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Operationalising Consequence Analysis Via a Digital Twin For Offshore Compressor Trains

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Natural gas compressor trains on offshore platforms present elevated fire and explosion risk due to methane's wide flammability and low ignition energy. This study models methane releases leading to dispersion and jet fires in a three-stage compressor train and embeds the outputs in a digital twin to enable predictive anomaly detection and decision support. Consequence modelling used DNV PHAST v8.7: the Unified Dispersion Model (UDM) for dispersion and the Johnson solid-flame model for jet-fire analysis. Three compressor discharge scenarios (low, medium, and high-pressure) were evaluated under two meteorological conditions (2 m s^{-1}/F and 5 m s^{-1}/D) for a representative 30 mm leak on an anonymised North Sea platform. Under worst-case stability (2 m s^{-1}/F), 100% LFL cloud extents reached 9.45 m, 16.75 m, and 30.55 m for the low, medium and high-pressure stages, respectively. Corresponding thermal-radiation footprints at 4 kW m^{-2} extended to 25.4 m, 46.31 m, and 78.95 m, with lethal 37.5 kW m^{-2} contours up to 52.59 m at high pressure; predicted flame lengths ranged 17.0–46.0 m. These outputs were integrated into the twin as software artefacts, hazard footprint overlays and triggerable scenario selection, supporting proactive anomaly detection, detector placement, exclusion zone definition, and emergency response planning. The work demonstrates how validated consequence models can be operationalised via a digital twin to provide live, spatially precise risk intelligence for offshore process safety.

Keywords: Digital Twin, Consequence Modelling, Methane Dispersion, Offshore Process Safety, Quantitative Risk Assessment

1. Introduction

Global natural gas consumption has increased by around 15% over the last decade, and demand is projected to continue rising towards 2030 and 2050, particularly in emerging economies (bp, 2024). This growth reinforces the need for robust process safety assurance for offshore gas production, where large inventories, congested layouts, and weather exposed operations can amplify the consequences of loss of containment.

Methane rich natural gas presents acute hazards because it has a wide flammability range (5 to 15% v/v) and low ignition energy, meaning that an ignitable cloud can form and ignite readily if an ignition source is present (Johnson et al., 2015). Offshore compressor trains are a particular concern because they handle high pressure gas, concentrate potential leak sources within a confined area, and operate near equipment that can provide ignition, including hot surfaces, mechanical damage, and electrical infrastructure. Emissions inventories also highlight the relevance of high pressure operating utilities, with a non trivial share of methane emissions associated with such conditions (Johnson et al., 2015).

Compressor trains are central to offshore production, providing the pressure rise needed for gas export (Zhao and Li, 2015). Their operating duty can introduce pressure fluctuations and vibration that contribute to fatigue and localised damage, which can increase leak likelihood if not effectively controlled (Jang and Choi, 2017). When a pressurised gas release ignites immediately, a jet fire can develop, producing high thermal radiation that threatens personnel, critical safety systems, and nearby equipment. Escalation and domino pathways are especially important offshore, where equipment spacing and congestion can allow a local event to cascade into wider loss (Gómez-Mares et al., 2008). The resulting hazard footprint is sensitive to release conditions (pressure, orientation, and leak size) and to atmospheric conditions that govern mixing and dilution, which are particularly variable in North Sea environments (Johnson, Brightwell and Carsley, 2023).

Consequence modelling tools, including DNV PHAST, are widely used to estimate dispersion and jet fire thermal radiation effects and to support engineering assessments (Witlox, 2010; Naemnezhad et al., 2017). However, these analyses are commonly performed as stand-alone studies, with outputs stored in reports or disconnected files. This limits operational value: hazard footprints are not routinely contextualised against live operating conditions, and decision makers may not see how changing process states alter the potential extent and severity of credible releases. As a result, latent risk can persist even when modelling has been completed.

Digital Twin technology offers a route to close this gap by synchronising geometry and operational data with analytics that support monitoring and prediction (Wang and Zhang, 2020; Moisescu et al., 2024). While twins are increasingly used in offshore settings for asset information management and visualisation, the integration of validated consequence models into the operational twin remains under developed. In particular, there is a practical need for a repeatable workflow that translates consequence modelling outputs into installation specific, operationally usable hazard layers that can be interrogated alongside live data.

This paper addresses that need by connecting installation specific dispersion and jet fire consequence modelling for an offshore three stage compressor train to a Digital Twin context. The novelty is the translation of PHAST derived dispersion and thermal radiation effect zones into a structured scenario library that can be aligned with operating states and visualised directly on the platform model to support decision making. The contribution is threefold: (i) a consistent, pressure dependent comparison of dispersion and thermal radiation footprints across representative compressor discharge conditions; (ii) bounding of credible hazard extents under representative offshore meteorology; and (iii) an integration workflow that enables Digital Twin based visualisation of consequence layers and provides a practical foundation for predictive anomaly detection that is linked to consequence severity (Witlox, 2010; Naemnezhad et al., 2017; Wang and Zhang, 2020; Moisescu et al., 2024).

2. Methodology

This paper quantifies the consequences of credible methane loss of containment events at an offshore compressor train and converts the outputs into a scenario indexed hazard layer library that can be overlaid on the platform Digital Twin. The workflow comprises (i) installation specific case definition (nodes and operating states), (ii) consequence modelling in PHAST v8.7 for unignited dispersion and immediate ignition jet fire, and (iii) export and spatial registration of contours onto the plot plan and 3D model for Digital Twin visualisation and comparison across scenarios (Witlox, 2010).

2.1 Case definition and node selection

The study boundary is the common gas compressor train discharge pipework on Platform Z. Release nodes were defined using an isolation based segmentation of the compressor discharge pipework, from each compressor discharge to the corresponding discharge cooler. The three analysed nodes represent the LP, MP and HP discharge isolatable sections, which are shown on the installation 3D model in Figure 1.

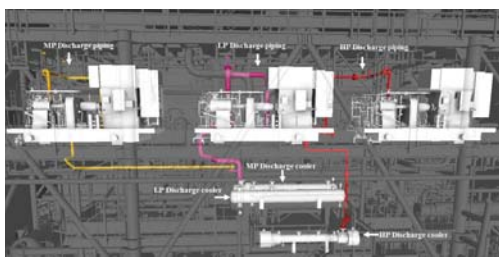

Fig 1. *Isolatable LP, MP and HP compressor discharge sections (release nodes) and associated discharge coolers on Platform Z used to define installation specific modelling cases.*

These sections provide the physical basis for associating each PHAST run with an isolatable inventory and a unique operating state. The operating states associated with these nodes were taken from platform data (LP 32 bar(g) at 138 °C, MP 98 bar(g) at 135 °C, HP 260 bar(g) at 111 °C), and combined with two representative offshore weather cases to form a six case simulation matrix.

2.2 Modelling tool and scenario matrix

Consequence modelling was performed using PHAST v8.7, which integrates source term estimation with atmospheric dispersion and jet fire consequence calculations. Methane was used as the representative fuel for all simulations to ensure consistent flammability and radiation assessment across discharge states.

To enable a focused comparison while retaining realism, the scenario matrix fixes leak geometry and varies only the operating state and meteorology:

- Leak basis: representative circular hole diameter 30 mm, horizontal release, elevation 2.5 m.
- Operating states: LP, MP, HP discharge conditions (Table 1).
- Meteorology: two bounding offshore cases, 2 m/s with stability class F and 5 m/s with stability class D (Table 2).
- Terrain: sea with roughness 0.06 (Table 1).

Table 1. Consolidated failure case and process inputs for the compressor train (LP, MP, and HP discharge sections).

Field	LP discharge	MP discharge	HP discharge
Piping number	PG-BN-300007	PG-EN-300010	Not specified
Operating pressure (bar(g))	32	98	260
Operating temperature (°C)	138	135	111
Hazard event (jet fire)	√	√	√
Gas composition	Methane (CH_4)	Methane (CH_4)	Methane (CH_4)
Terrain	Sea	Sea	Sea
Roughness parameter	0.06	0.06	0.06

Table 2. Input weather conditions.

Parameters	Case-1	Case-2
Wind speed (m/s)	2	5
Stability class	F	D
Stability	Low wind, stable	Moderate wind, Neural
Air temperature (°C)	6	6
Ground temperature(°C)	5	6
Relative humidity (%)	86	86
Solar radiation heat(kW/m²)	0	0.1–0.2

This produces a compact six case matrix (3 representative discharge states × 2 weather cases) that isolates the effects of discharge pressure and atmospheric stability on hazard extent.

2.3 Dispersion endpoints and jet fire consequence metrics

Unignited dispersion was simulated using PHAST's Unified Dispersion Model, and hazard extents were reported using methane concentration contours at 100% LFL (50,000 ppm, ignitable boundary) and 50% LFL (25,000 ppm, early warning envelope); the upper flammability limit was taken as 150,000 ppm for completeness when interpreting rich mixtures.

Immediate ignition was modelled as a jet fire anchored at the release location, with wind effects represented through flame tilt and flame length in the PHAST jet fire model formulation consistent with the Johnson solid flame approach (Johnson, 1994; Witlox, 2010). The geometric basis used for radiation estimation and view factors is illustrated in Figure 2. Jet fire outputs were reported as thermal radiation contours at 4, 12.5, and 37.5 kW/m², selected to provide decision relevant severity layers for personnel and asset exposure.

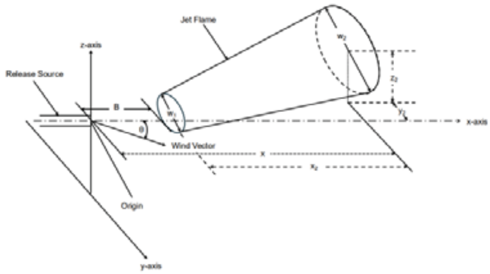

Fig 2. Tilted cylinder model for horizontal jet release.

2.4 Digital Twin integration and output handling

For each scenario, PHAST outputs (dispersion and radiation contours) were exported and converted into a scenario library indexed by (i) isolatable section, (ii) compressor discharge state (LP, MP, HP), and (iii) meteorological case. Contours were spatially registered to the platform plot plan and 3D model coordinate basis so they can be visualised as Digital Twin hazard overlays. This structure enables direct comparison of hazard extents across operating states and supports future coupling to live data or anomaly detection by selecting the scenario consistent with the current operating envelope.

2.5 Scope assumptions

The modelling represents steady state consequences prior to effective isolation. Depressurisation transients, detailed congestion induced turbulence, and mitigation systems were not explicitly modelled; these factors are treated as outside scope for this paper and are discussed when interpreting results.

3. Results and discussion

3.1 Dispersion results: flammable cloud extent

Figure 3 presents the PHAST predicted plan view dispersion contours for the three discharge states (LP, MP and HP) under 2/F and 5/D. Contours are reported at 150,000 ppm (UFL), 50,000 ppm (100% LFL) and 25,000 ppm (50% LFL). For operational interpretation, 100% LFL defines the ignitable boundary, while 50% LFL provides a conservative early warning envelope.

Two consistent trends are observed. First, the dispersion footprint increases strongly with discharge pressure. Under 2/F, the 100% LFL downwind distance increases from 9.45 m (LP) to 16.75 m (MP) and 30.55 m (HP). The corresponding 50% LFL envelope expands from 18.02 m to 33.84 m and 66.76 m, respectively. Second, moving from 2/F to 5/D reduces the flammable envelope, consistent with higher wind speed and increased mixing. Under 5/D, the 100% LFL distances reduce to 9.04 m (LP), 15.48 m (MP) and 27.42 m (HP), with the 50% LFL envelope reducing to 16.16 m (LP) and 30.02 m (MP), while remaining comparable for HP (66.10 m).

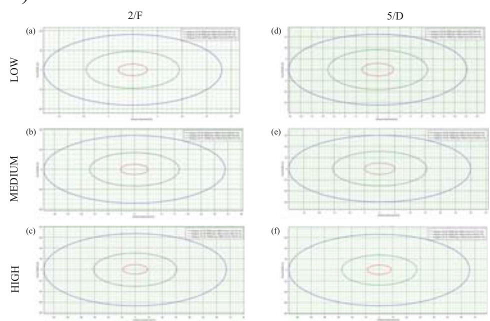

Fig 3. Plan view methane dispersion contours for LP, MP and HP compressor discharge releases under two meteorological cases: 2/F (a-c) and 5/D (d-f). Contours show 150,000 ppm (UFL), 50,000 ppm (100% LFL) and 25,000 ppm (50% LFL) envelopes.

Key finding: the pressure state dominates dispersion extent, while the meteorological shift from 2/F to 5/D produces a secondary reduction in the LFL envelopes. In practice, the 50% LFL contour is the most useful layer for screening detector coverage and defining conservative temporary exclusion zones during abnormal operations, especially for HP discharge where the envelope extends substantially beyond the near field around the release.

3.2. Jet fire results: thermal radiation footprints

Figure 4 presents the jet fire thermal radiation ellipses for the same discharge states under 2/F and 5/D, reported at 4 kW/m², 12.5 kW/m², and 37.5 kW/m². These thresholds provide decision oriented severity layers, ranging from low level injury potential to lethal exposure and equipment damage risk.

Radiation footprints scale strongly with discharge pressure. Under 2/F, flame length increases from 17.04 m (LP) to 27.99 m (MP) and 44.51 m (HP), with corresponding 4 kW/m² downwind distances of 25.40 m, 46.31 m, and 78.95 m. The 37.5 kW/m² contour extends to 18.69 m, 31.85 m, and 51.04 m, respectively. Under 5/D, flame lengths remain similar (17.02 m, 28.47 m, 45.96 m) and radiation distances change only modestly, with the HP case remaining the controlling scenario (for example, 37.5 kW/m² increasing slightly to 52.59 m).

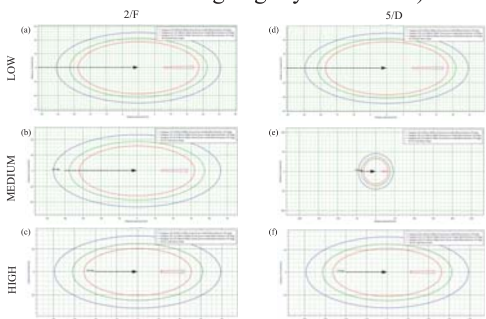

Fig 4. Plan view jet fire thermal radiation ellipses for LP, MP and HP discharge releases under two meteorological cases: 2/F (a-c) and 5/D (d-f). Contours show 4, 12.5 and 37.5 kW/m² heat flux thresholds.

Key finding: compared with dispersion, jet fire radiation is less sensitive to the 2/F versus 5/D change within the tested envelope. This supports using radiation contours as a conservative, pressure driven screening layer for identifying escalation exposure around the compressor module, while dispersion contours remain the primary layer for weather sensitive detector and exclusion zone considerations.

3.3 Cross scenario synthesis and worst case identification

Figure 5 condenses the scenario matrix into decision relevant metrics by comparing (i) dispersion distances to 100% LFL (50,000 ppm) and 50% LFL (25,000 ppm), (ii) jet fire downwind distances at 4, 12.5 and 37.5 kW/m² together with flame length, and (iii) a combined screening view of dispersion and radiation for worst case interpretation. The figure confirms that discharge pressure is the dominant driver of both flammable and thermal hazard extent, with the HP discharge consistently controlling the envelope across the two weather cases.

Meteorology has a clearer effect on dispersion than on jet fire. Moving from 2/F to 5/D contracts the LFL based envelope modestly, while the radiation distances and flame length remain broadly similar, indicating that within the tested conditions the jet fire footprint is governed primarily by source term and momentum. This supports a practical interpretation in which dispersion layers are weather sensitive (useful for detection and temporary exclusion), while radiation layers are pressure driven (useful for escalation screening and protection of critical equipment).

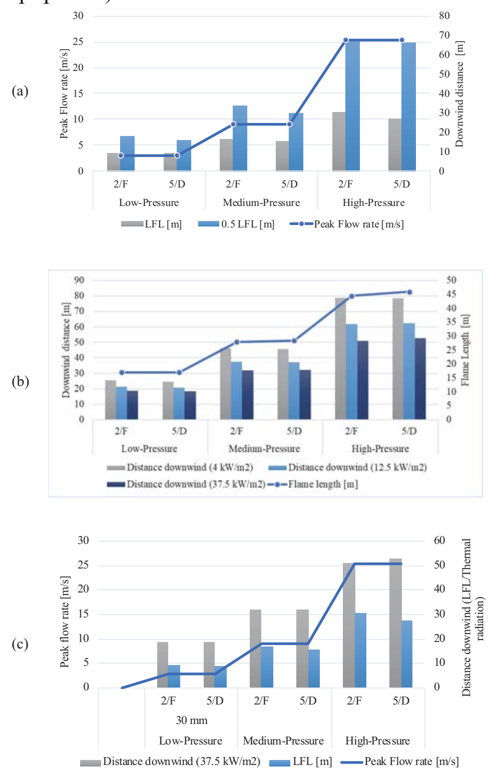

Fig 5. Cross scenario comparison across LP, MP and HP discharge states and weather cases: (a) dispersion downwind distances at 100% LFL and 50% LFL with peak release flow rate; (b) jet fire downwind distances at 4, 12.5 and 37.5 kW/m² with flame length; (c) combined screening view for worst case interpretation.

3.4 Digital Twin hazard overlays

The main novelty of this paper is not the PHAST calculations themselves, but the translation of consequence results into a scenario indexed library of spatial hazard layers that can be overlaid on an installation model. Figure 6 demonstrates this mapping for LP, MP and HP discharge cases using the platform 3D model in front and lateral views. Each overlay represents a consequence layer that is (i) tied to a specific isolatable discharge node (Figure 3) and operating state, and (ii) spatially registered so that the exposed equipment and deck regions can be interrogated directly in the Digital Twin.

The overlays highlight the operational value of pressure state differentiation. Moving from LP to HP expands the affected volume from a localised module envelope to a footprint that can intersect wider deck areas, which is critical for interpreting escalation exposure and potential constraints on access and egress. In practice, this scenario library enables a Digital Twin to display consequence severity alongside operating state, and it provides a direct bridge to anomaly detection: once an abnormal condition is detected and classified to a discharge state envelope, the corresponding consequence layer can be surfaced immediately for decision making.

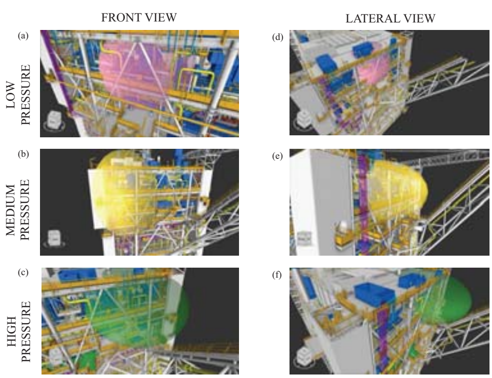

Fig 6. Digital Twin overlay of consequence layers for LP, MP and HP discharge cases (front and lateral views), demonstrating spatial registration of PHAST derived hazard footprints to the installation 3D model for operational visualisation.

3.5 Digital Twin model extension for predictive consequence visualisation

While Sections 3.1–3.4 report the dispersion and radiation footprints and demonstrate their spatial overlay on the installation model, Figure 7 summarises how the same outputs can be operationalised in a Digital Twin as a lightweight, scenario indexed consequence service. The proposed architecture retains the existing twin data layers (asset model, geometry, tag catalogue and operating history) and adds a PHAST scenario database containing pre computed consequence outputs (dispersion and radiation contours and associated metadata) aligned with the case definitions in Sections 2 and 3.

Real time process data from the PI system is treated as the primary trigger and context layer. PI tags (for example discharge pressure, temperature and flow) are periodically extracted in a structured table format and linked to a PHAST scenario definition file (JSON) using a simple Python mapping routine. The selection logic is designed to identify the most appropriate pre computed scenario when thresholds are exceeded or when an anomaly detection model flags abnormal behaviour. Once selected, the corresponding consequence layer is rendered as a hazard overlay on the 3D model and plot plan and simultaneously summarised on the dashboard as quantified indicators (loss of containment basis, scenario state, flammable envelope distances, thermal radiation distances and hazard radius), enabling rapid interpretation by operations and process safety users.

A key design feature is a bidirectional navigation path between physical and digital representations. The dashboard provides the primary interface for analytics and process safety teams to trace an alert back to underlying PI evidence and assumptions, re validating the scenario mapping where required. Maintenance users can enter via laser scan or 3D model views and link directly to the same consequence layers and dashboard summaries for deviation analysis and work prioritisation. This shared view supports consistent decision making across analytics, maintenance and process safety governance.

In practical terms, this extension enables three high value use cases. First, anomalies identified during pre start up checks or during Prestart-up Review (PSSR), maintenance or

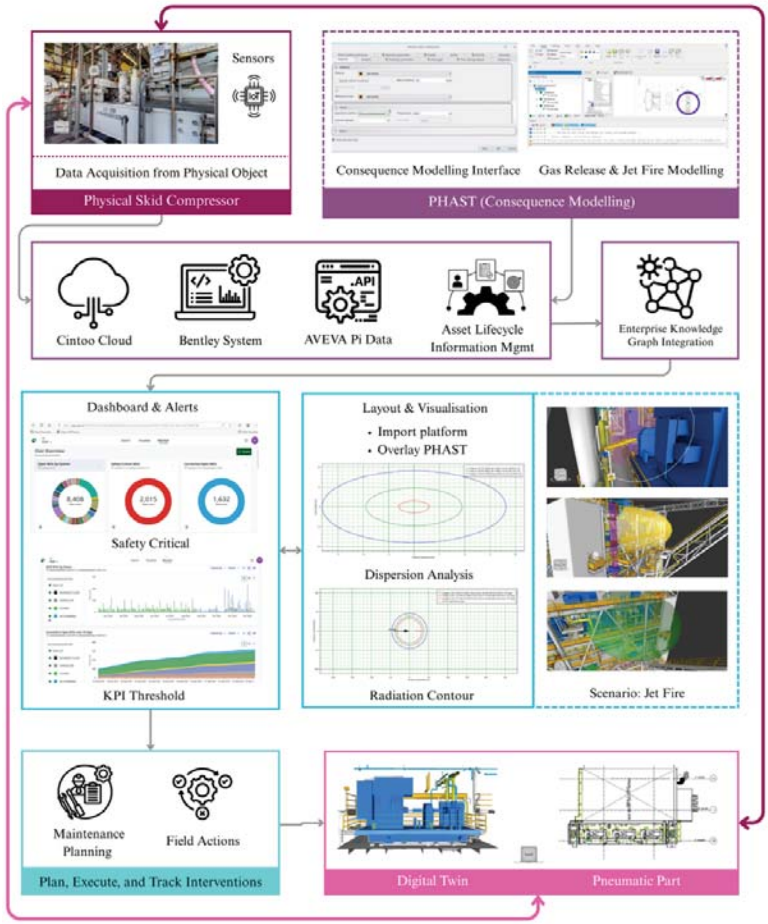

Fig 7. Digital Twin framework for integrating PHAST based consequence modelling into an operational environment: scenario database and model linkage to PI data, dashboard alerts and spatial hazard overlay on the 3D installation model.

normal operations can be contextualised against consequence severity by selecting the nearest matching discharge state and weather envelope rather than relying on deviations alone. Second, equipment vulnerability screening can be supported by querying whether specific assets fall within high consequence contours (for example regions exceeding 12.5 kW/m²). Third, emergency response benefits from clear hazard visualisation, where flammability and radiation zones are displayed through dashboard alerts to support evacuation decisions and alternative route selection.

4 Conclusions

This paper developed an installation specific consequence modelling workflow for methane loss of containment at an offshore compressor train and translated the outputs into Digital Twin ready hazard layers. Using PHAST v8.7, dispersion contours were reported at 25,000 ppm (50% LFL) and 50,000 ppm (100% LFL), and jet fire consequences were reported as thermal radiation contours at 4, 12.5 and 37.5 kW/m². Across the analysed matrix, discharge pressure was the dominant driver of both flammable cloud extent and thermal radiation footprint, with the high pressure discharge consistently defining the controlling hazard envelope. The meteorology change from 2/F to 5/D produced a secondary contraction of the LFL based dispersion envelope, while jet fire radiation distances and flame length changed only modestly within the tested conditions.

The key contribution is operational rather than computational: consequence outputs are structured as a scenario indexed library tied to isolatable discharge sections (Figure 3) and spatially registered to the installation model for overlay and querying. Extending this, the proposed Digital Twin framework (Figure 7) shows how pre computed PHAST scenarios can be linked to real time PI data through a lightweight mapping routine, enabling automated scenario selection when thresholds are breached or anomaly detection flags abnormal behaviour. This supports consequence informed decision making during operations and maintenance by surfacing quantified hazard extents through dashboards and 3D visual overlays, and by enabling bidirectional traceability from alarms to underlying process evidence.

Limitations and future work: Results represent steady state footprints prior to effective isolation and do not include blowdown transients, detailed congestion effects, or mitigation performance. Future work should incorporate time dependent isolation and couple scenario selection to live meteorology and operating mode classification to improve operational fidelity.

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