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Cost-Informed Risk-based Inspection (CIRBI) for Hydrogen Systems Components: A Novel Approach to Prevention Strategies

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ABSTRACT

The evolving energy landscape in Europe is showing concrete signals that hydrogen will play a central role in the energy transition scenario. In this light, a report of the European Hydrogen Backbone pinpoints no less than forty existing projects focused on the commissioning of several kilometers of hydrogen pipelines in the following years. Hence, ensuring a safe operability of these systems represents a topic worthy of investigation and marked by significant challenges, especially given the unique properties that make hydrogen a potentially hazardous substance. Established techniques may prove helpful in supporting the development of dedicated prevention and mitigation strategies for hydrogen systems. Among these, Risk-Based Inspection (RBI) could represent an effective tool to design inspection programs aimed at the detection of hydrogen-induced damages, especially for components working in pressurized environments, including pipeline materials. However, the lack of operational experience associated with emerging technologies may lead to the adoption of over-conservative safety measures, which could impact the economic attractiveness of these systems. Therefore, this study proposes an evolution of conventional RBI planning by implementing concepts of safety economics and optimization modelling, thus building a novel approach named "Cost-Informed Risk-Based Inspection" (CIRBI). The proposed methodology is therefore applied to a case study of inspection techniques potentially suitable for pipeline materials (i.e., API X-series pipeline steels), showcasing its potential as a self-standing approach for inspection planning while also demonstrating the insight that it may provide to ensure a safe operability of hydrogen pipelines.

1. Introduction

The API X-series steels [1] are typically in use for the pan-European pipeline network and extensively implemented for natural gas transportation [2]. Such steels have constantly evolved during the past decades [3], undergoing a technological advancement that has improved their mechanical characteristics. However, they are typically characterized by microstructures with a body centered crystal structure [3], which makes them susceptible to hydrogen diffusion and induced degradation. In fact, the diffusivity of hydrogen in these steels can be several orders of magnitude higher than in austenitic stainless steels [4]. While the phenomenon of hydrogen embrittlement has been investigated for several decades, an agreement upon a comprehensive model to describe the resulting effect on a macroscopic level is still missing [5,6]. This, along with a limited experience on the operability of vast scale hydrogen systems [7], explains the lack of risk analysis tools [8] specifically dedicated to the safety of such technologies. Therefore, uncertainties concerning the effectiveness of standard safety practices for pipeline materials exposed to hydrogen degradation were pinpointed in previous publications [9], showcasing potential mis-calculations of risk and unsustainable costs associated to overconservative safety programs [10]. On a broader perspective, it is not unreasonable to suppose that over-precautionary safety and integrity requirements could inhibit a prompt rollout of these systems by burdening their economic feasibility. In fact, previous research pointed out that the toughness-based material qualification tests for hydrogen piping available in the current standards (i.e., the ASME B31.12 [11]) can be typically time-consuming and costly [7].

An existing tool for the planning of inspection activities aimed at tackling the effects of degradation mechanisms in industrial components exposed to corrosive, harsh or detrimental environments is Risk-based Inspection (RBI) [12]. RBI provides a tool for a continuous monitoring

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of the risk associated with critical equipment, thus allowing for a tailored prevention plan to ensure a safe operability of an industrial plant. However, RBI currently has several limitations hindering its applicability to hydrogen systems. In fact, the American Petroleum Institute Recommended Practice 581 (API RP 581) – Risk-based Inspection Methodology [13] – normally considers damage mechanisms governed by corrosion processes (e.g., stress corrosion cracking, stress-oriented hydrogen-induced cracking) in which hydrogen embrittlement is present – but not dominating – in causing an accelerated crack propagation [14]. In such cases, the induced damage is governed by the presence of sour water, wet hydrogen sulfide or hydrochloric acid [13]. Therefore, the adoption of non-specific methodologies may lead to misinterpretation of the real integrity of materials and to the implementation of inadequate safety practices. Moreover, while indicating inspection intervals, the current RBI methods do not provide indications on specific inspection activities, which are suggested in other standards [15].

The methodology proposed in this work aims at evolving conventional RBI methods by including aspects of safety economics [16,17] and optimization modelling. This approach allows for the evaluation of several inspection techniques, and it provides an optimized inspection program as its main output by weighting the effectiveness of the prevention activities on the associated costs. Thus, this paper presents a systematic approach – Cost-Informed Risk-Based Inspection (CIRBI) – for the realization of inspection programs that not only focus on the mitigation of risk, but that consider the budget dedicated to the preventive actions (i.e., the detection of defects and cracks) and the costs associated with each procedure. As such, the overall goal of the current work is to foster an effective adoption of prevention strategies for hydrogen systems, meaning that optimal actions aimed at accident prevention can be evaluated and then suggested or rejected by the model. On the other hand, mitigation strategies – aimed at the minimization of consequences after the occurrence of an accident (e.g., safety barriers) – are currently not included, and the adoption of random inspection campaigns [18] is not considered in the proposed approach.

It should be noted that strategies for optimal maintenance optimization in the context of oil and gas transmission pipeline networks were already proposed in previous works [19], which highlighted the potential for knowledge transfer to hydrogen systems. Therefore, the application of the current model to inspection techniques for the detection of hydrogen damages in pipeline steels is a natural development of the current research trends, especially considering the severity of hydrogen-induced material degradation [20–23] and the inapplicability of conventional RBI planning [8,9]. More specifically, the goal of the current work is to depict the CIRBI methodology and show how it may bridge knowledge gaps affecting inspection programming by considering information on inspection practices and allowing an optimization of the related costs. As such, the proposed discussion delves into:

- the potentially suitable inspection activities that are commonly used for detection of hydrogen embrittlement;
- the implementation of an optimization model to weight inspection costs and expected risk against a safety budget, which can be relevant to address real-world scenarios;
- the inclusion of a weight that allows for a case-specific orientation towards risk mitigation or costs reduction, which may result relevant to get an informed perspective on safety costs.

Throughout the proposed case study, the step by step application of the CIRBI method showcases the effort put in designing optimal inspection programs, corroborating previous research that recently pointed out risks and failure causes of hydrogen pipelines [24]. Therefore, Section 2 of this paper describes the considered inspection techniques, addressing their suitability for the detection of hydrogen-induced degradation. Section 3 depicts the CIRBI methodology, pinpointing the novel steps evolving RBI planning. Section 4 presents the results of the case study, highlighting the potential and the limitations of the model. Finally, some conclusions are drawn in Section 5. As such, the structure of the paper follows a conventional IMRAD (Introduction, Methodology, Results and Discussion) structure [25].

2. Inspection Techniques for Hydrogen Pipelines

The field of non-destructive test (NDT) techniques aimed at the detection, sizing and imaging of flaws and defects is broad and multidisciplinary [26]. Pressure vessels, piping and pipelines typically undergo NDT procedures with the goal of minimizing their likelihood of failure and determining their fitness for service [27]. When it comes to hydrogen embrittlement (or hydrogen damage in general), such detection and subsequent damage quantification is typically challenging, and it demands advanced procedures. Today, a number of NDT methods are available [28,29] for the detection of cracks initiated and promoted by the hydrogen detrimental effect on a macroscopic level [30]. In the present work, the focus is given to these NDT tests, considered as "potentially suitable inspection procedures". In general, a first distinction may be applied between NDTs:

- NDTs that rely on ultrasounds and acoustic waves: generally the most advanced [31], they offer optimal performance, flexibility and good imaging. They require sophisticated equipment, such as transducers that can be individually pulsed with varying time delays to control the direction and focus of an ultrasonic beam [32].
- NDTs that are based on the physical properties of materials applied during testing (e.g., the application of liquids and magnetic particles). These NDTs are very common [33] in the oil and gas industry and offer good capabilities in terms of surface and near surface crack detection [28].
- Visual Inspections: relying on the experience and ability of operators [34], they are commonly used as early warning systems and can be supported by autonomous systems [35].

Table 1 reports the procedures available in the literature and can be used as a reference for the nomenclature. Each technique is addressed with a brief description and indications on its advantages and disadvantages. The evaluation of the costs associated with these procedures is generally case specific, and models aimed at economic evaluations of inspection and maintenance programs were proposed in other works [36]. However, while some of these models rely on the definition of numerical inspection cost functions [37], very limited literature is available on the cost-effectiveness of preventive measures for hydrogen systems. Hence, the terms expensive/cheap that are used in Table 1 should be considered as relative measures and they only serve as generic indication based on the literature [15,29]. In addition, other inspection techniques might be considered when applying the CIRBI methodology to cases other than hydrogen pipelines [38]. The procedures in Table 1 are henceforth considered in this work.

Most of the procedures reported in Table 1 are identified based on the available standards for detection of hydrogen embrittlement [15] and the same nomenclature is therefore implemented (i.e., SWUT, PAUT, PT, MT, WFMT). In addition, a literature search was conducted on the Scopus database with the goal of expanding the used dataset and adding details to the already considered techniques, especially relying on previous literature reviews [30,31] and consolidated information [41,42]. Such techniques are in fact referenced as commonly used for structures under stress (i.e., AE, TOFD) and piping exposed to environmental degradation. For each inspection technique in Table 1, an exact estimation of its effectiveness in reducing the risk of unwanted events and its unitary cost (i.e., the cost of carrying out one inspection) is not straightforward and heavily application dependent. Section 2.1 describes the inspection effectiveness classes [13] and the unitary costs

Table 1
Potentially suitable inspection procedures.

Procedure	Advantages	Disadvantages
Phased-Array Ultrasonic Testing (**PAUT**)	Often indicated as an advanced inspection technique, effective in both defect detection and sizing and potentially automated [39]. It is typically used for piping and pipelines, and it allows for a periodic monitoring of cracks growth [15]. Studies show that can be effectively used for the detection of defects with the size of around 2 mm [32], with an optimal imaging accuracy and defect characterization capability [40].	The testing results might be difficult to interpret [31], and original fabrication flaws might be mistaken for hydrogen-induced cracks. It requires advanced equipment and specialized personnel, resulting typically expensive [15].
Shear-Wave Ultrasonic Testing (**SWUT**)	It has similar advantages and characteristics of PAUT [15], allowing for a targeted inspection of specific welds and defected areas [41].	It may result less effective than PAUT since it relies on fixed angle ultrasonic waves (shear waves) [31]. It may not be adequate for materials with parallel surfaces [41].
Time-of-Flight Diffraction (**TOFD**)	Long-known technique [42] for rapid and reliable flaw detection coupled with an accurate assessment of flaw size [43]. It allows for a precise defect sizing through the diffraction of ultrasonic waves at the edges of cracks, potentially depicting hydrogen distribution in the alloy microstructures [44].	Special scanners and equipment are needed for the inspection of complex geometries [43], which may make TOFD an expensive solution requiring skill and specialized personnel.
Acoustic Emission (**AE**)	It is based on the acoustic emissions that are detected with sensors consisting of piezoelectric ceramic elements [28].It is commonly well suited for inspecting structures under stress [26] and useful to locate and monitor crack growth [15].	Results may be difficult to interpret [30] and may require expensive equipment [28], often used as early warning system.
Liquid Penetrant Testing (**PT**)	Useful as a preliminary screening procedure for surface crack detection [15], it does not require advanced equipment since it is based on capillary action of liquid in cracks [28].	Limited by capillary action, where low surface tension fluid penetrates into clean and dry surface-breaking discontinuities [26]. Limited applicability to surface cracks, may not be effective if cracks are oxide filled [15].
Magnetic Particle Testing (**MT**)	It shows crack edges through formation of particles clusters in the proximity of a crack [28]. It is based on the concept that if there is a discontinuity such as a crack or a flaw on the analyzed surface, the magnetic flux will be broken and a new south and north pole will form [26], representing a useful tool for surface and near surface defect detection in ferromagnetic materials [26].	It heavily relies on the experience and skills of inspectors, which can be problematic for prolonged periods, leading to fatigue and exhaustion [33]. For surface cracks only [28], it does not allow to obtain a thorough evaluation of the crack size and its evolution over time [26].
Wet Fluorescent Magnetic Particle Testing (**WFMT**)	Based on the same principle as MT, it relies on wet magnetic particles coated with a layer of fluorescent material to obtain high-contrast colors. It might result more advantageous than MT since fluorescent particle can highlight cracks more effectively [33].	Similarly to MT, it relies on the experience and skills of inspectors, which can be problematic for prolonged periods [33]. Moreover, its effectiveness also depends on surface preparation before inspection [15].
Computer-aided Remote Visual Inspection (**CARVI**)	Completely automated systems – described in recent studies – that uses a drone to capture pipeline images and assesses corrosion with the aid of machine learning algorithms [34].	Only for a qualitative evaluation on the pipeline integrity from an external perspective [26], it is not able to effectively detect and size small cracks and cracks.
Radiographic Testing (**RT**)	Advanced instrumentation able to detect and size internal defects and fractures of several infrastructures [8]. Considerable experience is available on this practice [45], especially from the oil and gas industry.	It might not be able to specifically detect hydrogen-induced cracks in their initial phases [15], and may suffer from insufficient penetration [32]. It requires specialized personnel and safety barriers for X-rays [45].
Remote Visual Inspection (**RVI**)	Remote visual inspections can be performed using drones or robots [35]. The evaluation of the integrity is typically conducted by an experienced operator.	Same disadvantages as CARVI, but potentially more prone to human error [34].
Visual Inspection (**VI**)	Basic inspection requiring minimum equipment [26] and often considered cheaper than the others. It may provide useful indications as a screening evaluation [27].	Not very effective in detection of small cracks, nor effective in detection of hydrogen embrittlement in its initial phase, prone to human error [46].

[17] that are considered in this work. Additionally, it should be noted that mandatory inspection practices typically exist, independently from their cost or expected effectiveness [27]. Moreover, each inspection technique should be limited in the number of times it is repeated to avoid redundancy (as indicated in the API RP 580 [12]). Hence, the specific inputs and constraints considered for the proposed case study are all reported in Section 2.1.

2.1. *Case-specific Input Data and Variables for Sensitivity Analysis*

The values reported in this section are used as input data for the CIRBI methodology described in Section 3. For the sake of completeness, a brief comment on the source of information is present in this section. The description of the parameters, their role and their meaning in the study is proposed throughout the paper – e.g., when they appear in the equations of Section 3 – to avoid unnecessary cross-references. The parameters in this section are specific for the current study and should only be considered as an indication. In fact, these inputs are decided referring to the available literature when possible or based on the authors' in-field experience and expert elicitation in cases where reliable literature is currently not available. Table 2 shows each input parameter henceforth considered:

Each input parameter reported in Table 2 is used in Section 3 and affects the results presented in Section 4. The 25-year timeframe is applied referring to a previous study [47], in which three Norwegian steel pipelines of different ages were addressed to predict hydrogen-induced degradation and failure costs, with the difference that the latter is expressed in monetary units in this work (instead of consequence area). Based on the results of that same study, a base damage factor of 10 is also selected. On this matter, a sensitivity analysis is proposed to show the effect of an uncertain damage factor definition on the optimized inspection plan, output of the model (Section 4.2). A management system factor and an online monitor adjustment factor are considered equal to 1, as this is the most generic case present in the API

Table 2
Input parameters used in the current study.

Parameter	Values	Ref
Timeframe of the Analysis	25 years	[47]
Cost of Failure	1 M€, 2.5 M€, 5M€	-
Base Damage Factor (prior to sensitivity analysis)	10	[47]
Management System Factor	1	[13]
Generic Failure Frequency	0.0001	[48]
Online Monitor Adjustment Factor	1	[13]
Mandatory Inspections	PAUT to be conducted at least once	-
Redundancy Limit	3	-
Target Failure Frequency	0.01	[48]
Redundancy Factor	2.5	[17]

NDTs:	Effectiveness Class	Unitary Cost:(baseline for sensitivity analysis)
PAUT	A	Expensive (≥8000 €/km)
SWUT	B	Significant (≥7000 €/km)
TOFD	B	Significant (≥7000 €/km)
AE	D	Considerable (≥6000 €/km)
PT	E	Moderate (≥5000€/km)
MT	D	Moderate (≥5000€/km)
WFMT	C	Moderate (≥5000€/km)
CARVI	F	Low (≥3000€/km)
RT	C	Expensive (≥8000 €/km)
RVI	G	Relatively Inexpensive (≥2000 €/km)
VI	E	Marginally Low (≥4000 €/km)

RP 581 [13] and given their marginal role in this study. The values of the failure frequencies are based on the DNV-ST-F101 for submarine pipeline systems [48], in which a target failure frequency is identified as a serviceability limit state – meaning that above this threshold (0.01) the pipeline is unsuitable for normal operations. Finally, information on the redundancy factor can be found in literature concerning operational safety economics [17]. Given the lack of a specific standard definition for the following, the redundancy limit and the number of mandatory inspections are decided by the authors based on reasonable values and the suggestions available in the standards API RP 580 [12] and API RP 581 [13]. A similar consideration applies to the effectiveness categories, which are usually defined based on expert elicitation and case-specific considerations in the same standards.

Along with this, a second sensitivity analysis is conducted to investigate the effect of a variable inspection cost. In fact, operational costs can prove to be highly fluctuating and time-dependent, so it is deemed valuable to show the effect of a variable cost on the output of the model (Section 4.3). Finally, it is noted that while specific input can – and should – be debated, the purpose of the current study is to develop a novel and ready-to-use method to support inspection planning, while a specific prediction of unitary costs, failure costs and effectiveness classes goes outside the scope of the current research. Hence, the CIRBI model is described in Section 3.

3. CIRBI Methodology

Including aspects of safety economics and optimization modelling, the CIRBI method aims at evolving RBI strategies by providing indications on optimal inspection techniques. The effort of evolving RBI into CIRBI follows the necessity of including economic aspects into operational safety. This is a common step for emerging technologies, since economic feasibility is typically a requirement in industrial development and technologic evolution. Safety economics studies are in fact rooted on the concept that a specific safety measure can be implemented only if it can be financially sustained, from which it follows that a gross disproportion between a safety investment and its benefit (e.g., the adoption of over-conservative measures) would deteriorate the feasibility and economic sustainability of a project [49]. In this context, the *Knapsack Problem* [17] typically sets the baseline for reasoning, stating that within a pool of safety measures, only a set of the measures whose combined cost does not exceed an established threshold can be considered, and the optimal combination is the one that guarantees the highest safety compared to each other set. Therefore, the development of the CIRBI method is grounded on this concept, with the difference that the proposed model is characterized by a second objective – along with the obtainment of a maximum benefit – which is the minimization of costs. Hence the adoption of a multi-objective approach that aims at both safety maximization and cost minimization.

Building upon this idea, it is possible to infer the input parameters and variables that are needed to design the model. These parameters include the effectiveness of an inspection and its related cost, the overall available budget and a weight to shift the focus from the first objective to the second one. In addition, rooted on the concept that risk can never be reduced to absolute zero, the method includes a step for the identification of the minimum budget requirements based on the boundary conditions of the case considered. This section depicts each of the core concepts now described, which are recalled in the step-by-step definition of the CIRBI methodology, encompassing effectiveness-cost ratios (*CERs*), benefit-cost ratios (*CBRs*), and the optimization model. To show the applicability of the method, the case study is tailored to industrial components and materials exposed to environmental degradation. A flowchart for the CIRBI methodology is therefore shown in Fig. 1, and each step is described as follows:

1. Description of Component and Expected Operative Life: in this phase, the analyzed component is selected and considered as the input parameter. The expected operative life or a specific timeframe can be used as the duration of the analysis.

2. Conventional RBI application: this phase follows the application of the standard RBI method [13]. For the sake of completeness, the main RBI milestones are summarized as follows:

2.1. Calculation of failure probability: using Equation (1), the failure probability of component *i* at time *t* can be estimated.

$$PoF_i(t) = \ gff_i \cdot F_{MSi} \cdot D_{F_i}(t) \tag{1}$$

The parameters considered in the equation are:

- gff_i, generic failure frequency of component *i*, indicates the failure frequency of equivalent components operating in relatively inert environments and is usually provided by the manufacturer or can be found in established standards.
- F_{MSi}, management systems factor, is an adjustment factor that considers the influence of the management system on the integrity of the component [13].
- $D_{F_i}(t)$, the damage factor, is determined considering the deterioration mechanisms affecting component *i*. In the case of hydrogen pipelines, this is the factor that should take into account the detrimental effect of hydrogen on the pipeline materials [50]. The damage factor – and therefore the failure probability – evolves with the time of exposure to the considered environment, increasing from an initial value named “base damage factor” (D_{FB}).

2.2. Estimation of Failure Consequences Cost: this parameter is the sum of the costs derived from the failure of component *i*. Equation (2) can be used for this calculation, where the nomenclature follows the API RP 581 [13].

$$FC_i = C_i^{cd} + C_i^{affa} + C_i^{prod} + C_i^{inj} + C_i^{env} \tag{2}$$

Where:

- C_i^{cd} is the direct cost of the component damage.

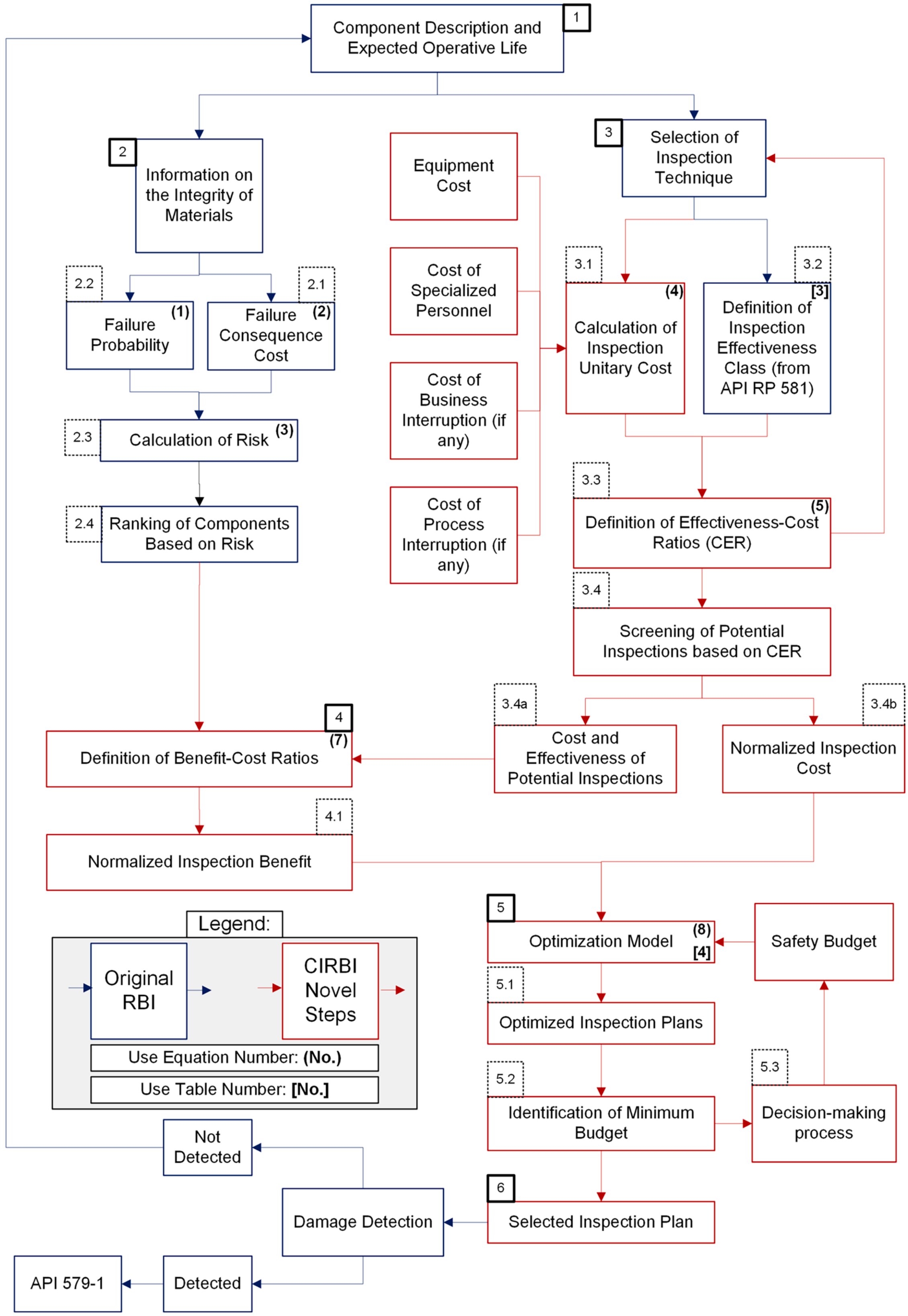

Fig. 1. The CIRBI methodology. In blue, the original RBI method (adapted from the API RP 581 [13]). In red, the novel contribution of the CIRBI methodology. The black square boxes indicate the main phases (in bold) and the intermediated steps (dashed squares). The numbers in parenthesis indicate the reference equation, while the numbers in brackets refer to the reference table.

- C_i^{affa} is the cost of the damage to surrounding components.
- C_i^{prod} is the cost of the lost production.
- C_i^{inj} is the cost of serious injuries to the personnel.
- C_i^{env} is the cost of environmental clean-up.

Particular attention should be paid to this evaluation, since some costs may be challenging to identify and accurately assess. In fact, other additional costs may derive from insurances, image damages, fees, legal expenses, etc. [16]. For hydrogen, the API RP 581 provides a standard procedure (Consequence Analysis Level 1 [13]) that can be used to calculate each term of Equation (2).

2.3. Calculation of Risk: The risk level of component i is calculated combining failure probability and failure consequences, as shown in Equation (3).

$$R_i(t) = PoF_i(t) \cdot FC_i \tag{3}$$

This procedure is repeated for a number of components of the analyzed system, $i = \{1, .., m\}$. In fact, the overall analyzed system is associated with a risk value, and the components associated with the highest risk values (ranking of components based on risk – Step 2.4 in Fig. 1) are the ones that are prioritized for inspection. From this step on, the proposed methodology differs from conventional RBI planning, indicated as the red boxes and arrows in Fig. 1.

3. Selection of Inspection Techniques: according to the description of an analyzed component, suitable inspection techniques ($j = \{1, \ldots, n\}$) need to be selected.

3.1. Calculation of Inspection Unitary Cost: For each considered NDT, the unitary cost of inspection (C_j) can be estimated using Equation (4):

$$C_j = C_j^e + C_j^{sp} + C_j^{bi} + C_j^{pi} \tag{4}$$

Where:

- C_j^e is the cost of the equipment for inspection activity j. It may include the rent of specific tools.
- C_j^{sp} is the cost of the specialized personnel associated with inspection activity j. According to the literature [17], this cost may take into account the transport and the wages of the dedicated personnel.
- C_j^{bi} is the cost of the business interruption caused by inspection activity j. In specific cases, business activities might be stopped while the inspection is being performed (for example if a section of a plant needs to be evacuated due to safety reasons before the inspection can be carried out).
- C_j^{pi} is the cost of process interruption caused by inspection activity j. Similarly to the cost of business interruption, this parameter might become relevant when a process needs to be interrupted before the inspection can be carried out. This might happen if piping or tanks need to be emptied before inspection.

Obviously, other additional costs may be included considering case specific conditions and characteristics.

3.2. Definition of Inspection Effectiveness Classes: according to the API RP 581 [13], the inspection activities under evaluation should be categorized according to their effectiveness. This process is conducted by labelling each NDT with a class (namely A, B, C, D, E, F, G) where each letter is associated with a confidence in defect detection. As such, this definition depends on the extension of the inspected area, the sensitivity of the inspecting tools, the ability of the personnel and the type of damage that must be detected. Expert elicitation may be considered for an accurate positioning of each technique in a specific class. Referring to the method proposed by the API RP 581 standard [13], the classes can be defined as shown in Table 3.

Once each inspection technique is associated with an effectiveness class, effectiveness-cost ratios [17] can be calculated by dividing the confidence in defect detection with the unitary cost of inspection (Step 3.3), as shown in Equation (5).

$$CER_j = \frac{eff_j}{C_j} \tag{5}$$

This procedure allows for a potential exclusion of the inspection procedures that are associated with low effectiveness-cost ratios, thus resulting in a screening procedure (Step 3.4). The costs and the effectiveness of the potentially suitable NDTs are then used in the following phase, which is the definition of a benefit-cost ratio (CBR_j).

4. Definition of Benefit-cost Ratios: CBR_js are defined based on the risk level calculated in Phase 2 and using the unitary cost of inspection. To do so, the inspection benefit of inspection activity j, B_j, is defined as a function of the residual risk as calculated with Equation (6). Note that R_j is the calculated risk when inspection j is conducted and $R_j\left(1 - eff_j\right)$ is the risk not removed by the inspection:

$$B_j = R_j - R_j\left(1 - eff_j\right) \tag{6}$$

Hence, it is possible to define benefit-cost ratios as follows:

$$CBR_j = \frac{B_j}{C_j} \tag{7}$$

Note that the subscript i (indicating a specific component) was dropped so as not to burden the notation. Defining benefit-cost ratios is essential to obtain a comparative measure between NDTs and to understand the scenario-dependency of the model. Once the CBR_js are defined, the inspection benefits and costs are then normalized (Step 4.1 and Step 3.4b) and inputted in the optimization model.

5. Optimization Model: Following the normalization of costs and benefits for each NDT under investigation, the optimization phase can take place. This is the main phase of the CIRBI methodology, which allows for an evolution of the conventional RBI planning by considering inspection costs, safety budget and other additional constraints, such as mandatory inspections and redundancy thresholds. Equation (8) encapsulates the mathematical formulation of the model, for n different inspection techniques:

Table 3
Inspection effectiveness classes.

Inspection Class	Confidence in Defect Detection (eff_j)
A	Above 90%
B	75% - 90%
C	60% - 75%
D	45% - 60%
E	30% - 45%
F	15% - 30%
G	Below 15%

$$\min_x\left(-\gamma\sum_{j=1}^{n}b_jx_j+\delta\sum_{j=1}^{n}c_jx_j\right),\gamma\in[0,1],\delta\in[0,1],\gamma+\delta=1 \quad (8)$$

This optimization problem aims at minimizing the inspection costs, c_j, while maximizing the benefits, b_j. The decision variable, $x_j\in\mathbb{N}^0$, is an element in the array that accounts for the number of times each inspection technique is used. It is noted that lowercase $b_j\in[0,1]$ and $c_j\in[0,1]$ indicate normalized benefits and costs with respect to the corresponding maximum value, so that the two objectives can be integrated into a single objective program. Inside the summations of Equation 8, the normalized costs and benefits are multiplied for the number of times each NDT is repeated (for each x_j), and this number of repetitions – which is the decision variable – is what needs to be calculated. To this end, a solving algorithm must identify the minimum of the total of the two summations for each possible set of decision variables (note that the first summation is preceded by a minus, so the benefit is actually maximized). This minimum value is hence associated with a specific solution vector containing each x_j, thus indicating how many times each NDT should be repeated. Then, this process is repeated for each of the parameters γ and δ, that are the weights given to the objectives, so a different solution vector exists for each specific weight combination. Formally, Equation (8) is a mixed-integer linear problem that can be solved with a variety of approaches and algorithms. In this work, the MATLAB Optimization Toolbox 24.1 is used. More specifically, the algorithm is specified for "Mixed-Integer Linear Programming (MILP)" [51] and uses a combination of "branch and bound" sub-algorithms to determine feasibility regions and eliminate fractional solutions. Given that the problem is convex, the identified solution will be the global optimal solution. Moreover, designing the problem as a MILP [51] allows for an effective – and computationally not demanding – design of an inspection plan.

Once the problem is solved, the output results in a series of optimal sets of inspection procedures (Step 5.1). Each of these solutions is associated with a specific value of γ and δ and a specific number of times that each NDT should be performed in order to manage the risk for the time span of the analysis. So, for each γ (or δ) value, one optimal set of NDTs exists, and one may choose among the different proposed sets based on the relative preference for any of these objectives. The chosen plan is therefore associated with a total cost and a total benefit, defined as the sums of the unitary costs and benefits of each NDT procedure. Therefore, the calculated cost of the plan can be used to identify the lower limit of the safety budget. Hence – along with the plan itself – the output of the model is a minimum budget for risk management which depends on the given weight (Step 5.2). Specifically, this phase is indicated by the loop in Fig. 1 (Phase 5 to Phase 6), meaning that an iteration may be required to adjust the given weight and the following minimum budget to a specific situation (Step 5.3). This process becomes relevant if the safety budget inputted in the optimization model is initially not sufficient, and a detailed explanation of this aspect is provided in Section 4. Once the minimum budget is established, the Pareto front [52] can be plotted directly and a preferred inspection plan can be selected (Phase 6). On the other hand, the results can be interpreted to perform a further modification of the safety budget, depending on specific circumstances and possibly considering a redundancy factor, which is explained in Section 4.

Additionally, the problem is constrained by the constraints given in Table 4.

Table 4
Constraints of the optimization problem.

Constraint		Meaning
$\sum_{j=1}^{n} C_jx_j\leq Bu$	(9)	The total cost of the inspection plan must be less or equal to the available budget *Bu*.
$x_j\geq 1,\ \forall j\in K$	(10)	Mandatory inspections must be performed at least once. *K* refers to the set of mandatory inspections.
$x_j\leq s_j,\ j=\{1\ldots n\}$	(11)	s_j indicates the maximum number of times inspection *j* can be selected. This ensures avoiding redundancy and is essential in RBI strategies [12].

6. Selected Inspection Plan: in this phase, the selected inspection activities are used for damage detection and the methodology falls once again under the API RP 581 standard [13]. If a damage is detected, the serviceability of the component needs to be assessed based on fitness for service criteria [27]. On the other hand – in the case that a damage is not detected – the results indicated by the inspection program are used to re-assess the initial input parameters, thus allowing for an updated and dynamic evaluation of the risk level.

4. Results and Discussion

The calculation of effectiveness-cost ratios (*CERs*) can be useful to perform a preliminary screening of the potentially suitable inspection procedures (Step 3.4), and it is conducted according to Equation (5). It is important to stress once again that the inspection costs can heavily fluctuate depending on case-specific considerations and the moment of the analysis, so the ratios here reported – based on the parameters presented in Section 2.1 – should only be taken as a generic indication of the economic efforts required for each inspection technique. A similar consideration may be applied to the effectiveness classes, which are defined referring to the method proposed in the API RP 581 [13], but that should be tuned according to each specific case and expert elicitation. Hence, Fig. 2 proposes the unitary costs and effectiveness classes (initially indicated in Table 2), from which *CERs* can be easily derived. To facilitate a smooth reading, the NDTs acronyms are also reported in Fig. 2.

The inspection techniques indicated in Fig. 2 are associated with different *CERs*, hinting that inspection procedures with higher *CERs* might be more suitable in terms of safety budget optimization. However, the eleven procedures depicted in Section 2 are all explored by the model in this case. In fact, benefit-cost ratios (*CBRs*) may provide additional information on the actual effect of the inspection on the risk level (*CBRs* consider the expected risk), depending also on the associated consequence category, the specific risk profile and the established threshold, as showcased in Phase 4 of Fig. 1. Fig. 3 highlights this aspect, presenting *CBRs* for three failure scenarios. The NDTs nomenclature and the input parameters are included in the figure for completeness.

While the *CER* is a constant parameter – it depends only on the effectiveness class and the cost of the single inspection – the benefit-cost ratios heavily depend on the consequence category and the calculated risk. As expected, the higher is the estimated cost of failure, the higher the inspection benefit results. This complicates the selection of optimal inspection procedures, since the benefit considerably varies with the cost of an accidental scenario. Moreover, each of the parameters indicated in Fig. 3 affects the results in terms of *CBRs*, so it is vital that a thorough evaluation is carried out along with the application of the CIRBI methodology, distinguishing between the type of possible failure, the expected release of substances, the active safety response and monitoring systems and the overall potential damages to equipment and operators. To avoid an excessive complication in the presentation of the data, the following results are shown for a consequence scenario of 1,000,000 €.

In accordance with the proposed model, the calculated costs and benefits are then inputted in the optimization model (Phase 5 in Fig. 1). As such, suitable inspections are selected depending on the available budget. Hence, a set of optimal inspection procedures is proposed in Table 5, considering an absolute preference for risk reduction (i.e., $\gamma=1,\ \delta=0$). This simply means that the budget is completely used.

Table 5 shows the effect of the available budget on the selected safety

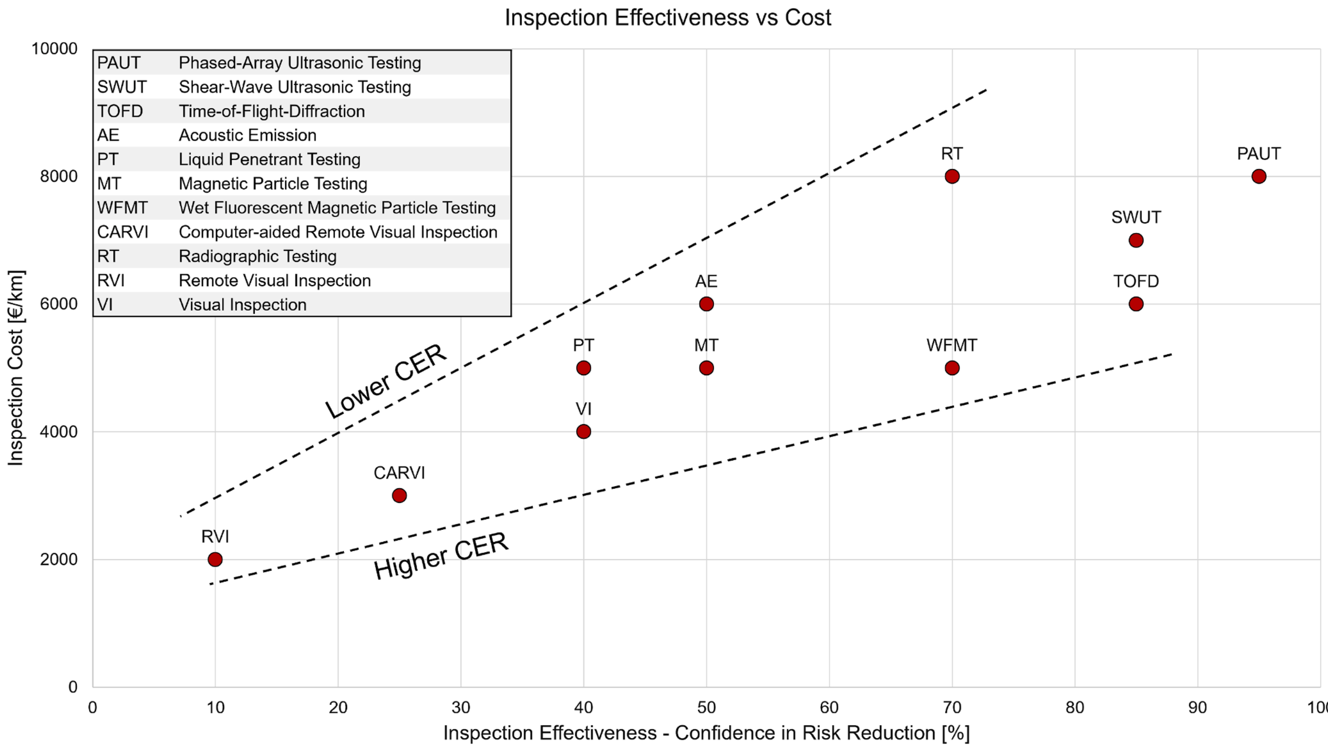

Fig. 2. Effectiveness-cost Ratios (CERs) for each considered inspection procedure.

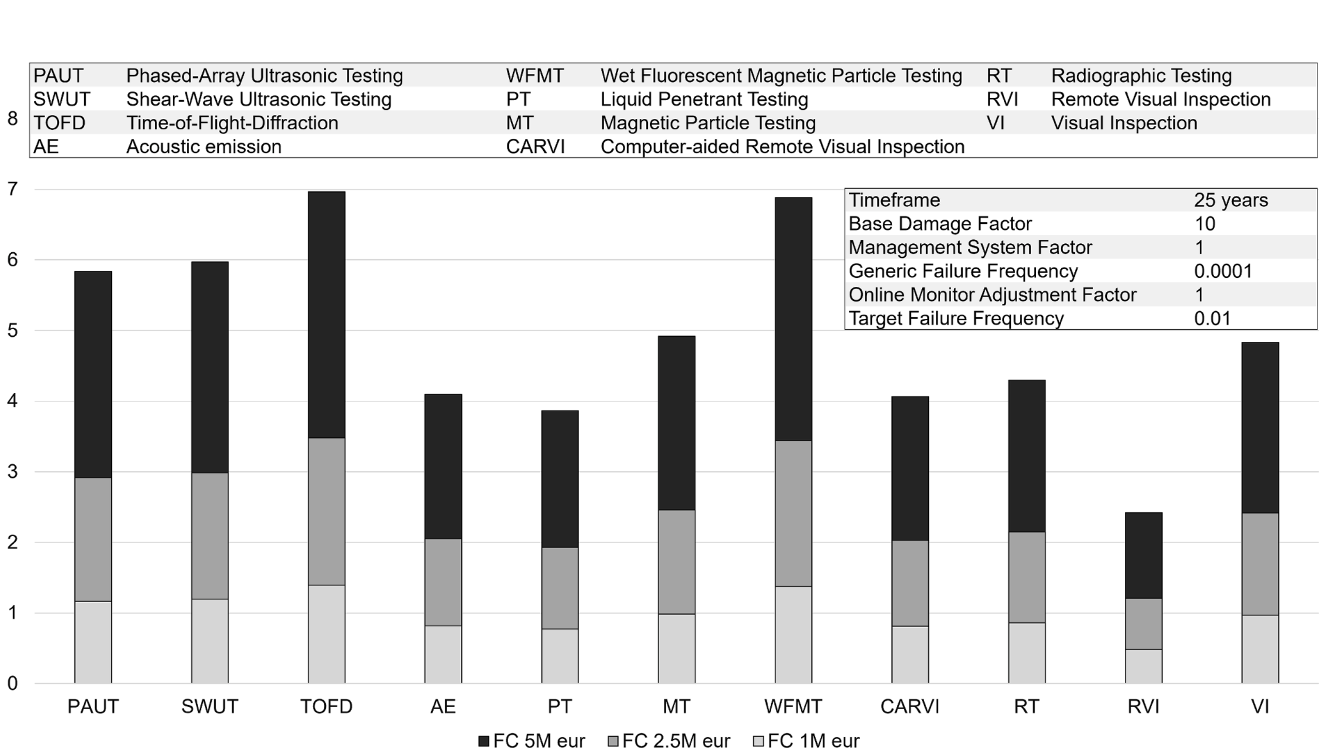

Fig. 3. Benefit-cost ratios for each inspection procedure and their scenario dependency. The parameters involved in the calculation are also indicated in the figure.

procedures. Depending on the economic availability, additional inspections are considered on not. Obviously, an infinite safety budget would allow the selection of only the most effective inspections, but reality imposes economic constraints that must be taken into account when allocating resources. As expected, procedures characterized by higher benefit-cost ratios are preferred when there is available budget. By increasing the budget, more expensive procedures (i.e., PAUT, TOFD) are preferred to the less demanding ones (RVI and VI). This indicates how the budget availability affects the optimal design of the inspection program. Moreover, the effect of the safety budget on the selected

Table 5
Selected inspection procedures with a 100% risk-oriented approach, with a cost of failure of 1 Meur. The numbers below the NDTs acronyms indicate the number of times each inspection should be repeated. A mandatory PAUT inspection is considered.

Budget [k€/km]	PAUT	SWUT	TOFD	AE	PT	MT	WFMT	CARVI	RT	RVI	VI
8	1	0	0	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	0	0	0	1	0
12	1	0	0	0	0	0	0	0	0	0	1
14	1	0	1	0	0	0	0	0	0	0	0
16	1	0	1	0	0	0	0	0	0	1	0

procedures does not limit to the chosen technique, but it also affects the time of inspection. In fact, depending on the effectiveness class of one procedure, the risk profile will be modified, and the inspection intervals change. To describe this more in detail, Fig. 4 presents different the risk profiles depending on the available safety budget. Fig. 4 represents the model output (Step 5.1 in Fig. 1) before entering the decision-making process (Step 5.3).

Fig. 4 depicts the expected risk profiles for the safety budget indicated (Bu). The impact of the selected techniques on the evolving risk is shown, and the latter hints at the minimum required budget for the considered base damage factor and consequence category. For the 25-year risk management, the minimum budget hence results equal to 16 k€/km. Budgets below this threshold (i.e., 8, 10, 12 k€/km) will lead to the selection of less effective inspections after 16 years of operations, and such techniques are not enough effective to keep the risk level under the established threshold – given by consequence category and target failure frequency – for the timespan of the analysis (pink, orange and green curve). Obviously, reducing the economic resources below the minimum requirements leads to a shorter capability of managing the risk. A budget of 14 k€/km allows for a better management of the risk, with respect to 8, 10 and 12 k€/km, but the risk reaches the threshold after 24 years, that is,1 year before the end of the analysis.

Hence, this approach allows defining the moment of an inspection, i.e., 9 years, 16 years and 24 years, while also providing indications on the minimum requirements in terms of the allocation of economic resources. Moreover, varying the base damage factor, the risk threshold and/or the cost of the procedures on a yearly basis, it is possible to obtain a dynamic evaluation of risk, which may be helpful to account for the changes in the actual operating conditions of the pipeline. Additionally, the model takes into account the existence of mandatory inspection activities. In fact, both Table 5 and Fig. 4 are developed imposing at least one PAUT inspection, which is known to be extremely effective in the detection of hydrogen embrittlement [32].

4.1. Optimization of the Inspection Budget

Up to this point, a 100% budget expenditure was considered. However, it is not possible to assume that economic resources will always be exactly the minimum required for managing the risk for the entire duration of the analysis. In operational safety economics [17], it is common for a redundant allocation of resources to be preferred to ensure safe operations, given that companies should prioritize safety rather than expenses reduction [53]. Hence, an exceeding safety budget might be typically considered, possibly ranging in the order of 2 – 4 times the minimum requirements. Such redundancy can also be referred to as a disproportion factor [49], which can be used by investors to bias decision-makers towards safety. In other words, this is often done so that companies may show to governments and policymakers that they are intrinsically biased towards safety [17]. In the case of an exceeding budget, a specific allocation of resources could be preferred in some cases [54]. Fig. 5 highlights this aspect presenting the Pareto Front [52] (i.e., the curve obtained by plotting the optimal solutions found by the MILP algorithm for each value of γ) and it shows the dependance of the latter on the allocated budget. This phase is indicated as Step 5.3 in Fig. 1 – decision-making process – because it allows to select a specific inspection plan by reasoning on a preferential budget allocation, which can be considered as a trade-off between maximizing the inspection benefit and reducing the related costs.

Fig. 5 shows the Pareto Front found by summing the total costs and the total benefits of each inspection plan proposed by the model. Hence, each marker identifies a set of optimal NDTs for a given budget and for a specific γ value. It can be noted how an increasing budget acts as an extending factor for the Pareto Front. In fact, the single fronts all share a common point at cost = 8 k€ and benefit = 88 k€ (indicated as the origin

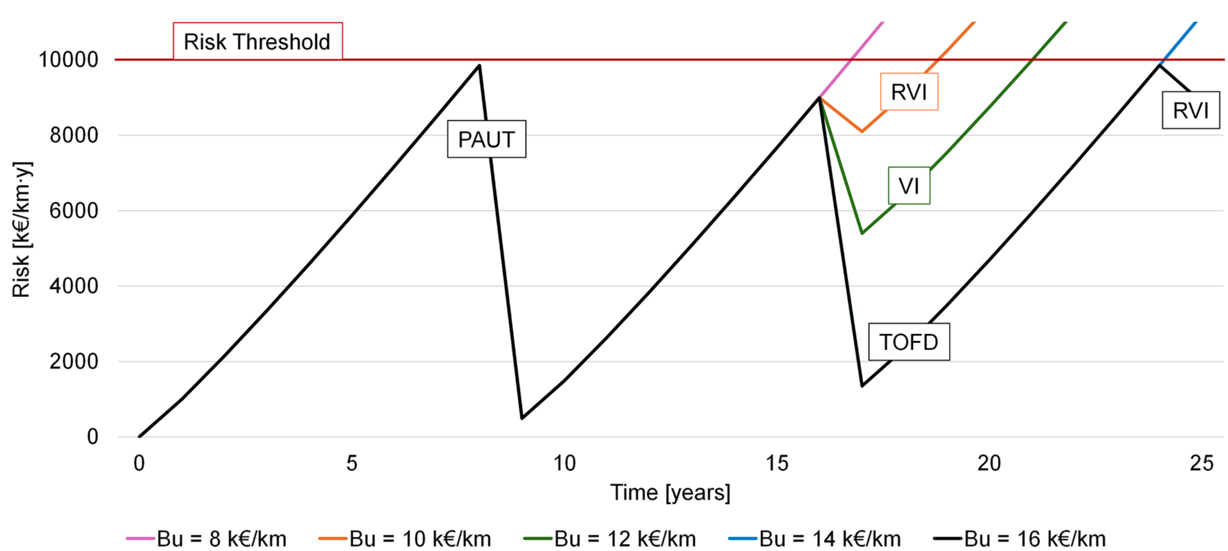

Fig. 4. The effect of the safety budget on the selected inspection practices. One mandatory Phased Array Ultrasonic Testing (PAUT) is considered, while the other suggested NDTs are Time of Flight Diffraction (TOFD), Wet Fluorescent Magnetic Particles (WFMT), Remote Visual Inspection (RVI) and Visual Inspection (VI).

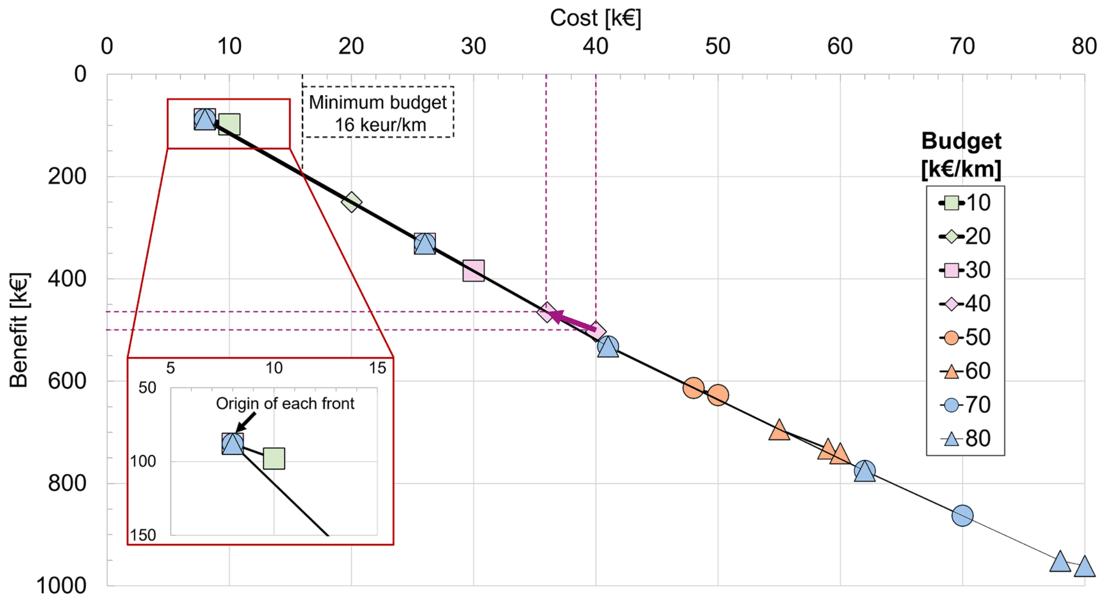

Fig. 5. Pareto Front showing different sets of optimal solutions depending on the inspection budget. Each marker identifies an optimal solution for the given budget. The purple arrow depicts a viable strategy to reduce the budget expenditure while ensuring risk management.

of each front in Fig. 5). This is because relatively low budgets (i.e., 10 k€/km) only allow for the mandatory inspection activity (PAUT), while higher budgets share this optimal solution for values of γ close to zero (i.e., focused on cost reduction). Increasing both budget and γ, higher benefit yields become available, up to a benefit of almost 1000 k€ for a budget of 80 k€. Fig. 5 can therefore be used to compare optimal sets of inspections for a variable budget, providing different solutions depending on the economic availability. However, in real applications a need to meet a fixed budget – imposed by a company, policymakers or governments – may arise. Fig. 5 then can be used to optimize the latter, either obtaining the maximum benefit possible in terms of reduction of risk or by potentially avoiding a complete depletion of the economic resources, thus leading to a reduction of expenses.

In this study, the minimum budget is found at 16 k€/km and a redundancy factor of 2.5 is considered. Therefore, it is possible to assume an overall budget of around 40 k€/km. As shown in Fig. 5, the optimal solution associated with this budget yields a benefit of 500 k€/km, indicated by the pink rhombus at the center of the figure (base of the pink arrow). Hence, a suitable strategy might be to spend the entire budget to realize the inspection plan associated with this solution. Another viable strategy could be the selection of the inspection plan found following the purple arrow in Fig. 5. This leads to a unique definition of the parameter γ and to a reduction of redundant expenses equal to 4 k€/km. Obviously, both plans allow for a management of the risk for the entire time span of the analysis. This procedure encapsulates the loop shown in Fig. 1 (Phase 5 to Phase 6), showcasing the optimization process achieved through budget refining. Therefore, the approach here proposed allowed for:

1. The definition of the minimum requirements in terms of safety budget.
2. The design of optimized inspection plans in function of the available budget.
3. The reduction of the required economic effort by means of a unique definition of the preference-based weight γ, when an exceeding budget is available.

Finally, in the case of a budget = 40 k€/km, the selected NDTs are collected in Table 6.

Table 6 indicates that along with a mandatory PAUT inspection, TOFD and WFMT should be preferred. Moreover, it hints that a visual inspection (VI) could be eliminated because redundant, and this allows for a reduction of costs while ensuring the management of the risk. However, a fixed base damage factor for hydrogen degradation – equal to 10 [47] – was considered so far. Given the lack of an established methodology for the estimation of this factor, the next section proposes a sensitivity analysis to show the effect of uncertainty on the base damage factor on the designed inspection plan.

4.2. *The effect of an uncertain base damage factor*

Uncertainties in the definition of the base damage factor are analyzed in this section. Table 7 shows the effect of an uncertainty level in the base damage factor definition on the selected procedures.

The effect of an increment or decrement in the base damage factor is depicted in Table 7. As expected, factors lower than the one originally set do not affect the proposed solution: 1 PAUT, 3 TOFD, 2 WFMT and 1 VI. However, in the case of +60% there is a change in the proposed procedures. In fact, three PAUT procedures are preferred instead of just

Table 6
Optimized inspection plans for a budget of 40 k€/km. Both strategies allow for a 25-year risk management. The NDTs nomenclature is reported as reference.

PAUT	Phased-Array Ultrasonic Testing	WFMT	Wet Fluorescent MT	RT	Radiographic Testing
SWUT	Shear-Wave Ultrasonic Testing	PT	Liquid Penetrant Testing	RVI	Remote Visual Inspection
TOFD	Time-of-Flight-Diffraction	MT	Magnetic Particle Testing	VI	Visual Inspection
AE	Acoustic emission	CARVI	Computer-aided Remote Visual Inspection		

γ	PAUT	SWUT	TOFD	AE	PT	MT	WFMT	CARVI	RT	RVI	VI	Benefit [k€/km]	Remaining Budget [k€/km]
47	1	0	3	0	0	0	2	0	0	0	0	**465**	**4**
100	1	0	3	0	0	0	2	0	0	0	1	**503**	**0**

Table 7
The effect of an uncertain base damage factor (D_{FB}) on the selected procedures, the table is built considering an approach that is 100% risk oriented ($\gamma = 1$). The uncertainty is defined as a possible reduction or increment of the damage factor.

	Uncertainty	PAUT	SWUT	TOFD	AE	PT	MT	WFMT	CARVI	RT	RVI	VI
4	**-60%**	1	0	3	0	0	0	2	0	0	0	1
6	**-40%**	1	0	3	0	0	0	2	0	0	0	1
8	**-20%**	1	0	3	0	0	0	2	0	0	0	1
10	**-**	1	0	3	0	0	0	2	0	0	0	1
12	**+20%**	1	0	3	0	0	0	2	0	0	0	1
14	**+40%**	1	0	3	0	0	0	2	0	0	0	1
16	**+60%**	3	0	1	0	0	0	2	0	0	0	0

one, meaning that a base damage factor of 16 results in a tilting point for the inspection program. This indicates that a +60% increment of the base damage factor causes the algorithm to prefer inspection procedures that are expensive but highly effective, as one might expect. However, while affecting the proposed solution, the budget of 40 k€/km results sufficient for each of the cases reported in Table 7, meaning that a redundancy factor of 2.5 in the definition of the budget is sufficient to tackle the damage factor increment. When the damage factor ranges from 4 to 12, the same inspection activities are selected by the algorithm. This suggests that the solution is robust and able to tackle a variation of the base damage factor. Nevertheless, one should take into account that the minimum requirements in terms of budget will potentially increase with an increasing base damage factor. A higher factor results in a steeper risk profile, which can reach the established threshold quicker. Therefore, the application of the CIRBI methodology provides additional insight regarding the effectiveness of an inspection plan when uncertainties affect the selection of the base damage factor, as it may happen with equipment exposed to hydrogen-induced degradation. Moreover, it should be noted that the concept of risk uncertainty seems to be also relevant in other areas of risk management for hydrogen systems, for example to assess the consequences of hydrogen leaks like fire generation and explosions [55] – which can be crucial in the prediction of failure costs – or in cases where uncertainties are handled through the implementation of probabilistic perspectives [56].

4.3. The Effect of a Variable Inspection Cost

So far, the unitary inspection costs were considered constant and equal to the values originally reported in Section 2.1. However, given the variable nature of costs and the unreliability of crisp values, this section provides a sensitivity analysis to show the effect of a variable cost on the output of the CIRBI model. Specifically, PAUT, TOFD, WFMT and VI were selected by the model (Table 6) as the preferred NDTs (to be repeated between 1 and 3 times for a base damage factor of 10). By singularly varying their unitary cost, the effect of the latter on the NDT selection can be highlighted, and it is shown in Fig. 6:

Fig. 6 identifies the number of times each NDT is selected by the CIRBI model in case its unitary cost varies between the minimum and the maximum considered for the proposed study. The circles identify the initial cost values. It can be noted how a cost variation affects each NDT selection, since by moving to a higher cost category the number of repetitions drops to zero for each case – with the exception of PAUT that has one compulsory application. This behavior underscores both the importance of reliable cost predictions and the existence of mandatory inspections, since these are critical parameters in the identification of NDT repetitions. Similarly, the redundancy threshold is another vital constraint for the model, since both TOFD and WFMT reach this repetition limit when moving to a lower cost category. This is particularly relevant because redundant inspections can prove to be not only detrimental in terms of higher costs, but also in terms of undermining proactive risk management efforts, as indicated in the API RP 580 [12]. Therefore, this study shows how costs and risk are closely connected and impact the final outcome in terms of a safe operability of a hydrogen pipeline. By presenting a model that incorporates and balances these two key factors, the current work is able to evolve conventional RBI approaches. It is safe to assume that the safety costs of an emerging technology can be extremely unpredictable, and reliable evaluations can be performed only referring to existing plants and facilities. However, showing the effect of an uncertain cost on the selection of safety procedures is important to underscore the existence of this issue to

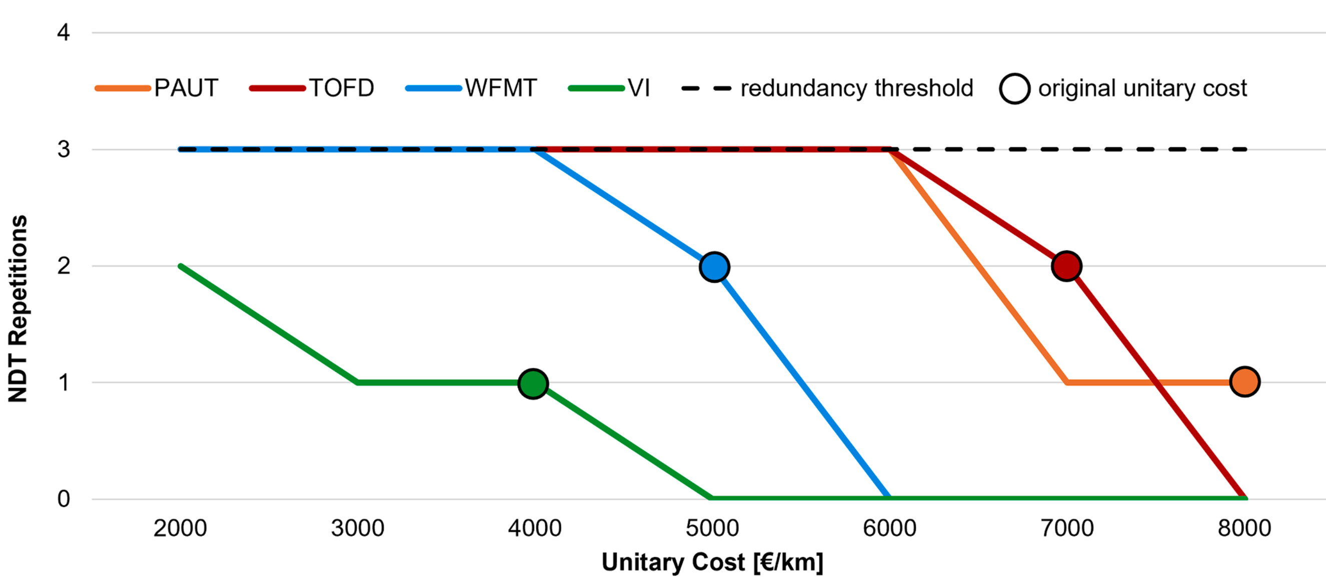

Fig. 6. Sensitivity to cost variation for Phased Array Ultrasonic Testing (PAUT), Time of Flight Diffraction (TOFD), Wet Fluorescent Magnetic Particles (WFMT) and Visual Inspection (VI). The chart indicates the number of times each inspection should be repeated when the cost varies.

researchers and industries. While this can be considered as an added value for this study, limitations that may hinder the current applicability of the CIRBI model to real-world cases should be acknowledged, along with recommendations for future research.

4.4. Limitations and Future Work

While providing indications on *when* and *how* to inspect (definition of inspection intervals and type of inspection), the application of the CIRBI methodology does not allow for a definition of the *order* of the inspection activities. This is because the proposed model does not take into account potential increased (or decreased) efficiencies of the inspection activities if these are performed in a particular order. However, there is still a dearth on the available literature concerning this topic, and an updated model – that considers variable efficiency due to the inspection order – may be developed when more data will become available. A dynamic efficiency could be inputted in the methodology, along with similar considerations on the inspection costs. In fact, a specific definition of the order of the inspection activities may allow for a clearer definition of the costs, since discounting cost ratios could be implemented when a specific NDT order is known. For this reason, discounting cost ratios are not considered in this work and modifying the unitary inspection costs according to the inspection intervals may even pose problems in terms of safety. In fact, the inspection techniques that would benefit the most from discounting cost ratios are the most expensive ones (and typically more effective). In other words, inputting discounted costs without other specific indications on the order of the inspections would only lead to a retardation of the expensive inspections, meaning that cheaper procedures would be prioritized so that expensive procedures may benefit the most from discounted costs. A preferential order of inspection should be therefore investigated in the future, possibly when additional literature on the topic will be available.

Another consideration on future evolutions of CIRBI can be rooted on the concept that pipeline infrastructures are often interconnected, meaning that the service demand involving one pipeline can depend on the availability of other transmission systems, along with the operation of upstream, midstream and downstream facilities. Therefore, an optimal planning of preventive actions for such interconnected structures may result vital in ensuring their resilience and reduce the related costs, aspect which is already remarked in previous research addressing different complex infrastructures [57]. In addition, while the application of the current model results in a preferential allocation of economic resources in the likely case of a budget constraint, the model does not weight case-specific governmental policies, risk-acceptance criteria and safety investment compulsory requirements. Building upon previous results targeting the challenges of including these aspects in optimization models [58], implementing these concepts may be considered to further evolve CIRBI towards a comprehensive methodology for system safety. Finally, given the intrinsic cost-benefit nature of the current approach, its potential support in ALARP analysis should be considered, for example by highlighting cases of gross disproportion [59] between the costs and effect (benefit) of a specific NDT.

5. Conclusions

This work addresses the problem of developing cost-informed inspection plans for risk management. To do so, the CIRBI model is proposed and discussed by means of a case study. Eleven NDTs – identified through a literature analysis on inspection techniques used in the oil and gas sector and for the detection of hydrogen embrittlement – are considered for the inspection of a pipeline material.

The main result of this work is the development of the CIRBI methodology itself. Based on conventional RBI planning, the proposed approach implements concepts of cost-benefit analysis and an optimization problem to design cost-informed inspection strategies. As such, the study supports the definition of a minimum inspection budget, required to effectively mitigate the risk of an accidental scenario. In fact – solving the optimization problem at the core of the CIRBI model – optimized inspection programs are developed depending on the available budget. The inclusion of a preference-based weight results in a selection of a specific optimized plan, allowing for the reduction of the costs while ensuring risk management.

An uncertain definition of a hydrogen-related base damage factor is addressed, showing how this uncertainty may impact the selection of the NDTs in the case considered. The results – limited to the analyzed case – suggest that an exceeding safety budget of 2.5 times the minimum requirement is enough to ensure that the proposed inspection plan is not affected by an error in the damage factor definition up to 40%. Above this level, the model suggests inspections associated with higher effectiveness-cost ratios. The proposed plan can be also modified due to variable costs, highlighting that a thorough evaluation of NDT costs is necessary to ensure cost-effective prevention strategies. Therefore, while the current work consists of a novel and ready-to-use tool for safety economics, the obtained results require thorough validation, which may be achieved by relying on data from pilot projects and previous applications of hydrogen transport systems (small scale gaseous hydrogen transport in piping is not a new concept in refineries and process industries). Such data may be used to define the costs of inspecting pipelines (Phase 3 in Fig. 1) and the output of the inspection itself, which usually provides information on the number of identified defects, their size, shape and severity (Phase 2 in Fig. 1). This, combined with other conventional assessments – such as leak-before-break criteria [60] and compliance with the standards API 579 and ASME B31.12 – can result in an optimal management of hydrogen transport via pipeline.

Finally, the proposed approach could be (and possibly will be) applied to conventional systems for which extensive data is already available – such as natural gas pipelines – thus proving its reliability as a self-standing methodology in defining high-safety and economically viable inspection solutions.

CRediT authorship contribution statement

Leonardo Giannini: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Genserik Reniers:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Ming Yang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Maria Nogal:** Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Nicola Paltrinieri:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, 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.

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Data availability

Data will be made available on request.

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