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Towards Cost Effective Inspection Strategies For Hydrogen Pipelines: Current Challenges And Potential Solutions

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Abstract

The utilization of hydrogen as a clean energy carrier has gained significant momentum in recent years. Hydrogen transport via pipeline may support the global transition towards clean energy sources, fostering the development of the hydrogen value-chain by using the existing infrastructure. However, this idea faces numerous challenges, particularly in the context of hydrogen-assisted fatigue failures. Such failures may be mainly caused by the detrimental effect of hydrogen on pipeline steels but are also promoted by the complex interactions among various operational and mechanical parameters, necessitating a comprehensive understanding of their combined effects for the development of effective prevention and mitigation strategies. In the past few years, numerous studies addressed critical operational variables, including loading frequency and amplitude, pressure, temperature, and gas impurities, that are known to influence the structural integrity of hydrogen pipelines and may ultimately affect the likelihood of a loss of containment. However, a comprehensive understanding of the phenomenon is still missing. Moreover, the implications of this hydrogen-induced reduction of fatigue performances on operational safety practices are still mostly unexplored. Knowledge gaps and research challenges derive from this concept, and this work identifies them by means of a gap analysis with the purpose of promoting effective inspection strategies. Along with the definition of research challenges, this work proposes potential solutions based on the current research activity on hydrogen technologies, highlighting favorable elements for the implementation of data-driven approaches for dynamic risk evaluations. In addition, this study points out innovative methods for consequence assessment, a vital procedure in the framework of risk-based inspection and maintenance plans. In fact, a well-designed inspection program – specifically conceived for hydrogen steel pipelines – may be susceptible of improving the overall safety of this technology, while also potentially allowing a cost-optimization of the safety strategy. To achieve this goal, this work proposes a roadmap towards cost-effective risk-based inspection programs in the framework of hydrogen pipelines. Finally, particular attention is paid to the uncertainties and methodological gaps affecting failure probability and consequence assessment when dealing with the loss of containment of a hydrogen pipeline.

Keywords: hydrogen transport, pipeline safety, dynamic risk analysis, inspection plan, hydrogen-enhanced fatigue, safety-cost optimization

1. Introduction

Hydrogen has received increasing interest from stakeholders in recent years, and the development of a hydrogen value chain is fostered by several projects and investments in Europe. As such, a strategic objective is the deployment of at least 40 GW of renewable hydrogen electrolyzers between 2025 and 2030 (European Commission, Secretariat-General, 2020). Initially, the produced hydrogen will be used in local clusters, relying on decentralized energy production for industrial and commercial applications. In the following phase, a hydrogen pan-European pipe grid will be needed for medium-range transport and for international trade with neighboring countries (European Commission, Secretariat-General, 2020). Hence, a significant fraction of the existing pipeline network, originally designed for natural gas transport, shall be retrofitted and/or repurposed for gaseous hydrogen transport to reduce the financial and economic burdens of developing new systems from scratch. Although representing a viable solution, the lack of operational experience and the unique properties of hydrogen pose engineering challenges that need to be tackled to ensure the safe operability of hydrogen pipeline systems. Such challenges interconnect matters of material science with aspects of operational safety, and this work aims to:

- Identify some of the main challenges to be faced to allow the development of effective inspection strategies for hydrogen pipelines;
- Propose suitable solutions to overcome such challenges by evaluating the probability and the consequences of hazardous scenarios (i.e., pipeline loss of containment);
- Introduce risk-based inspection strategies in the framework of safety economics, indicating how uncertainties concerning material compatibility and risk evaluations may affect the economic potential of hydrogen pipelines.

In this light, the scenario of a generic loss of containment (LOC) can be depicted by a bow-tie diagram (Villa et al., 2016), in which the critical event (i.e., the hydrogen release) is situated in the center, with possible causes and consequences indicated on the left and on the right sides of the diagram, respectively. The illustrative nature of a bow-tie diagram (Figure 1) can prove its effectiveness in conceptualizing the key aspects of the problem. Hence, the elements in the diagram are identified and discussed in the following sections.

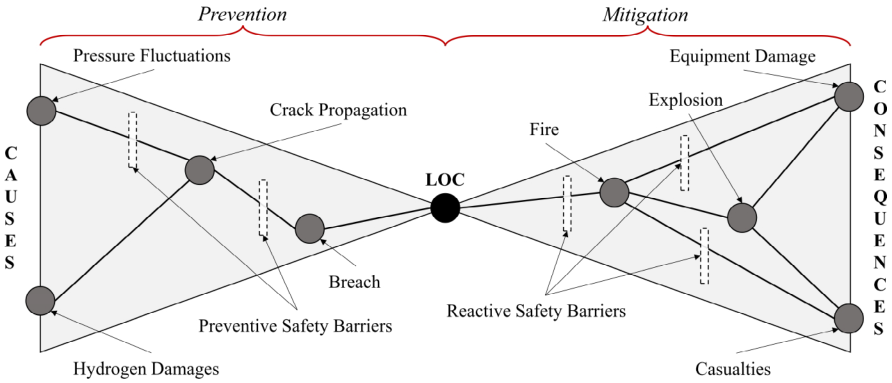

Fig. 1. Depiction of a generic LOC scenario by means of a bow-tie diagram. The gray circles indicate potential (but not exhaustive) causes that may lead to a LOC scenario and the potential following consequences.

The red brackets in Figure 1 divide the diagram into two sections: prevention (before the LOC) and mitigation (after the LOC). The safety measures usually conducted in the prevention (or proactive) phase (e.g., the design and development of preventive safety barriers – dashed rectangles in the left side of Figure 1) are connected to the minimization of the likelihood of failure of a piece of equipment and to avoid cascading scenarios that may lead to the critical event (Khan et al., 2016). On the other hand, the safety measures connected with the mitigation (or reactive) phase aim at limiting the consequences of the critical event (e.g., the design and development of reactive safety barriers – dashed rectangles in the right side of Figure 1 (Landucci et al., 2016)). This bi-folded structure is often considered in the overall definition of risk, which can be expressed as follows (American Petroleum Institute, 2019):

$$Risk(t)_i = PoF(t)_i \cdot CoF_i \tag{1}$$

Where *PoF* and *CoF* are respectively probability and consequence of failure. The subscript i indicates a specific component, and the risk profile of a facility or system is usually determined for several pieces of equipment to define the critical items (associated with a relevant fraction of the total risk (American Petroleum Institute, 2016)). However, this calculation can be performed considering different scenarios for each specific component, so – for a given item – the subscript i may also indicate a specific scenario (e.g., a small, medium, or large leakage). Again, a generic LOC scenario is considered in this analysis. In Equation 1, the probability of failure is usually considered to evolve with time, which is a vital element for dynamic risk analysis (Paltrinieri and Reniers, 2017) – particularly in the case of hydrogen equipment. Hence, probability and consequence evaluations are crucial to determine the risk level, and they are also central to risk-based safety optimization (RBSO) (Chen et al., 2021), a commonly used method in safety economics to optimize the costs of a safety strategy. To achieve a reliable calculation of the cost of a safety strategy, RBSO weights the cost of a safety strategy (in this case, the inspection plan) on the cost of a potential accident scenario (Eslami Baladeh et al., 2019). The objectives of RBSO (Table 1) are considered as key elements for cost-effective inspection strategies for hydrogen pipelines and discussed in this study to identify current research and knowledge gaps.

Table 1. Objectives of a risk-based optimization process (RBSO) for inspection programs of hydrogen pipelines.

Objectives of a generic RBSO (Chen et al., 2021)	RBSO of Inspection Programs for Hydrogen Pipelines.
Hazard and Scenario Identification.	Pipeline Loss of Containment (LOC) and other unwanted events.
Probability Assessment.	Evaluation of Hydrogen Damages and their Effect on Fatigue Crack Propagation.
Consequence Assessment.	Evaluation of the Consequences of a Hydrogen Release.
Risk Calculation.	Definition of the Risk Level Associated to the Event/Scenario.
Identification of possible Safety Strategy.	Development of an Inspection Plan to Mitigate the Calculated Risk of a Scenario.
Cost Calculation and Minimization.	Optimization of the Inspection Plan in Terms of Intervals and Measures.

2. Methodology

To identify the existing challenges that need to be addressed to ensure an effective operability of hydrogen pipelines, the following methodology (gap analysis) was developed, referring to the suggestions present in the literature (Suriadi et al., 2014).

1) Definition of the current state: Description of the recent research activity concerning metal-hydrogen interactions in pipeline steels, the existing standards for risk-based inspection programs (probability and consequence assessment) and the framework of cost-optimization of inspection strategies.
2) Gap Definition and Analysis: Identification of the aspects that need further investigation with the goal of evolving and improving the current state.
3) Definition of the future state: Description of the overall goal of the research, providing suggestions on potential solutions that may enable an effective inspection program for hydrogen pipelines.
4) Roadmap Development: Implementation of the discussed key concepts to highlight the steps towards cost-effective inspection plans for hydrogen pipelines.

This method offers a structured yet dynamic way to navigate the evolving landscape of hydrogen infrastructure research and development. What makes this methodology particularly effective is its adaptability and its foundation in continuous improvement. As new research findings emerge and technologies evolve, this approach allows for a re-evaluation of the current state, identification of new gaps, and updating of the roadmap accordingly. This iterative process ensures that the research remains relevant, forward-looking, and responsive to the changing landscape of hydrogen pipeline technology.

3. Intermediate results

While the intermediate results from steps 1, 2 and 3 are presented in the following, Table 2 summarizes their implications in terms of the key concepts of hydrogen-enhanced fatigue, probability of failure and consequence of hydrogen releases.

Table 2. Implemented methodology and paper structure.

Sections / Method. steps	1. Current State of the Research	2. Identified Gap(s)
Hydrogen-enhanced fatigue.	Investigation of the variables influencing fatigue crack acceleration.	Comprehensive understanding of the combined effects and the hierarchy of operational and mechanical variables to predict the crack development.
Data Driven Approaches to Predict Hydrogen-Enhanced Fatigue Crack Growth Rate.	Models based on tensile properties of steels and characteristics of corrosive environments.	Models' variables and parameters potentially not relevant for the working conditions of hydrogen pipelines.
Probability of failure in the RBI framework.	Methodology developed by the American Petroleum Institute (API) to assess failure probability.	Inexistence of a dedicated methodology for hydrogen-induced deterioration.
Consequence of hydrogen releases.	Consequence Evaluation in RBI for hydrogen releases.	Lack of records and inexistence of specific models to support the standard evaluations.

3.1. Hydrogen-enhanced fatigue

Some criticalities emerge when considering hydrogen transport via pipeline (Briottet et al., 2012; Giarola et al., 2022; Li et al., 2022; Nykyforchyn et al., 2021). Hydrogen compatibility with ferritic steels (typically used for pipeline systems) is a long-debated topic, but some key aspects are still not fully understood (Briottet et al., 2012; Li et al., 2022; Melania et al., 2013;). Hydrogen is known to negatively influence the fatigue performances of pipeline steels, thus promoting crack propagation (Slifka et al., 2018). This phenomenon is usually referred to as hydrogen-enhanced fatigue (HEF) (Laureys et al., 2022), and several studies identified the parameters and conditions governing this degrading effect. When testing ferritic steels in hydrogen environments, such variables involve operative conditions (e.g., hydrogen pressure, temperature, hydrogen purity, and loading frequency) and material characteristics (e.g., steel grade, microstructure, chemical composition, and surface conditions). The effect of some of these variables has been extensively described in previous research and review papers. In fact, hydrogen-induced fatigue crack acceleration is a long-known phenomenon, but researchers have highlighted a complex synergy of factors governing crack initiation and propagation that is not fully understood yet (Li et al., 2022). Such factors influence the operating life of hydrogen transport pipelines, but the specific influence of each parameter is still debated. In general, the loading history of the steel can foster hydrogen accumulation in areas characterized by high triaxial stress (Alvaro et al., 2019; Christmann, 1983; Matsunaga et al., 2017). In fact, loading peaks, critical loading frequencies and amplitudes – which could be common during the life of a pipeline due to daily fluctuations in the pressure level – are known to influence the susceptibility to fatigue crack propagation (Slifka et al., 2014). Similarly, the role of the pipe surface conditions in assisting hydrogen absorption and the behavior of welds and heat-affected zones has not been described in detail yet (Alvaro et al., 2014; Davis and King, 1994).

Some studies (Faucon et al., 2023) point out that the detrimental effect caused by hydrogen is more severe on the welded metal under fatigue conditions, while others (Chatzidouros et al., 2011; Giarola et al., 2022) found out that the microstructure of the heat-affected zone was less susceptible to hydrogen degradation. Hence, further experimental evidence is needed to assess weldment compatibility with hydrogen environments and to ensure the safe transport of hydrogen via pipeline. Moreover, future experimental campaigns focusing on a thorough description of the variables influencing the hydrogen-enhanced fatigue crack growth rate (HEFCGR) are of utmost importance. However, different approaches could be considered to evaluate the effect of hydrogen on the fatigue crack growth of pipe steels and could represent a support for operational safety.

3.2. Data-driven approaches to predict hydrogen-enhanced fatigue crack growth rate

The combined effect of the different variables and conditions affecting HEFCGR is still debated, but experts already proposed different innovative approaches – based on data-driven predictions – to assess hydrogen degradation. In general, machine learning (ML) algorithms were implemented to estimate different hydrogen-induced detrimental effects, ranging from loss of ductility (i.e., prediction of embrittlement index, loss of elongation, and reduction of ultimate tensile strength (Campari et al., 2023b; Kim et al., 2022; Malitckii et al., 2020)) to the decreased resistance to crack propagation (i.e., reduction of fracture toughness (Phan et al., 2022)). According to such studies, machine learning algorithms have a considerable potential in providing insight on the hierarchy of the variables governing hydrogen detrimental effects, with the recommendation of using large databases and accurate datasets to ensure the models' performances (Phan et al., 2022).

However, researchers (Slifka et al., 2018; Stalheim et al., 2012) pointed out that the variables governing the severity of the ductility loss (e.g., yield strength) may not have a dominant effect on the characterization of the fatigue performances. This crucial consideration implies that the existing studies concerning machine learning models to evaluate hydrogen damages may not provide reliable indications for equipment subjected to cyclic loads (i.e., hydrogen pipelines). Hence, the development of dedicated models to estimate HEFCGR could provide precious and insightful results describing steels' susceptibility to hydrogen-enhanced fatigue. Ideally, a ML model for predicting the HEFCGR should facilitate the selection of compatible materials and suitable operating conditions for hydrogen transport pipelines, and estimate the remaining lifetime of such components, thus enabling risk-informed inspection and maintenance planning.

In general, the development of a ML model consists of four main phases:

- Database creation and data pre-processing;
- Definition of the target to predict;
- Model selection and training;
- Performance evaluation and optimization.

The first step is the most demanding since gathering enough experimental data is challenging and requires an accurate selection of features capable of describing the phenomenon. In addition, most fatigue tests are conducted at frequencies between 0.1 and 1 Hz (to reduce the overall test duration and cost), significantly higher than the daily pressure fluctuations in the pipeline network (around 10^{-5} Hz). Considering that fatigue degradation in hydrogen environments is a time-dependent phenomenon (Laureys et al., 2022) and that the hydrogen effect tends to increase at lower loading frequencies (Matsunaga et al., 2017), tests under realistic operating conditions should be conducted. Moreover, the presence of welds obtained through different techniques should be accounted for. Stated that data quality and quantity are crucial to develop reliable ML models, it is also possible to consider other data-driven approaches. In fact, the complex interaction among the variables governing the HEFCGR could be modelled by means of Bayesian Networks (BN).

A previous study (Yoon et al., 2021) used in-field inspection data and a Bayesian model to predict the hydrogen-assisted crack growth of a nickel alloy for nuclear applications. A Dynamic Object-Oriented Bayesian Network (DOOBN) was developed in another work (Dao et al., 2023) to investigate the safety of pipelines where hydrogen was blended with natural gas. Although being of high relevancy for risk analysis of hydrogen pipelines, the directed acyclic diagram (DAG) proposed for the BN study considers elements and parameters critical for corrosion processes (hydrogen sulphide corrosion, hydrogen stress cracking, corrosion fatigue, stress corrosion cracking) and not for the dominant degradation mechanisms active in high purity hydrogen environments (i.e., HEFCGR). Hence, a non-exhaustive DAG is proposed as follows (Figure 2), based on the results of existing literature on hydrogen-assisted fatigue damages (Laureys et al., 2022; Li et al., 2022).

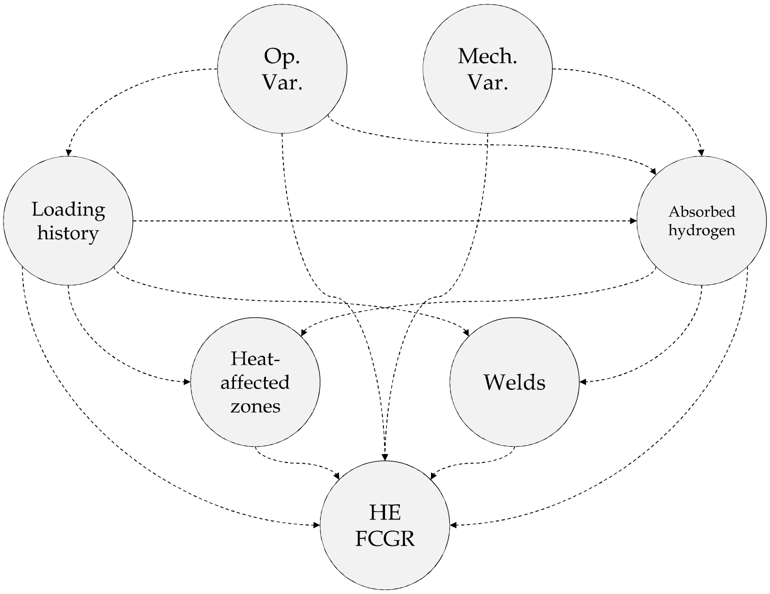

Fig. 2. Descriptive DAG of relevant variables influencing the crack growth rate of a hydrogen pipeline.
Op. Var.: Operational variables, Mech. Var.: Mechanical Variables.
The arrows indicate that a particular parameter influences the susceptibility to hydrogen degradation of the others.

In the diagram of Figure 2, operational and mechanical variables are assumed to influence the HEFCGR while also affecting the other variables. Operational variables include parameters such as pressure, temperature, and hydrogen purity, which are known to directly affect the crack propagation. On the other hand, mechanical variables such as yield strength, microstructure, fracture toughness, and chemical composition are also crucial in the determination of the resistance to crack propagation. Moreover, operational parameters such as daily pressure fluctuations may influence the loading history of the pipe, determining loading peaks, frequency, and amplitude.

Overall, these first-order variables can affect the absorbed hydrogen and its accumulation in areas characterized by residual stress, which may co-determine the susceptibility to cracking of heat-affected zones and welds. So, the scope of Figure 2 is to point out that operational variables and mechanical characteristics influence other various parameters (interdependent variables) while also affecting the resulting HEFCGR. In fact, the loading history (especially the loading frequency) is known to influence the permeation of hydrogen in the metal lattice (Alvaro et al., 2019; Laureys et al., 2022; Matsunaga et al., 2017; Nanninga et al., 2012; Slifka et al., 2014) , while also influencing the susceptibility to cracking of heat-affected zones and welds (Alvaro et al., 2014; Chatzidouros et al., 2011; Faucon et al., 2023). In fact, the overall hydrogen damage is the result of a complex interaction of interlinked variables that encompasses operative conditions and mechanical envelop.

Hence, a probabilistic model built on the variables above could provide useful indications on areas – or even pipe sections – particularly prone to crack propagation and support dynamic risk modelling. However, a thorough and comprehensive study on the hierarchy and actual co-influence of the proposed variables is currently missing, and an attempt to build a complete BN based on the proposed (and additional) variables could be object of research. In any case, other additional steps are necessary to bridge the gap between HEFCGR and failure probability.

3.3. Probability of failure in the RBI framework

Risk-based inspection strategies refer to the definition of risk presented in Equation 1 (American Petroleum Institute, 2019). Within this framework, the probability of failure needs to be as accurate as possible to ensure a reliable calculation of risk, and it is calculated as follows:

$$PoF(t)_i = gff_i \cdot F_{MS_i} \cdot D_f(t)_i \tag{2}$$

where:

- gff is the generic failure frequency of the component, often obtained from failure databases for similar equipment;
- F_{MS} is the management system factor, a parameter accounting for the role of the facility management;
- $D_f(t)$ is the damage factor, which considers the age of the equipment and the actual working conditions of the analyzed components. Hence, the hydrogen-enhanced fatigue fracture propagation in pipe steels working in a high-pressure hydrogen environment should be taken into consideration in the assessment of this coefficient;
- i indicates once again the specific component. When addressing different scenarios for a component, different probabilities can be calculated for each item, thus identifying the most hazardous and critical scenarios.

According to literature, a specific methodology for the calculation of this factor does not exist for most hydrogen-induced damages (Campari et al., 2023c). However, a preliminary methodology for this calculation – based on the structure of the API Recommended Practice 581 (American Petroleum Institute, 2019) – was proposed in a previous study (Campari et al., 2023a). Hence, to develop an effective risk-based inspection strategy for hydrogen pipelines one should rely on an accurate evaluation of the damage factor. This goal can be achieved only if a widely accepted and standardized methodology will be developed in the future.

In fact, the existing methodologies for damage factor evaluations related to hydrogen damages (American Petroleum Institute, 2019, 2016) consider hydrogen degradation to be active only if fostered by corrosive processes (Anderson, 2005; Campari et al., 2023c; Giannini et al., 2023; Ustolin et al., 2021) or at high temperatures (e.g., high-temperature hydrogen attack (American Petroleum Institute, 2020)). Hence, a link between HEFCGR and the damage factor is currently missing. An effective understanding of the variables governing HEFCGR and models to predict it may constitute the basis of an *ad hoc* methodology for hydrogen-enhanced fatigue. Hence, such methodology – rooted in the RBI framework – may support an accurate evaluation of failure probability for equipment working in hydrogen environments.

Moreover, the overall risk calculation is also based on the evaluation of the other coefficient in Equation 1, the consequence of failure (CoF). The lack of operational experience and records concerning hydrogen pipelines implies that limited knowledge is available on this topic, an aspect that is explored as follows.

3.4. Consequences of hydrogen releases

In RBI programs (American Petroleum Institute, 2019), consequence analysis (CA) is implemented to estimate the financial consequences of the release of a hazardous substance. The API Recommended Practice 581 (American Petroleum Institute, 2019) indicates two different procedures for this purpose: Level 1 and Level 2 CA. The Level 1 consequence analysis evaluates the consequences of hazardous releases for a limited number of reference fluids (among which there is hydrogen).

In this procedure, different scenarios are addressed through the assumption of a range of hole sizes, which results in the definition of different released masses. Hence, the output of the Level 1 CA methodology – which depends on the considered scenario – is often expressed in monetary units, and the procedure is summed up in the flow chart in Figure 3.

Figure 3 indicates the steps and the inputs needed to calculate the economic consequences of the release of a hazardous substance. This methodology can be used to assess the consequences of the loss of containment of a hydrogen pipeline. However, the boxes associated with “equipment to repair”, “production loss”, and “potential injuries” can be affected by considerable uncertainties, given that all these costs can be exposed to relevant fluctuations. Hence, researchers proposed innovative approaches – mostly based on artificial intelligence – to try to overcome the issue of consequences evaluation.

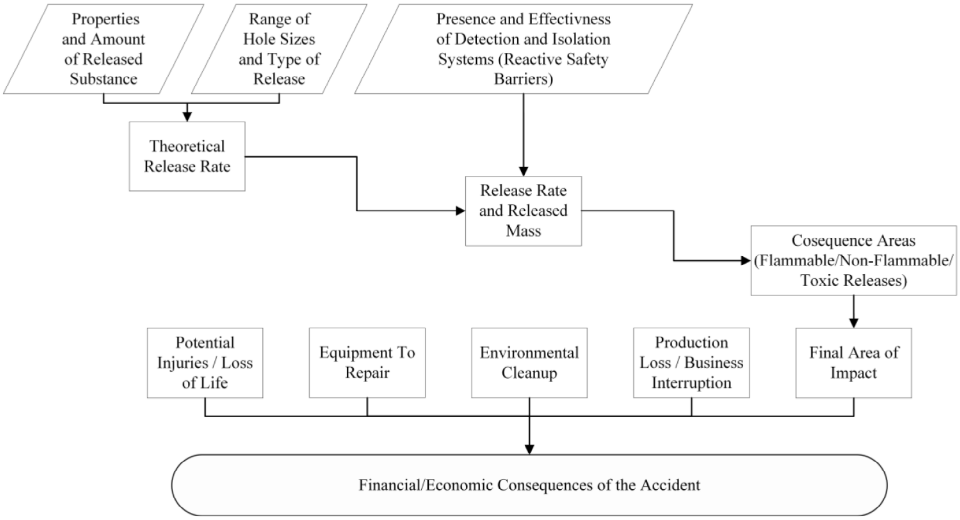

Fig. 3. Consequence analysis in the RBI framework (adapted from (American Petroleum Institute, 2019)).

To give an example, a previous study (Tamascelli et al., 2022) trained three ML algorithms to extract knowledge from accident records with the purpose of predicting possible injuries and casualties from major industrial accidents. This approach showed notable potential in supporting the practice of consequence categorization, which often provides useful data when the order of magnitude of the consequence is more relevant and could be adopted for hydrogen systems. In fact, the API Recommended Practice 580 (American Petroleum Institute, 2016) suggests considering the following consequence categories for an industrial accident, as reported in Table 2.

Table 2. Example of consequence categories (adapted from (American Petroleum Institute, 2016)).

Category	Description	Economic Loss
I	Catastrophic	CoF > $ 100,000,000
II	Major	$ 10,000,000 < CoF < $ 100,000,000
III	Serious	$ 1,000,000 < CoF < $ 10,000,000
IV	Significant	$ 100,000 < CoF < $ 1,000,000
V	Minor	$ 10,000 < CoF < $ 100,000
VI	Insignificant	CoF < $ 10,000

However, the lack of data concerning hydrogen accidental releases is once again a bottleneck for data-driven approaches, but a reliable estimation of the consequences' magnitude could support RBI planning in the risk calculation, therefore providing information for the inspection program. Moreover, an accurate prediction of a loss of containment magnitude in terms of financial/economic consequences may be relevant for the cost-optimization of the inspection plan, as reported in Section 4.

4. Overall results and Roadmap

As mentioned, there are several aspects and key challenges that need to be addressed to allow an effective cost-optimization of a risk-based inspection plan for hydrogen pipelines. Given the uncertainties (indicated in the previous sections) concerning metal-hydrogen interactions, failure probability and consequence evaluation for a hydrogen pipeline LOC, it is now clear that the RBSO can also be affected by critical uncertainty. Section 3.1 indicated a lack of understanding of the complex interactions among the variables influencing hydrogen-enhanced fatigue in pipeline steels. Along with this, the knowledge gaps identified in Section 3.2 showed that novel approaches should be considered to predict the effects of hydrogen on the propagation of fatigue cracks, thus potentially estimating the reduction of the components' operative life. In addition, Section 3.3 was dedicated to the calculation of failure probability in the RBI framework, and a methodological gap concerning the damage factor definition for equipment working in hydrogen environments was highlighted. Moreover, the analysis indicates that an *ad hoc* methodology for the damage factor definition suitable for hydrogen pipelines should be based on the findings of studies focused on the hydrogen-enhanced fatigue. Therefore, an accurate definition of this factor could support failure probability estimations, critical in the definition of inspection intervals in RBI programs. On top of this, the lack of records concerning hydrogen accidental releases is pointed out in Section 3.4, advocating for the inclusion of innovative approaches – based on ML models – to support consequence categorization in RBI planning. The overall goal of the research was to provide a perspective concerning risk-based inspection programs for hydrogen pipelines, and the discussion above indicated that an over-conservative approach (to mitigate the risk associated with a hydrogen release) can result in ineffective inspection programs (i.e., very short inspection intervals) which may pose unsustainable economic burdens with respect to conventional transport via pipeline of natural gas (that is not exposed to hydrogen-induced degradation effects). On the other hand, the neglection of hydrogen damages can result in less frequent inspections and in the missed detection of fatigue cracks. In this case, the cost associated with a potential accident can increase, given that the probability of failure of the system could increase. Surely, such inspection programs are scenario-dependent, since the calculated risk – vital parameter for the development of the risk-based inspection strategy – is intimately connected to the considered scenario (e.g., small, medium, or large leakages). In this work, a generic LOC scenario was considered, and all the considerations above are collected and summed up in Figure 4, which depicts the final output of this paper, defining the identified steps towards cost-effective risk-based inspection plans for hydrogen pipelines. The structure of the roadmap in Figure 4 refers to the objectives of the initial RBSO described in Table 1, adding the highlighted solutions in the yellow circles. In such a risk-based framework, this work identified criticalities and challenges to be tackled to allow the development of an optimal risk-based inspection program that both mitigates the risk of a hydrogen release, and it is associated with minimal costs. As such, the indications proposed in Figure 4 do not aim to be comprehensive and other aspects may be included to extend the current gap analysis to several different accidental scenarios and individuate other challenges potentially hindering the spread of this technology.

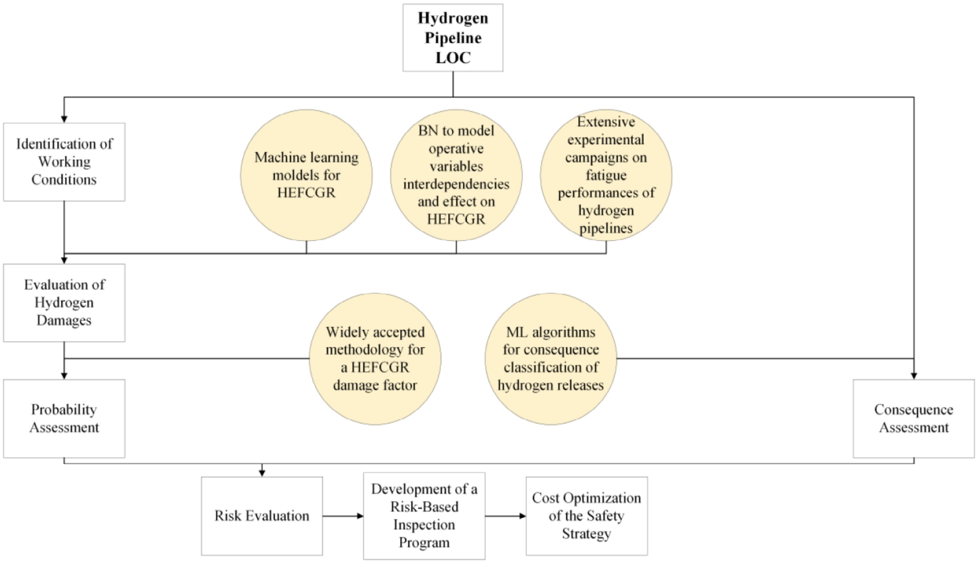

Fig. 4. Identified potential solutions to the existing criticalities hindering the RBSO of inspection strategies for hydrogen pipelines.

5. Conclusion

This work addressed criticalities and challenges concerning hydrogen transport via pipeline. Adopting a gap analysis method, uncertainties concerning material compatibility with hydrogen transport were discussed to assess the safety implications of this technology. The effect of knowledge gaps affecting failure probability and consequence estimations was analyzed to identify possible approaches that may allow a risk-based optimization of an RBI program. Such suggestions comprehend:

- Comprehensive experimental campaigns to cast light on the still disputed aspects affecting the crack growth rate in pipe steels working in hydrogen environments.
- Development of ML algorithms for predicting the HEFCGR on pipeline steels.
- Development of data-driven Bayesian models to assess the complex interdependencies among the variables governing the propagation of fatigue cracks in pipeline steels.
- Development of a widely accepted methodology for the evaluation of a damage factor for hydrogen-enhanced fatigue, rooted on experimental evidence and model estimations.
- Development of ML algorithms to support consequence categorization for RBI planning.

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