PHMSA Pipeline Risk Model Working Group

Critical Review of Candidate Pipeline Risk Models

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Overview

1. Project Objectives
2. Summary & Recommendations
3. Industry Survey – Key Model Attributes
4. Literature Review – Pipeline Industry
5. Literature Review – Other Industries
6. Probabilistic Risk Guidelines

Project Objectives

Create guidelines for developing and assessing probabilistic quantitative pipeline risk models based on the following:

- A survey of the industry participant, regulators and subject matter experts on the attributes of a quantitative pipeline risk assessment
- A critical review of existing quantitative risk models (including models used in other industries)

The guidelines define:

- Standard requirements – for example:
  - Minimum risk model attributes
  - Minimum list of threats considered
  - Risk measures to be evaluated by the model

- Levels of analysis
  - Ability to achieve desirable attributes
  - Degree of analytical rigor and data completeness

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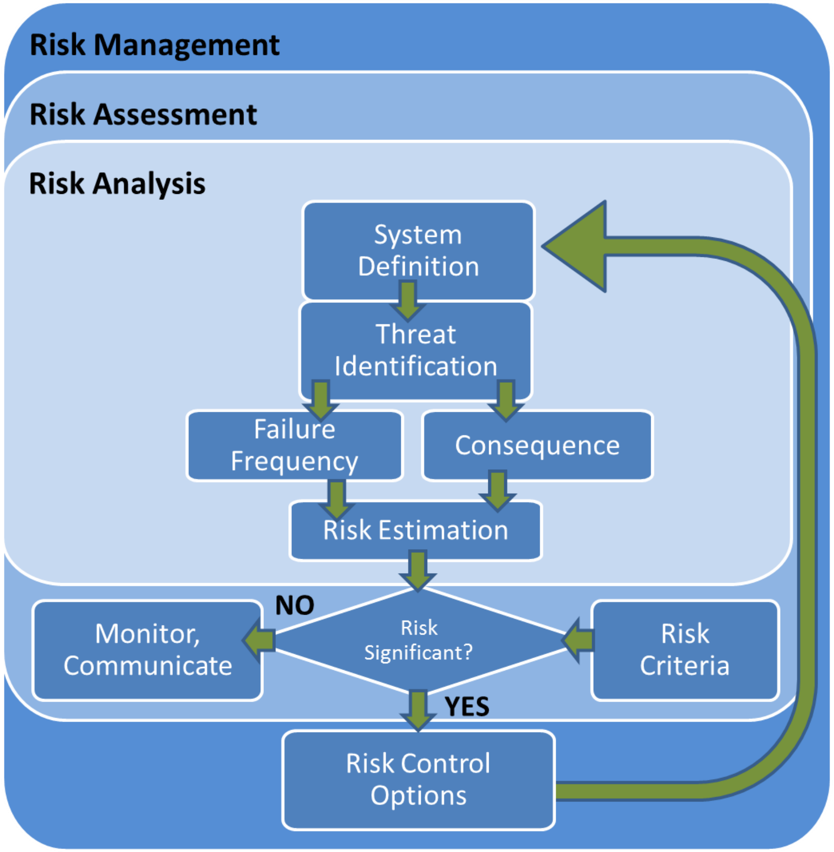
Scope

- Quantitative models
- Failure frequency
- Consequence in measurable units
- Identifying various modelling categories
- Not within scope:
  - develop or validate a model
  - develop risk criteria
  - Identify rare-event threats



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Summary I

Literature Review

- Extensive use of QRA models
- Frequency methods: SME opinion, historical data and probabilistic models
- Established risk measures for life safety
- Established consequence models for natural gas releases
- Proprietary consequence models for hazardous liquids
- Environmental risk measures are not standardized

Other Industries: Nuclear, Offshore, Aviation and Power Transmission

- Common methods to quantify frequency
- Consequence models are not common between industries
- Criteria for frequency and consequence may be defined separately
- Standardization of methods eases use
- Standardization of data collection allows for aggregate analysis
- Integration pipeline and facility QRA is possible for some risk measures

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Summary II

<u>Guidelines</u>

- Purpose: develop, improve or evaluate QRA models
- Are consistent with the international risk assessment standards
- Describes methodologies to estimate failure frequency and consequences
- Suggest various outputs for risk estimates
- Enables models that are repeatable, traceable, and treat uncertainties consistently
- Describes levels of analysis to use available information, identify areas of incremental improvement and to move towards more objective risk models

Recommendations for Future Work

- Development of the necessary model components to address the gaps:
  - A standardized list of interacting threats;
  - Risk measures for environmental impacts; and
  - Simplified life safety models for hazardous liquids pipelines

- A pilot study for the application of guidelines to a quantitative risk model

- Development of a suite of benchmark problems to facilitate independent risk model validations by a third party

Industry Survey

Purpose

- Find quantitative risk models not in open literature
- Determine what industry considers as key attributes of the ideal quantitative risk model
- Evaluate readiness of industry to adopt quantitative risk models

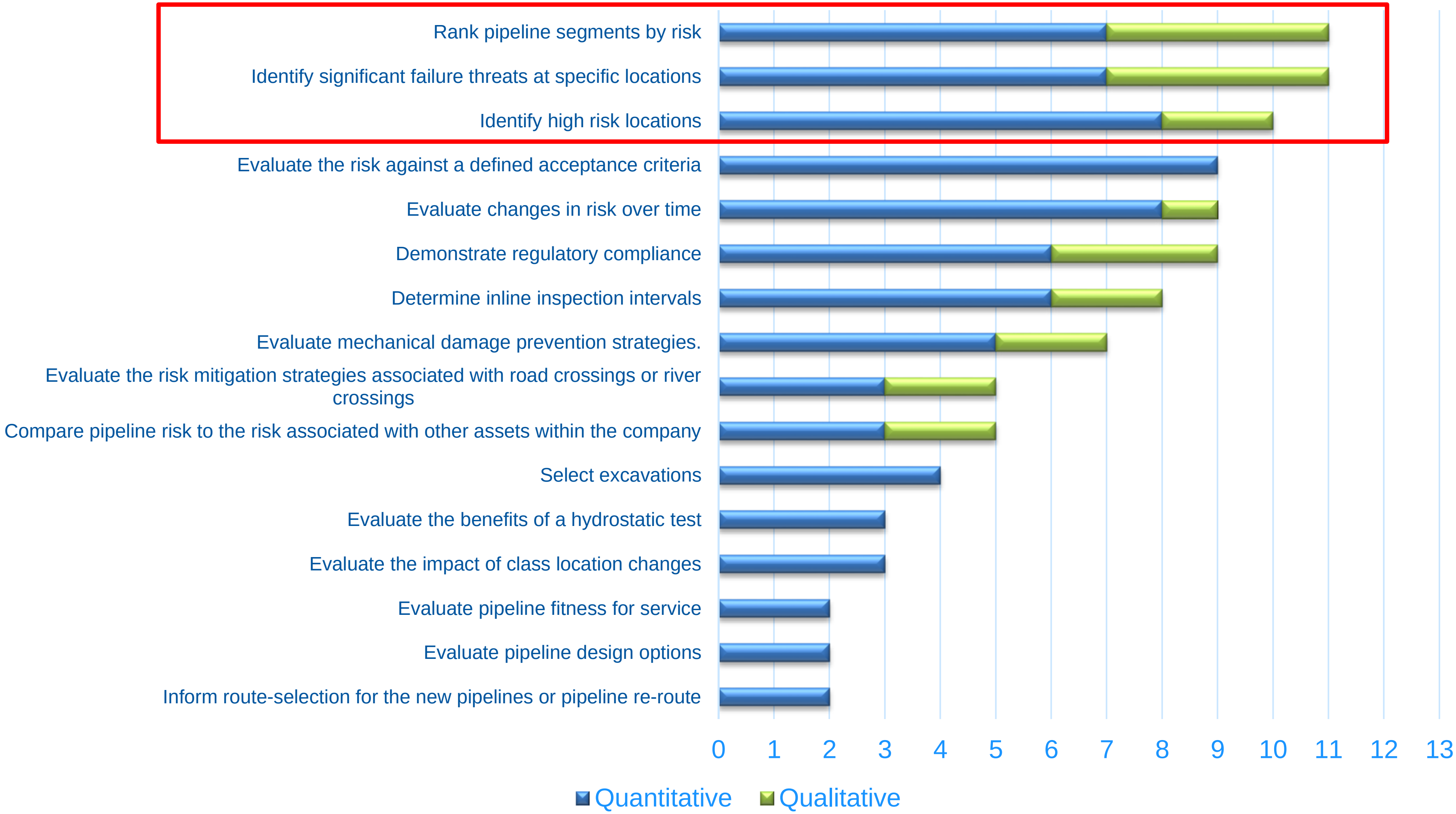
Question Types

- Current models
- Model uses
- Key attributes of ideal quantitative model
  - Ease of use, analytical rigor, model outcomes
- Obstacles to the application of quantitative risk assessment
- Desirable attributes for standardization

Industry Survey - Overview

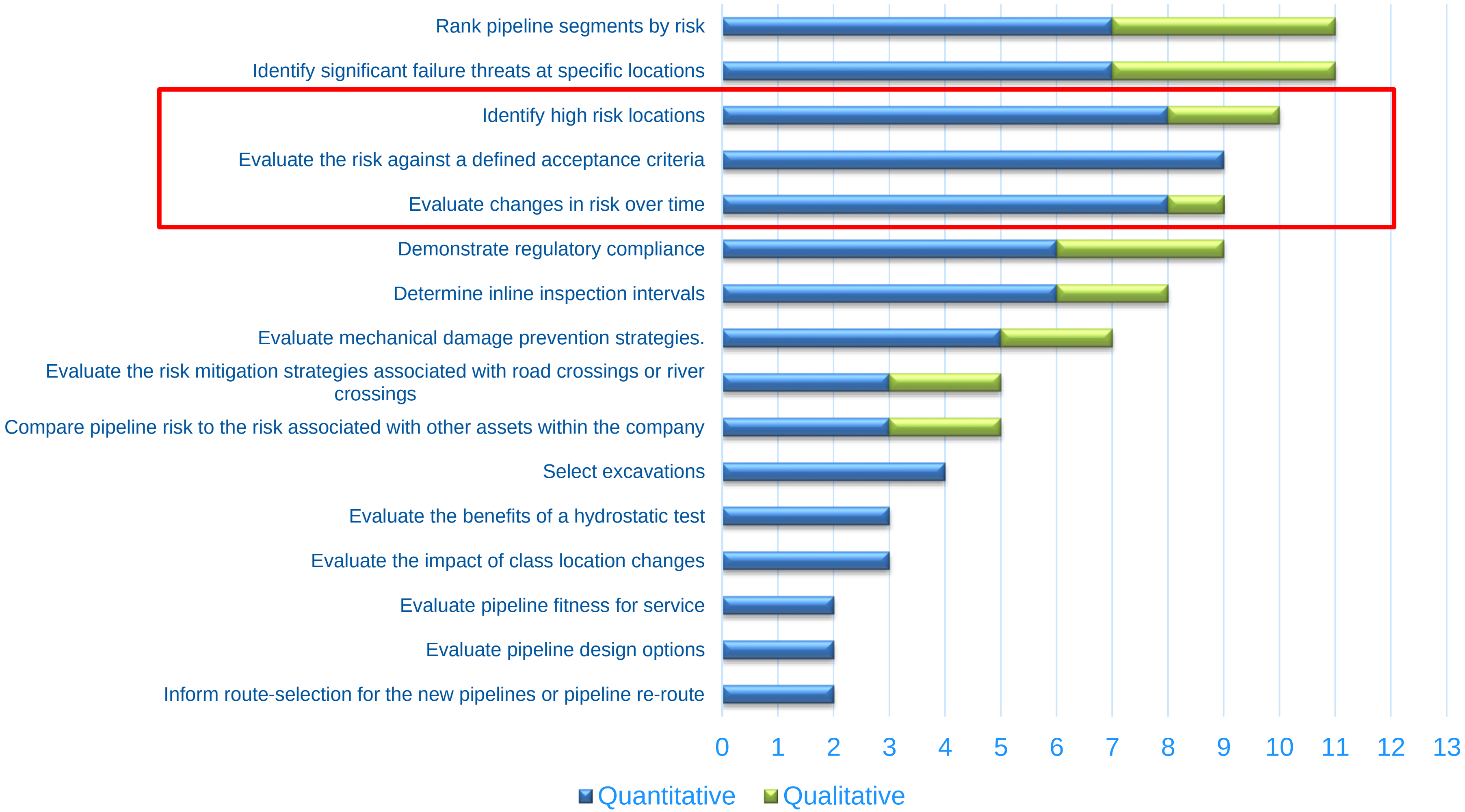
- Requests for survey participation – 17
  - Operators & Consultants
  - Follow-up twice
- Responses – 8
  - 6 different operating companies
- Models described – 13
  - Qualitative : 4
  - Quantitative: 9

Industry Survey – Model Uses

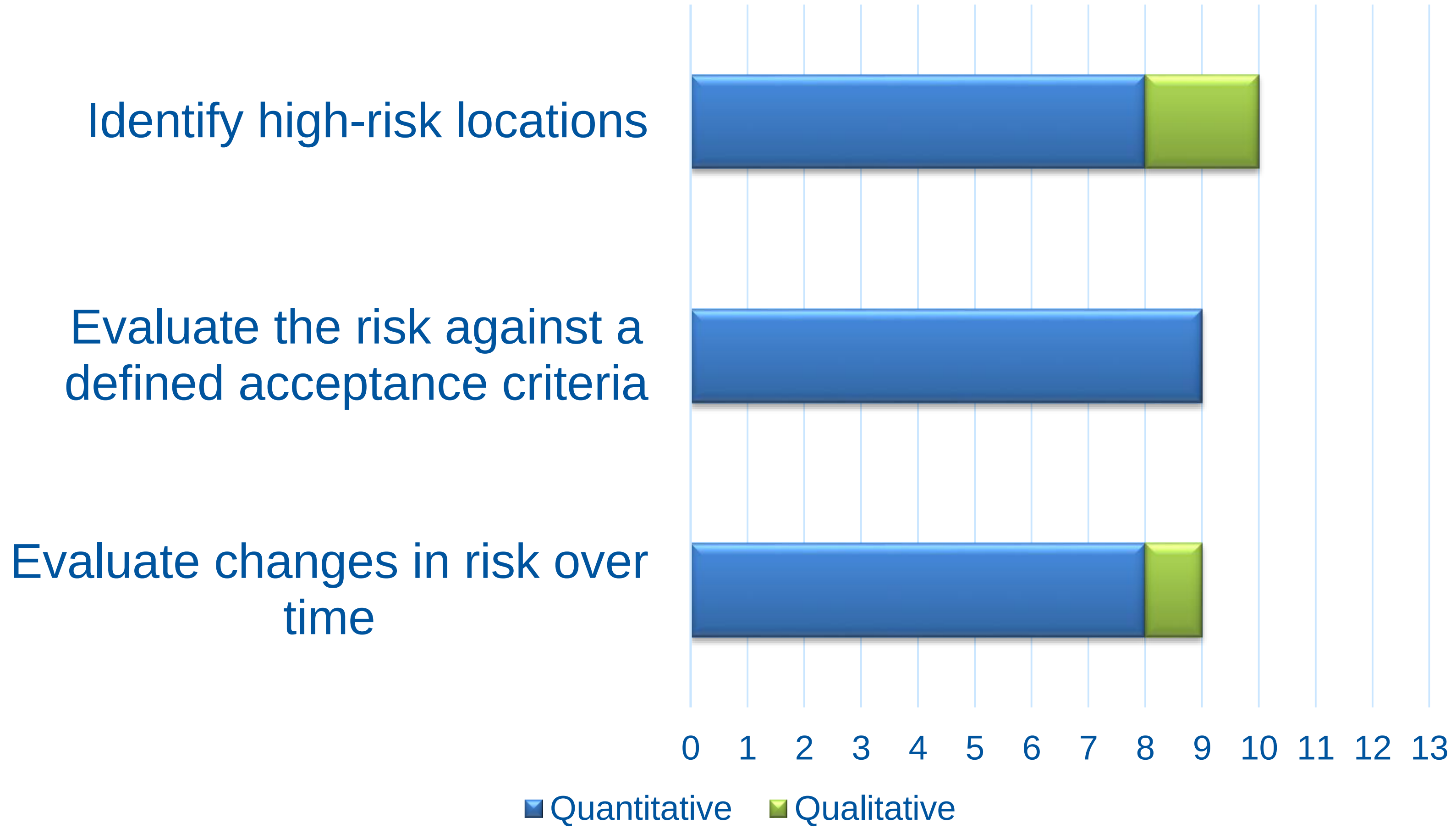


Most Common Uses – All Models

Survey Results – Model Uses



Most Common Uses – Quantitative



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Ideal Model Attributes

- *Inputs*: Considers all forms of evidence available
- *Defaults*: Suggests appropriate defaults
- *Transparency*: documented algorithms
- *Flexibility*: Considers pipeline-specific factors
- *Repeatability*: Produces consistent results
- *Threats*: covers the standard threats
- *Rare threats*: covers interacting threats and rare threats
- *Validation*: has been validated, allows validation by a third party
- *Output type*: results that can be compared to a criteria
- *Resolution*: risk by location and by threat
- *Decision-making*: results used for decision-making;
- *Uncertainty*: uncertainty is properly handled
- *Value of new data*: assess whether additional effort is beneficial

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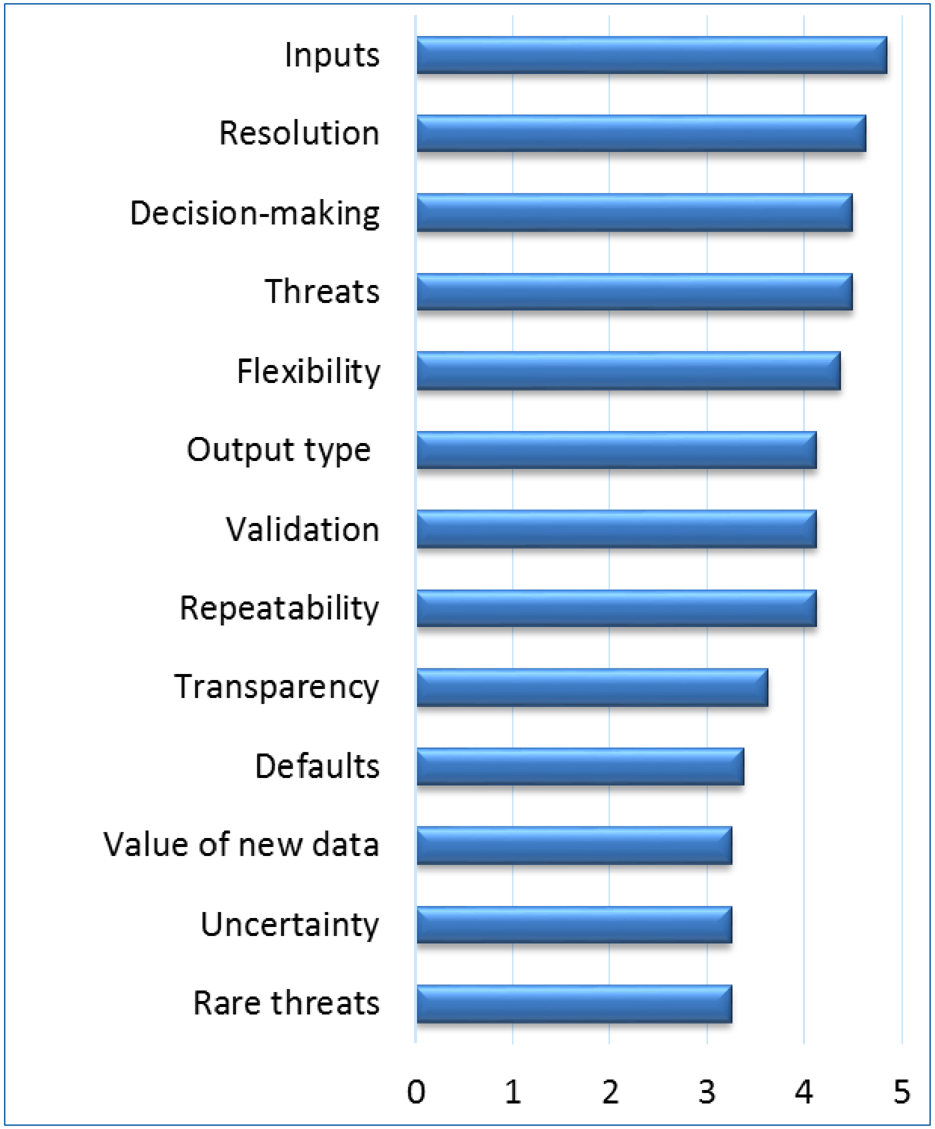
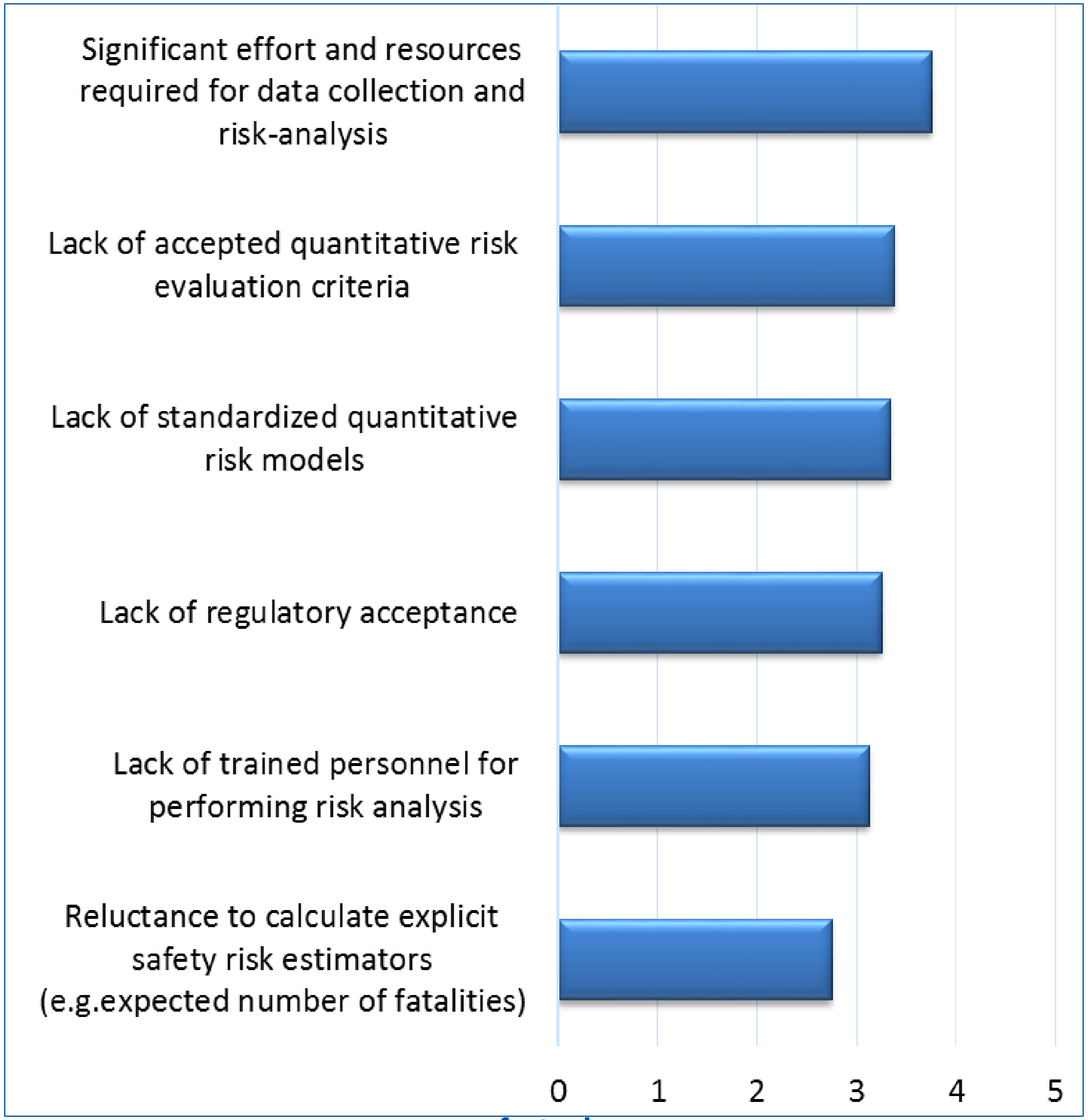
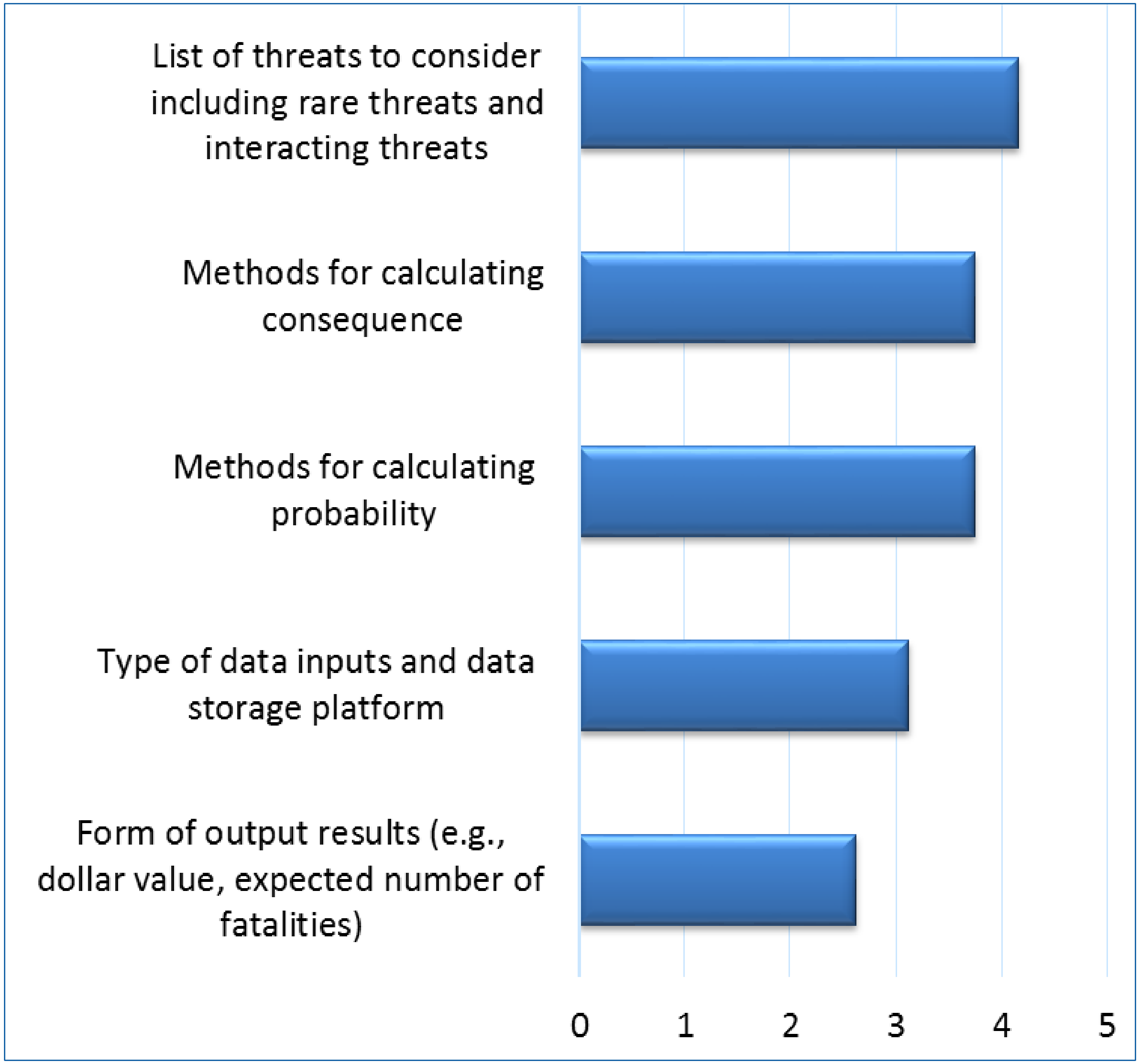


Obstacles to Implementation



Standardization



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Survey Key Learnings

- Several quantitative risk models already in use
- Qualitative models for ranking pipeline segments by risk and for identifying locations of high risk segments
- Quantitative risk models are used for the selection of excavations, hydrostatic test simulation, the evaluation of class location changes, fitness-for-service assessments, and pipeline design and route selection
- All desirable model attributes were scored high
- Lack of a quantitative risk criteria was ranked as the second highest obstacle
- All of the respondents using QRA use a defined acceptance criteria
- Reluctance to standardize the data inputs and the data storage platform – the use of existing data in all available formats to reduce the data collection effort, was preferred instead

Literature Review

Literature Sources

- 34 Engineering and Technology Databases
  - SciSearch (6,000+ science journals)
  - Inspec (15M papers – engineering and physics)
  - Ei Compendex (17M papers – engineering)
- Prior C-FER expertise
- 70 publications reviewed
  - 8 system wide, 33 likelihood, 29 consequences

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QRA Uses

- Purpose
  - Meeting regulatory requirements
  - Integrity management
  - Asset risk management
  - Comparison of design options
- Granularity
  - System-wide assessments
    - Dynamic segmentation
    - Individual pipe joints
  - Annualized probabilities
- Failure modes
  - Loss of containment as failure
  - Distinction between leak and rupture is rare – usually only rupture considered
- Risk Measures and Presentation
  - Total risk profile of all threats combined
  - Separate risk profiles for each threat

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Threats

Standard Threats (ASME B31.8S)

- External corrosion
- Internal corrosion
- Stress corrosion cracking
- Manufacturing-related defects
- Welding/Fabricated related
- Equipment
- Third party/Mechanical damage
- Incorrect operations
- Weather-related and outside force

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Manufacturing-related defects, Welding/Fabricated related, Equipment → Cracks

Weather-related and outside force → Earth movements

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Threats

Standard Threats (ASME B31.8S)

- External corrosion
- Internal corrosion
- Stress corrosion cracking
- Manufacturing-related defects
- Welding/Fabricated related
- Equipment
- Third party/Mechanical damage → Vandalism
- Incorrect operations
- Weather-related and outside force → Floods

Non-Standard
• Theft • Sabotage • Seismic shaking • Interacting threats

Risk Outputs

- Life safety measures
  - Individual risk (IR)
    - Risk to specific individuals near a pipeline
  - Societal risk (SR): F-N curves
    - Risk as a set of frequency of incidents and a number of fatalities resulting from the incident
  - Expected number of fatalities
  - IR and SR are commonly estimated
- Financial measures
  - Dollar values including all costs
  - Conversion of environmental impacts to dollar amounts
  - Conversion of fatalities to dollar amounts
- Environmental Measures
  - Volume lost, receptor sensitivity, size of area affected

Probability Estimation

- Approaches for combining probabilities from different threats
  - Summation of frequencies of failures
    - Assumes that all threats are mutually exclusive
    - Occurrence of failure due to one threat does not prevent occurrence of failure due to a different threat
    - Multiple failures possible for a given segment
    - Accounts for risk of each threat and total risk is a direct summation of risks from individual threats
  - "Weakest-link" methodology
    - Assumes that all threats are statistically independent
    - Accounts for risk due to occurrence of the first failure due to any threat
    - Possibility of a second failure on the same segment is ruled out
    - Total risk is not a direct summation of risks from individual threats
- Both approaches give same result for total risk at small values of probability

‘Weakest Link’ vs Failure Rate

Probability of one or more failures

- the probability that none happen:

$P1 = (1-a)(1-b)\ldots$

- The probability that at least one happens

$P = 1 - P1$

- Does not scale with length

Failure Rate for a given length

$P1 = a + b + \ldots$

- Scales with length

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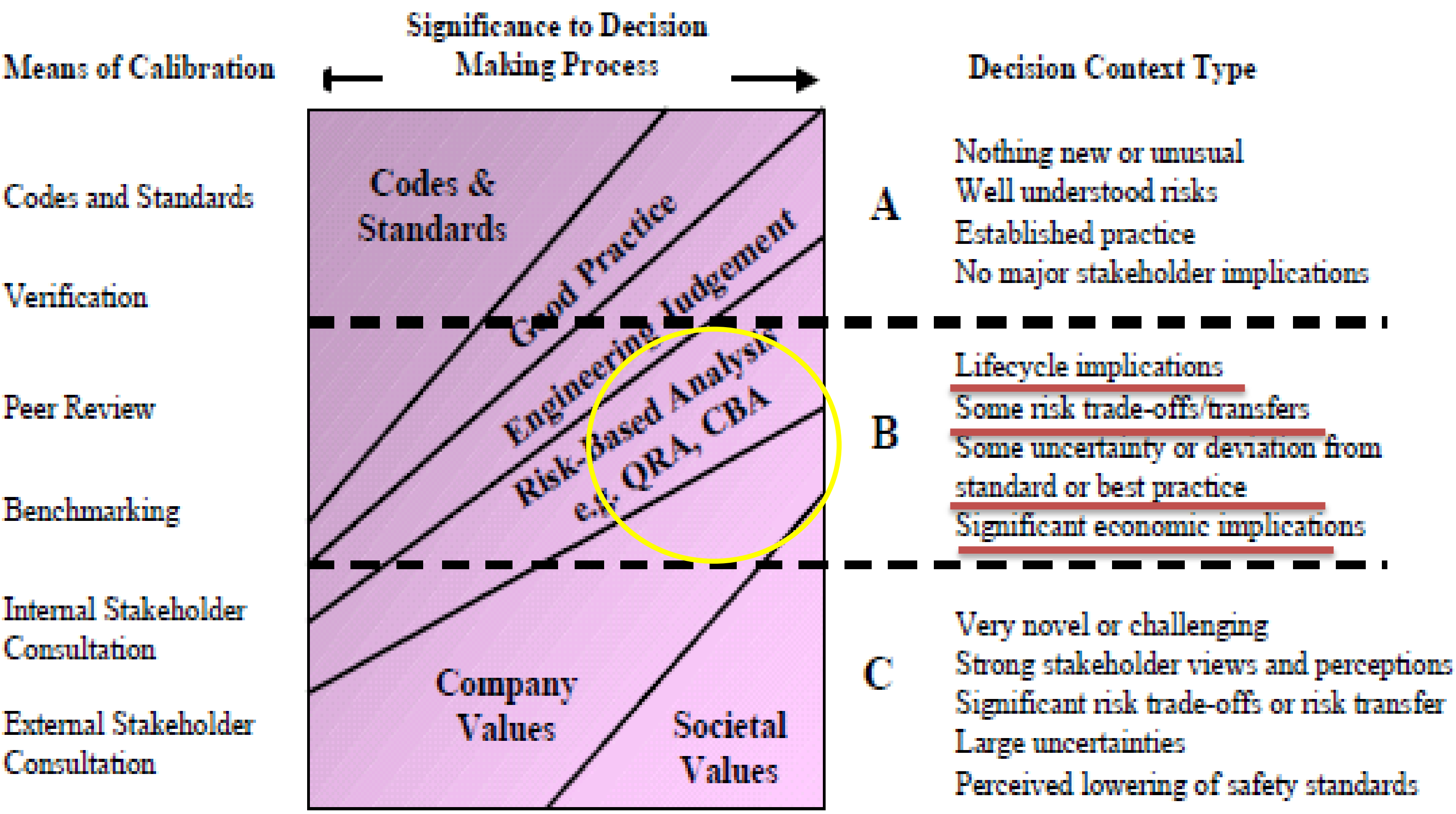
Summary of Other Industries

- Methods for quantitative risk analysis
  - Probability estimation methods similar to pipeline industry
  - Consequence models specific to each industry
- Levels of analysis
  - Based on the availability of well-developed models
  - Purpose of assessment
- Human reliability analysis
  - Human error quantified as probabilities
  - Detailed methodologies for expert elicitation
- Establishing risk or reliability criteria
  - Reliability criteria for high consequence triggering events
  - Risk criteria for consequence mitigation

Nuclear Industry

- Standardization of models and analysis approaches for selected threats
- Guidelines on sources of uncertainties and strategies to reduce them
- Approaches for setting criteria
  - Risk criteria
  - Reliability criteria
- Stages in risk evaluation
  - Availability of standardized models
  - Level of uncertainty in the analysis

Offshore Industry



DNV: Marine Risk Assessment (2001)

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Offshore Industry

- Guidance on levels of analysis based on assessment objectives
  - Risk screening
  - Broadly focused detailed analysis
  - Narrowly focused detailed analysis
- Identifying key factors in selection of assessment methods
- Examples of assessment methodologies based on decision contexts
- Approaches to characterize environmental impact from oil spill volumes

Aircraft Industry

- Methods of probability estimation similar to pipeline industry
  - SME opinion
  - Probabilistic/Engineering models
- Common threats for integrity
  - Fatigue crack growth
  - Stress corrosion cracking
  - Models not directly applicable due to material differences
- Operations and safety systems
  - Detailed data recording methods to facilitate human factors analysis
  - Standardization of data collection methods specific to industry

Power Transmission

- Primary threat: network failure
  - Hidden component interdependency
  - Component failures are triggering events for system failure
- Methods of probability estimation similar to pipeline industry
  - SME opinion
  - Historical data
  - Graphical network methods
- Guidelines for risk assessment
  - Limited to qualitative and semi-quantitative methods
  - Component failure risk is well defined
  - Network failure risks methods

Summary of Literature Review

- Extensive use of quantitative risk models in the pipeline industry
  - Well-established probability estimation for frequently occurring threats
  - ‘Weakest link’ methodology and failure rate are fundamentally different, but provide similar results for small probabilities
  - Some standardized QRA incorporated into codes in Canada and Europe
  - Consequences are specific to industry and product type
  - Life safety measures for gas transmission pipelines: individual risk and societal risk
  - Hazardous liquids pipeline consequences are expressed as environmental impacts (equivalent dollar value). There is no standardized methodology for life safety
- Other Industries
  - Guidelines, standards, best practices
  - Structured examples of levels of analysis
  - Human reliability analysis

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Risk Guidelines

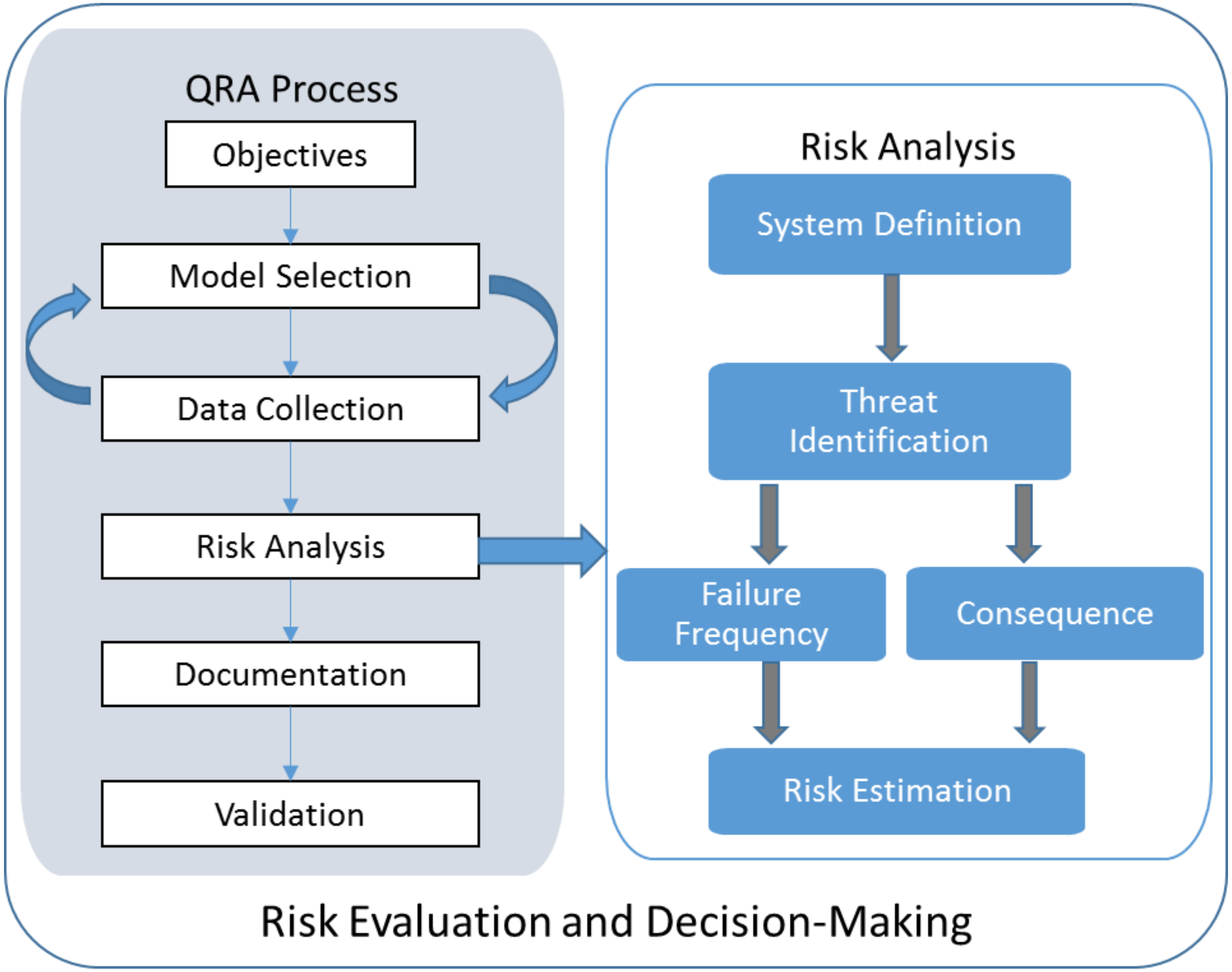
- Purpose
  - Provide a framework for performing QRA
  - assist operators in developing new QRA models
  - identify gaps in existing models
  - help to evaluate the accuracy, completeness, and effectiveness of the QRA models

Risk Guidelines

- Guidelines scope
  - Quantitative methods only
  - Failure frequency: an estimated rate of failure events
    - defined in units *per mile-yr*
  - Consequence: a physical quantifiable parameter
    - dollar value, number of fatalities, spill volume, or area affected

- Not within guideline scope
  - Hazard identification methodologies
  - Risk acceptance criteria
  - Risk mitigation strategies

Risk Framework



Purpose of a QRA

Purpose

- identify high-risk locations and the main contributing threats
- evaluate the risk against an acceptance criterion
- evaluate changes in risk over time
- make integrity management decisions
- demonstrate regulatory compliance

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Model Selection – Failure Frequency

Based on the degree of objective data and the use of engineering models:

- Level 1: Subject matter experts (SME) opinion
  - Quantified to probability values
- Level 2: Historical data
  - Based on adjustment factors
  - Use of regression equations
- Level 3: Probabilistic/Engineering models
  - Structural reliability methods
  - Graphical models (Fault-tree methods/Bayesian Networks)

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SME Opinion

- Approaches
  - Rule-based conversion
    - Risk index scores → quantitative conditional probabilities
  - Direct evaluation of failure rates
  - Assessment of damage rates
    - Damage rates → e.g., dents, coating holidays
    - Conversion to required failure rates
    - Rule-based algorithms on combination of damage rates

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SME Opinion

Advantages

- Requires limited resources and is simple to implement
- Uses SME experience to compensate for data gaps
- Does not require an engineering model

Disadvantages

- Validation is difficult
- High uncertainty due to subjective nature
- Difficult to quantify the level of conservatism in the results
- Influence of uncertainty cannot be quantified
- Effects of mitigation are difficult to estimate

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SME Guidelines

- Estimate the failure frequency as a product of the rate of occurrence of an initiating event and a series of conditional probabilities of intermediate events
- Separate failure frequency estimates by threat category
- Express failure frequencies as a function of three elements representing exposure, mitigation, and resistance
- Use structured approaches to elicit SME opinion:
  - the Delphi method - an iterative process used to reach a consensus amongst a panel of experts, resulting in a reduction of bias in the opinion of any single expert; and
  - the guidelines for expert elicitation used by the U.S. Nuclear Regulatory Commission - a simplified version of the Delphi method with guidance on developing customized questionnaires for expert opinion elicitation.

Historical Data

Types

- *Generic Failure Frequencies*: historical data from industry-wide failure databases is used to estimate the failure frequency for individual threats and combinations of attributes

- *Failure Frequencies with Modification Factors*: modification factors applied to the historical data to estimate pipeline-specific failure frequencies. Modification factors can be developed using engineering models, statistical analysis or SME opinion.

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Historical Data

Advantages

- Improves objectivity compared to SME opinion
- Based on actual incident occurrence
- Pipeline specific factors can be considered

Disadvantages

- Significant effort required to develop realistic modification factors
- Pipeline-specific adjustment factors may be subjective
- Lack of data to address new and emerging threats
- May not fully represent future probability of failure

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Historical Data Guidelines

- Develop modification factors based on engineering models and probabilistic methods where possible
- Consider the guidelines for SME opinion if expert opinion is used in the development of modification factors
- Consider other levels of analysis for rarely occurring threats because the small sample size of the data can underestimate frequency

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Probabilistic Models

- ***Structural reliability methods***: Input parameters of deterministic engineering models and model errors are characterized as random variables the frequency of failure is estimated using standard reliability methods

- ***Graphical Models***: Fault tree methods are a logical representation basic events connected with ‘AND’ and ‘OR’ gates combined to estimate the frequency of failure. Bayesian networks are a graphical representation of the causal links between basic events leading to failure

- ***Other Methods***: Novel mathematical approaches to estimate failure rate, such as fuzzy logic, do not have well-established mathematical and theoretical basis compared to probability theory. The advantages of these approaches is not clear

Probabilistic Models

Advantages

- Most objective compared to other levels
- Based on recognized engineering models
- Uses all types of pipeline specific evidence as input
- Directs data collection efforts
- Can address rare and interacting threats
- Accounts for specific integrity maintenance actions
- Allows for sensitivity analysis and uncertainty reduction efforts

Disadvantages

- Needs more effort to characterize inputs
- Requires greater computational resources
- Skepticism of outputs is necessary due to the complexity of models

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Probabilistic Model Guidelines

- Include all possible sources of uncertainty
- Consider input parameter bounds when selecting probability distributions
- Ensure goodness-of-fit in the tails of the distributions
- Consider the guidelines for SME opinion if subjective judgement is used to characterize model inputs
- Apply appropriate probabilistic techniques (sample size, model convergence)

Model Selection - Consequences

Consequence: the effect of a pipeline failure on individuals or populations, property, or the environment. Models are often divided into:

- Life safety
- Environmental impact
- Financial impact

Life Safety Hazards

- Natural Gas: Jet fires
  - Simplified models: potential impact radius (PIR) model
  - Detailed proprietary models: PIPESAFE and DNV PHAST
- HVP Liquids: Flash fires, toxic effects and blast pressure
  - General purpose consequence software models: CANARY, DNV PHAST, EFECTS by TNO, and TRACER by Safer Systems.
  - CFD modelling: IOGP (2010) and the Norwegian Standard NORSOK Z-13 Annex F (NORSOK 2010)
- Flammable LVP Liquids: Pool fires
  - proprietary software and CFD models

Environmental Impact

Environmental impact is dependent on:

- product type
- exposure of receptors
- toxicity of the product for each receptor
- socio-economic importance of the affected resources

Important Factors:

- total volume released
- receptor identification
- pathway to receptors
- habitat recovery and duration of recovery

Environmental Impact

Levels of analysis:

- SME opinion
- Historical data models
  - Recorded data often limited to clean up costs
- Detailed models
  - Release volume
  - Area affected
  - Habitat assessment

Financial Impact

The appropriate cost components and models depend on the operator's corporate values and the objectives of the QRA

Direct costs:

- cost of lost product
- repair cost
- costs associated with downtime (e.g. lost revenues, penalties and restart costs)
- third-party property damage costs
- legal costs

Indirect costs:

- loss of customer satisfaction
- loss of reputation
- costs of increased regulatory oversight.

Summary of Consequence Models

Natural Gas

- Life safety
  - PIPESAFE
  - Potential impact radius (PIR) formula
  - Other proprietary models
- Environmental impact
  - No standard quantification
  - Proprietary models in equivalent dollar value
- Financial impact
  - Proprietary models (available for licensing)
  - Company-specific models

Liquids

- Life safety
  - Proprietary models
  - No standardized methodology
- Environmental impact
  - No standard quantification
  - Proprietary models in equivalent dollar value
- Financial impact
  - Proprietary models (available for licensing)
  - Company-specific models

Risk Analysis – Failure Modes

- The magnitude of the consequences associated with each failure mode is very different
- The frequency and risk associated with each failure mode is calculated separately and added up to arrive at an estimate of total risk
- Failure Modes: release as a function of size:
  - small leak
  - large leak
  - rupture

Risk Analysis – Risk Measures

- Life Safety:
  - Expected number of casualties (includes injuries and fatalities)
  - Individual Risk (IR) is defined as the probability of fatality for a person at a particular location. It varies with the distance from the pipelines and the likelihood that the person will be present at the location being considered.
  - Societal Risk (SR) as is represented by an F-N curve, a plot of the frequency of incidents resulting in N or more fatalities associated with a specified length of pipeline.

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Risk Analysis – Risk Measures

- Environmental Impact:
  - Monetary costs that account for environmental sensitivity and include clean-up costs, and second order socio-economic impact.
  - Spill volumes adjusted for site sensitivity.
  - Habitat recovery time estimated as the time for restoration of an environmental resource. The estimation of habitat recovery is ideally based on a clearly-defined natural resource and a quantified measure of restoration (e.g. population density of a particular aquatic species or the allowable residual spill volume in the soil).

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Risk Analysis – Risk Measures

- Financial impact:
  - Monetary costs including third-party property damage and other business impacts. Acceptance criteria depends on the business priority of the operator

Risk Model Validation

- The standard validation - comparing their results to empirical data is not applicable to risk models unless large sets of data are available
- Statistical estimates of the frequencies of occurrence for rare or moderately rare events is often not possible
- Alternative validation approaches include:
  – component verification
  – hindcasting
  – error bounds
  – benchmarking
  – sensitivity analysis

Decision Making

QRA results facilitate decision-marking in the following ways:

- comparing pipeline risk to risks to the risks associated with other facilities
- ranking segments within a pipeline system
- identifying dominant failure threats
- cost-benefit analyses

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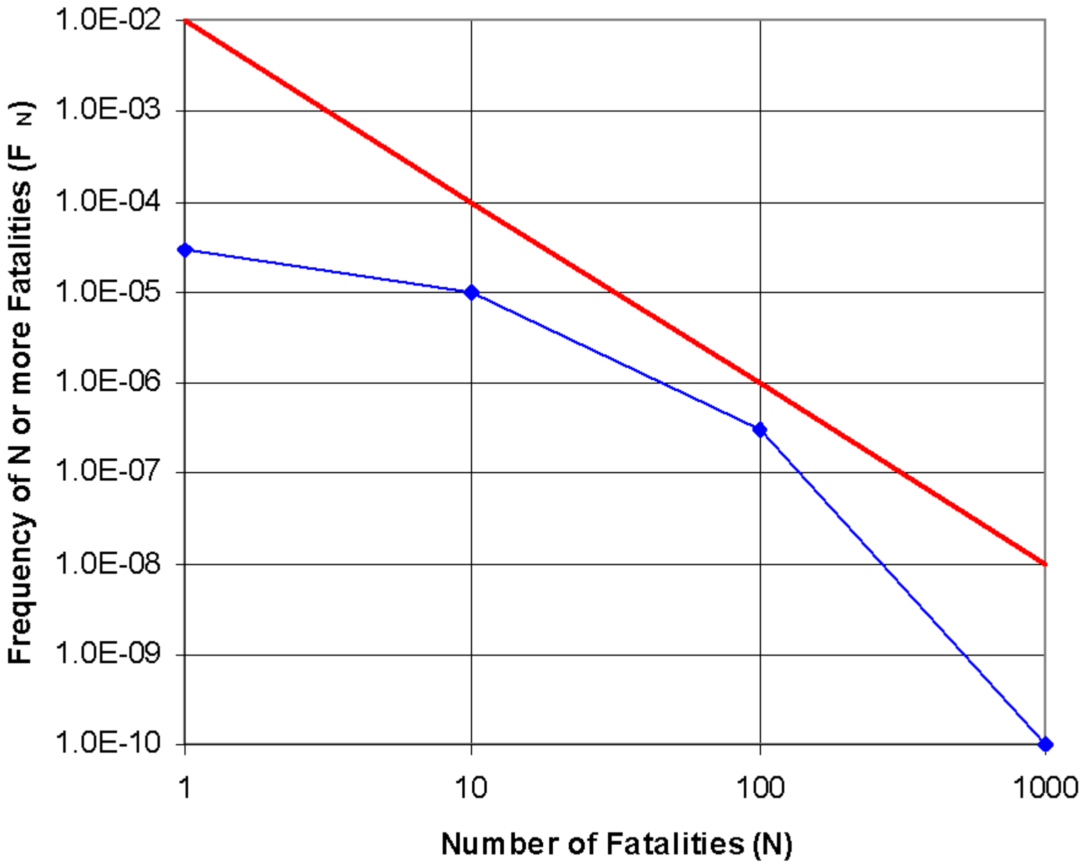
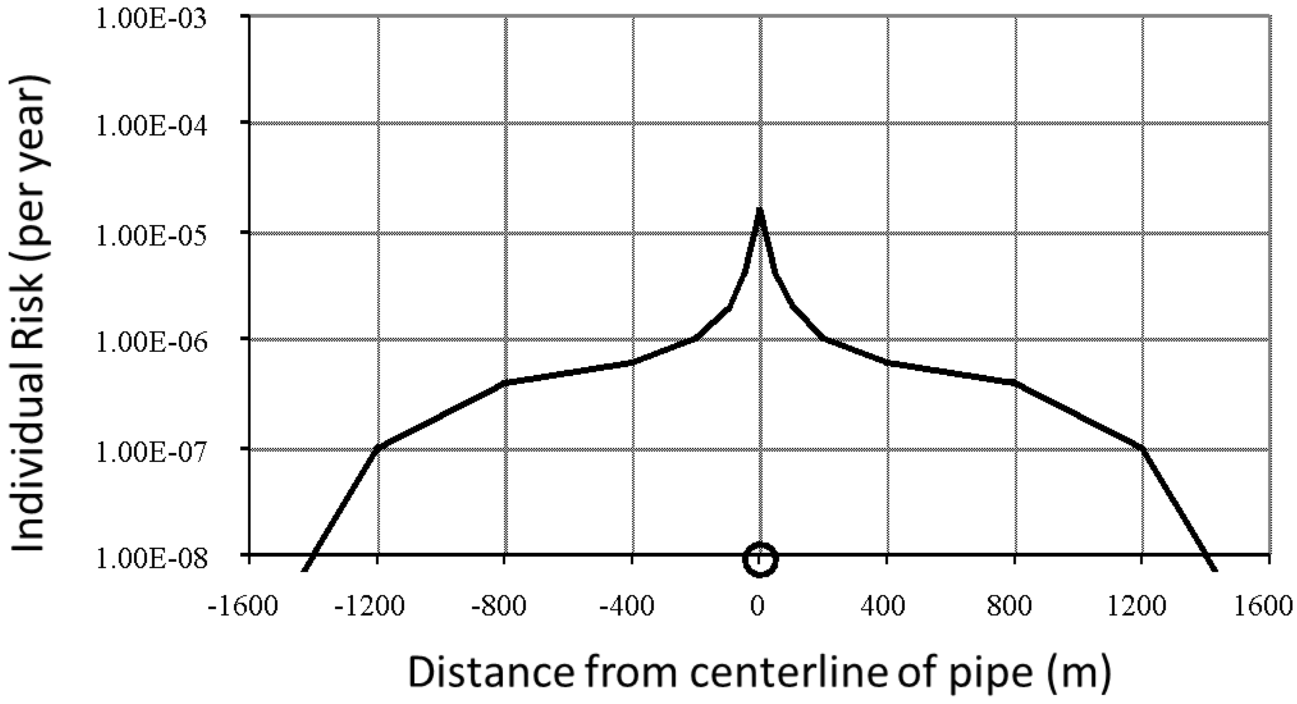
Decision Making

- IR contours and F-N curves enable the evaluation of risks against recognized acceptance criteria
- Risk profiles along the pipeline length enable identification of high-risk locations by threat categories
- Risk matrices can be used to display the failure frequencies and failure consequences
- A plot of risk as a function of time enables risk forecasting and decision-making regarding time-dependent threat mitigation including inspection intervals and defect repair planning.

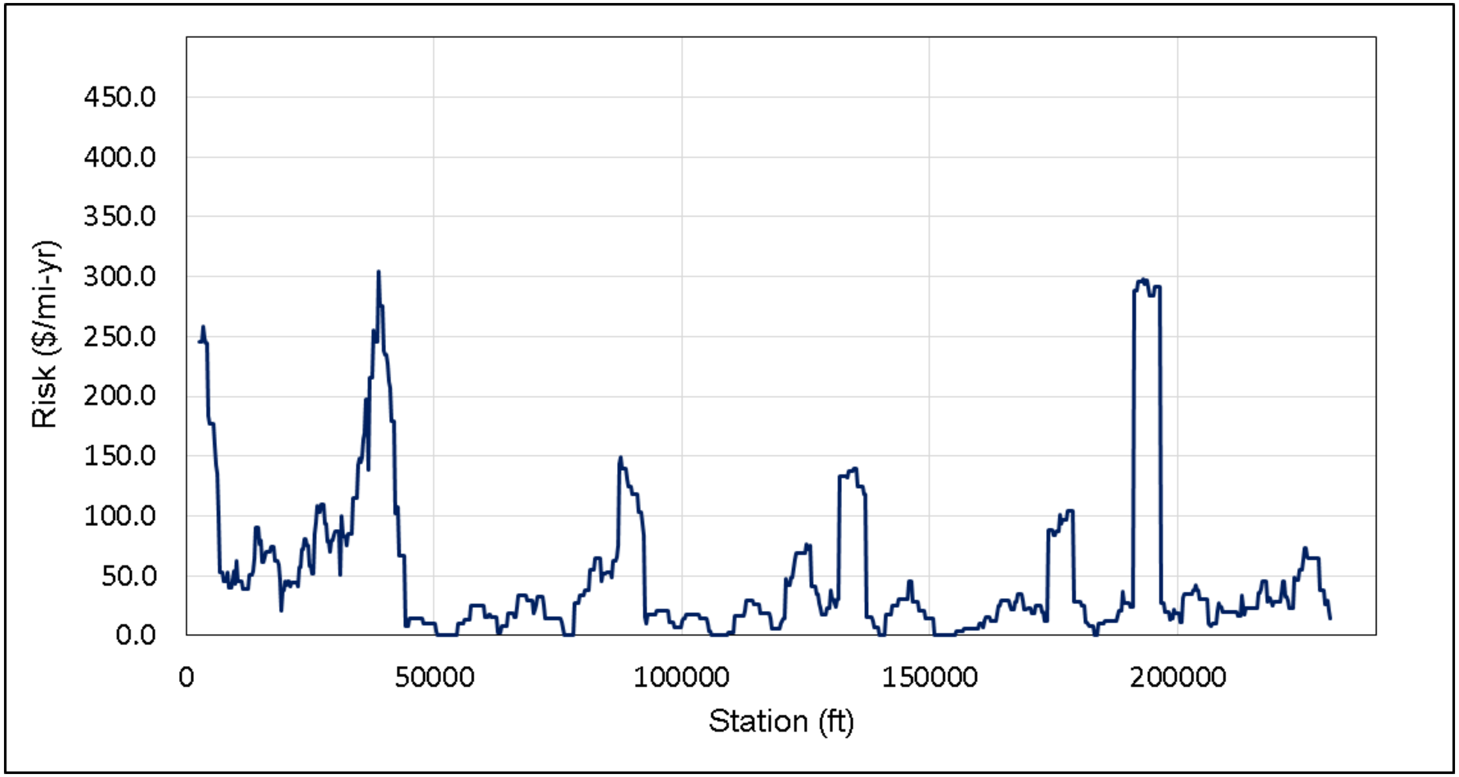
Example: FN Curve



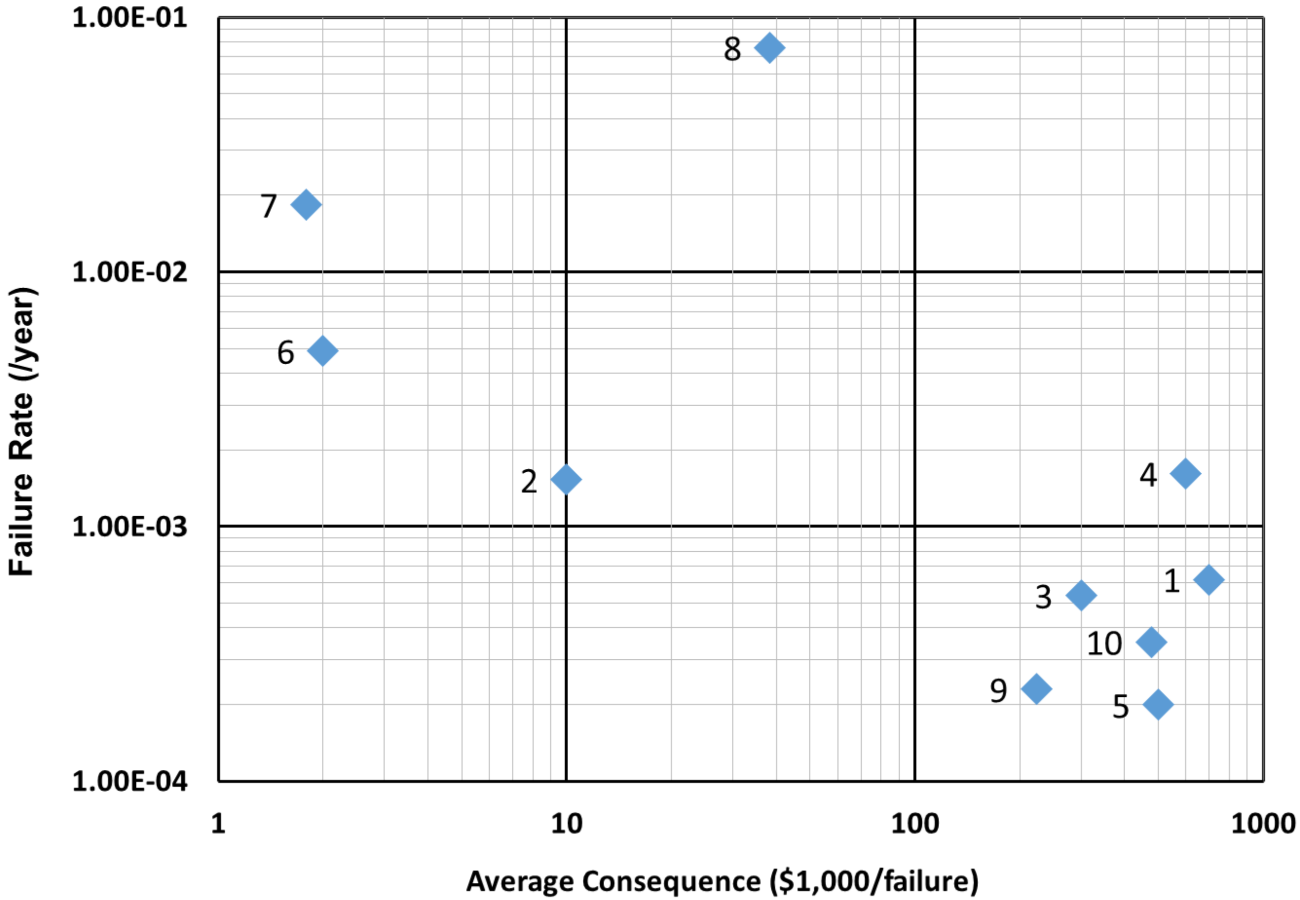
Example: Risk Contour



Example: Risk Profile



Example: Risk Matrix



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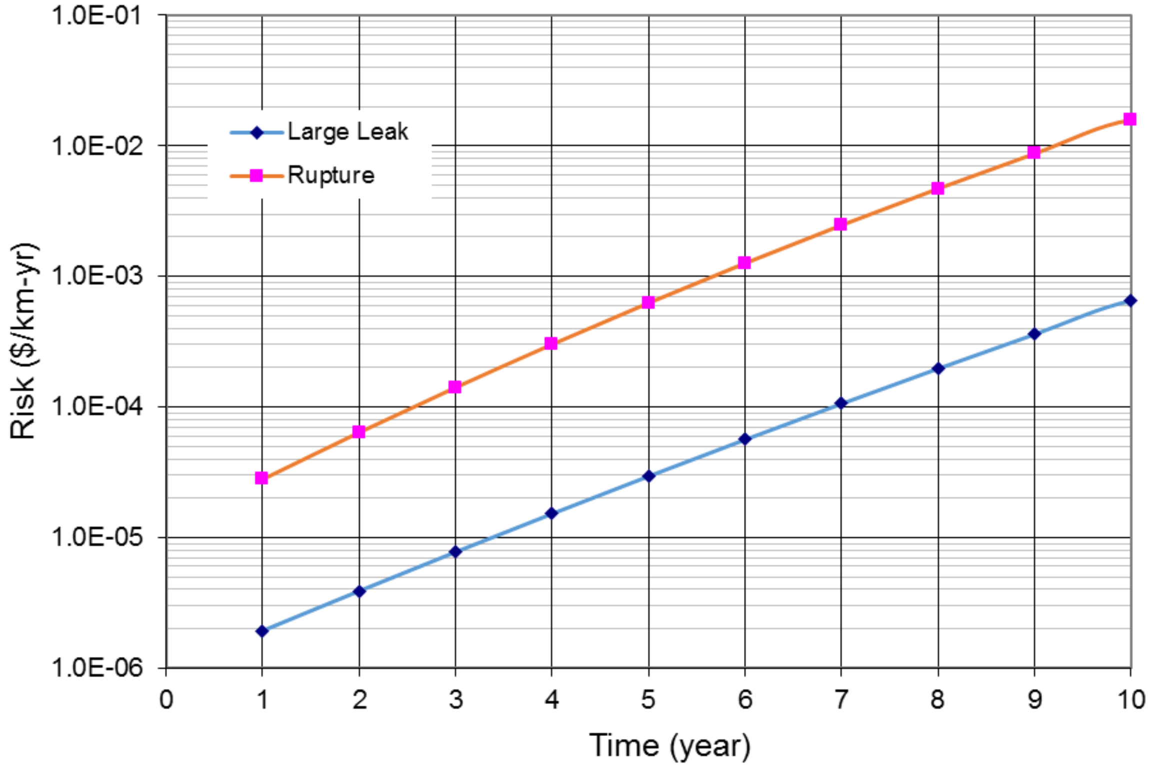
Example: Risk Over Time



Thankyou!