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# A Generalized Prognosis and Health Monitoring Platform for Network-Based Systems Using Hybrid Causal Logic Modeling Approach

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Over the past few years, the authors have developed a system-level Prognosis and Health Monitoring (PHM) modeling framework for gas pipeline integrity management. The original framework (Chalgham et al. 2020), based on Hybrid Causal Logic (HCL) with embedded Dynamic Bayesian Networks (DBNs), provided a comprehensive methodology and software platform for real-time risk assessment, failure prediction, and optimal mitigation planning. While effective for gas pipelines, the framework's domain-specific structure limited its applicability to other complex infrastructure systems.

In this paper, we introduce a generalized PHM framework designed to model and monitor a broader class of systems that involve pipelines and similar transmission networks such as electric power grids, water distribution systems, and transportation infrastructure. This new implementation retains the HCL and DBN-based architecture but introduces configurable abstractions to enhance flexibility and reusability.

Systems are modeled as networks composed of segments and station points, each may experience failure through diverse mechanisms. Segment failures can be modelled using templates based on fault trees or event sequence diagrams, with failure mechanisms (e.g., corrosion, wear, overloading) modeled as modular components linked to customizable Bayesian belief networks. These modules support evidence injection and model updating based on periodic observations, facilitating more accurate and adaptive risk quantification.

The framework is implemented in the NSIM software platform (Network System Integrity Management Platform) that supports interactive configuration and real-time health monitoring. Its flexibility makes it suitable for a wide range of applications beyond oil and gas pipelines, including smart grid reliability, water infrastructure resilience, and logistics network risk management. This work represents a step toward a unified, data-informed decision-support system for integrity management across complex engineered systems.

*Keywords*: Network Systems, Prognosis and Health Monitoring, Hybrid Causal Logic, Dynamic Bayesian Networks, Risk Assessment, Transmission Infrastructure, Consequence Modeling, Geospatial Integration

## 1. Introduction

Transporting fuel and energy through transmission networks is a vital national requirement and a complex logistical process. In the United States alone, the infrastructure for oil and gas pipelines exceeds 2.6 million miles. Despite its criticality, system integrity management remains a challenge, as evidenced by an average of 287 annual incidents resulting in significant fatalities, injuries, and billions of dollars in property damage (U.S. Department of Transportation, PHMSA, 2020)

Previous research by the authors (Chalgham et al. 2020) introduced a system-level Prognosis and Health Monitoring (PHM) modeling framework specifically for gas pipeline integrity management. This original framework leveraged Hybrid Causal Logic (HCL) (Groth et al., 2010; Wang, 2007; Groen and Mosleh, 2006) and Dynamic Bayesian Networks (DBNs) (Chalgham et al. 2019) to perform real-time risk assessment and failure prediction based on streaming sensor data. While this approach successfully integrated defect detection, growth prediction, and mitigation optimization, its implementation was constrained by a domain-specific structure.

A critical review of current PHM approaches reveals several persistent gaps:

- Lack of Generalization: Most existing models are developed for component-level analysis or specific domains, such as gas pipelines, and are not easily adaptable to other transmission networks like electric power grids or water distribution systems.
- Limited Consequence Modeling: Traditional models often focus strictly on failure probability, neglecting a multi-dimensional quantitative assessment of risk magnitude across different consequence categories such as safety, financial, or environmental.
- Spatial Data Inflexibility: While some models consider localized damage, they often lack a unified method to ingest global geospatial datasets (heat maps) to dynamically update model priors based on specific geographic locations.
- Fragmented Mitigation Planning: The industry lacks a centralized, user-friendly platform that can aggregate and compare competing mitigation strategies across a diverse network in real-time.

The objective of this paper is to introduce a generalized PHM platform designed to monitor a broader class of systems involving transmission networks. This new implementation retains the robust HCL and DBN-based architecture of its predecessor but introduces configurable abstractions to enhance flexibility and reusability. The framework models systems as networks composed of modular segments and station points, supporting evidence injection from geospatial heat maps and enabling a comprehensive, data-informed decision-support system for integrity management across varied complex engineered systems.

## 2. Generalized System Architecture

The primary innovation of the proposed platform is the shift from a domain-specific pipeline model to a generalized network abstraction. This architecture allows the same HCL-based engine to represent diverse infrastructure types through modular configuration.

### 2.1. *Network abstraction: segments and stations*

In previous iterations, the framework utilized a "transmission phase" concept specifically for pipelines, consisting of a compressor station and a fixed pipe segment. The new framework generalizes this by modeling all systems as networks composed of two primary entities: segments and station points:

- Station Points: Represent localized nodes where specific operations or transitions occur (e.g., city gates, electrical substations, or pumping stations).
- Segments: Represent the transmission links between stations, such as power lines, water mains, or transportation routes.

The integrity of the network is currently modeled under the assumption that all constituent segments and stations are connected in a serial relationship. In this configuration, the failure of any individual element—whether a station point or a network segment—results in the failure of the entire system. While this provides a robust baseline for real-time monitoring, future iterations will incorporate complex network maps to support parallel redundancies.

### 2.2 *Modular template-based modeling*

To ensure reusability across different industries, the platform utilizes a template-based modeling approach. Templates serve as the structural standard, defining the failure logic for a specific type of segment or station before it is instantiated in a real-world network, and contain:

- Failure Logic Layers: Each template integrates three modeling tools: Event Sequence Diagrams (ESDs) to map operational paths, Fault Trees (FTs) to capture inter-correlated failure modes, and Bayesian Belief Networks (BBNs) to model soft causal dependencies and physical environments.
- Modular Quantifier Items: Templates define three types of modular items: BBN Items for evidence setting, FT/ESD Items for internal event updating, and Service Items for external quantification via web services.
- Entry Point Definition: Segment failure is quantified via a specific entry point in the template—either the top gate of a Fault Tree or a selected end state of an ESD.

## 3. Dynamic instantiation and modularity

The framework architecture decouples structural failure logic from site-specific data. While every segment created from a template shares an identical initial configuration, the system supports dynamic, coordinate-based instantiation. This allows a single template to be applied thousands of times across a network, with each instance potentially receiving different environmental data or mitigation interventions. This modularity represents a critical step toward a unified integrity management system for complex engineered systems.

### 3.1 *Geospatial Data Integration (Heat Maps)*

The platform introduces NSIM Heat Maps to capture the spatial variability of risk, allowing for location-dependent model updates.

A NSIM Heat Map is defined as a global dataset comprising a collection of geospatial data points. Each data point maps a specific coordinate (Latitude/Longitude) to a vector of probabilistic parameters. These parameters redefine the underlying behavior of the model components at that specific location. It allows a single heat map entry to capture a multi-dimensional snapshot of conditions.

#### 3.1.1. *Search zone and lookup logic*

To handle the spatial relationship between a linear segment (e.g., a power line or pipeline) and point-based geospatial data, the system employs a "Search Zone" strategy:

- Anchor Point Selection: Users specify whether to use the Start, End, or Mid-Point of a segment as the center of the lookup.
- Search Radius: A defined numeric distance (in meters) establishes the valid zone for a data match.
- Tie-Breaking: If multiple data points are found within the radius, the system selects based on the "Nearest Point" or the "Highest Value" (for numerical probabilities).

#### 3.1.2. *Dynamic model updating*

During the segment creation phase, the system queries the Heat Map and automatically injects the retrieved data into the local model instance:

- BBN Root Nodes: Mapped values from the Heat Map update the Prior Probability Distribution of nodes
- FT/ESD Events: Update base failure probability using the Heat Map value

This architecture ensures that downstream processes, such as system-level analysis, utilize location-specific evidence baked directly into the model instance at the moment of creation.

### 3.2 *Modular Quantifier Items*

Inside these templates, NSIM defines three types of modular quantifier items that allow for precise, localized quantification:

- BBN Items: These items link to customizable Bayesian Belief Networks, allowing users to set specific evidence for selected BBN nodes. This is ideal for modeling variables with high uncertainty or complex dependencies, such as soil corrosivity or coating degradation.
- FT/ESD Items: These items link directly to events defined internally within the template's Fault Tree (FT) or Event Sequence Diagram (ESD). They provide the deterministic backbone for the failure logic.
- Service Items (External codes): These items allow users to quantify FT/ESD events using external web services or simulation codes. Because service management is independent of template definition, a single service can be reused across multiple templates to process inputs and generate risk outputs.

### 3.3 *Temporal Risk Modeling (Year-by-Year Analysis)*

The NSIM framework extends the discussed modularity into the time domain by allowing users to provide inputs for all quantified items on a year-by-year basis. This enables the system to model the evolution of network risk over a defined operational horizon.

While the requirement for temporal data is universal, the method of delivery varies by item type:

#### 3.3.1. *Standard Manual Input (BBN and FT/ESD Items)*

For BBN and FT/ESD items, the user typically provides a discrete value or state for each individual year. This granular control allows the user to manually define how specific environmental factors or internal events change over time.

#### 3.3.2. *Advanced Computational Flexibility (External codes)*

Service items (External codes) offer a more sophisticated approach to temporal modeling. For these items, the user is provided two pathways:

- Year-by-Year Inputs: Similar to BBN/FT items, the user provides manual data points for every year in the forecast.
- External Simulation: The user provides a single set of initial inputs, and the system leverages an external simulation engine to compute the year-by-year outputs. This is specifically designed for complex, time-dependent phenomena—such as corrosion growth or coating degradation—where the future state is a mathematical function of the current state.

## 4. Risk-Informed Decision Support Framework

To address the limitations of traditional, probability-centric models, the generalized framework introduces a unified environment for consequence modeling and mitigation planning. By integrating these two pillars, the platform provides an adaptive decision-support system that evaluates the full magnitude of risks and identifies the most effective interventions across a diverse network.

### 4.1 *Multi-Dimensional Consequence Modeling*

While the previous framework (Chalgham et al. 2020) primarily quantified system-level failure probability, this implementation evolves to support comprehensive risk magnitude assessment. It allows users to define and calculate specific impacts for each End State Category defined within the Event Sequence Diagram (ESD).

#### 4.4.1. *Consequence categories and severity*

The framework supports configurable impact categories to suit various infrastructure domains, such as:

- Safety: Modeling lives lost or injury rates.
- Financial: Capturing monetary impacts in USD.
- Environmental: Quantifying ecological impacts, such as carbon emissions.

Each category is divided into distinct severity levels with assigned Weight Factors. This allows the system to calculate the total impact as follows:

- Impact = Probability * Weight Factor

To ensure the integrity of the results, the system enforces an Exhaustive Mapping Requirement, preventing a configuration from being activated until every possible end state is mapped to a consequence level.

## 5. Unified Mitigation Planning Framework

A core component of the generalized platform is the ability to perform optimal mitigation planning across diverse transmission networks. This framework allows users to simulate targeted interventions to analyze how specific mitigations impact the system-level risk profile.

### 5.1 *Global mitigation actions*

Mitigation actions are administered at the top level of the platform, parallel to service and template management. This decoupling allows a single, immutable mitigation strategy to be reused across multiple different templates and network segments.

- Identification: Each action is characterized by a unique ID and a descriptive name.
- Event Targeting: An action comprises a list of specific Fault Tree or ESD events identified by name and type.
- Lifecycle Management: Actions must be "Published" to become available for template association, at which point they become locked and immutable to ensure simulation integrity.

### 5.2 *Targeted intervention strategies*

For each targeted event within a mitigation action, users can apply one of two distinct strategies to modify risk parameters:

- Absolute Replacement: This defines a constant failure probability that completely overwrites the original event probability.
- Probability Reduction: This utilizes an "effectiveness" parameter to proportionally reduce the original failure probability (e.g., a 50% effectiveness reduces the probability by half).

### 5.3 *Template integration and automated binding*

Because the proposed framework is generalized, the system must bridge the gap between global mitigation definitions and local template structures. Each template contains a dedicated section to associate one or more published mitigation actions.

The platform utilizes an Event Binding Algorithm to establish these links:

- Auto-Discovery: The system scans all Fault Trees and ESDs within the template to find event names matching those in the mitigation action.
- Ambiguity Resolution: If multiple events share the same name, the user is presented with a disambiguation interface for manual target designation.
- Link Persistence: Once mapped, these bindings allow for a "Relink" or "Refresh" operation if the underlying template structure is updated.

### 5.4 *Comparative risk simulation*

The final phase of the framework involves aggregating these potential actions at the network level. Users can define Mitigation Strategies, which are named collections of one or more identified mitigation actions.

The system executes a Comparative Simulation that calculates risk for every user-defined strategy alongside the original baseline results. This enables immediate visual comparison to identify the optimal mitigation plan for the specific network configuration.

## 6. Software Implementation & GUI

The framework is realized through the NSIM platform, a generalized software environment that supports interactive configuration and real-time health monitoring. NSIM is designed to move beyond the limitations of domain-specific tools by providing a modular interface for diverse network infrastructures.

### 6.1 *System Architecture*

NSIM is built as a modern web application to ensure accessibility and high-performance computing for complex risk simulations:

- Frontend: Developed using the React framework to provide a responsive, single-page interface for network building and results visualization.
- Backend: Powered by Django, which serves as the management layer for the global repositories of templates, heat maps, and mitigation actions.
- Quantification Engine: Core quantification for the HCL, DBN, and FT models is implemented in C++. This ensures the computational efficiency required for large-scale networks and real-time evidence injection.

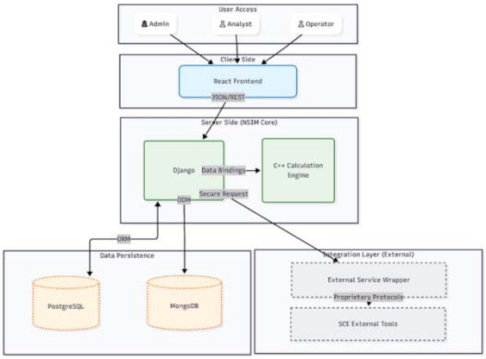

Fig. 1.NSIM System Architecture

### 6.2 *User hierarchy and deployment workflow*

The platform distinguishes between three primary user roles to ensure consistency and quality control across the organization:

#### 6.2.1. *Operator (Execution & Decision Support)*

- Designed for Field Engineers, Planners, and Control Rooms.
- Focus: A visualization-first interface for situational awareness. Operators view Risk Results on interactive maps, perform "What-If" Simulations by applying pre-approved mitigation actions, and compare different strategies—all without altering the underlying mathematical models.

#### 6.2.2. *Risk Analyst (Standardization & Model creation)*

- Designed for Risk Engineers and Data Scientists.
- Focus: The central workspace where the network topology and risk logic are defined and configured. Analysts are responsible for Defining Risk Logic (creating Master Models, Templates, and Global Resources), Building the Network (via GIS import or manual drawing), and Configuring Inputs to parameterize the models with specific data sources.

### 6.2.3. *Administrator (Governance & Control)*

- Designed for Program Managers and System Administrators.
- Focus: Managing the organization, not the models. Admins control User Access (defining teams and permissions) and Asset Lifecycle—reviewing and "Publishing" the templates and risk standards created by Analysts. This ensures that the entire organization uses approved, version-controlled risk logic and models.

### 6.3 *GUI and visualization features*

The figures below show some of the main GUI pages of the NSIM software platform.

Fig. 2.NSIM Landing Dashboard showing User hierarchy: Operator, Analyst, and Admin

Fig. 3. Analyst Features: Network creation, Model creation, Network Risk Assessment, Global Datasets, and Risk Management

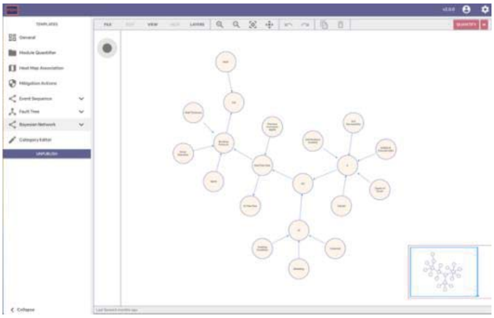

Fig. 4. BBN model building example

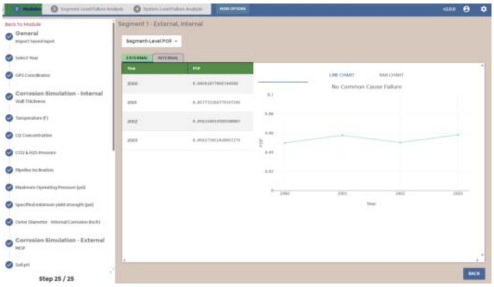

Fig. 5. Risk Module Results page

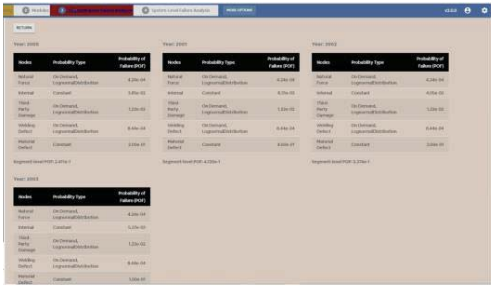

Fig. 6. Segment-level Quantification Results

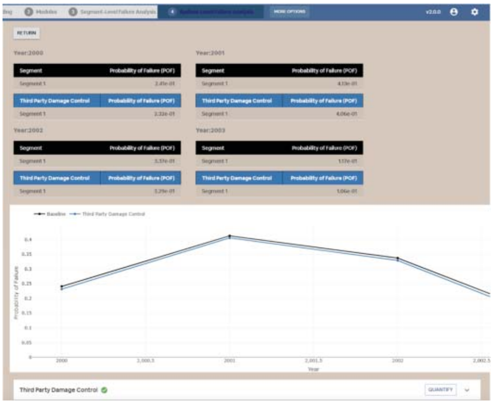

Fig. 7. System-level Quantification Results with an example of Mitigation Impact on the Results

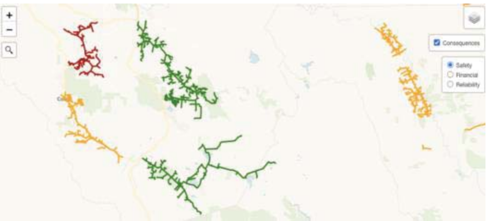

Fig. 8. Operator Dashboard: color-coded Network Risk Assessment based on system-level quantification results

## 7. Conclusion

This paper presents a generalized PHM framework and its software implementation, NSIM, representing a significant step toward a unified decision-support system for complex transmission networks. By evolving from the gas-pipeline-specific structures of previous models, this framework introduces the flexibility required to monitor diverse systems such as electric power grids or water distribution networks.

The core contributions include:

- Network Abstraction: A "Segment and Station" paradigm that allows for domain-agnostic system modeling.
- Quantitative Risk Magnitude: An HCL-based consequence module that integrates safety, financial, and environmental impacts.
- Spatially Aware Modeling: A heat map integration logic that automates model updates based on geospatial context.
- Collaborative Governance: A deployment model that balances administrative standardization with user-level flexibility through a robust template inheritance system.

While the current implementation of NSIM utilizes a serial logic for system-level failure—where the failure of any single component leads to system failure—the next phase of development focuses on the integration of advanced network topology analysis. Future research will incorporate graph-theoretic models to support complex connectivity analysis of failure propagation. This integration will allow the platform to perform system-level reliability analysis on more sophisticated infrastructure maps, providing a truly comprehensive decision-support tool for global network systems.

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