-based approach (API RP 581, 2016). As a result, inspection and resources are mostly focused on the highest risk items, and downtime and shutdowns can be reduced at the minimum to keep the risk under control, allowing longer periods of continuous operation.

In shifting towards a predictive RBI type, the plant's performance certainly increases, but also the costs and resources associated with them, sometimes considerably (Lee et al., 2023). For this reason, since predictive maintenance is the most desired strategy for plant management, the cost becomes as crucial as the benefit that this type of maintenance induces then before (Saleh et al., 2023).

Maintenance expense has continuously risen over the past decades: depending on the industry, the proportion of production expenses related to maintenance duties ranges from 15 % to 70 %. (Ilangkumaran & Kumanan, 2012). Besides, it has been established that about one-third of the maintenance, expenditures are wasted due to the uncertainties and inefficiencies associated with the lack of knowledge of the wear state or the improper use of the received data (Mobley, 2002).

This phenomenon is also connected to the changing maintenance purpose. In fact, the scope of plant maintenance is not only to keep working any equipment or item to prevent disruptions in plant activities (Al-Najjar et al., 2001; Henriques & Sadorsky, 1999) but also to ensure efficient and quality production, equipment availability, worker well-being and environmental safety (Al-Najjar et al., 2001; Bennett, 2006; Hussain et al., 2023; Joung et al., 2020).

Therefore, maintenance management cannot be seen as a punctual or a short-term activity but necessarily needs medium-long-term strategic objectives from a risk management perspective in order to ensure operational, economic, environmental and social continuity of the plants (Bokrantz & Skoogh, 2023; Duffuaa et al., 2002).

Since the heterogeneous nature of the necessary information for the correct management of the maintenance phase and its dependence on a large number of people and processes, it emerges the need for a cutting-edge decision support system (DSS) aimed to collect all this information and give a global and complete idea of the state of maintenance of the systems: in order to allow choosing the best possible solutions (Liang et al., 2023) not only in the company interest but also for the benefit of people and environment (Peron et al., 2022).

With this premise, the objective of this research is to develop and make available a DSS based on the guidelines of the RBI procedure that is easy to use and open to access focusing in the field of the oil and gas industry and specifically in the middle field phases of process and storage that results to be the more complex and item-rich of the entire stream. Besides, a comparison between different RBI strategies and a TBI approach will be tested to validate different solutions for the case study examined.

The assessment has been performed on a shell and tube heat exchanger, based on the data provided by the company SGS specialised in industrial components' certification and inspection. The referred equipment is affected by the following damage mechanisms: thinning, external corrosion, and corrosion under insulation (CUI). Therefore, the analysis has been performed only for those damage mechanisms. All of the considered damage mechanisms are corrosion-based. Moreover. The damage mechanisms that have been assessed are considered to be some of the most typically found in the industry. However, many other multiple damage mechanisms could affect the industrial equipment and that are caused due to other types of corrosion, cracking, erosion, temperature, stress, and/or combinations of various of those factors (such as stress corrosion cracking, corrosion-erosion). None of these damage mechanisms has been considered in this work.

Therefore, the current study is proposed as an introduction and could be expanded to other possible scenarios, including additional or other damage mechanisms.

The paper is organized as follows: section 2 provides an overview of the research topic of maintenance in the oil and gas sector (with a focus on RBI approach) and the decision-support systems approach that is used; section 3 clarifies the detail about the methodology used and the main results obtained, and the conclusion can be found in section 4 there is, limitations and future research directions.

2. Materials and methods

2.1. Decision support systems (DSS)

To implement the RBI analysis and understand its benefits, this research uses a DSS approach to investigate the results of an RBI approach versus the TBI approach and support decision-makers in choosing methodologies and parameters that optimise the maintenance process and the risk level. The case study is focused on a relevant equipment, such as a shell and tube exchanger as a part of an industrial ethylene production plant.

Generally, a DSS is a software system that makes available to the user (i.e. the decision-maker) a series of functionalities of data analysis and the use of models interactively and straightforwardly to increase the efficiency and effectiveness of the decisional process (Marsden & Pingry, 1993).

Several DSSs have been developed for specific applications in various domains, such as farming activities (Fuchigami et al., 2021), portfolio investment construction and selection (Xidonas et al., 2011), waste disposal selection (Demesouka et al., 2019), energy planning with uncertainty (Moret et al., 2020), and supplier selection (Kellner et al., 2019). Burstein and Holsapple (2008) extensively cover the theoretical background, design principles, historical and latest development, and practical implementations of DSSs classifying them in various ways (Smedberg & Bandaru, 2023).

Essential aspects of a DSS are the ease of use and flexibility of the user interface, the interactive environment, effectiveness in using models and analysing data of interest and the possibility for the system to become an integral part of the decision-making process (Marsden & Pingry, 1993).

Very often, it is not only the intuition or the decision-makers' ability that determines the development or survival of a company but the speed with which a decision is made and, therefore, the reduction of the problem-action gap. What is required from a DSS is the ability to consolidate information, produce reports or forecast data, and allow simulations, all flexibly and simply (Centobelli et al., 2017).

The concepts described so far can be simplified and summarised in Fig. 1. During the operating phases, a data interchange occurs between operators, users, and devices within the organisation. A portion of this data has the potential to be integrated into a database that functions as a comprehensive repository for the DSS. The DSS is capable of generating output data that enables managers to make informed decisions within the specific environment for which the DSS was created. This capability is achieved by a prioritisation model that considers the limits imposed by corporate strategies.

In general, monitoring the integrity of industrial assets based on fixed inspection frequencies could result economically unproductive, as the condition of the assets which is verified during the inspection is not taken as an input to define the inspection plan. This could result in an unnecessary high inspection frequency, which would carry to excessive downtime. In addition, it would result in sweeping inspection plans on all components rather than prioritisation plans for the components to be inspected.

A risk-based decision support system is a tool that allows a decision-maker to identify the factors that influence failures on specific segments and analyse their effects by determining the likelihood of these risk factors occurring (Berardi et al., 2008). The severity of the fault is determined through the analysis of the consequences. From this, the impact of a failure caused by each risk factor can be established in terms of cost, and the cumulative effect of failure is determined through probability analysis. The model can optimise the cost of inspection and maintenance operations (Dey, 2004).

Risk-based decision support systems can significantly reduce the time required to assess the integrity of the assets, because the estimated risk allows the decision-maker to quickly establish the required inspection effectiveness to be applied for every identified damage mechanism (Bousdekis et al., 2019). Therefore, these tools can determine an added value not only in the inspection plans but also in the maintenance plans that derive from them as the risk-based DSSs by providing helpful information on the health status of the components, allowing to identify which ones are the components to be inspected that do not meet the risk target desired by the managers. This process enables building maintenance plans aimed at the integrity of the priority assets without having to inspect all the components, as the decision-maker has information on the risk of breakage of the components released by the system that can discriminate which are the components that do not require maintenance as they fall within the desired risk (Riis et al., 1995). The above are the main reasons why the development of this system has been undertaken, which will be described in the following.

2.2. Maintenance procedures in the oil and gas plants

Over history, oil and gas companies have begun to scale up their gas facilities with exploration and production activities to meet the growing demand for a growing industrial base and the integrity of the assets of these facilities had historically been achieved through a TBI approach (Giridhar Kumar et al., 2020). However, the TBI involves three main implications:

- It is necessary to inspect all the equipment; therefore, the resources used are enormous if the number of items is high;
- The costs related to the inspections are high, as it also inspects a potentially intact asset that does not show significant degradation states;

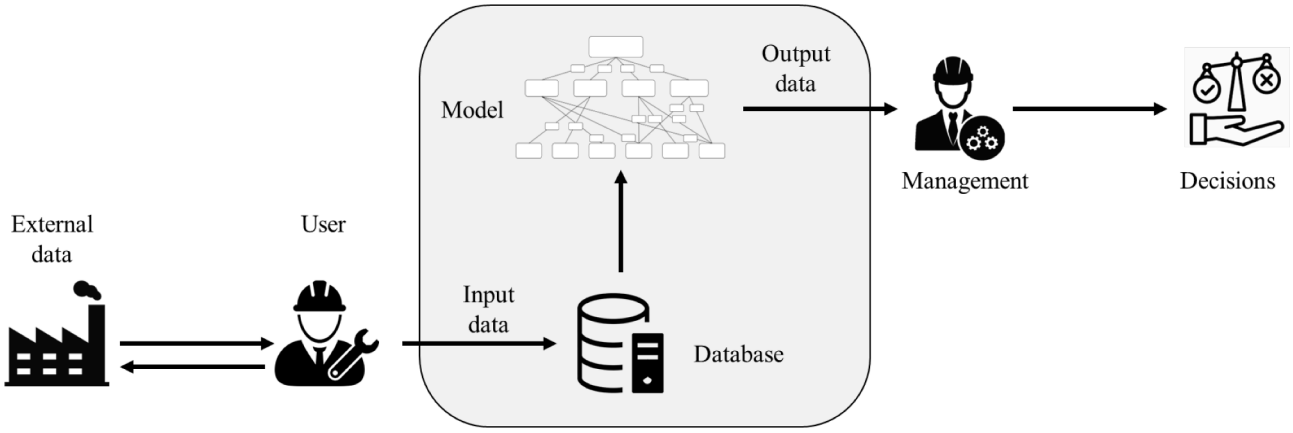


Fig. 1. General DDS Flow Chart.

- This approach determines the systematic shut-down of all equipment, even the intact ones; consequently, the costs related to production losses tend to rise.

While this type of inspection has allowed oil and gas companies to maintain equipment integrity in compliance with corporate standards and objectives, this model has gone into crisis over time, as equipment to be inspected within a plant has increased to excess. As a result, the oil and gas industry has constantly felt the urgent need to optimise its inspection approach (Rodríguez-Prieto et al., 2020).

Nevertheless, most operating companies are aware of RBI: it represents a fundamental step as it allows to evaluate the integrity of the assets within an industrial plant and consequently allows it to go and prioritise the inspection and maintenance interventions based on the probability of failure and the consequence of failure associated with the components (Arena et al., 2022). It could result in a reduction of the needed inspection time and the number of assets to be inspected, which would decrease the resources that would be needed (Bertolini et al., 2009; Straub & Faber, 2005). Moreover, it also could allow expanding the inspection intervals, reducing production downtime and related losses (Bertolini et al., 2009; Straub & Faber, 2005). However, reservations about transitioning from a TBI to an RBI approach exist yet. Using the particularly challenging but successful transition from a TBI approach to an RBI approach in the plant, the following four main benefits realised by the RBI implementation could be outlined (Al-Shdifat et al., 2020; Bhatia et al., 2019; Khan et al., 2019; Shafiee & Adedipe, 2023):

- Extended inspection intervals
- Reduced inspection scope / increased plant availability;
- Greater operational awareness;
- Optimised inspections and maintenance costs;

As stated in API RP 581 Best Practice, *"The primary work products of the RBI Assessment and Management approach are plans that address ways to manage risk at the individual equipment level"* (API RP 581, 2016). In addition to risk reduction and an overall improved security environment, RBI plans can lead to cost reductions by helping to identify equipment that does not require inspection or requires minimal inspection (Bokrantz et al., 2020). Therefore, inspection and maintenance activities can be more cost-effective and provide enough space for efficient planning and scheduling (Giridhar Kumar et al., 2020; Liang et al., 2023). This results in a significant reduction in the number of inspections performed.

By focusing on risk control, RBI provides a better link between the damage mechanisms that may lead to the equipment failure mode (e.g. loss of containment) and inspection approaches that effectively reduce associated risks. Statistically, a significant percentage of the risk is usually associated with a small portion of the equipment in any operational facility. Adopting an RBI methodology for planning inspection activities allows the inspection/maintenance department to provide higher coverage on high-risk items and adequate effort on low-risk equipment (Bhatia et al., 2019). Besides, safely extending a facility's lifespan and reducing downtime due to a turnaround directly increase plant availability, and the significant improvement in resource availability is another positive effect of implementing RBI (Bertolini et al., 2009; Krishnasamy et al., 2005).

Cost reduction is not the primary goal that promotes the implementation of a RBI approach, but it certainly can generate cost optimisation as a side effect of cost reallocation (Han et al., 2019; Shafiee & Adedipe, 2023). A RBI program justifies the ineffective, unnecessary, or inadequate inspection techniques. According to the damage mechanism, intrusive inspections can be replaced in some cases with online or non-intrusive inspections that do not require equipment shutdown. RBI also provides a basis for reducing or eliminating inspection in low-risk equipment (those below the risk target). Finally, a combination of more specific inspections, in terms of used inspection techniques and effectiveness, with a frequency adapted to the risk level can be used instead of non-specific inspections with a generic frequency. This should result in the application of inspection resources where they are needed and, consequently, in an increase in the cost-effectiveness of inspections. Another opportunity to manage inspection costs is to identify items in the inspection plan that can be performed non-intrusively and on-stream. If non-intrusive inspection is able to be applied and provides sufficient information to assess the condition of the component, there is the potential for net savings based on not having to open, clean and inspect internally during downtime. If the element considered is the main stopping factor of an operating unit, a non-intrusive inspection can help increase the uptime of the unit (Khan et al., 2019).

From a technical point of view, the RBI technique involves a quantitative assessment of the Probability of Failure (*PoF*) and the Consequences of Failure (*CoF*) associated with each item in a plant (Khan & Haddara, 2004). This analysis allows the estimation of optimal inspection and maintenance intervals that maximise the availability of a system while minimising its risk (Khan & Haddara, 2004). In this way, RBI helps determine the most economical use of maintenance resources, allowing organisations to prioritise and plan maintenance activities based on the quantified risk of equipment failure. Consequently, an effective RBI helps to increase the life cycle of equipment and reduce inspection costs and instances of failure (Khan et al., 2006).

RBI techniques were formalised through risk calculations to make decisions about inspection schedules. They can be qualitative when referring to a non-numerical representation using graphics, flow charts, and data sources (Khan et al., 2015, 2016), using analytical estimates in which subjective scores are given to numerous factors identified as causes of equipment damage. In this case, the results represent a perception rather than a measurement. In contrast, when discussing quantitative methods, the risk Is estimated using a numerical or statistical method (Wintle et al., 2001). In this way, the *PoF* and *CoF* are obtained based on complex models that return much more reliable and accurate results than qualitative approaches (Drozyner & Veith, 2002). Unfortunately, these calculations are not always easy and can result in significant cost increases in maintenance strategies. For this reason, semi-quantitative techniques have been introduced to provide a more detailed prioritisation of the risks of qualitative assessments and reduce the arduous task of calculating the risk factors of quantitative assessments (Mohammed, 2023). However, *PoF* and *CoF* are crucial elements in each RBI approach.

According to the API RP 581, *PoF* is recognised globally as (API RP 581, 2016):

$$PoF(t) = gff_{total} \cdot D_f(t) \cdot F_{MS} \quad (1)$$

Looking at equation (1), the *PoF* is a function of time and is given by the product of three different parameters. The generic failure frequency (*gff*) is a value of the average failure rate for a similar asset type that is taken from the specific industry database and is adjusted through the damage factor ($D_f(t)$) and the management system factor (F_{MS}). There is a clear distinction between the meaning of these two adjustment factors; in particular, the D_f adjusts the generic failure frequency according to the active damage mechanisms to which the component is subjected and considers the susceptibility to the damage mechanism and/or the damage accumulation rate. The D_f also assesses historical inspection data and the effectiveness of past and future inspections. On the other hand, the F_{MS} explains the plant management systems' influence on the plant' mechanical integrity. Another difference is that the D_f is linked to a specific component and damage mechanism, whereas the F_{MS} is applied equally to all plant components (API RP 581, 2016).

To calculate the damage factors related to the considered damage mechanisms in this case (thinning, corrosion under insulation on ferritic component and external corrosion on ferritic component), the future corrosion rate needs to be estimated.

In the case of thinning, the future corrosion rate was obtained based on the past corrosion rate that was calculated by thickness measuring. The wall thickness reduction is produced from the component's interior for this damage mechanism.

Regarding the damage factor for external corrosion on ferritic components, the future corrosion rate is calculated through equation (2).

$$C_r = C_{rB}\hat{A}\cdot max[F_{EQ}, F_{IF}] \quad (2)$$

Where:

C_r is the estimated future corrosion rate.

C_{rB} is the base corrosion rate. The value for this parameter was taken from table 15.2M of API RP 581, based on the operating temperature and the driver (atmospheric condition causing the corrosion rate).

F_{EQ} is the adjustment factor for equipment design/fabrication detail. A value of 2 is given if the equipment has a design which allows water to pool and increases metal loss rates. Otherwise, a value of 1 is assigned.

F_{IF} is the adjustment factor for the interface. If there is an interface where it enters soil or water, a value of 2 is given. Otherwise, this parameter is set as 1.

The corrosion rate for corrosion under insulation on ferritic component damage factor is calculated through equation (3).

$$C_r = C_{rB}\hat{A}\cdot F_{INS}\hat{A}\cdot F_{CM}\hat{A}\cdot F_{IC}\hat{A}\cdot max[F_{EQ}, F_{IF}] \quad (3)$$

Where:

C_r is the estimated future corrosion rate.

C_{rB} is the base corrosion rate. The value for this parameter was taken from table 16.2M of API RP 581, based on the operating temperature and the driver (atmospheric condition causing the corrosion rate).

F_{INS} is the adjustment factor for insulation type. It is determined according to Table 16.3 of API RP 581.

F_{CM} is the adjustment factor for complexity. Values of 0.75, 1 or 1.25 are given if the complexity is below average, average or above average, respectively.

F_{IC} is the adjustment factor for insulation condition Values of 1.25, 1 or 0.75 are given if the insulation condition is below average, average, or above average, respectively.

Although it can be considered that API RP 581 can have some limitations as a model to predict the corrosion rate, API RP 581 has been chosen for reference, in this work, because its use is widely extended in the industry. Nevertheless, to minimize the possibility of equipment failures earlier than expected due to the estimation of an improperly low corrosion rate, conservative values have been applied to calculate this parameter.

It must be noted that there are different types of corrosion, depending on the material of the component, the environment, the fluid process, the process conditions (pressure, temperature, flow…), the service type, etc. Most of the models focus on the analysis of sweet corrosion, and they are not suitable for predicting the corrosion rates due to those other types of corrosion. The uncertainties associated with corrosion prediction can significantly affect the result of the damage factor calculation, therefore, it has a relevant influence in the risk value.

Adopting a conservative approach is normally an effective measure to partially mitigate the possibility of estimating a risk too low, which would be the most adverse effect of the referred uncertainness.

Since the corrosion rate is based on an estimation, three possible scenarios (future damage states) are introduced in the calculation to consider possible variations of this parameter. The damage state 1 is such that the damage is no worse than expected, the damage state 2 is somewhat worse than expected and the damage state 3 is considerably worse than expected. Factors 1, 2 and 4 for the described damage states are applied to the expected corrosion rate.

The expected metal loss fraction since last inspection is calculated by application equation (4).

$$A_{rt} = \frac{C_r\hat{A}\cdot age}{t_{rd}} \quad (4)$$

Where:

A_{rt} is the expected metal loss fraction since the last inspection.

C_r is the estimated future corrosion rate.

t_{rd} is the measured thickness reading from previous inspection, from internal side (for thinning) or from external side (for external corrosion and corrosion under insulation).

age is the in-service time that damage is applied. When the damage is internal (thinning), the value of this parameter corresponds to the in-service time since the last internal inspection thickness measurement (age_{tk}). When the damage is external (external corrosion or corrosion under insulation), this parameter is calculated based on the external age_{tk}, the age of the coating (age_{coat}) and the coating quality.

The flow stress is calculated through equation (5).

$$FS = \frac{(YS + TS)}{2}\hat{A}\cdot E\hat{A}\cdot 1.1 \quad (5)$$

Where:

FS is the flow stress.

YS is the yield strength.

TS is the tensile strength.

E is the weld joint efficiency.

Equation (6) is used to calculate the strength ratio parameter.

$$SR_P = \frac{P\hat{A}\cdot D}{\alpha\hat{A}\cdot FS\hat{A}\cdot t_{rd}} \quad (6)$$

Where:

SR_P is the strength ratio parameter.

P is the operating pressure.

D is the external diameter of the component.

α is the component geometry shape factor (a value of 2 is used for cylinder).

FS is the flow stress.

t_{rd} is the measured thickness reading from the previous inspection, from internal side (for thinning) or from the external side (for external corrosion and corrosion under insulation).

The damage factor is calculated using equation (7).

$$D_f = \left[\frac{\left(Po_{p1}\Phi(-\beta_1)\right) + \left(Po_{p2}\Phi(-\beta_2)\right) + \left(Po_{p3}\Phi(-\beta_3)\right)}{1.56\hat{A}\cdot 10^{-4}}\right] \quad (7)$$

Where:

D_f is the damage factor. In the case of thinning, the result of the equation above is the base damage factor (D_{fB}), which needs to be furtherly adjusted to get the final damage factor.

$Po_{p1}, Po_{p1}, Po_{p1}$ are the posterior probabilities for damage states 1, 2

Table 1
Inspection effectiveness categories (API RP 581, 2016).

Inspection effectiveness		Description
A	Highly effective	The inspection methods will correctly identify the true damage state in nearly every case (or 80 % to 100 % confidence)
B	Usually effective	The inspection methods will correctly identify the true damage state most of the time (or 60 % to 80 % confidence)
C	Farily effective	The inspection methods will correctly identify the true damage state about half of the time (or 40 % to 60 % confidence)
D	Poorly	The inspection methods will provide little information to correctly identify the true damage state (or 20 % to 40 % confidence)
E	Ineffective	The inspection method will provide no or almost no information that will correctly identify the true damage state and are considered ineffective for detecting the specific damage mechanism (less than 20 % confidence)

and 3, respectively. These parameters are calculated from the inspection effectiveness factors, which depend on the number of inspections of every level of effectiveness (A, B, C and D), and the conditional probabilities and the prior probabilities. They are calculated for each of the considered damage states.

$\beta_1, \beta_2, \beta_3$ are the β reliability indices for damage states 1, 2 and 3, respectively. These parameters depend on the expected metal loss fraction since the last inspection, the corrosion rate factors for each of the considered damage states, the coefficient of variance for thickness and the strength ratio parameter.

Φ is the standard normal cumulative distribution function.

The inspection effectiveness is classified in four levels or categories (API RP 581, 2016), as shown in Table 1.

The calculated damaged factor calculated as described above is the final value for external corrosion and corrosion under insulation damage factors, but it still needs to be adjusted for thinning. It is done by application of equation (8).

$$D_f = max\left[\left(D_{fB}\hat{A}\cdot F_{IP}\hat{A}\cdot F_{DL}\right), 0.1\right] \tag{8}$$

Where:

D_f is the final damage factor for thinning.

D_{fB} is the base damage factor for thinning.

F_{IP} is the adjustment factor for injection points. If any injection/mix point exists in the component, this factor is equal to 3. Otherwise, a value of 1 is applied.

F_{DL} is the adjustment factor for dead legs. If there is the presence of dead legs, this factor is equal to 3. Otherwise, its value is 1.

The consequence of failure methodology defines the *CoF* used with *PoF* to obtain a risk assessment and inspection programme for a component subject to process and environmental conditions typically found in the refining, petrochemical, exploration, and production industries. The consequences, calculated using the procedures, are not intended to be used in a rigid consequence analysis of a component. The categories of consequences examined using different techniques are flammable and explosive consequences, toxic consequences, non-flammable and non-toxic release consequences and financial consequences, as illustrated in Fig. 2. Each category is evaluated according to the type of damage, the phase, temperature, and volume of material released and the area where it happens.

The consequence's calculation is based on a failure which would happen due to the release of the fluid contained in the component. Four release hole sizes are taken as reference: small (diameter = 6.4 mm), medium (diameter = 25 mm), large (diameter 102 mm) and rupture (diameter 406 or component diameter, whichever is higher).

The equation generically calculates the component damage / personnel injury toxic / flammable / non-flammable, non-toxic consequence areas **(9)**.

$$CA_y^x = \frac{\sum_{n=1}^{4} gff_n\hat{A}\cdot CA_{y,n}^x}{gff_{total}} \tag{9}$$

Where:

CA_y^x the final probability-weighted consequence area can be calculated for component damage flammable consequence or personnel injury flammable/toxic / non-flammable, non-toxic consequence.

gff_n are the generic failure frequencies for each of the n release hole sizes.

$CA_{y,n}^x$ is the blended component consequence area, associated with the n^{th} release hole size, determined for the component damage flammable consequence or for personnel injury flammable/toxic / non-flammable, non-toxic consequence.

gff_{total} is the sum of the individual release hole size generic frequencies.

The final personnel injury consequence area is given by equation (10).

$$CA_{inj} = max\left[CA_{inj}^{flam}, CA_{inj}^{tox}, CA_{inj}^{nfnt}\right] \tag{10}$$

Where:

CA_{inj} is the final personnel injury consequence area.

CA_{inj}^{flam} is the final probability weighted personnel injury flammable consequence area.

CA_{inj}^{tox} is the final probability weighted personnel injury toxic consequence area.

CA_{inj}^{nfnt} is the final probability weighted personnel injury non-flammable, non-toxic consequence area.

The final component damage consequence area is given by equation (11).

$$CA_{cmd} = CA_{cmd}^{flam} \tag{11}$$

Where:

CA_{cmd} is the final component damage consequence area.

CA_{cmd}^{flam} is the final probability weighted component damage flammable consequence area.

The final consequence area is calculated through equation (12).

$$CA = max\left[CA_{cmd}, CA_{inj}\right] \tag{12}$$

Where:

CA_{cmd} is the final component damage consequence area.

CA_{inj} is the final personnel injury consequence area.

The financial consequence is calculated trough equation (13).

$$FC = FC_{cmd} + FC_{affa} + FC_{prod} + FC_{inj} + FC_{environ} \tag{13}$$

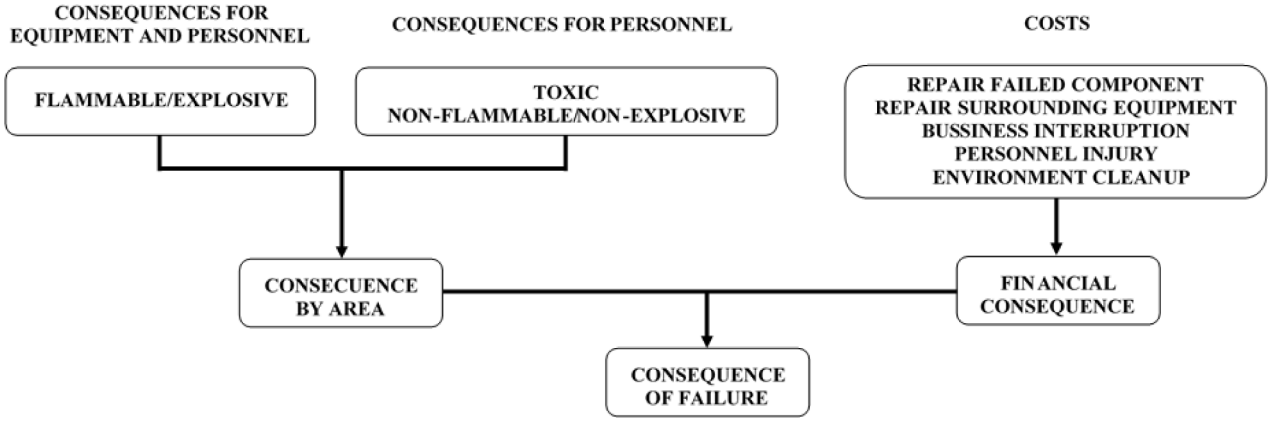


Fig. 2. Consequence of failure.

Where:

FC is the final financial consequence.

FC_{cmd} is the financial consequence of component damage.

FC_{affa} is the financial consequence of surrounding equipment on the unit.

FC_{prod} is the financial consequence of lost production on the unit.

FC_{inj} is the financial consequence as a result of serious injury to personnel.

$FC_{environ}$ is the financial consequence of environmental clean-up.

Plotting *PoF* and *CoF* values on a risk matrix is possible to obtain the risky evaluation through an effective graph way (API RP 581, 2016).

Defining a goal by applying this methodology and defining a risk target is always possible. This risk target is the maximum risk level that the installation's owner-user can assume. Once the goal has been met or exceeded, an activity such as inspection is triggered. Several objectives can be defined in an RBI program to initiate and determine risk mitigation activities like risk target (an acceptable risk level that triggers the inspection planning process), *PoF* target (a failure or loss rate that is considered unacceptable and triggers the inspection planning process), D_f target (a damaged state that reflects an unacceptable failure rate factor more significant than generic and initiates the inspection planning process), *CoF* target (an unacceptable consequence level in terms of area of consequence or financial consequence based on owner-user preference), target thickness (a specific thickness, often the minimum thickness, is considered unacceptable, triggering the inspection planning process) or maximum inspection interval target (a particular inspection frequency considered unacceptable triggers the inspection planning process. The decision maker can set a maximum inspection interval or can be set based on a jurisdictional requirement as a mitigation solution.

As summarised in Fig. 3, the RBI methodology combines knowledge of damage mechanisms and consequences, damage progression rates, inspection effectiveness, and mitigation models to determine the likelihood of failure causing losses. And this makes RBI a compelling methodology; indeed, an RBI approach allows inspection and maintenance resources to be shifted to provide a higher level of coverage on high-risk and impact items and appropriate commitment on risky equipment with a lower and limited impact.

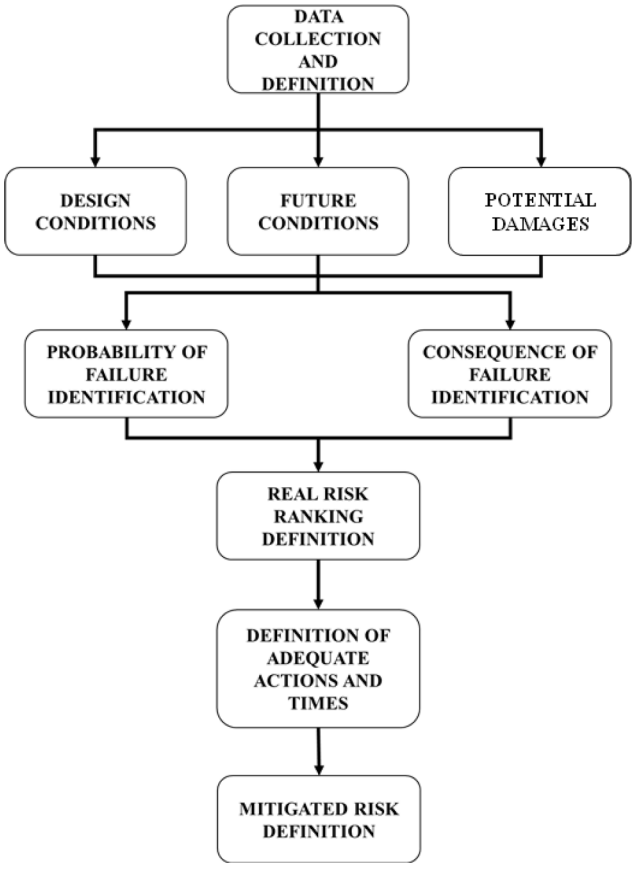


Fig. 3. RBI methodology flowchart.

Once the risk has been ranked, a risk target must be established. The risk target can be defined as the maximum risk that the asset owner can assume. Therefore, the risk should be always kept below the risk target.

In order to comply the risk target, it is necessary to define the adequate actions and times to be applied. In other words: an inspection plan needs to be developed. This inspection plan must provide information about the following:

- Damage mechanisms whose condition needs to be verified through inspection, based on the result of the risk calculation.
- Type of inspection (inspection method and technique) will be applied to verify each specific damage mechanism.
- Effectiveness of inspection, based mainly on the inspection's scope and the technique's type. It must be enough to reduce the risk below the risk target, but a higher effectiveness could be applied to keep the risk lower than the risk target for a longer period, which allows for increasing the intervals between inspections.
- Date for inspection (target date). The inspection must be planned to be performed before the date when the risk target is reached.

The inspection plan is scheduled within a defined plan period. Once an inspection is performed and at the end of the plan period, the RBI assessment should be performed again by application of the information provided by the inspections (evergreening). This cyclic process is repeated during the whole life of the asset.

2.3. Case study

The DSS has been developed based on the guidelines of the RBI procedure established in the scientific literature for its applications in the oil and gas sector and following what is defined in the API RP 581 manual to set as the ultimate goal the assessment of both the risk associated with the area affected by the failure of the heat exchanger and the evaluation of the financial risk linked to the failure of the latter. To test the software, it was used real data collected from a petrochemical plant in Spain whose maintenance and reliability program was managed by the company SGS.

Following the definition of the ultimate goals of the system, these were decomposed by identifying the elements necessary for the development of the model. The assessment of the financial risk and the area affected by the failure of the heat exchanger are obtained respectively from the product of the financial consequence and the Consequence by area with the *PoF*.

Therefore, the DSS design has foreseen the introduction of a gateway to allow the end-user to choose which purpose to evaluate. The gateway introduced the need in the system to separate the procedure for calculating the Financial Consequence and the Consequence by Area into two different sections. According to the API RP 581 manual, a first macro-identification of the factors affecting the calculations of the financial consequence and the Consequence by area was conducted to structure the skeleton of the calculation procedure. Besides, the factors characterising the *PoF* calculation also exploded: the gff_{total}, D_f and F_{MS} of the component under analysis. The D_f is a damage factor that can contain multiple sub-factors. Considering the case study of a heat exchanger, it was decided to consider only the Thinning Damage Factor, the External Damage Factor and the CUI Damage Factor. This decision was made after an in-depth discussion with the inspector and RBI technician of the company. At this point in the design process, it was also necessary to introduce baseline data containing all the variables and parameters

needed to activate the calculation procedures.

Once this level of detail of the system structure was obtained, the perimeter of the model was defined accordingly. The next step was to adopt a bottom-up approach to complete the system design phase. This approach identified the need for the user to populate the baseline data section with all the parameters defined by the API RP 581 manual for applying RBI and the operational data of the heat exchanger and the plant in which it operates. Fig. 4 provides the DSS built for the current RBI case study.

The final calculations are listed in the previous DSS flowchart. Specifically, the values obtained from the individual calculations were retrieved to complete the RBI analysis model. The main factors making up the risk assessment were obtained for present and future values.

The asset under assessment is the shell of a heat exchanger containing steam as fluid process. The component was made in carbon steel according to ASTM A-106 Gr. B.

The main general data of the equipment that was used for calculation is collected in Table 2.

Internal corrosion rate is applicable for the calculation of the thinning damage factor. The value for this parameter was estimated based on the characteristics of the process fluid. A conservative position was assumed to define it. A value of 0.05 mm/year was estimated for this parameter.

External corrosion rates for calculating external corrosion and corrosion under insulation on ferritic damage factors were obtained from tables 15.2M and 16.2M in API RP 581 for driver marine (API RP 581, 2016; API, 2021). Values of 0.025 mm/year and 0.127 mm/year were applied for these parameters, respectively.

Based on the designed external and internal corrosion rates, the total estimated corrosion rate is 0.132 mm/year. The score from the plan's management system assessment questionnaire according to API RP 581 / Annex 2.A was 750.

Some inspections were performed on the equipment in the past. However, these inspections were considered ineffective for the calculation because they involved a reduced scope.

Regarding the adjustment factors for the calculation of the thinning damage factor, all of them were set as 1. The detection system was assessed as composed of instrumentation designed specifically to detect material losses by changes in operating conditions in the system. The isolation system consists of isolation devices activated by operators in the control room. The mitigation system consists of inventory blowdown.

Table 2
Main general data for calculation.

Parameter	Value
Design Temperature	120°C
Operating Temperature	120°C
Design Pressure	114 bar
Operating Pressure	114 bar
Internal Diameter	203 mm
Volume	0.90^3
Yield strength	240 MPa
Tensile strength	415 MPa
Allowable stress	151 MPa
Weld joint eficiency	1
Installation date	1974
Last measured thickness	8.3
Date where the last measured thickness was measured	2018
Date of last coating application	2015
Coating condition	Medium
Level of confidence data	Low

The costs for calculation of financial consequence were applied as follows, considering the plant evaluations:

– cost of replacement of equipment in the affected area: 4,000 $/m^2.
– daily production in the unit: 40,000 $/m^2.
– cost due to relevant injury/fatality: 10,000 $/person

A density of 0.1 person/m^2 was estimated.

The referred costs have been estimated based on data of projects developed by SGS for some petrochemical plants in Spain. Those projects consisted of implementation of RBI systems according to API RP 581. Within each of these projects, the financial data were estimated mainly based on the information given by the owner of the facilities and, in some cases, they were adjusted by the SGS technicians involved in the

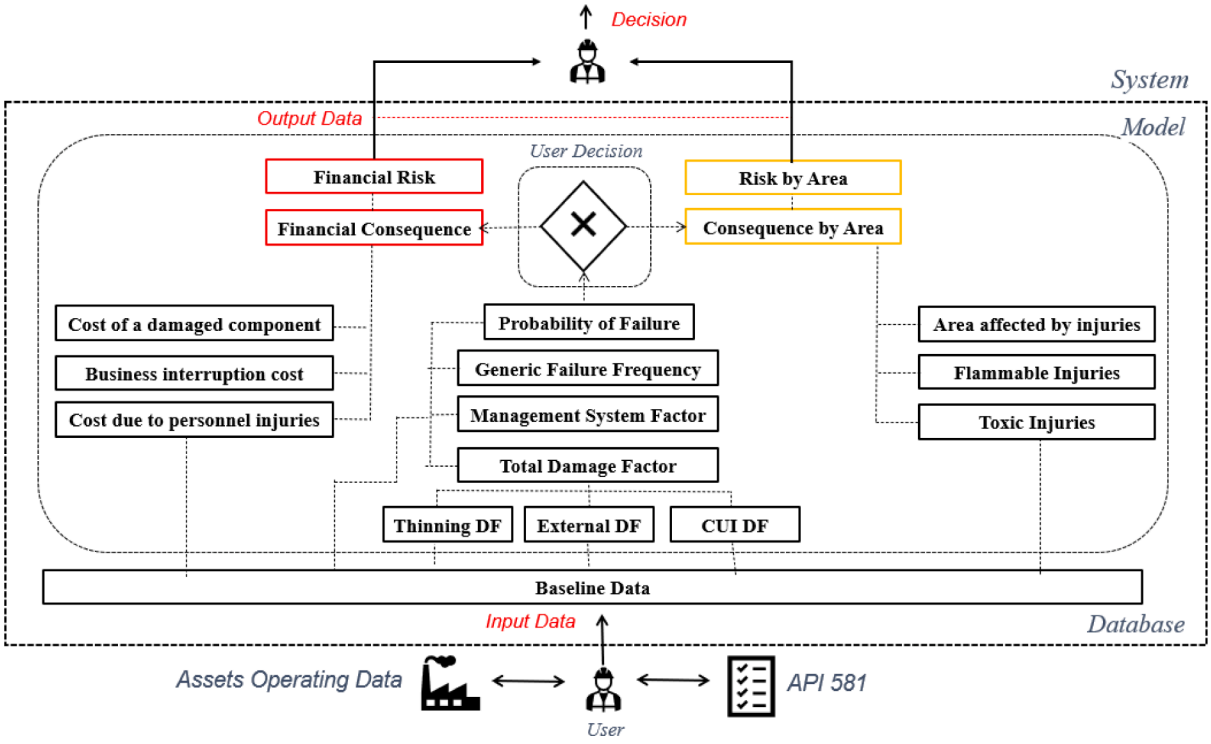


Fig. 4. DSS based on RBI procedure.

project.

The TBI strategy that had been applied to the asset until the performance of this assessment was an external inspection every 3 years and an internal inspection every 9 years. This plan has been defined considering that the inspections would be performed during the turnaround of the plant, whose frequency is every 3 years. This is approximately according to the requirements established by Spanish regulations (Real Decreto, 2060/2008 - ITC EP-3) for equipment class 1 in refineries and petrochemical plants.

The RBI study has been developed using the unbalance risk matrix according to API RP 581 as reference. The risk target has been fixed in the medium risk level (no medium–high nor high risk is allowed). A plan period from 2023 until 2056 has been considered.

Four different RBI strategies have been designed within the referred period. A different inspection effectiveness prioritisation is applied for every strategy, as described in Table 3.

The principles to define the referred strategies are as follows:

- The effectiveness of the first inspection is different for each strategy, in order to cover the four possible effectiveness (A, B, C and D).
- The effectiveness of the second, third inspection (except for the last inspection within the plan period) is aimed to be the same as the effectiveness of the first inspection. However, this effectiveness could result not enough to reduce the risk below the risk target. If so, a higher effectiveness would be selected, following the prioritisation as indicated in the previous table, in order to keep the risk below the risk target until the next inspection.
- For the last inspection, the inspection effectiveness is set in such way that it is as low as possible, but enough to reach the end of the plan period keeping the risk below the risk target.

The referred strategies include several options within a range of different inspection effectiveness (from the highest one −A- to the lowest one −D-). The cost of an inspection when a higher effectiveness is applied will be higher than if a lower effectiveness is applied, but a higher effectiveness will result in a higher risk reduction, therefore it will allow to extend the period until the next inspection. The optimal among the proposed strategies is the one which have a rate cost per inspection/number of inspections with the lowest estimated total cost within the plan period.

The approach used in this work to design the strategies to set the RBI inspection plan is proposed as a systematic way, easily adaptable to other cases of study, which allows to get different options, allowing the decision maker choses the optimal among them.

Other possible strategies could have been designed combining different inspection effectiveness. In case a more optimized combination exists, it is expected that it will be close to one the four designed strategies, since they cover a wide range of different inspection effectiveness.

Table 3
Description of prioritisation criteria to stablish the inspection effectiveness for each designed RBI strategy.

RBI strategy No.	Typically applied effectiveness	Effectiveness of the 1st inspection	Prioritization for the effectiveness of the next inspections (*)	Prioritization for the effectiveness of the last inspection within the plan period (*)
1	Highest	A	A	D > C > B > A
2	Medium-high	B	B > A	D > C > B > A
3	Medium	C	C > B > A	D > C > B > A
4	Low	D	D > C > B > A	D > C > B > A

(*) Following the described prioritisation, a sufficiently high inspection effectiveness is selected to avoid the risk target is exceeded.

In any other particular case, based on the analyst's judgement, a deeper analysis could be made to get the optimal RBI strategy. For the purposes of the current work, the applied approach is considered enough to get an overview that allows to compare the estimated costs of the execution of an inspection plan according to a RBI methodology versus another inspection plan according based on a TBI strategy.

The execution of any inspection involves a cost that depends on the type of inspection and the scope of the inspection, which is directly related to the inspection effectiveness. External inspections may be executed in service, but internal inspections are performed during shutdowns, with the equipment out of service, which involves additional costs due to the production loss.

The summary of estimated unitary costs and the estimated time of production stop for each type of inspection are contained in Table 4.

As explained previously, it has been assumed that the performance of internal inspections requires setting the equipment out of service. However, it could be considered the possibility to perform non-intrusive inspections, based on non-destructive testing techniques, such as profile radiography, ultrasonic scanning, etc. that allow (in some cases) to verify the internal condition of the component during operation. The cost per hour of these techniques is higher than the cost of the direct visual inspection, but they may be applied from the external surface of the equipment, therefore, access to the interior is not needed, in advantage. The estimated costs of the non-intrusive alternatives for the previously referred inspections (only for the inspections addressed to verify the internal surfaces) are indicated in Table 5.

In addition, implementing an RBI system is estimated at 210 $ per asset. The RBI system maintenance cost (evergreening) has been considered within the referred costs for the inspections.

The uncertainness about the condition of the asset can be reduced through the inspection appropriately selected for the specific damage mechanism. The reduction of the uncertainness will depend on the type of inspection (inspection method / inspection technique) and the scope of the inspection, which is related to the inspection effectiveness. However, even when the maximum inspection effectiveness is applied, a remaining uncertainness (remaining risk) is expected.

In addition, it must be noted that the different inspection techniques

Table 4
Estimated costs and time of production stop per inspection type.

Description	Estimated time of production stop (hours)	Inspection cost
Inspection for thinning effectiveness A	12	720 $
Inspection for thinning effectiveness B	10	600 $
Inspection for thinning effectiveness C	8	480 $
Inspection for thinning effectiveness D	6	360 $
Inspection for external corrosion effectiveness A	0	660 $
Inspection for external corrosion effectiveness B	0	540 $
Inspection for external corrosion effectiveness C	0	420 $
Inspection for external corrosion effectiveness D	0	300 $
Inspection for CUI on ferritic effectiveness A	0	720 $
Inspection for CUI on ferritic effectiveness B	0	600 $
Inspection for CUI on ferritic effectiveness C	0	480 $
Inspection for CUI on ferritic effectiveness D	0	360 $
Internal inspection (TBI strategy)	6	360 $
External inspection (TBI strategy)	0	240 $

Table 5
Estimated costs and time of production stop per inspection type (non-intrusive inspections).

Description	Estimated time of production stop (hours)	Inspection cost
Non-intrusive inspection for thinning effectiveness A	0	1,440 $
Non-intrusive inspection for thinning effectiveness B	0	1,200 $
Non-intrusive inspection for thinning effectiveness C	0	960 $
Non-intrusive inspection for thinning effectiveness D	0	720 $
Non-intrusive internal inspection (TBI strategy)	0	480 $

will present different detection capabilities. As a general rule, the non-intrusive inspection techniques are considered less reliable than the inspection techniques based on direct examination.

3. Results analysis

Regarding the calculations for the RBI strategy, based on the applied baselined data, the current financial risk category has resulted as 1C, which means that the probability category is "1″ and the financial consequence category is "C". The representation of this risk and the established risk target (medium risk) in the risk matrix is as shown in Fig. 5.

The financial consequence category has resulted as "C" since no plant or equipment variations have been assumed. The consequence is not time-dependent, so it does not change within the plan period. On the other hand, the probability may vary with the time, due to the increase of thickness loss. The maximum allowed probability category is "3" based on the established risk target. A sufficiently effective inspection has been indicated to be performed just before that probability is reached. The prioritisation for the inspection effectiveness in each case depends on the specific strategy.

The RBI inspection plans that have resulted for every proposed strategy, are detailed in Table 6.

It is observed that the application of more effectiveness inspections trends to increase the intervals between inspections and even reducing the number of interventions for inspection during the considered period in some cases (2 interventions in the case of the strategies 1 and 2; and 3 interventions in the case of the strategies 3 and 4).

The evolution of the future risk vs time is represented for each of the referred strategies in Fig. 6.

Fig. 6 shows how the risk increases over time (due to the increase of the *PoF*) until an additional inspection is introduced in the calculation. The time when this inspection is performed and its effectiveness must be appropriate to avoid exceeding the risk target (the line that represents the risk target is never reached, as the charts show).

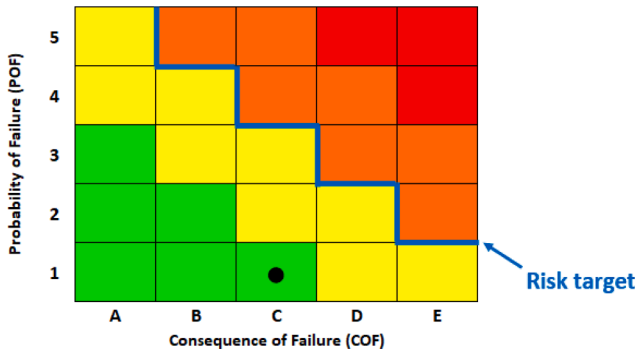


Fig. 5. Present financial risk calculated for the asset.

Table 6
Inspection RBI plan for each proposed strategy.

Year	Activities per RBI strategy			
	Strategy 1	Strategy 2	Strategy 3	Strategy 4
2023	Initial RBI study	Initial RBI study	Initial RBI study	Initial RBI study
2032	–	–	–	CUIF-D
2033	CUIF-A	CUIF-B	CUIF-C	–
2044	–	–	–	CUIF-C
2045	–	–	CUIF-C	–
2050	–	CUIF-B	–	–
2053	–	–	–	CUIF-D
2056	CUIF-D + THIN D	–	CUIF-B	–

Meaning of the abbreviations in this table: CUIF-A: Inspection for corrosion under insulation on ferritic component damage mechanism with effectiveness A; CUIF-B: Inspection for corrosion under insulation on ferritic component damage mechanism with effectiveness B; CUIF-C: Inspection for corrosion under insulation on ferritic component damage mechanism with effectiveness B; CUIF-D: Inspection for corrosion under insulation on ferritic component damage mechanism with effectiveness D; THIN-D: Inspection for thinning component damage mechanism with effectiveness D.

The expected costs due to inspection and RBI implementation and the costs due to the production loss for each proposed RBI strategy, depending on intrusive or non-intrusive inspections are applied, are shown in Table 7 and Table 8, respectively.

It is observed that the most profitable option is the application of the strategy 2, if a direct visual inspection is chosen, but the strategy 1 is the best choice when a non-intrusive inspection technique is selected, instead, and the total estimated cost of such strategy is lower if a non-intrusive technique is applied than if a direct inspection is performed, even though the inspection costs are higher in the first case. This is because the reduction of costs due to production loss is higher than the increase of inspection cost in that case.

The expected costs due to inspection according to TBI plans and the costs due to the production loss, depending on intrusive or non-intrusive inspections are applied, are shown in Table 9 and Table 10, respectively.

It is verified that when a TBI strategy is selected, applying a non-intrusive inspection technique results in a higher cost-benefit than the one based on direct visual internal inspection. This is because the reduction of costs due to production loss is higher than the increase in inspection cost.

The resulting cumulative costs vs time for the TBI strategy with the intrusive inspection are compared with those for the best RBI strategy with intrusive inspection (strategy 2) in Fig. 7.

The resulting cumulative costs vs time for the TBI strategy with non-intrusive inspection are compared with those for the best RBI strategy with non-intrusive inspection (strategy 1) in Fig. 8.

It is observed that in both cases (whether intrusive inspection or non-intrusive inspection is applied) the RBI strategy results relatively more profitable than the TBI strategy and this difference increases over time.

The proposed DSSs as design artefacts are the design-science contributions of this research from a theoretical point of view. This contribution improves our understanding of managing maintenance operations in a complex and hazardous environment. March and Smith (1995) contend that empirical papers produced in collaboration with organisations blur the distinction between academic research and industrial adoption of technological solutions. The publication of these findings will assist organisations to develop domain-independent and scalable solutions to large-scale information system problems.

4. Conclusions, limitations, and future research directions

This study focuses on the issues of selecting the appropriate maintenance policy to achieve an optimised acceptable level of safety and

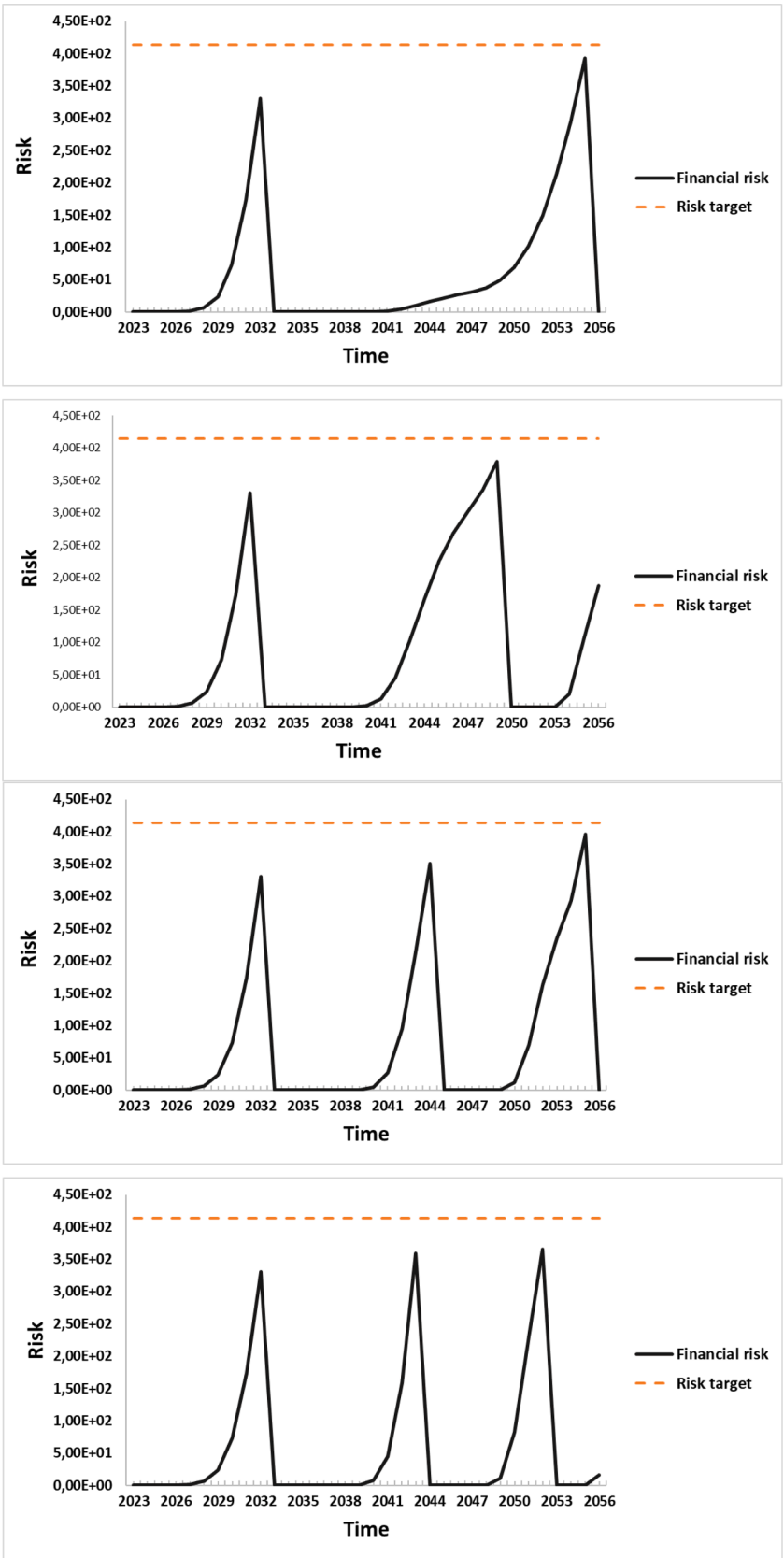


Fig. 6. Evolution of future risk vs time within the plan period for strategy 1, 2, 3 and 4, respectively from left to right and from up to down. The continuous lines represent the calculated risk, and the dashed lines represent the risk target.

Table 7
Estimated costs for each proposed RBI strategy (intrusive inspection).

Year	Costs							
	Strategy 1		Strategy 2		Strategy 3		Strategy 4	
	Inspection & RBI system	Production loss	Inspection & RBI system	Production loss	Inspection & RBI system	Production loss	Inspection & RBI system	Production loss
2023	210 $	0 $	210 $	0 $	210 $	0 $	210 $	0 $
2032	–	0 $	–	0 $	–	0 $	360 $	0 $
2033	720 $	0 $	600 $	0 $	480 $	0 $	–	0 $
2044	–	0 $	–	0 $	–	0 $	480 $	0 $
2045	–	0 $	–	0 $	480 $	0 $	–	0 $
2050	–	0 $	600 $	0 $	–	0 $	–	0 $
2053	–	0 $	–	0 $	–	0 $	360 $	0 $
2056	720 $	10,000 $	–	0 $	600 $	0 $	–	0 $
Total	**11,650 $**		**1,170 $**		**1,770 $**		**1,410 $**	

Table 8
Estimated costs for each proposed RBI strategy (non-intrusive inspection).

Year	Costs							
	Strategy 1		Strategy 2		Strategy 3		Strategy 4	
	Inspection & RBI system	Production loss	Inspection & RBI system	Production loss	Inspection & RBI system	Production loss	Inspection & RBI system	Production loss
2023	210 $	0 $	210 $	0 $	210 $	0 $	210 $	0 $
2032	–	0 $	–	0 $	–	0 $	360 $	0 $
2033	720 $	0 $	600 $	0 $	480 $	0 $	–	0 $
2044	–	0 $	–	0 $	–	0 $	480 $	0 $
2045	–	0 $	–	0 $	480 $	0 $	–	0 $
2050	–	0 $	360 $	0 $	–	0 $	–	0 $
2053	–	0 $	–	0 $	–	0 $	360 $	0 $
2056	1,080 $	0 $	–	0 $	600 $	0 $	–	0 $
Total	**1,080 $**		**1,170 $**		**1,770 $**		**1,410 $**	

Table 9
Estimated costs for TBI strategy (intrusive inspection).

Year	Activity	Cost	
		Inspection	Production loss
2023	External inspection	240 $	0 $
2026	External inspection	240 $	0 $
2029	Internal inspection	360 $	10.000 $
2032	External inspection	240 $	0 $
2035	External inspection	240 $	0 $
2038	Internal inspection	360 $	10.000 $
2041	External inspection	240 $	0 $
2044	External inspection	240 $	0 $
2047	Internal inspection	360 $	10.000 $
2050	External inspection	240 $	0 $
2053	External inspection	240 $	0 $
2056	Internal inspection	360 $	10.000 $
Total		**43,360 $**	

Table 10
Estimated costs for TBI strategy (non-intrusive inspection).

Year	Activity	Cost	
		Inspection & RBI system	Production loss
2023	External inspection	240 $	0 $
2026	External inspection	240 $	0 $
2029	Internal inspection	480 $	0 $
2032	External inspection	240 $	0 $
2035	External inspection	240 $	0 $
2038	Internal inspection	480 $	0 $
2041	External inspection	240 $	0 $
2044	External inspection	240 $	0 $
2047	Internal inspection	480 $	0 $
2050	External inspection	240 $	0 $
2053	External inspection	240 $	0 $
2056	Internal inspection	480 $	0 $
Total		**3,840 $**	

operational expenditure in a real case for a petrochemical processing industrial facility. The goal has been to design, build, and validate a decision support system based on the guidelines of the RBI procedure to assist decision-makers in evaluating the complex situation of predictive maintenance in a processing plant and selecting the best suitable maintenance strategy for employee and environmental safety. This allows choosing the best practices to reduce the probability of accidents that could affect workers and the environment and the cost that the company can afford in managing accidents.

Thus, this paper presents a DSS framework that addresses several critical aspects of a decision-support system solution when dealing with maintenance and safety issues.

This research has demonstrated the possibility of incorporating complex real-life maintenance policies (time- and risk-based inspections) into a decision support system artefact functioning.

The relevance of this research is also supported by the use of data of regular inspections and the appropriate proof testing policy for the examined pieces of equipment of a real oil and gas plant.

The results of this research are several. The construction of a decision-support system has made it possible to empirically verify that the adoption of risk-based inspection techniques is actually advantageous for the company that implements them compared to time-based ones, not only for resources optimisation and possible cost reduction but also to ensure better levels of safety for both people and the environment.

Furthermore, it was possible to verify that the benefits of this approach are incremental over time also considering the implementation process as well as automatable, allowing high digitisation of the process through sensors positioned on the most sensitive components that are able to give real-time information to the system on the status of

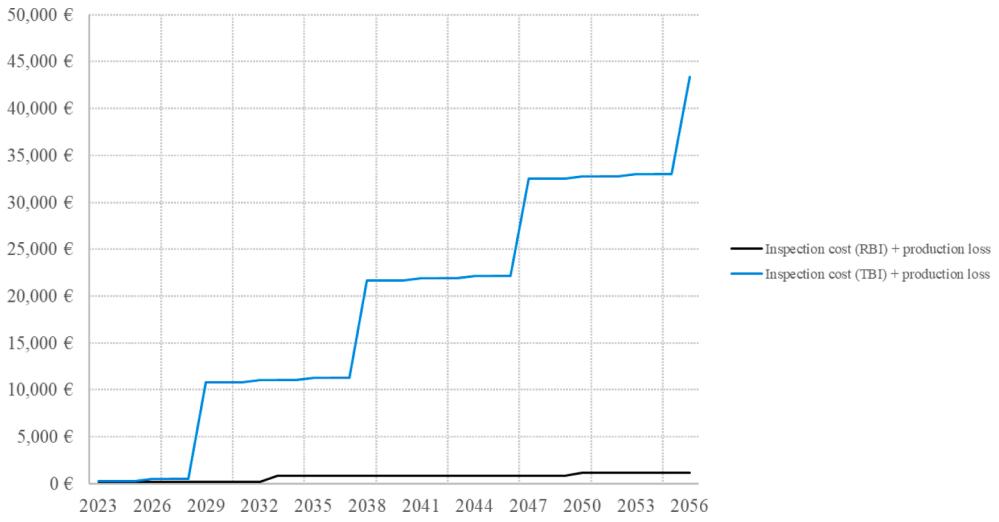


Fig. 7. Evolution of cumulative total costs vs time for TBI strategy with intrusive inspection (blue line) and for RBI strategy 2 with intrusive inspection (black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

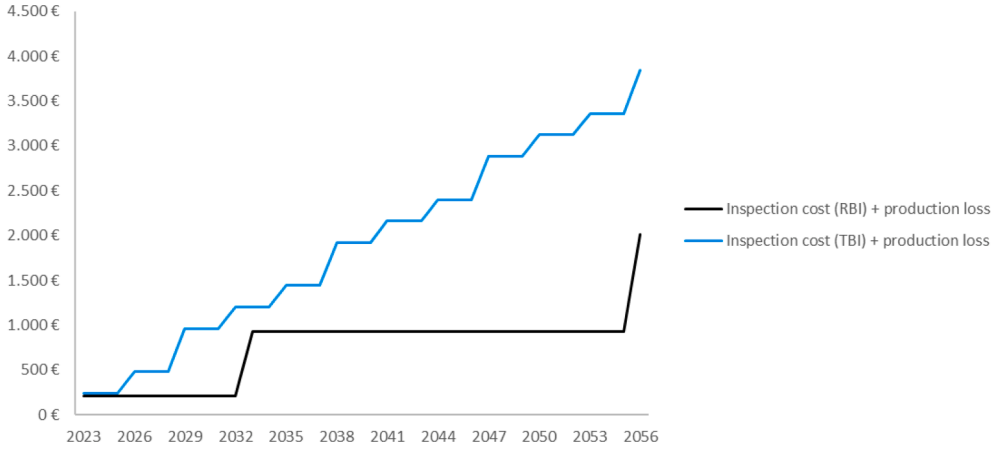


Fig. 8. Evolution of cumulative total costs vs time for TBI strategy with non-intrusive inspection (blue line) and for RBI strategy 1 with non-intrusive inspection (black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the equipment. Even the cost associated with risk-based policies appears to be competitive over time compared to time-based ones, given that there is an increasing amount of time in which the costs of adopting and implementing risk-based systems are amortised. Furthermore, it should also be considered that the adoption of risk-based approaches makes it possible to reduce plant shutdowns as well as destructive checks connected to maintenance processes, which appears to be an indirect effect of undoubted significance. In fact, if the non-destructive tests have a higher cost than the destructive ones, these costs are covered and overcome by savings relating to the missed periods of plant downtime.

Based on the case presented in the paper, it can be concluded that the management can use the results to facilitate the formulation of comprehensive and simple policies oriented to risk management, which is intended to ensure the safety of people and the environment, as well as the preservation of business processes and facilities. Furthermore, both downstream users can use the obtained decision-support system to update baseline data or monitor processes, as well as upstream decision makers to fix the company's goal and select the best solution to treat risky situations.

The primary limitation of this study is that the analysis is specific to this particular case, so future investigations are required to generalise the results. Furthermore, it is specific for a storage facility, so using it for extraction or production plants is impossible. However, the built decision-support system is adaptable and can be easily implemented in other scenarios.

Besides, the estimated calculations in the future are theoretical. When any RBI strategy is applied in the future, it will be necessary to reassess the risk after every inspection (evergreening), in order to update the information with real data collected from the inspection, such as the current thickness, the corrosion rates, the condition of the insulation, and the condition of the coating. To overcome the limitations of the current software, digitalising it further through the adoption of sensors along shells and tube heat exchangers can help in having RBI calculations that are closer to reality than the theoretical current. As a result, one direction for future research in this area could be to incorporate additional and more multifaceted situations to make the artefact more generally applicable. Another line of future research would be to use artificial intelligence technologies to transform the decision support system into an intelligent DSS capable of automating some functions and providing decision-makers with higher-quality knowledge. Furthermore, the current study has the potential to be extended to other cases. The possibility of applying the proposed DSS to various types of equipment is not dismissed. Therefore, future research could focus on equipment that operates on demand or rarely, such as emergency equipment.

Declaration of generative AI in scientific writing: Nogenerative

artificial intelligence (AI) and AI-assisted technologies were used in the writing process.

Funding source

No funding agencies or sponsors have provided financial support for the conduct of the research and/or preparation of the article, in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

CRediT authorship contribution statement

Eugenio Oropallo: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Formal analysis. **Paolo Piscopo:** Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Piera Centobelli:** Visualization, Supervision, Project administration, Methodology, Conceptualization. **Roberto Cerchione:** Writing – review & editing, Visualization, Validation, Methodology. **Eduardo Nuevo:** Writing – original draft, Validation, Software, Investigation, Formal analysis, Data curation. **Alvaro Rodríguez-Prieto:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was developed within the framework of the PhD Research Stay of Eugenio Oropallo and MSc Research Stay of Paolo Piscopo both at ETSI Industriales of UNED under the supervision of Prof. Rodríguez-Prieto, being also an industrial research performed jointly within SGS Tecnos and the Industrial Research Group “Advanced Failure Prognosis for Engineering Applications” from the UNED, framed under the spectrum of activities of the research-results transfer contract with reference 2022-CTINV-0084 and the research project with reference 2021V/-TAJOV/006.

References

Adedipe, T., Shafiee, M., Zio, E., 2020. Bayesian network modelling for the wind energy industry: an overview. Reliab. Eng. Syst. Saf. 202, 107053 https://doi.org/10.1016/j.ress.2020.107053.

2016 API RP 581. (2016). Risk-Based Inspection Methodology. American Petroleum Institute, USA.

Al-Najjar, B., Alsyouf, I., Salgado, E., Khoshaba, S., Faaborg, K., 2001. The Economic Importance of Maintenance Planning When Using Vibration-Based Maintenance.

Al-Shdifat, A., Emmanouilidis, C., Khan, M., Starr, A., 2020. Ontology-based context modeling in physical asset integrity management. Front. Comput. Sci. 2 https://doi.org/10.3389/fcomp.2020.578673.

Antomarioni, S., Ciarapica, F.E., Bevilacqua, M., 2022. Association rules and social network analysis for supporting failure mode effects and criticality analysis: Framework development and insights from an onshore platform. Saf. Sci. 150, 105711 https://doi.org/10.1016/j.ssci.2022.105711.

Api, R. (2021). Recommended Practice API-RP-580: Risk Based Inspection. API Recommended Practice 580: Risk-Based Inspection.

Arena, S., Florian, E., Zennaro, I., Orrù, P.F., Sgarbossa, F., 2022. A novel decision support system for managing predictive maintenance strategies based on machine learning approaches. Saf. Sci. 146, Scopus. https://doi.org/10.1016/j.ssci.2021.105529.

Bennett, D., 2006. Operations Management: Vol. 4,5,6. SAGE Publications.

Berardi, L., Giustolisi, O., Kapelan, Z., Savic, D.A., 2008. Development of pipe deterioration models for water distribution systems using EPR. Journal of Hydroinformatics, 10(2), 113–126. Scopus. Doi: 10.2166/hydro.2008.012.

Bertolini, M., Bevilacqua, M., Ciarapica, F.E., Giacchetta, G., 2009. Development of risk-based inspection and maintenance procedures for an oil refinery. J. Loss Prev. Process Ind. 22 (2), 244–253. https://doi.org/10.1016/j.jlp.2009.01.003.

Bhatia, K., Khan, F., Patel, H., Abbassi, R., 2019. Dynamic risk-based inspection methodology. J. Loss Prev. Process Ind. 62 https://doi.org/10.1016/j.jlp.2019.103974.

Bokrantz, J., Skoogh, A., 2023. Adoption patterns and performance implications of smart maintenance. Int. J. Prod. Econ. 256 https://doi.org/10.1016/j.ijpe.2022.108746.

Bokrantz, J., Skoogh, A., Berlin, C., Wuest, T., Stahre, J., 2020. Smart maintenance: a research agenda for industrial maintenance management. Int. J. Prod. Econ. 224 https://doi.org/10.1016/j.ijpe.2019.107547.

Bousdekis, A., Lepenioti, K., Apostolou, D., Mentzas, G., 2019. Decision making in predictive maintenance: literature review and research agenda for industry 4.0. IFAC-PapersOnLine 52 (13), 607–612. https://doi.org/10.1016/j.ifacol.2019.11.226.

Centobelli, P., Cerchione, R., Esposito, E., 2017. Efficiency and effectiveness of knowledge management systems in SMEs. Prod. Plan. Control 30 (9), 779–791.

Chris, K.M., Wang, Z., 2001. Using fuzzy linguistics to select optimum & condition based strategies. Int. J. Mech. Syst. Signal Process. 15 (6), 1129–1140.

Demesouka, O.E., Anagnostopoulos, K.P., Siskos, E., 2019. Spatial multicriteria decision support for robust land-use suitability: The case of landfill site selection in Northeastern Greece. Eur. J. Oper. Res. 272 (2), 574–586. https://doi.org/10.1016/j.ejor.2018.07.005.

Dey, P.K., 2004. Decision support system for inspection and maintenance: a case study of oil pipelines. IEEE Trans. Eng. Manage. 51 (1), 47–56. https://doi.org/10.1109/TEM.2003.822464.

Di Nardo, M., Madonna, M., Addonizio, P., Gallab, M., 2021. A mapping analysis of maintenance in Industry 4.0. J. Appl. Res. Technol. 19(6), 653–675. Scopus. Doi: 10.22201/icat.24486736e.2021.19.6.1460.

Drozyner, P., Veith, E., 2002. Risk-based inspection. Methodol. Overview 82–88.

Duffuaa, S.O., Al-Ghamdi, A.H., Al-Amer, A., 2002. Quality function deployment in maintenance work planning process. Proc. 6th Saudi Eng Conf 4, 503–512.

Fuchigami, H.Y., Tuni, A., Barbosa, L.Q., Severino, M.R., Rentizelas, A., 2021. Supporting Brazilian smallholder farmers decision making in supplying institutional markets. Eur. J. Oper. Res. 295 (1), 321–335. https://doi.org/10.1016/j.ejor.2021.02.047.

Giridhar Kumar, V., Chandraiah, B., Amarnath, Y., Charan Kumar, P., 2020. Prediction of Corrosion Levels in Reinforced TMT Bars in SCC Exposed to Marine Environment. In: Babu, K.G., Rao, H.S., Amarnath, Y. (Eds.), Emerging Trends in Civil Engineering (pp. 369–379). Springer. Doi: 10.1007/978-981-15-1404-3_31.

Han, Y., Zhen, X., Huang, Y., Vinnem, J.E., 2019. Integrated methodology for determination of preventive maintenance interval of safety barriers on offshore installations. Process Saf. Environ. Prot. 132, 313–324. https://doi.org/10.1016/j.psep.2019.09.035.

Henriques, I., Sadorsky, P., 1999. The relationship between environmental commitment and managerial perceptions of stakeholder importance. Acad. Manage. J. 42 (1), 87–99. https://doi.org/10.2307/256876.

Holsapple, C.W., 2008. DSS architecture and types. Handbook Decis. Supp. Syst. 163–189.

Hussain, M., Mehboob, K., Ilyas, S.Z., Shaheen, S., 2023. Decision-making during urgent phase of a nuclear accident under extreme conditions. Saf. Sci. 164, 106158 https://doi.org/10.1016/j.ssci.2023.106158.

Ilangkumaran, M., Kumanan, S., 2012. Application of hybrid VIKOR model in selection of maintenance strategy. Int. J. Inform. Syst. Supply Chain Manage. 5 (2), 59–81. https://doi.org/10.4018/jisscm.2012040104.

Joung, B. G., Lee, W. J., Huang, A., Sutherland, J.W., 2020. Development and application of a method for real time motor fault detection. In Y. R. Gao R.X. (Ed.), Procedia Manufacturing (Vol. 49, pp. 94–98). Elsevier B.V. Doi: 10.1016/j.promfg.2020.07.002.

Keers, B.B.M., van Fenema, P.C., 2018. Managing risks in public-private partnership formation projects. Int. J. Proj. Manag. 36 (6), 861–875. https://doi.org/10.1016/j.ijproman.2018.05.001.

Kellner, F., Lienland, B., Utz, S., 2019. An a posteriori decision support methodology for solving the multi-criteria supplier selection problem. Eur. J. Oper. Res. 272 (2), 505–522. https://doi.org/10.1016/j.ejor.2018.06.044.

Khan, F.I., Haddara, M., 2004. Risk-Based Maintenance (RBM): a new approach for process plant inspection and maintenance. Process Saf. Prog. 23 (4), 252–265. https://doi.org/10.1002/prs.10010.

Khan, F.I., Haddara, M.M., Bhattacharya, S.K., 2006. Risk-based integrity and inspection modeling (RBIIM) of process components/system. Risk Anal. 26, 203–221.

Khan, F., Rathnayaka, S., Ahmed, S., 2015. Methods and models in process safety and risk management: past, present. Process Saf Environ Prot 98, 116–147.

Khan, F., Hashemi, S.J., Paltrinieri, N., Amyotte, P., Cozzani, V., Reniers, G., 2016. Dynamic risk management: A contemporary approach to process safety management. Curr. Opin. Chem. Eng. 14, 9–17. https://doi.org/10.1016/j.coche.2016.07.006.

Khan, M.A., Shahid, M.A., Ahmed, S.A., Khan, S.Z., Khan, K.A., Ali, S.A., Tariq, M., 2019. Gear misalignment diagnosis using statistical features of vibration and airborne sound spectrums. Measurement 145, 419–435. https://doi.org/10.1016/j.measurement.2019.05.088.

Krishnasamy, L., Khan, F., Haddara, M., 2005. Development of a risk-based maintenance (RBM) strategy for a power-generating plant. J. Loss Prev. Process Ind. 18 (2), 69–81. https://doi.org/10.1016/j.jlp.2005.01.002.

Lee, W.J., Joung, B.G., Sutherland, J.W., 2023. Environmental and economic performance of different maintenance strategies for a product subject to efficiency erosion. J. Clean. Prod. 389 https://doi.org/10.1016/j.jclepro.2022.135340.

Lees, F.P., 1996. Loss Prevention in the Process Industries (2nd ed.).

Liang, B., Liu, J., You, J., Jia, J., Pan, Y., Jeong, H., 2023. Hydrocarbon production dynamics forecasting using machine learning: a state-of-the-art review. Fuel 337, 127067. https://doi.org/10.1016/j.fuel.2022.127067.

Marsden, J.R., Pingry, D.E., 1993. Theory of decision support systems portfolio evaluation. Decis. Support Syst. 9 (2), 183–199.

Mobley, R.K., 2002. 17—Maintaining the Program. In R. K. Mobley (Ed.), An Introduction to Predictive Maintenance (Second Edition) (pp. 389–393). Butterworth-Heinemann. Doi: 10.1016/B978-075067531-4/50017-8.

Mohammed, A., 2023. Data driven-based model for predicting pump failures in the oil and gas industry. Eng. Fail. Anal. 145, 107019 https://doi.org/10.1016/j.engfailanal.2022.107019.

Moret, S., Babonneau, F., Bierlaire, M., Maréchal, F., 2020. Decision support for strategic energy planning: A robust optimization framework. Eur. J. Oper. Res. 280 (2), 539–554. https://doi.org/10.1016/j.ejor.2019.06.015.

Peron, M., Arena, S., Micheli, G.J.L., Sgarbossa, F., 2022. A decision support system for designing win–win interventions impacting occupational safety and operational performance in ageing workforce contexts. Saf. Sci. 147, 105598 https://doi.org/10.1016/j.ssci.2021.105598.

Ramotsoela, D., Abu-Mahfouz, A., Hancke, G., 2018. A survey of anomaly detection in industrial wireless sensor networks with critical water system infrastructure as a case study. Sensors (Switzerland), 18(8). Scopus. Doi: 10.3390/s18082491.

Rawat, A., Gupta, P. (Dr) S., Rao, T., 2022. A review on prospective risks and mitigation for oil and gas projects: Implication for Indian CGD companies. Int. J. Energy Sector Manage., ahead-of-print. Doi: 10.1108/IJESM-01-2021-0016.

Real Decreto 2060/2008 - ITC EP-3. (2008). Reglamento de equipos a presión y sus instrucciones técnicas complementarias. https://www.boe.es/buscar/act.php?id=BOE-A-2009-1964.

Riis, J.O., Johanesen, J., Mikkelsen, H., 1995. Simulation games in production management—An introduction, (1st ed.). Chapman & Hall.

Rodríguez-Prieto, A., Camacho, A.M., Callejas, M., Sebastián, M.A., 2020. Fitness for service and reliability of materials for manufacturing components intended for demanding service conditions in the petrochemical industry. IEEE Access 8, 92275–92286. https://doi.org/10.1109/ACCESS.2020.2994619.

Saleh, A., Chiachío, M., Salas, J.F., Kolios, A., 2023. Self-adaptive optimized maintenance of offshore wind turbines by intelligent Petri nets. Reliab. Eng. Syst. Saf. 231, 109013 https://doi.org/10.1016/j.ress.2022.109013.

Sellitto, M.A., 2020. Analysis of maintenance policies supported by simulation in a flexible manufacturing cell [Análisis de políticas de mantenimiento soportada por simulación en una célula de fabricación flexible]. Ingeniare 28 (2), 293–303. https://doi.org/10.4067/S0718-33052020000200293.

Shafiee, M., Adedipe, T., 2023. A Bayesian network model for the probabilistic safety assessment of offshore wind decommissioning—2023. Wind Eng. 47 (1), 104–125. https://doi.org/10.1177/0309524X221122569.

Sharma, R.K., Gurjar, B.R., Singhal, A.V., Wate, S.R., Ghuge, S.P., Agrawal, R., 2015. Automation of emergency response for petroleum oil storage terminals. Saf. Sci. 72, 262–273. https://doi.org/10.1016/j.ssci.2014.09.019.

Smedberg, H., Bandaru, S., 2023. Interactive knowledge discovery and knowledge visualization for decision support in multi-objective optimization. Eur. J. Oper. Res. 306 (3), 1311–1329. https://doi.org/10.1016/j.ejor.2022.09.008.

Straub, D., Faber, M.H., 2005. Risk based inspection planning for structural systems. Struct. Saf. 27 (4), 335–355. https://doi.org/10.1016/j.strusafe.2005.04.001.

Tamilselvan, P., Wang, P., 2013. Failure diagnosis using deep belief learning based health state classification. Reliab. Eng. Syst. Saf., 115, 124–135. Scopus. Doi: 10.1016/j.ress.2013.02.022.

Velmurugan, R.S., Dhingra, T., 2015. Maintenance strategy selection and its impact in maintenance function: a conceptual framework. Int. J. Oper. Prod. Manag. 35 (12), 1622–1661. https://doi.org/10.1108/IJOPM-01-2014-0028.

Wintle, J.B., Kenzie, B.W., Amphlett, G.J., Smalley, S., 2001. Best practice for risk based inspection as part of plant integrity management. www.hse.gov.uk.

Xidonas, P., Mavrotas, G., Zopounidis, C., Psarras, J., 2011. IPSSIS: An integrated multicriteria decision support system for equity portfolio construction and selection. Eur. J. Oper. Res. 210 (2), 398–409. https://doi.org/10.1016/j.ejor.2010.08.028.

Yang, J., Wong, C.W.Y., Lai, K., Ntoko, A.N., 2009. The antecedents of dyadic quality performance and its effect on buyer-supplier relationship improvement. Int. J. Prod. Econ. 120 (1), 243–251.