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RESEARCH

Building resilience through the dynamic assessment of ageing process safety critical equipment

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Abstract

In the oil and gas industry, process safety critical equipment (PSCE) plays a vital role in ensuring the safe operation of facilities by preventing catastrophic incidents and mitigating risks. In this novel study, various methods were integrated to establish criteria for identifying PSCE and to assist employees, regardless of their safety background, in minimising risks associated with major accident hazards to a level as low as reasonably practicable (ALARP). A key challenge addressed by this study is the possibility of over-under classification of PSCE, which could lead to either recourse strain or dilute the focus on genuinely critical equipment. Instead, a targeted PSCE list enables more effective maintenance, inspection and safety strategies. Furthermore, upon identifying PSCE, this study also proposes an ageing assessment using an approved ontology that considers factors like equipment failure rates, near-misses, time in operation and deterioration mechanisms. These insights enable management to make risk-based decisions. The proposed methodology was successfully applied in a case study, demonstrating its effectiveness in optimizing PSCE within a facility. The research concludes with highlighting limitations, and recommendations for standardising PSCE identification methodologies across the industry and emphasizes the need for ongoing collaboration between industry stakeholders, researchers and regulatory bodies.

Keywords Qualitative risk assessment · Process safety critical equipment · Oil and gas · Process safety events · Ageing assessment

Abbreviations

PS	Process safety
PSE	Process safety event
SCE	Safety critical equipment
PSCE	Process safety critical equipment
RBA	Risk-based approach
RBD	Risk-based decision
RBI	Risk-based inspection
MAH	Major accident hazard
FTA	Fault tree analysis
ETA	Event tree analysis
FMEA	Failure mode and effects analysis
HAZOP	Hazard and operability study
IChemE	Institute of Chemical Engineers
CCPS	Center for Chemical Process Safety
SGs	Safeguards
FPD	Failure per demand
MOC	Management of change
MTBF	Mean time between failure
MARS	Major accident reporting system
ALARPAs	Low as reasonably practicable
P&IDs	Piping and Instrumentation Diagrams
PTW	Permit to work

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Introduction

Background and motivation

Equipment plays a crucial role across allindustries, regardless of their size. Equipment fulfils various functions such as separation, processing, and transportation. Certain equipment is particularly important for ensuring safe operations within a plant, preventing significant process safety incidents and securely containing hazardous materials (Maurya

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and Kumar 2020; Singh 2019). This category of equipment is known as process safety critical equipment (PSCE) and must be managed within a stringent safety management system. This paper focuses on the identification of Process Safety Critical Equipment (PSCE). The term PSCE is sometimes referred to as [Process Safety Containment Event]. However, for consistency, we will use PSCE throughout this paper to refer to process safety critical equipment. Process safety critical equipment (PSCE) refers to installations that, if they fail, can lead to or significantly contribute to a major incident. The occurrence of catastrophic events linked to PSCE failures has led to the evolution of process safety management systems within the oil and gas sector (Broadribb and Freiburger 2018; Lu 2024).

A comprehensive review of PSCE within the oil and gas sector revealed several gaps, largely stemming from unclear definitions or criteria. These ambiguities often led to confusion or excessive inclusion of equipment not classified as PSCE (over-specification), which in turn resulted in unnecessary maintenance and inspection costs, accounting for about 20% of the operational budget at a chemical plant (Tan and Kramer 1997). Conversely, under-specification or exclusion of PSCE could result in serious process safety events (PSE), which could be a catastrophic event resulting from an unplanned or uncontrolled discharge of any substance (API 2021). Additional issues included burdening employees with superfluous information, increasing maintenance workloads, and diluting the focus on truly critical PSCE. Streamlining the PSCE list to include only genuinely critical equipment has multiple advantages, such as reducing resource demands, clarifying safety procedures for operators, and enhancing focus on essential inspection and maintenance tasks (Wincek 2014).

The core challenge with PSCE is the ambiguity in its criteria, which often emphasises certain operations while neglecting others, leading to an overextended and potentially misleading list (Leva et al. 2018). Moreover, previous research has highlighted industry statistics and several incidents that were attributed to inadequate monitoring and maintenance of ageing PSCE. Therefore, inspection, maintenance and testing of such equipment must be given top priority above all other activities to prevent incidents (Safety 2018).

To tackle these challenges, a comprehensive strategy is introduced, starting with hazard and operability (HAZOP) studies to identify major accident hazards (MAH), which could be defined as incidents resulting in loss of life, toxic chemical releases, or process safety events. These events lead to on-site or off-site emergencies, asset damage, process shutdowns, or environmental impacts (Kelly 2021).

The strategy is then followed by a decision tree to implement a risk-based approach. An ageing assessment is then proposed, using an approved ontology that incorporates various factors to accurately evaluate equipment against ageing. This approach is anticipated to more effectively identify potential risks related to PSCE, improve system reliability by concentrating on ageing equipment, and help manage maintenance and inspection costs.

The primary focus of this research is selecting the most effective approach to identify PSCE within a facility and assess the susceptibility of PSCE to ageing. This includes evaluating PSCE performance under ageing conditions, testing PSCE resilience, and conducting a risk assessment in response to any changes. Although extensive work has been conducted in the oil and gas sector to identify PSCE utilising various methods, few efforts have targeted the development of a PSCE list by personnel without safety expertise. Additionally, there has been limited research on maintaining PSCE in acceptable operating conditions to minimise safety risks to a level that is as low as reasonably practicable (ALARP).

Relevant work

This review identifies three primary methods for PSCE identification as explained below.

- Quantitative or Semi-Quantitative Approaches: These include lean tools like fishbone diagrams combined with FMEA for risk identification and mitigation (Aqlan and Ali 2014; Pirbalouti et al. 2023), HAZOP for hazard identification, bow-tie and Bayesian networks for probabilistic cause–consequence analysis, and consequence modelling for a risk-based approach. These methods, though they are comprehensive, they can be time-consuming and may not fit for large or complicated facilities due to the detail required (Loughney and Wang 2018; Amin et al. 2018).
- Qualitative Approaches: This category includes methods like HAZOP and FMEA that focus on identifying initiating events. Despite their effectiveness within the petrochemical industry, these methods have their own drawbacks, such as being time intense, different guidewords could be misinterpreted, loosing track due to large amount of data, expensive and sometimes repetitive work (Chia and Naraharisetti 2023).
- Generic Approaches: These methods involve identifying a wide range of equipment, such as those listed by the Center for Chemical Process Safety (CCPS) (Risked 2014; Guidelines 2016). However, these lists can be vague if they do not align with the PSCE definition. For example, the Oil Companies International Marine Forum defines PSCE as equipment whose failure could result in a hazardous situation or directly cause an accident; this

definition is not specific (Safety 2018). Other examples include approaches which list various safety equipment within or beyond the oil and gas industry (Smith 2020). Most approaches begin by identifying major accident hazards (MAH) (Vince 2011). The UK Energy Institute developed guidelines on MAH and a general list of PSCE to consider in studies (Guidelines 2020). However, the PSCE designation is often misapplied, leading to inadequate prioritisation in maintenance and inspection tasks such as risk-based inspection (RBI).

Objective

Given the constraints of the previously mentioned studies, the research aims to cover four main pillars, with a focus on the pillars (a & b), as illustrated below:

a) Develop criteria for identifying PSCE within a facility using a qualitative risk assessment approach (e.g. hazard and operability study [HAZOP]) and failure mode and effects analysis (FMEA) to identify major accident hazards.
b) Assess if the identified PSCE items are ageing or degrading.
c) Test PSCE resilience to disturbances.
d) Assess PSCE in relation to risk.

This research is novel, as it aims to prevent adverse events within a facility by accurately identifying PSCE be accessible by personnel with varying levels of safety expertise, while maintaining technical aspect utilising a qualitative risk assessment approach, thereby safeguarding personnel, assets and the environment. Additionally, it incorporates ageing assessments specifically for PSCE, a focus not commonly found in general equipment studies, and integrates resilience and risk assessments.

Relevant incidents

The below catastrophic incidents are examples that were attributed to PSCE failures and resulted in fatalities and business interruptions.

a) In 1988, the Piper Alpha disaster in the North Sea occurred due to an unassessed pump start-up leading to 167 deaths.
b) In 1984, the Bhopal incident occurred when a critical valve opened and discharged methyl isocyanate (MIC) into the atmosphere causing approximately 5000 indirect deaths.
c) In 1970, a freight train derailed due to a mechanical failure of a journal bearing on one of the rail cars. Two passengers were killed and 13 injured.

Statistics of accidents in chemical plants across Europe and the UK were reported in the CCPS book (Dealing 2018). In the book, the UK's Health and Safety Executive (HSE) investigated data from 1980 to 2006 to determine how many incidents were due to equipment ageing and categorised the incidents into different classes.

Ageing of PSCE

Assessing whether identified PSCE equipment is fit for purpose and not deteriorating was the second focus of this research. Recently, the safe ageing of equipment has become a significant issue, particularly in industries with MAHs like the oil and gas industry (Bragatto and Milazzo 2016). In this context, 'ageing' refers not to the time elapsed since production or commissioning, but to the equipment's condition and how it changes over time. Ageing-related failures can be physical, such as deformation or stretching, or functional, such as instrumentation faults or flashovers (Plant 2006).

To manage PSCE ageing, it is recommended to start by identifying the risks associated with recognised equipment, such as classifying factors that can affect safety equipment. A range of competencies for managing equipment ageing, including technical knowledge about design, materials and the operating environment, is crucial for facility employees and management.

Key steps when assessing PSCE ageing to help management make risk-based decisions (RBDs) include:

- Organising operating data, inspection reports and condition monitoring.
- Investigating loss of containment events to identify equipment deterioration causes.
- Analysing evidence indicating deterioration phenomena.
- Reviewing current monitoring and inspection regimes to ensure they are still effective.
- Paying special attention to equipment nearing the end of its lifespan, considering safety and replacement costs.
- Creating an annual report on the known or expected condition of critical equipment at high-hazard installations.
- Ageing modelling varies based on the rate of a component's functional degradation and data availability and quality.

Multiple methods can be used to assess PSCE ageing within a facility and identify factors contributing to ageing, such as the failure-in-time distribution function, where the failure rate λ increases over time.

Atwood et al. used a probabilistic safety assessment (PSA) to evaluate ageing effects on energy facility safety within the European Network framework (Atwood 2007). Other methods include the ‘ageing step model’ (Clarotti et al. 2004), which led to the development of IBTV software, which covers ageing detection, reliability prediction and corrective measures.

Ancione et al. developed a ‘virtual sensor’ system that gathers ageing-related data, analyses it using various models, and predicts corrosion rate, critical pitting likelihood, corrosion progression and remaining lifespan, displaying results in augmented reality (AR). They also conducted a case study of a tank in service from 1965 until 2022 (Ancione et al. 2022).

Bragatto et al. developed a compensated index method based on a previous study. This index, derived from the fishbone analysis, identifies factors that accelerate or decelerate ageing. However, it does not consider rotating equipment, which is a significant cause of incidents. The ageing management method developed involves compensation and penalty factors that accelerate or mitigate ageing, with a weight and score assigned to each factor (Bragatto and Milazzo 2016).

Several methods measure ageing for static equipment like piping, valves and process vessels, including ultrasonic testing, x-rays, magnetic particle testing and fitness-for-service methods. Kelly identified and compared strategies to manage ageing (Kelly 2021).

Ansaldi et al. developed the ‘ontoAgeingFishBone’ ontology, which uses taxonomies to describe knowledge about ageing and support its management (Ansaldi 2020), referencing the ‘Ageing FishBone model’ explained by (Milazzoa 2018). However, most of the methodologies discussed are either time-consuming, require significant experience and resources, or do not include all types of equipment.

Resilience of PSCE

The term ‘resilience’ has been widely used in the literature but is defined differently depending on the industry and the intent behind its use (Vesey et al. 2023). Although resilience is crucial for maintaining safe and functional systems, it can be difficult to measure, especially in the safety industry, where its use is relatively new (Hollnagel 2008). Even though resilience is a relatively new concept in process safety, both qualitative and quantitative approaches have been used to identify resilience, with qualitative approaches having more limitations (Shirali et al. 2012). Quantitative approaches rely on data, such as operational data, incident history and operational process data. However, insufficient data, knowledge and experience can lead to varying levels of uncertainty (Hoseyni and Cordiner 2024).

Risk review in relation to PSCE

The final focus of this research is the integration of risk assessment with PSCE. PSCE must be identified as it is critical to facility safety. For example, management of change (MOC) systems within a facility typically require a risk review to prevent changes to any equipment that could introduce new risks or affect the PSCE safeguards, ensuring that existing risks are managed to a level ALARP. In other words, any changes to PSCE systems or indirect changes affecting PSCE must be thoroughly assessed by an experienced team (Pike et al. 2020; Baybutt 2014).

Another example includes activities performed on PSCE, such as maintenance, inspection, isolation, or testing. Procedures such as PTW operations, maintenance manuals, and operator qualifications must be current to prevent adverse impacts.

Additionally, identifying and updating PSCE on piping and instrumentation diagrams (P&IDs) is essential, as they are widely used across various organisational roles. Project engineers rely on P&IDs for designing process upgrades, while process engineers and operations management use them for troubleshooting (Toghraei 2014). Operations and maintenance staff use P&IDs to locate isolation points and understand the overall process, and hazard study teams depend on P&IDs to accurately depict the processes under review. Furthermore, as part of a high-level operational and organisational process safety strategy, it is essential to incorporate methodologies such as a safety case (SC) or bow-tie analysis, outlining the PSCE identified during the design phase (Loughney and Wang 2018).

Another approach is the use of a quantitative risk assessment (QRA), which evaluates failure causes, the likelihood of safety equipment functioning and the impact of failed safety equipment. This approach is particularly beneficial for calculating risks in process facilities (Amer et al. 2024). A similar approach is used in the layer of protection analysis (LOPA), which identifies a hazardous scenario and assesses the likelihood and severity of the outcome if a particular layer fails (Wagner and Champion 2012; Layer of protection analysis: simplified process risk assessment, 2001).

Research method

The study adopts a structured 2-step approach to identify ageing Process Safety Critical Equipment (PSCE) within a facility and assess their ageing conditions. Following identification, the method emphasizes on prioritizing the identified ageing PSCE when conducting risk assessments and evaluating their resilience under potential failure scenarios.

Identification of PSCE

Based on current research, we recommend a qualitative risk assessment approach to identify PSCE within a facility using: by starting with identifying MAHs from a facility's HAZOP report using the 5 × 5 risk matrix shown in below steps and Fig. 1. Then, validate the outcome from the 1 st step using the logic tree shown in Fig. 2"logic tree was adapted from the reference (Broadribb and Freiburger 2018)" which serves as a validation tool to identify PSCE according to a risk-based definition.

a) Equipment that falls under the red category: 'very high likelihood and very high consequence' (HLHC). Indicated as (A) in Fig. 1.

   The ***high likelihood – high consequence*** category is selected if both the likelihood and consequences are high, that is, a high chance of an incident occurring and, if an incident occurs, a high chance it could lead to catastrophic consequences.

b) Equipment that falls in the yellow boxes that are from the category 'very low likelihood and very high consequence' (LLHC). Indicated as (B) in Fig. 1.

   The ***low likelihood – high consequence***is selected if the likelihood of a major incident is not easy to determine but the consequences are known based on the process. In other words, the failure of equipment that falls under this category could lead to a 'black swan event' – an unpredictable event with a high impact on personnel safety, the environment, and the financial stability and reputation of the company (e.g. the Deepwater Horizon oil spill and the COVID pandemic) (Aven 2013).

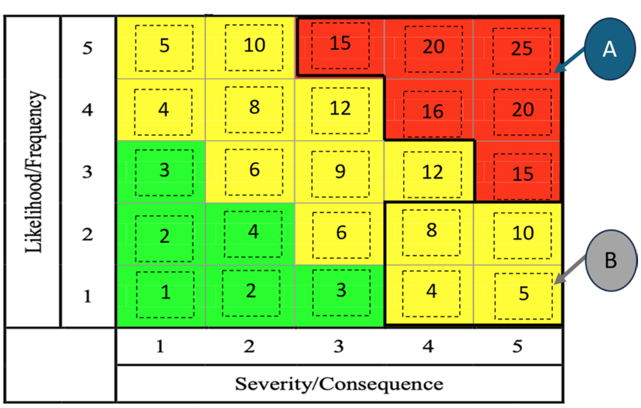

Fig. 1 5 × 5 Risk matrix

Note:*Equipment that falls under both categories (a and b) should be treated as top priority*

Definition of Terms of Logic Tree

Even though companies may have their own definitions of some of the terms used in the logic tree in Fig. 2, we will define them to ensure a consistent approach. These terms include:

- *Stored energy*.

The energy retained within a system or component can become hazardous if released unintentionally.

- *Major release and hazardous material*.

In the United States, 'hazardous material' and 'major release' are defined by certain regulations. However, users must establish their own criteria for what constitutes hazardous materials and determine the scale of a release that could lead to a significant incident within their facilities.

- *Process safety event (PSE)*.

'An unplanned or uncontrolled discharge of any substance, including non-toxic and non-flammable from a process, or any undesired situation or event that, under slightly different conditions, might have resulted in a release of a material' (API 2021).

The 5 × 5 risk matrix shown in Fig. 1 has 5 categories in each side following a scale from 1 to 5. The (x axis) corresponds to likelihood/frequency, while the (y axis) corresponds to severity/consequence. The risk matrix is a crucial tool that is used by companies from different industries during the risk assessment phase of job hazard analysis, operations, projects, etc. It assesses the likelihood and consequences of potential incidents that could cause harm to the facility employees, assets, environment and the workplace in general.

Ageing assessment of PSCE

When PSCE are identified from the previous step, it is crucial to assess their condition and performance against ageing to prevent any PSE or catastrophic incident. We suggest the following step:

> Assess the ageing of PSCE within a facility. Multiple methods can be used; however, it is recommended to utilise the approach proposed by (Ansaldi 2020)and (Milazzo and Bragatto 2019).

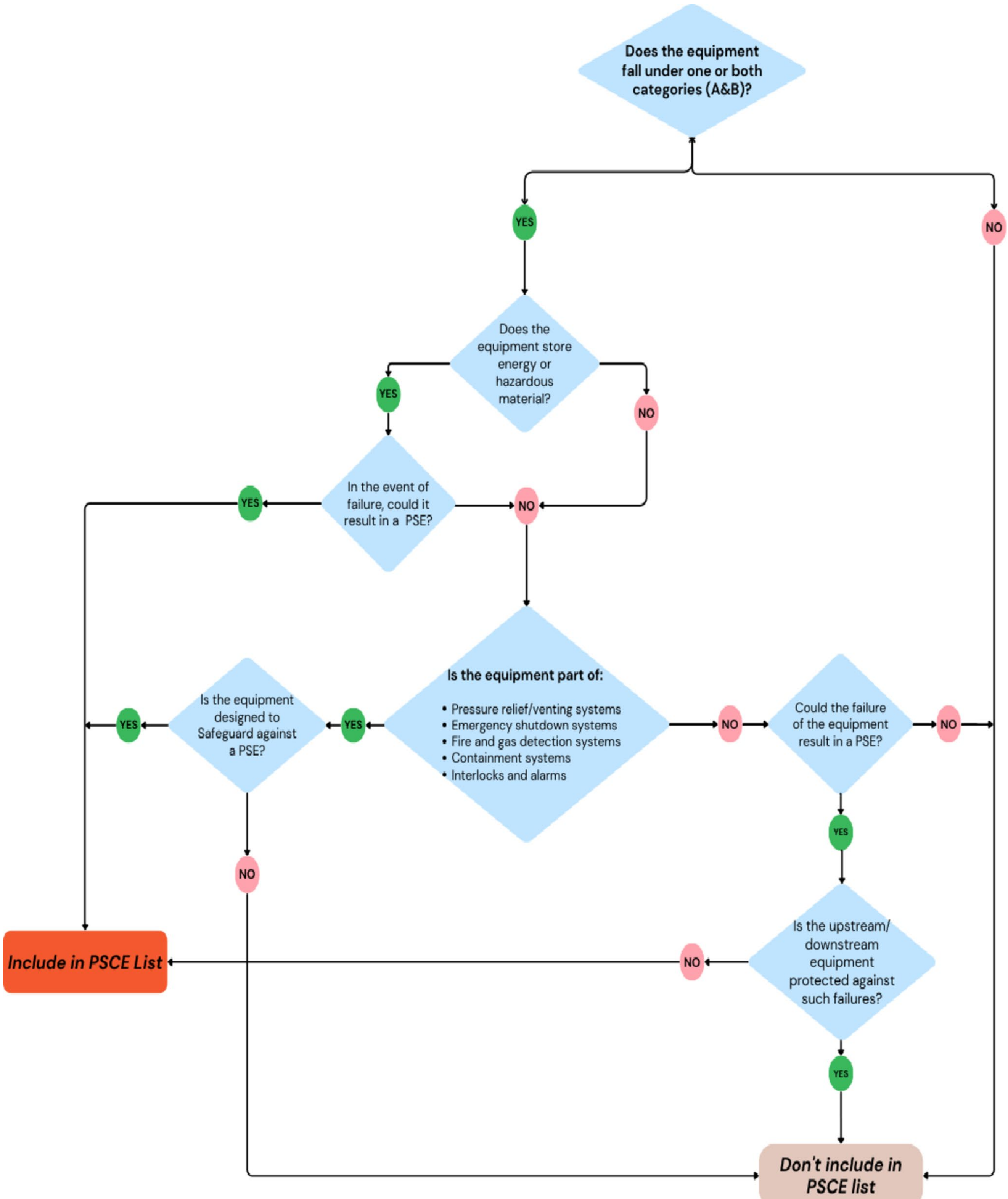

Fig. 2 Logic tree for identifying PSCE

a) Identify and then assess deterioration mechanism factors that could impact equipment ageing depending on the process from API 571, and find the average of each factor on a scale (1 being the lowest and 4 being the highest). Refer to Table 1.
b) Categorise accelerating and retarding factors depending on their effect on ageing. Refer to Tables 2 and 3. As the retarding factors are factors that slowdown equipment ageing (e.g., effective inspection and maintenance), and the accelerating factors expedite degradation (e.g., vibration).
c) Assign a score to each factor by referring to a four-level scale (1–4), with a positive sign for retarding factors and a negative sign for accelerating factors.
d) Calculate the total index: the difference between the average of the positive factors and the average of the negative factors, as shown in Fig. 3.
e) From the outcome of step (d), if the result of the calculation is negative, then a multidisciplinary team should select a strategy from Table 4 to determine the path depending on the criticality of the equipment and the process.

Document the outcome of the assessment in Table 17.

Equipment:

The proposed scoring system to assess ageing would be effective as it is structured to quantify and standardise the assessment of biological ageing process across different equipment within a facility. Furthermore, the system works effectively as it takes into account accelerating and retarding factors that are technically linked based on the severity and availability of the identified factors. The scoring of the factors could be a reward for retarding and a penalty for accelerating factors.

The reliability and effectiveness of the scoring lies on the following:

- Identification of deterioration/degradation mechanisms which could vary from an equipment to another.

Table 1 Deterioration mechanism (Milazzoa 2018)

Mechanism Type (API 571)	Detectibility 1	Propagation velocity 2	Consequence 3	Average

(1) Detectability, which is linked to the challenge of identifying the phenomenon, assesses the impact it creates

(2) Propagation velocity describes the time progression of the phenomenon

(3) Consequences are the most severe outcomes that the mechanisms can produce

Deterioration mechanisms could be referred to from (API 571)

Table 2 Retarding factors and their scores (Milazzoa 2018)

Factor	Score
Management system	**(1)** compliant with legislation; **(2)** risk-based inspection planning; **(3)** updated after changes; **(4)** frequently reviewed and updated
Audit	**(i)** % of minor non-compliances, **(ii)** % of major non-compliances
Inspection scheduling and results	**(i)** equipment performance test outcomes, **(ii)** integrity test results, **(iii)** frequency of inspection
Inspection efficiency	**(i)** effectiveness of inspections, **(ii)** competency of inspectors, **(iii)** availability of inspection program
Process control	**(1)** local control system; **(2)** control system with data recording; **(3)** data recording system with automatic blockage system; **(4)** comprehensive control system
Specific protections	Average score of sub-factors: **(i)** frequency of inspections, **(ii)** condition of protective measures

Table 3 Accelerating factors and their scores (Milazzoa 2018)

Factor	Score
In-service time (age)	(1) ≤ 90%; **(2)** 90–100%; **(3)** 100–120%; **(4)** >120%
Number of unplanned stops	**(1)** ≤ 10%; **(2)** 10–25%; **(3)** 25–60%; **(4)** >60%
Actual/expected failure rates	**(1)** $f \leq 0.5\ f_{ref}$; **(2)** $0.5\ f_{ref} < f \leq 1\ f_{ref}$; **(3)** $0.5\ f_{ref}; < f \leq 2\ f_{ref}$; **(4)** $f > 2\ f_{ref}$
Near misses due to deterioration	**(1)** ≤ 5%; **(2)** 5–15%; **(3)** 15–35%; **(4)** f >35%
Deterioration mechanisms	Refer to Table 1
Damage/defects	**(1)** ≤ 1%; **(2)** 1–3%; **(3)** 3–5%; **(4)** >5%

- Assigning a scoring weight per factor depending on the risk it could impose.
- This scoring system would help in identifying the critical parts of ageing to allow end-users to prioritize maintenance and inspection activities.

Note: *If the final score of the retarding and accelerating factors is qual, then this is an indication that the systems in place for ageing management are effective.*

The novelty in scoring is the fact that it is integrated with wider risk management practices, such as the process safety critical equipment and will assess management apply the concept of risk-based inspections for the identified ageing PSCE. This approach indicates that equipment with negative scores (accelerating factors higher than retarding factors) require more attention which will eventually lead to extending the lifespan of an asset.

Now that we have identified ageing PSCE from the previous steps, we recommend considering ageing PSCE in relation to risk and resilience, referring to the below steps.

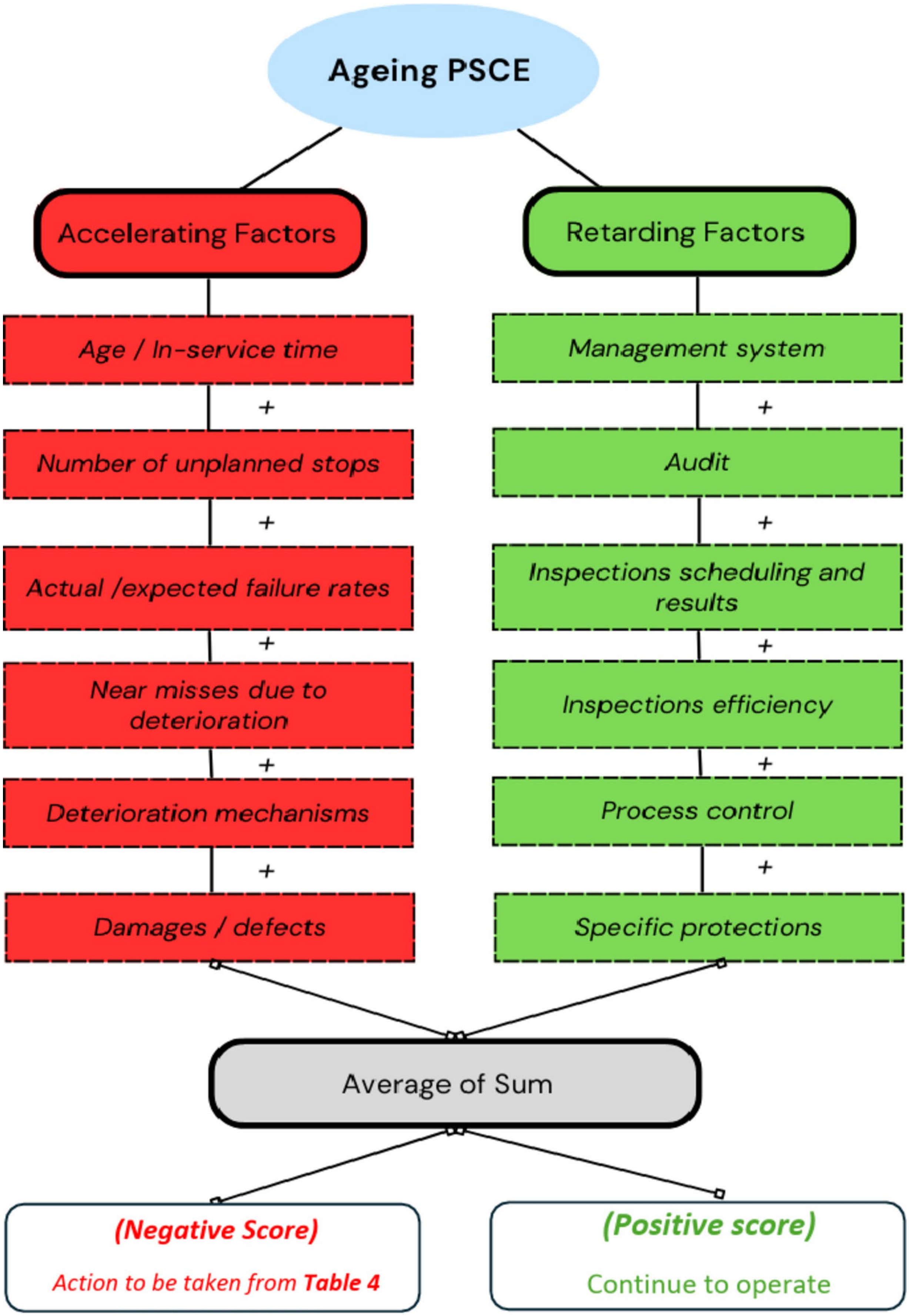
Ageing PSCE
Accelerating Factors
Retarding Factors
Age / In-service time
+
Number of unplanned stops
+
Actual /expected failure rates
+
Near misses due to deterioration
+
Deterioration mechanisms
+
Damages / defects
Management system
+
Audit
+
Inspections scheduling and results
+
Inspections efficiency
+
Process control
+
Specific protections
Average of Sum
(Negative Score)
Action to be taken from Table 4
(Positive score)
Continue to operate

Fig. 3 Flow-chart for the assessment of ageing of PSCE (Ansaldi 2020)

PSCE in relation to risk

To integrate risk assessment and PSCE, we need to consider the following:

a) Management of change (MOC) systems within a facility usually necessitate a risk review to prevent modifications to any equipment that might introduce new risks or affect the PSCE safeguards, ensuring that existing risks are managed to levels ALARP. Thus, any alterations to the PSCE systems or indirect changes impacting the PSCE must be thoroughly assessed by a skilled team which should result in updating Table 17.
b) Activities involving PSCE, such as maintenance, inspection, isolation or testing, require up-to-date procedures (e.g., PTW, operations and maintenance manuals, operator qualifications, etc.) to avoid any negative impacts.
c) It is essential to identify and update PSCE in P&IDs, other crucial documents and distributed control systems (DCSs). P&IDs are used for designing process upgrades, and DCSs are used by process engineers, operations and operations management for troubleshooting purposes.
d) Alarm management: alarms for such equipment need to be quickly actioned upon and assessed thoroughly.

Table 4 Strategies and considerations for managing ageing of process safety equipment (Kelly 2021)

Strategy	Considerations
No action, continue to operate	• Capability to monitor equipment condition and performance through a risk assessment • Cost-effectiveness for ongoing operation
Repair and/or modify	• Availability of technical competencies and resources • Evaluate repair approach options, and availability of spare parts • Closely monitor and control the repair under management of change (MOC) • Need for fit-for-service testing
Temporary repairs	• Might not serve as the same function as the primary equipment • Does not meet safety standards and workplace safety • High in cost • Closely monitor and control the replacement under management of change (MOC)
Halt the operation, and repair	• Financial costs • Disposal costs and logistics • Environmental impact due to a process safety event, flaring

Resilience of PSCE

a) Integrate PSCE into the facility's safety management system to systemise the frequent identification and updating of the PSCE list following any changes.
b) Risk reduction, by identifying, assessing and maintaining PSCE, could result in reducing the likelihood of incidents.
c) Effective implementation of the aforementioned pillars should result in a facility having resilient systems.

Chapter 3: case study

Introduction

A case study was conducted based on a HAZOP report from the University of Karachi conducted on a mini chemical plant to produce ammonia (NH_3). The HAZOP details, as shown in Table 5 highlights possible deviations from standard operating parameters for essential equipment within the plant such as a pump, compressor, valves, vaporizer and a reactor. For the purpose of this study, we assumed the likelihood and consequence to calculate the risk ranking due to limitations in data. Furthermore, a column was added to the table to answer the question from the 1 st step on whether the identified PSCE shall be carried to the next stop or not. Therefore, to apply the methodology, the HAZOP was divided into four nodes containing around 19 primary and auxiliary equipment items, as shown in Fig. 4.

The results provide insights into the condition and management strategies for two pieces of equipment, PCV-01 A and LCV-01, which met the PSCE criteria. Other items, such as PU-01 and C-01, were excluded from the assessment as they did not meet the initial screening for PSCE. The evaluation focused on the interplay between deterioration mechanisms, retarding factors, accelerating factors and the strategic options for managing ageing equipment. Here is a breakdown and discussion based on the findings.

3.2. Application

Step 1:

PSCE Identification:

As mentioned in the Research Methods (Chap. 3), the first step is to analyse the HAZOP report to determine the MAHs within the chemical plant. Using the 5 × 5 risk matrix shown in Fig. 1, we identified the equipment that fell under one of the two categories:

Table 5 Node breakdown from Fig. 4

Node	Equipment	Deviation	Causes	Consequences	L	S	Carry to 2nd step?
Node 1	Pump (PU-01)	Flow (Less)	• Ammonia (NH_3) storage tank is empty • LCV-01 is stuck in close position • NRV-01 is stuck in close position • Blockage in Lines 100 and 101 • LIC-1 failure causing LCV-01 to close	PSE due to pump failure	3	3	No
		Flow (More)	• LCV-01 is stuck in close position • LIC-1 failure causing LCV-01 to open	Overfill in vaporizer	3	3	
		Pressure (More)	• LCV-01 valve stuck closed • NRV-01 valve stuck closed • LIC-1 failure causes LCV-01 to close • Line 101 blockage	Pump malfunction	3	4	
		Pressure (Less)	• LCV-01 valve stuck open • LIC-1 failure causes LCV-01 to close • Ammonia storage tank is empty • Blockage in Line 100	• Liquid level increases • Pump cavitates	3	3	
Node 2	Vaporizer (VE-01)	Level (Less)	• Blockage or rupture in Line 101 • PCV-01 valve stuck open • PIC control failure, causing PCV-01 to open • LCV-01 and NRV-01 valves stuck closed • LIC-1 failure causes LCV-01 to close • FCV-01 stuck open • FFC-1 control failure opens FCV-01 • PCV-01 valve stuck closed • PIC-1 control failure causes it to close	• Heat/steam loss • Excessive vaporization • Insufficient vaporization	2	4	Yes
		Level (More)	• FCV-01 stuck closed • FFC-1 control failure closes FCV-01 • LCV-01 valve stuck open • LIC-1 failure causes LCV-01 to open	Vaporizer Overflow	2	4	Yes
		Level (No)	Similar causes as "Level (Less)," including Line 101 blockage, ruptures, and various valve/control failures.	• Heat/steam loss • Excessive vaporization • Insufficient vaporization	3	4	No
		Pressure (More)	• LCV-01 valve stuck open • LIC-1 failure causes LCV-01 to open • FCV-01 stuck closed • FFC-1 control failure closes FCV-01 • PCV-01 valve stuck open • PIC-1 control failure opens it	Rupture of tank	4	5	Yes
		Pressure (Less)	• Ruptures in the discharge or Line 101 • Tank rupture • Various valve failures (FCV-01, PCV-01, LCV-01) and control issues with PIC-1 and NRV-01	• Loss of NH_3 • Vaporization seizes	2	4	Yes
		Temperature (More)	• LCV-01 and NRV-01 valves stuck closed • FCV-01 stuck closed • FFC-1 control failure closes FCV-01	Excessive vaporization	4	5	Yes

Table 5 (continued)

			• PCV-01 valve stuck open • PIC-1 control failure opens it				
		Temperature (Less)	• PCV-01 valve stuck closed • PIC-1 control failure closes it • LCV-01 stuck open • LIC-1 failure causes LCV-01 to open	• No / less vaporization happens in VE-01	2	4	Yes
Node 3	Compressor (C-01)	Flow (More)	Filter material becomes dislodged	Damage to compressor	3	4	No
		Flow (Less)	• Filter becomes clogged • Rupture in Line 103	Damage to compressor	3	4	
		Composition (As well as)	• Rupture in Line 103 • Filter becomes clogged • Increased ambient humidity	Increase of load on compressor	3	4	
		Pressure (More)	• Filter material dislodges • Line 106 blockage	• Damage to compressor • Surge in the compressor	3	4	
		Temperature (More)	Increase in ambient temperature	Performance decreases	3	3	
Node 4	Reactor (RE-01)	Composition (Other than)	Wrong reagent used	• No reaction • Another possible reaction	2	4	Yes
		Composition (As well as)	Presence of impurities in the reagent	Another possible reaction	2	4	Yes
		Pressure (More)	• FCV-01 valve stuck open • FFC-1 control failure opens FCV-01	Stress on catalyst bed	4	5	Yes
		Pressure (Less)	• Ruptures in Line 106 or 107 • FCV-01 valve stuck closed • FFC-1 control failure closes FCV-01	• Loss of NH_3 and O_2	2	4	Yes
		Temperature (More)	• PCV-01 valve stuck open • PIC-1 control failure opens it • FCV-01 stuck open • FFC-1 control failure opens FCV-01	Thermal stress on catalyst bed	3	3	No
		Temperature (Less)	• Rupture in Line 106 • FCV-01 stuck closed • FFC-1 control failure closes FCV-01	• NH_3 and O_2 loss • Desired reaction seizes	3	3	No

a) Red category 'very high likelihood and very high consequence'.
b) Yellow category 'very low likelihood and very high consequence'.

We identified the vaporiser (VE-01) and reactor (RE-01) as vessels which may include PSCE due to the fact that hazards categorised as a and/or b were associated with their failure; failure in this equipment could result in a catastrophic incident (Table 5). These PSCE are summarised in Table 6.

For example, we chose PCV-01 and LCV-01 as PSCE from the vaporizer (VE-01), now after completing the initial screening, we further validated the outcome by referring to the logic tree shown in Fig. 2 from Chap. 3.

a) Does the equipment fall under one of the categories?

Yes, the equipment falls under both categories a and b.

b) Does the equipment store energy or hazardous material?

Yes, the equipment stores NH_3 (ammonia), which is a hazardous chemical.

c) If the equipment fails, could it lead to a PSE?

Yes, the failure could result in a rupture which could lead to a material release.

Knowing that PCV-01 and LCV-01 satisfy the criteria, we included them as part of the facility's PSCE list. This completes the first step of the identification methodology of the research.

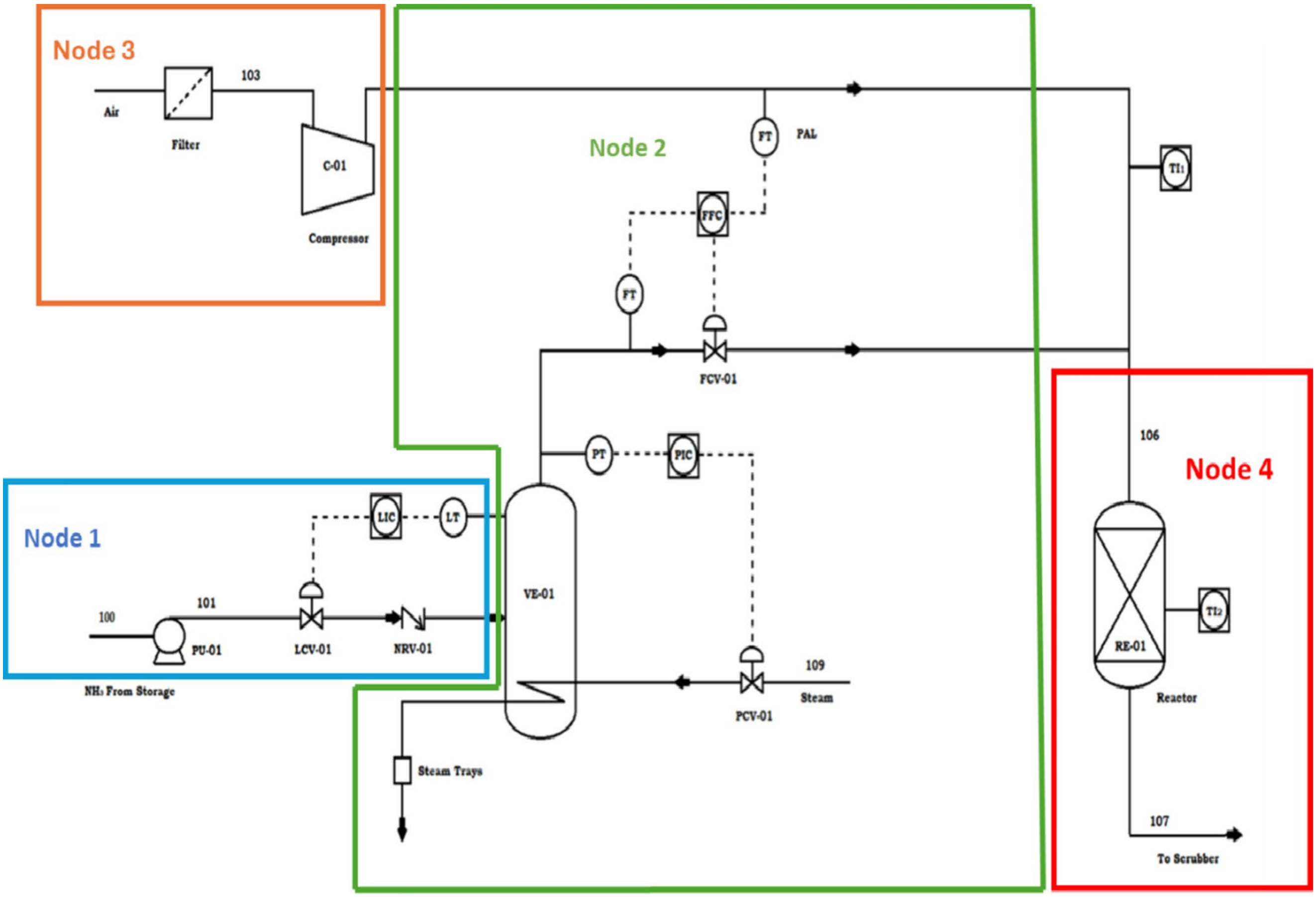

Fig. 4 Diagram of a chemical plant

Step 2:

Ageing Assessment:

After identifying both PCV-01 and LCV-01 within the vaporiser as part of the PSCE list, we then assessed their ageing following the guidelines presented in Chap. 3. This involved analysing equipment deterioration mechanisms and retarding and accelerating factors, and then summing the averages. This led to a final decision.

Equipment 1: PCV-01

Referencing API 571, we identified and assessed deterioration mechanisms that could impact PCV-01 ageing depending on the process, and then determined the average of each factor. The mechanisms can be chosen based on equipment performance for the previous years (failure data) or industry data if the facility is newly constructed. We concluded that erosion was the highest deterioration mechanisms for PCV-01 (Table 7). This highlights the need for increasing the inspection maintenance frequency. Next, we categorised accelerating and retarding factors depending on their effect on PCV-01 ageing. The data can be gathered from different entities within the facility (inspection, maintenance, reliability, process, etc.). This part is crucial as it contributes the most to the score of the equipment. Refer to Tables 8 and 9.

After identifying the accelerating and retarding factors, we calculated the total index: the difference between the average of the positive factors and the average of the negative factors from Fig. 3, as shown in Table 10. Finally, the score from the previous step was used to determine a strategy from Table 11. This strategy helps determine the path forward and the action to be taken by facility management.

As the retarding factors scored slightly higher than the accelerating factors, we concluded that the ageing management systems in place as functional and equipment could continue to operate with the following recommendations:

- Increase the frequency of inspection to assess the deterioration over time.
- Apply a risk-based inspection on the equipment.
- Closely monitor the performance of the equipment.

Table 6 Equipment identified as PSCE

Node	Main Equipment	Deviation	Sub Equipment	PSCE?
Node 2	Vaporiser (VE-01)	Level (Less)	• PCV-01 stuck open • PIC controller fails, causing PCV-01 to open • LCV-01 stuck closed • NRV-01 stuck closed • LIC-1 failure leads to LCV-01 closing • FCV-01 stuck open • FFC-1 control failure opens FCV-01 • PCV-01 stuck closed • PIC-1 control failure causes it to close	1. Line 101 2. PCV-01 3. LCV-01 4. LIC-1 5. FCV-01 6. FFC-1 7. NRV-01
		Level (More)	• FCV-01 stuck closed • FFC-1 control failure closes FCV-01 • LCV-01 stuck open • LIC-1 failure leads to LCV-01 opening	
		Pressure (More)	• LCV-01 stuck open • LIC-1 failure opens LCV-01 • FCV-01 stuck closed • FFC-1 control failure closes FCV-01 • PCV-01 stuck open • PIC-1 control failure opens it • Discharge line rupture • Line 101 rupture • Tank rapture	
		Pressure (Less)	• FCV-01 stuck open • FFC-1 control failure opens FCV-01 • PCV-01 stuck closed • PIC-1 control failure causes it to close • LCV-01 stuck closed • LIC-1 failure closes LCV-01 • NRV-01 stuck closed	
		Temperature (More)	• LCV-01 stuck closed • LIC-1 failure closes LCV-01 • NRV-01 & FCV-01 stuck closed • FFC-1 control failure closes FCV-01 • PCV-01 stuck open • PIC-1 control failure opens it	
		Temperature (Less)	• PCV-01 stuck closed • PIC-1 control failure causes it to close • LCV-01 stuck open • LIC-1 failure opens LCV-01	
Node 4	Reactor (RE-01)	Composition (Other than)	• Incorrect reagent	• Pipe line 106 • Pipe line 107
		Composition (as well as)	• Impurities in reagent	
		Pressure (More)	• FCV-01 stuck open • FFC-1 control failure opens FCV-01	
		Pressure (Less)	• Line 106 & 107 rupture • FCV-01 stuck closed • FFC-1 control failure closes FCV-01	

In summary, we identified the PSCE for the facility and conducted an ageing assessment for one piece of equipment PCV-01. Next, we conducted the same ageing assessment for LCV-01 to ensure that the methodology is clear.

Equipment 2: LCV-01

Referencing API 571, we identified and assessed deterioration mechanisms that could impact LCV-01 ageing depending on the process, and we calculated the average of each factor. We concluded that erosion and fatigue were the most important deterioration mechanisms (Table 12). This highlights the need for increasing the inspection, maintenance and testing frequency.

Next, we categorised accelerating and retarding factors depending on their effect on LCV-01 ageing. The data can be gathered from different entities within the facility

Table 7 Deterioration mechanisms for PCV-01

Mechanism type (API 571)	Detectability[1]	Propagation velocity[2]	Consequence[3]	Average
Corrosion under insulation (CUI)	3	3	3	3
Erosion	4	4	4	4
Thermal fatigue	3	2	2	2
Cavitation	3	1	2	2
Galvanic corrosion	2	2	3	2
Mechanical fatigue	1	2	4	2
Oxidation	3	1	2	2

(1) Detectability, which is linked to the challenge of identifying the phenomenon, assesses the impact it creates

(2) Propagation velocity, which describes the time progression of the phenomenon

(3) Consequences, which pertain to the most severe outcomes that the mechanisms can produce

Table 8 Retarding factors and scores for PCV-01

Factor	Score
Management system	2
Audit	3
Inspections scheduling and results	2
Inspections efficiency	2
Process control	4
Specific protections	3

Table 9 Accelerating factors and scores for PCV-01

Factor	Score
In-service time (age)	3
Number of unplanned stops	2
Actual/expected failure rates	3
Near misses due to deterioration	1
Deterioration mechanisms	2
Damages/defects	1

Table 10 Scoring index for PCV-01

Accelerating	Sum	Retarding	Sum
Age	3	Management system	2
Stops	2	Audit	3
Failures	3	Inspection scheduling	2
Near misses	1	Inspection efficiency	2
Deterioration	4	Process control	4
Damages	1	Specific protections	3
Total	***2.5***	***Total***	***2.67***

(inspection, maintenance, reliability, process, etc.). This part is crucial as contributes the most to the score of the equipment (Tables 13 and 14).

Table 11 Strategies and considerations for managing ageing of PCV-01

Strategy	Considerations
No action, continue to operate	● Capability to monitor equipment condition and performance through a risk assessment ● Cost-effectiveness for ongoing operation
Repair and/or modify	● Availability of technical competencies and resources ● Evaluate repair approach options, and availability of spare parts ● Closely monitor and control the repair under management of change (MOC) ● Need for fit-for-service testing
Temporary repairs	● Might not serve as the same function as the primary equipment ● Does not meet safety standards and workplace safety ● High in cost ● Closely monitor and control the replacement under management of change (MOC)
Halt the operation, and repair	● Financial costs ● Disposal costs and logistics ● Environmental impact due to a process safety event, flaring

Table 12 Deterioration mechanism for LCV-01

Mechanism Type (API 571)	Detectability[1]	Propagation velocity[2]	Consequence[3]	Average
Corrosion	3	4	3	3
Erosion	3	3	3	3
Fatigue	4	2	2	3
Cavitation	2	2	3	2
Stress Corrosion Cracking	3	2	2	2
Embrittlement	3	2	1	2

(1) Detectability, which is linked to the challenge of identifying the phenomenon, assesses the impact it creates

(2) Propagation velocity, which describes the time progression of the phenomenon

(3) Consequences, which pertain to the most severe outcomes that the mechanisms can produce

Table 13 Retarding factors and scores for LCV-01

Factor	Score
Management system	3
Audit	2
Inspections scheduling and results	3
Inspections efficiency	2
Process control	4
Specific protections	3

After identifying the accelerating and retarding factors, we calculated the total index: the difference between the average of the positive factors and the average of the negative factors, as shown in Table 15.

Table 14 Accelerating factors and scores for LCV-01

Factor	Score
In-service time (age)	3
Number of unplanned stops	1
Actual/expected failure rates	1
Near misses due to deterioration	2
Deterioration mechanisms	2.6
Damages/defects	3

Table 15 Scoring index for LCV-01

Accelerating	Sum	Retarding	Sum
Age	4	Management system	3
Stops	4	Audit	2
Failures	3	Inspection scheduling	2
Near misses	2	Inspection efficiency	1
Deterioration	2.6	Process control	4
Damages	2	Specific protections	2
Total	***2.93***	***Total***	***2.33***

Finally, the score from the previous step was used to identify a strategy from Table 16. This strategy determines the path forward and the action to be taken by facility management.

As the accelerating factors scored higher than the retarding factors, we concluded that the ageing management system is ineffective, therefore operations should be halted, and the equipment shall be repaired.

After conducting the assessment, Table 17 was filled out to be included in the facility's safety management system under one or more elements to ensure it is consistently updated. In addition, it is crucial to ensure that the identified PSCE operate within a resilient system. This will allow facility management to keep track of the underperforming PSCE, and ensure that they are treated differently if they undergo any changes, interruptions in the system which they operate in, increase in the number of alarms, bypass, etc. This methodology allows faculties to assess the ageing conditions of PSCE using a structured and reputable process that supports risk-based decisions.

Table 16 Strategies and considerations for managing ageing of LCV-01

Strategy	Considerations
No action, continue to operate	• Capability to monitor equipment condition and performance through a risk assessment • Cost-effectiveness for ongoing operation
Repair and/or modify	• Availability of technical competencies and resources • Evaluate repair approach options, and availability of spare parts • Closely monitor and control the repair under management of change (MOC) • Need for fit-for-service testing
Temporary repairs	• Might not serve as the same function as the primary equipment • Does not meet safety standards and workplace safety • High in cost • Closely monitor and control the replacement under management of change (MOC)
Halt the operation, and repair	• Financial costs • Disposal costs and logistics • Environmental impact due to a process safety event, flaring

Table 17 Post PSCE selection and ageing assessment template

No	PSCE Tag #	Process	Ageing Score[1]	Strategy[2]	Comments
1	PCV-01	Vaporizer (VE-01)	+0.17	No action, continue to operate	• Increase the frequency of inspection to assess the deterioration over time. • Evaluate applying a risk-based inspection of the equipment • Closely monitor the performance of the equipment
2	LCV-01	Vaporizer (VE-01)	−0.60	Halt the operation, and repair	N/A

(1) The sum of the accelerating and retarding factors (positive or negative)

(2) Select applicable strategy from Table 4 based on the calculated score from Fig. 3.*f*science

Chapter 5: Discussion

The case study findings demonstrated that not all equipment within a facility qualifies as Process Safety Critical Equipment (PSCE). The proposed assessment framework effectively distinguished between genuinely critical assets and those not requiring PSCE designation, thereby reducing the risk of over classification.

Among the identified PSCEs, the condition varied significantly. For example, LCV-01 exhibited a higher risk profile with a negative ageing score (–0.60), indicating an urgent need for repair or replacement. This outcome was primarily attributed to the dominance of accelerating degradation factors such as erosion and fatigue, combined with a lack of effective retarding mechanisms. These findings underscore the critical need for timely intervention and highlight the risk posed by ageing infrastructure when not actively managed.

In contrast, PCV-01 received a positive score (+0.17), suggesting acceptable operating conditions. This can be linked to the presence of strong retarding factors, such as robust maintenance, inspection routines, and environmental control. This variation reinforces the value of the ageing assessment approach, which enables risk-informed decisions based on specific degradation mechanisms and condition profiles.

The analysis highlights the importance of adopting a predictive equipment monitoring approach to ageing risk management. Facilities that understand the difference between accelerating and retarding factors can allocate resources more effectively, optimize maintenance strategies, and improve overall safety performance.

Moreover, when compared to traditional methodologies such as RBI (Risk-Based Inspection), the proposed qualitative tool offers greater accessibility and ease of application. Its design allows safety personnel — even those without advanced process safety backgrounds — to make informed decisions quickly.

Importantly, the method promotes a sharper focus on PSCE performance within the safety management system. It encourages facilities to track the condition of ageing PSCEs over time, enabling updates to be made proactively. This reinforces resilience, reduces the likelihood of process safety events, and enhances operational continuity.

Chapter 6: conclusions and future work

This study presents a novel approach for identifying and managing ageing Process Safety Critical Equipment (PSCE) in the oil and gas industry. The method incorporates a logic-tree-based identification tool and an ageing factor scoring system to assess equipment condition, and recommend appropriate maintenance strategies.

Key findings include:

- The value of distinguishing PSCE from non-critical equipment to avoid overburdening safety systems and facility personnel.
- The ageing assessment framework's effectiveness in highlighting condition-based differences between equipment (e.g., PCV-01 vs. LCV-01).
- The method's accessibility to a broader range of personnel, enabling quicker, risk-informed decisions even in resource-constrained facilities.

The study also shows how ageing management can be embedded into safety management systems to ensure continuous monitoring, timely intervention, and alignment with risk reduction goals.

Nonetheless, limitations exist. The current method uses qualitative scoring and relies on the consistency of cross-functional input. Its effectiveness may vary based on facility type, data availability and accuracy, and team experience. Furthermore, the static nature of the assessment means it may miss dynamic operational or environmental changes that impact PSCE performance over time.

Future research could develop a systematic approach to link PSCE with any changes that may affect their performance, whether directly or indirectly. These changes could be physical, such as alterations in equipment condition or functionality, or operational, such as equipment removal or replacement. By systematising this process, organisations could better identify and monitor PSCE, ensuring that the most critical equipment is prioritised. This would contribute significantly to maintaining the safety of personnel, protecting assets and safeguarding the environment within the facility. Additionally, the systematic approach could incorporate predictive maintenance strategies, enabling proactive management of PSCE based on real-time data, which would further enhance the reliability and safety of the system.

In conclusion, this research provides a valuable framework for improving safety and resilience in high-risk industries, although further work is needed to address its limitations and improve the approach for broader applicability.

Appendix

Author contributions S.A.: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.S. H. : Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. J.C. : Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Conceptualization.

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