CHEMICAL ENGINEERING TRANSACTIONS

VOL. 116, 2025

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Bruno Fabiano, Valerio Cozzani

ISBN 979-12-81206-18-2; **ISSN** 2283-9216

DOI: 10.3303/CET25116045

Monitoring Optimisation of a Retrofitted Hydrogen Pipeline Using Markov State Model

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The lower volumetric energy density of hydrogen compared to natural gas requires cost-effective transport solutions. Compressed hydrogen transport via pipelines has been considered the most economical for distances under 3000 km. Retrofitting existing natural gas pipelines is crucial for efficiently delivering hydrogen since it is expected to penetrate and decarbonize several sectors. However, its interaction with most metallic materials makes this approach challenging. Pipelines are often subject to cyclic loads due to pressure fluctuations, which can result in accelerated fatigue crack growth in hydrogen environments. This enhanced degradation reduces the expected lifetime of the infrastructure. Ensuring rigorous maintenance and inspection protocols is essential to detect potential structural defects and prevent failures. This study investigates further the issue of retrofitting pipelines for hydrogen transportation. Combining a physical model and the Markov state model, which helps consider the variable and stochastic nature of the pressure fluctuations, provides an inspection and maintenance plan for an existing pipeline connecting Norway and the United Kingdom.

1. Introduction

The urgent need to mitigate climate change has stimulated significant interest in hydrogen (H_2) and its potential as a versatile and clean energy carrier able to pivot the decarbonisation of different sectors, including transportation, industry, and power generation (IEA, 2021). Therefore, the emerging hydrogen supply chain requires building an infrastructure for hydrogen transmission. Nevertheless, the physiochemical properties of this energy carrier make its handling and transport extremely challenging. In fact, H_2 has a very low density (0.089 kg/m^3) and low boiling point (20.39 K), calling for critical transportation solutions (Guo et al., 2024). Hydrogen can be delivered to consumers either in compressed or liquefied form or through chemical carriers such as ammonia or liquid organic hydrogen carriers. For distances shorter than 3000 km, transporting compressed hydrogen via pipelines is considered the most cost-effective option (Ortiz et al., 2016). However, the experience with large-scale hydrogen transport is limited, and constructing dedicated new pipelines is costly. Hence, the retrofit of the existing pipeline grid, originally designed for natural gas transportation, acquires interest. Besides its critical flammability properties (Guo et al., 2024), hydrogen can also permeate and embrittle metallic materials due to its small size (Abohamzeh et al., 2021), making the retrofit of existing infrastructures challenging. A pipeline is frequently exposed to cyclic loads, which may result from pressure fluctuations due to variable hydrogen demand during the day (addressed through the line packing) and/or seabed movements in the case of subsea pipelines. Although not fully understood, the presence of hydrogen can decrease the threshold stress intensity factor (ΔK_{th}), facilitating crack initiation and propagation and determining a shorter operational lifespan for the pipeline (Lipiäinen et al., 2023).
Given these challenges, the importance of rigorous maintenance and inspection protocols cannot be understated. Implementing advanced monitoring techniques and predictive maintenance strategies will be crucial in ensuring the safety and efficiency of hydrogen systems. A few studies on maintenance approaches for hydrogen services have been recently published, addressing the possibility of adopting Risk-Based Maintenance approaches and highlighting the limitations and challenges (Campari et al., 2024), (Collina et al., 2024). Unlike previous research, this study proposes the application of a Markov State Model to optimise the

Paper Received: 21 November 2024; Revised: 1 February 2025; Accepted: 25 March 2025
Please cite this article as: Collina G., Campari A., Vatn J., Bucelli M., 2025, Monitoring Optimisation of a Retrofitted Hydrogen Pipeline Using Markov State Model, Chemical Engineering Transactions, 116, 265-270 DOI:10.3303/CET25116045

maintenance and inspection planning for an existing pipeline connecting Norway and the United Kingdom. It is assumed that the pipeline will be used for hydrogen transport instead of natural gas. The main advantage of this methodology lies in combining a physical model with a stochastic approach. While the former is used to predict hydrogen-enhanced fatigue crack growth, the latter considers load variability and allows for optimizing pipeline monitoring under realistic operating conditions.

2. Methodology

Figure 1 shows the procedure to develop a monitoring plan for a natural gas pipeline repurposed for hydrogen transport. The characteristics of this pipeline are thoroughly analysed, and the data processed from a physical model feeds the Markov State Model, allowing monitoring optimisation.

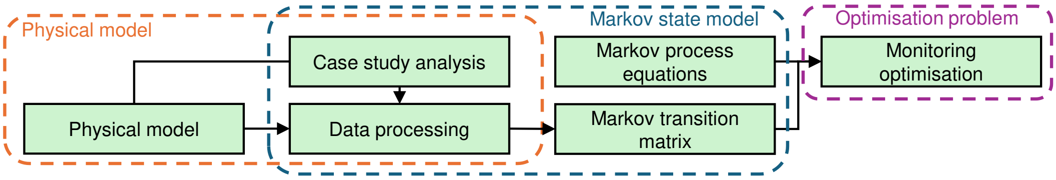
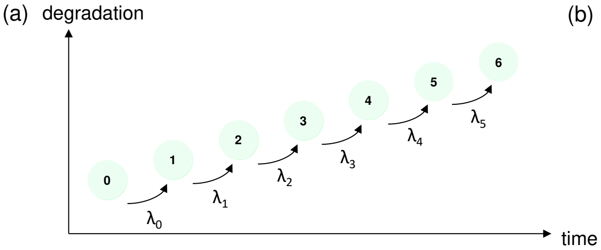


Figure 1: Methodology used in this study.

2.1 Markov State Model

A Markov model is a stochastic model using probabilities to predict the future states of a system based on its current state. In monitoring optimisation, Markov models help decide when and how to perform inspection and maintenance to minimise costs and maximise system reliability. This model is suitable for analysing systems having different states, from "perfect function" to "total fault" state. The key steps are: (1) definition of the number of states for the system, (2) identification of the transition rates (i.e., the probabilities of switching from a specific state to another), (3) definition of the transition matrix and, (4) the simulation of the model, which allows understanding the behaviour of the system over the time (Sun and Vatn, 2024), (Kellen, 2007). Based on this result, a monitoring plan is developed after defining the cost items.

Figure 2a shows the behaviour of the system as a function of time. The transition rate from state i to state $i+1$ is denoted λ_i. The system is inspected at periods of times $\tau, 2\tau, 3\tau, \dots$, and if the system state is equal to or above the state corresponding to the maintenance limit l, an immediate repair is carried out, and the system returns to the "perfect function" state.



(b)

$$\begin{bmatrix} 0 & \lambda_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Figure 2: (a) Markov transition diagram. (b) Markov transition matrix.

By standard Markov considerations (Rausand and Hoyland, 2003) the differential equation is Eq.(1).

$$P_i(t+\Delta t) \approx P_i(t)(1-\lambda_i \Delta t) + P_{i-1}(t)\lambda_{i-1}\Delta t \quad (1)$$

The transition rate from state i to state $i+1$ is calculated as the reciprocal of the expectation of state i. Generalising the problem and considering that the transition could happen from any state to any other and that the transition rate is not always the same leads to the necessity of expressing the Markov model in matrix terms, as in Eq.(2).

$$P(t+\Delta t) \approx P(t)[A\Delta t + I] \quad (2)$$

where A is the transition matrix depicted in Figure 2b, and $P(t)$ is the time-dependent probability vector for the various states defined in A. The integration of Eq.(2) allows the assessment of the effective failure rate and the expected number of renewals, which are the inputs for the following steps. The solution of the model relies on previous studies on Markov state model (Sun and Vatn, 2024), (Kellen, 2007). The general model in Figure 2 lacks physical foundations and assumes exponentially distributed sojourn times, though to introduce a more realistic physical context, it is common to assume that $\lambda_i = (1 + v_i)\lambda_{i-1}$ for some $v > 0$ indicating that due to, e.g., higher stress at higher degradation level.

2.2 Physical model

A physical model is required to calculate the transition rate (λ_i) to input to the Markov state model. A retrofitted pipeline is primarily exposed to fatigue degradation due to the pressure cycles caused by line packing. The internal pressure variations determine an applied load at the crack tip, which is described by linear-elastic fracture mechanics with the stress intensity factor, as described in Eq.(3):

$$K = \frac{D_o}{2\,t} \cdot p \cdot \sqrt{\pi\, a} \cdot F_\varphi \tag{3}$$

whereD_o and t indicate the outer diameter and thickness of the pipeline respectively, p is the operating pressure, a is the crack depth, and F_φ is a correction factor depending on the geometry and orientation of the crack. The stress intensity factor can be calculated at the deepest point of the crack and along the plate surface, varying the correction factor according to the Raju-Newman equation for semi-elliptical surface cracks in finite-thickness cylinders (Rajuand and Newman, 1982). The maximum and minimum stress intensity factors correspond to the maximum and minimum operating pressures. The stress intensity range is the difference between maximum and minimum stress intensity factors ($\Delta K = K_{max} - K_{min}$), and the stress ratio is the ratio between the minimum and maximum stress intensity factors ($R = K_{min}/K_{max}$). The per-cycle fatigue crack growth in hydrogen environments can be determined using the bilinear master curve (DVGW, 2023) in Eq. (4):

$$\begin{aligned} \frac{da}{dN} &= 4.4 \cdot 10^{-13}\,(1 + 3R)\,\Delta K^7 \sqrt{p_{H_2}} & \Delta K &\le \left[3.6667 \cdot 10^{-6} \sqrt{p_{H_2}}\right]^{-0.25} \\ \frac{da}{dN} &= 1.2 \cdot 10^{-7}\,(1 + 3R)\,\Delta K^3 & \Delta K &> \left[3.6667 \cdot 10^{-6} \sqrt{p_{H_2}}\right]^{-0.25} \end{aligned} \tag{4}$$

where ΔK is the stress intensity range (MPa·m$^{1/2}$), and p_{H_2} (bar) is the hydrogen partial pressure. The crack growth increments at the crack depth ($da\,/\,dN$) and surface ($dc\,/\,dN$) are added to the initial crack depth (a_0) and semi-length (c_0) after each pressure cycle, updating continuously the stress intensity ranges until a critical number of cycles is reached. The continuous increasing of the crack propagation justifies the connection with the Markov state model.

2.3 Optimisation problem

The optimisation problem aims to minimise the cost function expressed in Eq.(5):

$$C(\tau, l) = \frac{C_I}{\tau} + C_{F,tot} \cdot \lambda_E(\tau, l) + C_{RC} \cdot \rho_E(\tau, l) \tag{5}$$

where τ is the inspection period, l is the maintenance limit. C_I is the cost of an inspection, $C_{F,tot}$ is the sum of the total expected cost of a failure, including downtime cost, trip cost, any safety costs, and cost of repair, C_{RC} is the cost of renewing a degraded item (i.e., not failed but above or equal to the maintenance limit). $\lambda_E(\tau, l)$ and $\rho_E(\tau, l)$ are the solutions of the Markov state model: the first term is the effective failure rate for an item inspected at regular intervals of length τ and renewed if the maintenance limit is reached at an inspection date; the second term is the expected number of renewals per unit of time for an item inspected at regular intervals of length τ and renewed if the maintenance limit is reached at an inspection date. An optimal value for the cost function can be estimated varying the inspection period and/or the maintenance limit.

3. Case study

The methodology is applied the Langeled subsea pipeline in the North Sea. Data about the pipeline geometry, material, and manufacturing process are collected in Table 1.
This pipeline is primarily exposed to fatigue degradation due to the pressure cycles caused by line packing. Seven states for the Markov models have been identified by selecting the initial crack size according to the standard DVGW G 464 for the fracture mechanical assessment of hydrogen transport pipelines (DVGW, 2023), as shown in Table 2. The physical model allows the estimation of the number of pressure cycles and time corresponding to each state for different load conditions. However, the exact values of the amplitude and frequency of pressure fluctuations, in the ranges in Table 1, are relatively unpredictable. Hence, the results of the physical model are obtained in different conditions and an average value for each state is used as the transition rate, i.e., the input to the Markov state model.

Table 1: Characteristics (left) and operating conditions (right) of the Langeled pipeline (Alvaro et al., 2021).

Parameter	Value/type	Parameter	Value/type
Length	1116 km	Coating	FBE
Outer diameter	1100 mm	Design pressure	15.0 MPa
Thickness	41 mm	Temperature	6 °C
Material	API 5L X60	Amplitude of pressure fluctuations	10.5 - 12 MPa
Yield strength	481 MPa		
Ultimate tensile strength	604 MPa	Frequency of pressure fluctuations	$1.16 \cdot 10^{-5}$ – $2.31 \cdot 10^{-5}$ Hz
Microstructure	Polygonal ferrite and pearlite		
Manufacturing process	UOE and longitudinally welded	Hydrogen volume fraction	1.0

Table 2: Definition of the states of the Markov model.

State	Description	Comment	Crack depth [mm]	Crack width [mm]
0	Detectable crack	Minor defects in the welded pipeline, often resulting from the manufacturing process. This state is considered as new.	2.0	50.0
1	AET recommended	In-line inspection through acoustic emission testing is recommended after the crack has reached a sufficient size.	3.5	52.0
2	AET required	In-line inspection through acoustic emission testing is required to locate the crack and start a monitoring program.	5	54.1
3	UT recommended	In-line inspection through ultrasonic testing is recommended to measure the crack depth and width	7.5	57.4
4	UT required	In-line inspection through ultrasonic testing is required to develop a model to predict the crack growth.	9	59.3
5	*Maintenance required*	*Replacement is necessary when the pipeline can withstand pressure spikes up to 50% above the nominal operating pressure.*	*14*	*65.5*
6	Pipeline failure	Rupture of the pipeline when the maximum operating pressure is reached.	21.1	73.8

In the optimisation problem phase, different ratios of cost of failure and inspection are considered by adapting a study for an onshore pipeline (Gomes and Beck, 2014). In the first step, the cost of inspection is viewed as the unit cost, the cost of repairing is 100 times the cost of inspection, and the cost of failure varies in the range of 500 – 10000 times the unit cost. Considering these values, the optimised inspection interval is evaluated, such as the maintenance is carried out when the system reaches state 5, as per Table 2. The second step allows the optimisation of the inspection interval and the maintenance limit. In this phase, only the intermediate value of failure and inspection cost ratio is considered. In the following section, this value is simply referred to as the cost ratio.

4. Results and discussion

The results from the physical model for different load conditions are presented in Table 3.

Table 3: Results of the physical model for different values of the stress intensity ratio (R) and cycle per day.

State reached	R = 0.2		R = 0.225		R = 0.25		R = 0.275		R = 0.3	
	1 cycle/d	2 cycle/d	1 cycle/d	2 cycle/d	1 cycle/d	2 cycle/d	1 cycle/d	2 cycle/d	1 cycle/d	2 cycle/d
1	1639 d	818 d	1723 d	861 d	1818 d	909 d	1927 d	964 d	2059 d	1639 d
2	850 d	427 d	894 d	445 d	945 d	475 d	1007 d	504 d	1073 d	850 d
3	792 d	398 d	832 d	416 d	880 d	438 d	931 d	467 d	993 d	792 d
4	307 d	153 d	321 d	164 d	339 d	172 d	361 d	179 d	387 d	307 d
5	653 d	325 d	686 d	343 d	726 d	361 d	770 d	387 d	821 d	653 d
6 (failure)	537 d	266 d	562 d	281 d	591 d	296 d	628 d	314 d	668 d	537 d

The variability of pressure fluctuations does not allow for any reliable decision regarding the monitoring plan. The application of the Markov State model allows the progress of degradation to be considered stochastic, bypassing the issue of unpredictable loads. The coupling with the Markov model tries to address the stochastic nature of the loads; for this reason, the components of the Markov matrix (λ_i) correspond to the arithmetic mean

of the physical model outputs in different loads. Table 3 shows that the number of cycles drops with increasing state, which is in accordance with $\lambda_i = (1+v_i)\lambda_{i-1}$. The failure rate of the last two jumps increases because the step is 7 mm, whereas the other steps are in the order of magnitude 3 mm.
Table 4 shows the results of the first phase of the analysis, when the maintenance limit is fixed at state 5 and the inspection interval is the only optimization parameter.

Table 4: Inspection interval optimisation results.

(Failure Cost) / (Inspection Cost)	Optimal inspection interval (τ)	Minimised cost
500	518 d	0.105
1000	286 d	0.153
2000	176 d	0.218
5000	101 d	0.312
7000	83 d	0.403
10000	66 d	0.479

Figure 3 shows, as an example, graphically the optimisation results corresponding to the lowest and highest cost ratio. The higher the failure cost, the more marked the minimum of the total cost and the smaller the suggested inspection interval. This result confirms the suitability of this approach when considering systems whose failure has very costly consequences, such as infrastructures dealing with hazardous substances like hydrogen or highly complex systems like subsea pipelines, or a combination of both, as in this case study.

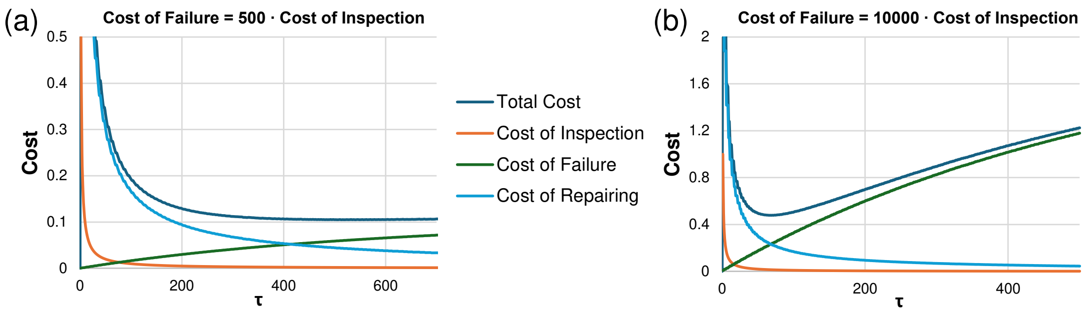


Figure 3: Optimisation results. (a) Cost ratio equal to 500, (b) Cost ratio equal to 10000.

To provide a complete maintenance optimisation plan, the maintenance limit should be considered an additional optimisation parameter to the inspection interval limit. In the second stage of the analysis, the focus was on identifying the maintenance state that would minimize the costs. For this step, an intermediate value of cost ratio was considered. Table 5 shows that the optimal solution would be to maintain the system every time it reaches state 4 (rather than state 5), corresponding to a crack depth of 9 mm. The final cost is almost three times lower than the corresponding value in Table 4, and the inspection interval is higher. The values in Table 5 clearly show that the optimization results from balancing three different cost items: inspection, failure, and repair costs. For instance, conducting maintenance activities when the system reaches state 2 is convenient for reducing failure costs, but it leads to an increase in the repair cost.

Table 5: Maintenance limit and inspection interval optimisation results. Cost ratio is equal to 5000.

Maintenance state	Optimal inspection interval (τ)	Total cost	Inspection cost	Failure cost	Repairing cost
1	892 d	0.143	0.001	0.033	0.109
2	549 d	0.120	0.002	0.022	0.096
3	329 d	0.136	0.003	0.031	0.102
4	163 d	0.119	0.006	0.030	0.082
5	101 d	0.342	0.010	0.166	0.166

Comparing the values in Table 5 could deceive the reader, but it is necessary to point out that these results are not directly comparable since the inspection interval also has an effect.
This study has a multidisciplinary approach, combining a popular model in the maintenance field and innovative studies on hydrogen and material interactions. However, it has several limitations regarding both the Markov model assumptions and those of the case study analysis. First, the considered model does not account for repairs from any arbitrary state to another or consider imperfect repairs. In addition, every time the system reaches the maintenance limit, no downtime is considered, and the maintenance is carried out as soon as the

system reaches that state. In addition, the model could be improved by considering different inspection intervals since the degradation proceeds faster as the state increases: a longer inspection interval would be assigned to the first stages and a shorter one to the latest stages. Furthermore, the practical use of this analysis relies on the possibility of considering real costs. In the next few years, more information on hydrogen technologies will be available, and this study could then be considered a basis for further analyses.

5. Conclusion

Hydrogen-enhanced fatigue crack growth rate is a serious concern for stakeholders and raises doubts about the technical feasibility of retrofitting natural gas pipelines to hydrogen infrastructure. Nevertheless, inspection and maintenance planning could ensure the reliability and safety of these infrastructures. This study proposes the application of a physical model and the Markov state model to develop an inspection and maintenance plan for the Langeled subsea pipeline, connecting Norway to the United Kingdom. A physical model was used to simulate the crack progression, while the stochastic Markov model ensured that the effect of the unpredictability of the pressure loads was considered when developing the inspection and maintenance plan. The balance of different cost items in selecting the optimal inspection interval and maintenance level is highlighted. This study presents an innovative methodology that can be used to optimize pipeline monitoring. However, before recommending an effective maintenance plan, it is necessary to collect accurate and real data on the various cost items involved.

Acknowledgments

This work was undertaken as a part of the research project H2GLASS (Decarbonising the glass industry with hydrogen technologies). The authors would like to acknowledge the financial support of the European Union Horizon 2020 research and innovation program (Grant No. 101092153). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or European Health and Digital Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

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