TOWARDS AN INTEGRATED PROBABILISTIC RISK ASSESSMENT AND MANAGEMENT FOR OFFSHORE PIPELINES: FROM SITE CHARACTERIZATION AND ROUTING TO OPERATION

A Thesis

by

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ABSTRACT

Offshore pipeline route selection is a multidisciplinary engineering task to determine the best alternative route by taking into account spatial project constraints, geohazards, safety procedures, environmental conditions, third-party activities, existing facilities, and construction and operation issues. Since the pipeline route selection operates with multiple threats and vulnerabilities, a Probabilistic Risk Assessment methodology for pipeline routing is introduced based on the integration of construction and operation constraints, and relevant serviceability and ultimate limit states from existing industry standard codes.

The Probabilistic pipeline routing conceptual model was developed by adopting a Risk framework represented in a Bayesian Network for Risk Assessment and Management. Physically based-models for each limit state were employed by defining dependencies between serviceability and ultimate limit states by the identification of control parameters that are common to both of them when representing a single state of Risk for pipeline route selection.

The Bayesian Network model is capable to quantify the uncertainties on the physically based model design parameters, and on the vulnerabilities regarding each pipeline failure mechanism considered in this research. The value of the consequences is qualitatively defined in three states (low, moderate, and high) for heuristic purposes, and can be easily modified by the user for other consequences such as economic, environmental, and life losses.

The proposed approach is a useful tool for decision-makers such as pipeline engineers, pipeline operators, project managers, environmental, civil, mechanical, geotechnical, and structural engineers, to assess the Lowest-Risk Path for an offshore pipeline project.

DEDICATION

I dedicate this work to my family who were supportive during my Master’s program, with special mention to my brother Elvis Duran who encouraged me to come to Texas A&M to pursue my Master’s degree. To my mother and father who always believed in me, and helped me in the difficult times. To my little sister whose characteristic attitude and taste of music always inspired me to do things differently.

I also dedicate this work to my sister in law Pilar Carrillo who supported me along with my brother since my first day in College Station.

Finally, but no less important, I dedicate this work to my grandparents whose blessings and good faith were always present during this journey.

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NOMENCLATURE

ABS	American Bureau of Shipping
AHP	Analytical Hierarchy Process
APM	Adaptive Penalty Method
BN	Bayesian Network
BP	Brown and Peterson
DSS	Decision Support System
GA	Genetic Algorithms
LCP	Least-Cost Path Method
LRFD	Load and Resistance Factor Design
SA	Simulated Annealing
SAW	Simple Additive Weighting
SCR	Steel Catenary Riser
SIAMEP	Artificial Immune System with Pareto External Memory
SLS	Serviceability Limit State
SWI	Simple Weighted Index
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
ULS	Ultimate Limit State
VIV	Vortex Induced Vibrations

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CHAPTER I

INTRODUCTION

Global offshore oil & gas production in deepwater has been increasing in the last decade accounting for 30% of the total production in the world [1]. Factors such as changing economics, increase in demand, exhaustion of shallow water resources, advancements in drilling technology, dynamic equipment, and floating production, have encouraged countries like Brazil, United States, Angola, and Norway to work on deepwater or ultra-deepwater projects [1].

To satisfy the energy demand for oil & gas, development of new submarine pipeline systems is required, which are its safest mean of transportation [2]. The pipeline design process involves integration of different engineering disciplines such as geotechnical, environmental, materials, hydraulic, mechanical, and structural [3].

The first and most important step in the design process is the selection of the pipeline route [4]. Pipeline route selection used to be a manual work operated by a group of experts who analyzed topography/bathymetry, thematic maps, and tried hundreds of routes based on experience and judgement. In the last 20 years, this handmade methodology has been replaced by GIS-based methods, which accounts environmental, economic, engineering, and social issues.

The proposed objective of this work is to improve the decision-making process of offshore pipeline routing by implementing a Probabilistic Risk Assessment and Management. The secondary objectives of this research are:

1. To incorporate all relevant structural design criteria based on Ultimate Limit States (ULS) and Serviceability Limit States (SLS) to the assessment of the offshore pipeline route.
2. To integrate the Dynamic, Quasi-Static, and Static design criteria with relevant spatial construction constraints that an offshore pipeline project may confront, and with hydraulic design criteria through a Probabilistic Risk Assessment framework represented in a Bayesian Network.
3. To study the control parameters of each one of the limit states in consideration in order to identify the ones that are in common between limit states to establish cause-effect relationships in the Bayesian Network model.
4. To study the relationships between Serviceability Limit States and Ultimate Limit States, and between other design criteria such as Free Span and Lateral Global Buckling, and the limit states to represent those relations in the Bayesian Network model.
5. To study how other methodologies are mitigating the spatial construction constraints in order to propose mitigation actions to be represented in the Bayesian Network model.

6. To identify the main sources of pressure loss that can generate a pressure drop in the system versus the operating pressure, and represent them in the Bayesian Network model.

The proposed methodology hypotheses are:

1. Route selection through an integrated Risk-based Assessment better represents the state of Risk of offshore pipeline projects.
2. Installation and operation costs of the pipeline project can be minimized by following Risk-based design approach.
3. The Probabilistic Risk-based method is less conservative because it analyze each control variable through probability densities in order to represent the variability corresponding to each variable, rather than using factors of safety.

The objective and hypotheses stated above are formulated to tackle the following problem.

There are two main pipeline routing methodologies in literature:

- Least-Cost Path (LCP) method.
- Optimization method.

The Least-Cost Path is a GIS-based method that assess pipeline routes by analyzing geospatial features such as slopes, existing submarine infrastructure, geological anomalies, and constructions constraints. The disadvantage in this method is that the severity of the threats to the pipeline are subjectively or empirically discretized, and strongly depends on decision-maker expertise. Moreover, this method do not consider any structural or hydraulic design criteria, and as a result, the optimum route is not reached, pipeline design process takes more time, and re-routing could be necessary to satisfy design standards.

The Optimization approach is based on the formulation of objective, cost, and violation functions, where the objective function incorporates design criteria, the cost functions take into account “soft” project constraints such as longitudinal declivity, and the violation functions manage “hard” project constraints like pipeline self-crossing. The objective function is optimized, and the cost and violation functions are restricted to assess the pipeline route. The objective function can include some Ultimate Limit State (ULS), and Serviceability Limit State (SLS) design criteria such as fatigue, on-bottom stability, and pressure drop.

One disadvantage of this method is that functions do not include geohazards such as landslides, or other threats like third-party interference. Other one is that function formulation relies on mitigation criteria such as the required ballast weight for on-bottom stability, and the total area of the spans required to cover in order to avoid fatigue induced by vortex induced vibrations (VIV), but do not consider the vulnerabilities of the system, and the environmental, economic, and social consequences of failure, which are described later in Chapter II.

It is important to point that both methods analyze threats as independent events, and so far, no effort to study how the combination of threats can generate different pipeline failure mechanisms and how serviceability and other design criteria can trigger particular failures when they are not fulfilled. It is also important to mention that it is well known that both methodologies content uncertainties due to how the threats are discretized, however no study has been conducted to quantify the uncertainties so far.

Therefore, it is necessary to solve the problem by developing an integrated approach that incorporates all failure mechanisms from ULS and SLS design criteria, spatial construction constraints, and hydraulic design criteria. It is also necessary that the method is capable to quantify the variability of the control parameters, and the uncertainties related to expert beliefs.

The following sections describe in detail the Least-Cost Path and Optimization methods.

Least-Cost Path Method

Feldman et al. [5] developed a prototype LCP analysis model for pipeline routing by incorporating pipeline length, topography, geology, land use, stream, wetland, road and railroad in an onshore location. Remote sensing data such as maps, aerial photography, satellite imagery, and Geographic Information System (GIS) analysis was adopted for this study. Thematic maps were generated by assigning cost factors to constraints such as crossing steep slopes, streams, wetlands, roads, railroads, rock, agricultural land, urban and industrial areas. A cumulative cost surface was produced by overlaying the thematic maps to finally compute the LCP analysis across the surface.

Montemurro, Barnett, & Gale [6] discuss the advantages of using GIS-based onshore routing to minimize public safety risk, environmental damage, construction and operation cost. Policy, regulatory, and cultural constraints were also addressed in this study. Route alternatives were analyzed and refined with more detailed data, and by considering provincial government, public, landowner, and expert's feedback.

The research conducted by Bade & Mackaness [7] apply the LCP analysis algorithm to an offshore pipeline routing case of study. Factors such as seabed and slope morphology, existing infrastructure, licensed exploration blocks, stability of sediments, wrecks and fishing grounds, were considered for modelling cost surfaces. Delavar & Naghibi [8] incorporated geological faults to the classic LCP approach.

Berry, King, & Lopez [9] introduced a web-based application for assessing pipeline routes and corridors. Route candidates were evaluated by hydraulic and economic cost models to optimize design factor such as maximum allowable operating pressure, pipe diameter, wall thickness, horsepower requirements, and station locations.

King, Phillips, & Johansen [10] broadened LCP method by presenting a methodology for protection against ice gouging for offshore/artic pipelines. The approach aims to optimize the pipeline and trenching cost, but limited to the quality and availability of data such as gouge rates, gouge geometry, and seabed characteristics.

Haneberg, Drazba, & Bruce [11] produced a “qualitative” landslide map by visually discretizing the geomorphological age of past slope failures in a bathymetric surface. A “probabilistic” slope stability map was also generated by using geotechnical data from different locations. Both maps were overlaid to create a composite cost surface map to compute LCP analysis. The resulted route was refined by employing an in-house application to comply with the minimum tolerance of radius of curvature.

Devine & Haneberg [12] presented a Fill method to detect depression features such as strudel scours and ice gouges, which influenced the final weighted composite map for artic pipeline routing.

The following Figure 1 illustrate the LCP methodology steps:

Figure 1 Least-Cost Path Flowchart Adapted From [13].

Collection of data implies the acquisition of information such as spatial, geophysical, metocean, geotechnical, and geological data.

- Spatial information:
    - Leasing areas for oil extraction.
    - Prohibited areas.
    - Boundary conditions.
    - Reef fish resource and coral reef areas.
    - Protected areas.
- Geophysical surveys (Table 1):

Table 1 Geophysical Survey Types Reprinted From [13, 15].

Survey Type	*Uses*	*Features Identified*	*Typical Horizontal Resolution*	*Typical Vertical Resolution*	*Advantages*	*Limitations*
3-D Seismic	Identifying stratigraphy and structural, regional bathymetry, exploration for hydrocarbon reservoirs	Faults, landslides, mass transport deposits, fluid expulsion features, channel systems, buried structure (faults and folds), buried stratigraphy, buried gas/hydrate	10 m to 25 m	10's to 100's of meters	Regional coverage and regional geologic interpretation	Lower resolutions compared to other surveys
HR or UHR 2-D seismic reflection	High resolution of stratigraphy and structure	Shallow seafloor features, buried structures, buried structure (faults and folds), buried stratigraphy, buried gas/hydrate	N/A	2 m to 4 m	Provides higher resolution than 3-D seismic to resolve subsurface conditions	Time consuming and costly to cover a large area
Sub-Bottom Profiler (SBP)	Identify near-seabed shallow stratigraphic and structural horizons	Manmade objects, faults, fluid expulsion features, shallow buried structure (faults and folds), shallow buried stratigraphy	N/A	10's of centimeters to 10's of meters	Provides higher resolution than 2-D and 3-D seismic to resolve shallow subsurface conditions	Features may not be detected depending on line spacing
Multibeam Echosounder (MBES)	High resolution bathymetry, backscatter (intensity showing hard or soft material), water column data	Faults, landslides, mass transport deposits, fluid expulsion features, channel systems at the seafloor	0.1 m to 15 m	N/A	Provides high resolution imagery of the seafloor	Resolution decreases with water depth depending on sensor height (e.g., hull-mounted versus AUV)
Side Scan Sonar	Detection of manmade objects, assess harder material versus softer material	Manmade objects, faults, fluid expulsion features, hardground	centimeters to decimeters	N/A	Provides high resolution imagery of seafloor objects	May not resolve features on steep slopes due to data shadows

Bathymetry, existing pipelines, platforms, and field unit information can be obtained from geophysical surveys as indicated in Table 1. Advantages and limitations of each survey are also discussed in Table 1 to better understand the quality of data that can be acquired and for what purpose.

- Metocean (meteorological and oceanographic) data [13]:
    - Statistical or historic data of wind, currents, and waves.
- Geotechnical Cores [13]:
    - Free-falling.
    - Gravity-driven boxes (box cores).
    - Piston cores and jumbo piston cores (JPC).
    - Robotic seafloor drilling rigs.
    - Geotechnical drill ships.
- In Situ Testing [13]:
    - Cone penetrometer (CPT).
    - Piezocone penetration test (PCPT).
    - Cyclic ‘full flow’ penetrometer testing.
- Geological cores to determine depositional events features [13].
- Specialized surveys [13]:
    - Seafloor video recording using ROVs.
    - AUV and ROV photo imagery.
    - Magnetometer surveys.
    - Seismic refraction surveys.

Hazard identification depends on the available information for the case of study. Devine et al. [13] categorized the hazards as follows:

- Geological hazards (Geohazards) as depicted in Figure 2:
  - Geohazard triggers.
  - Geometric Geohazards.
  - Static Geologic Geohazards.
  - Dynamic Geologic Geohazards.

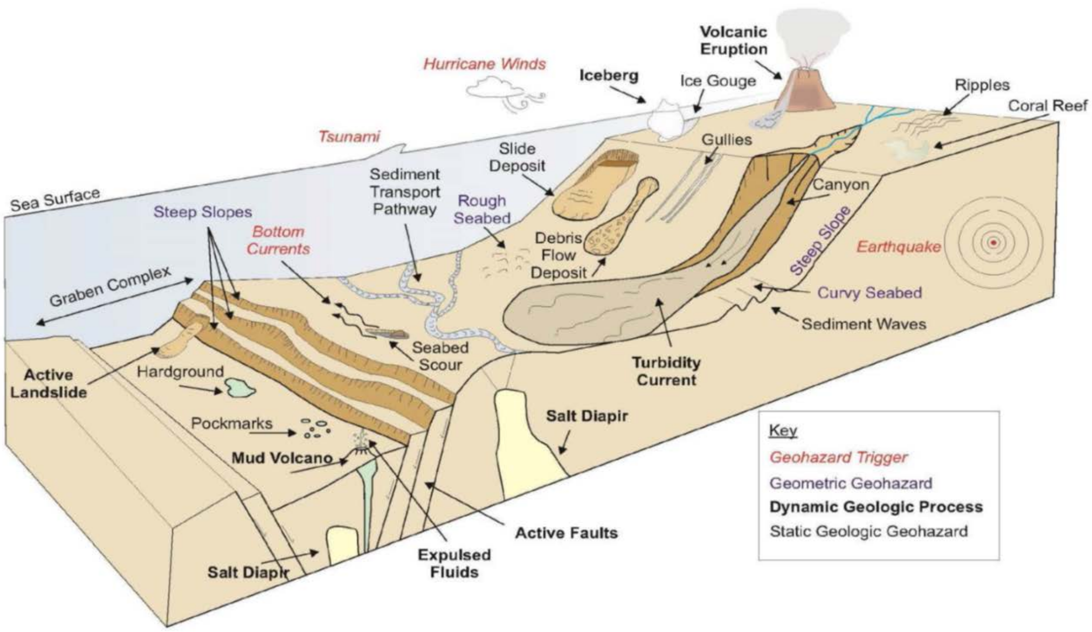

Figure 2 Offshore Geohazards Reprinted From [13].

- Manmade hazards like military and industrial debris, marine industries, subsea infrastructure, etc.
- Ecological and environmental constraints:
  - Near-shore areas.

- Environmentally sensitive areas.
- Fishing areas.
- Benthic communities in deepwater settings.
- Coldwater corals.

- Cultural constraints.

Hazard discretization implies how the severity of the hazard to the pipeline is discretized. Seel & Phillips [14] qualitatively discretized the constraints of the project in four classes: low, medium, high, and no-go. American Bureau of Shipping (ABS) [15] recommends a broader discretization in five classes: negligible, low, moderate, high, and impermissible. Quantitative scales to discretize the severity of the hazards range from 0 to 5 [16], 1 to 9 [9], 1 to 10 [15], and so on. Generally, hazards are discretized in classes with a corresponding weight or cost (Table 2):

Table 2 Seafloor Slope Weighting Criteria Adapted From [15].

Seafloor slope class (degrees)	**Cost/weight**
0° to 3°	1
3° to 5°	2
5° to 10°	4
10° to 15°	8
15°+	10

Quantitative methods based on physical models to classify the severity of hazards are also employed, such as the research conducted by Haneberg, Drazba, & Bruce [11] who produced a "probabilistic" slope stability map using geotechnical data from different locations to compute the probability of failure against sliding at any cell using undrained infinite slope model.

Fuzzy logic is also employed for discretization of hazards. Unlike quantitative methods based on crisp sets where each raster cell belongs to a class or not, Fuzzy Logic allows cells to be partially in a class, by defining how likely the cell is part of the class or set [17]. The Fuzzification process will transform the original raster values to a 0 to 1 scale where "0" represents a total non-membership of the set, and "1" a fully membership of the set [17].

Once the hazards are independently discretized, the next step is to produce suitability maps by overlaying the hazards. Three overlay methods has been identified in literature: Binary, Weighted, and Fuzzy Logic. Binary overlay analysis is based on Boolean Logic where only two values are possible, 0 and 1. This method has no criteria prioritization of hazards, all hazards has the same weight. No second best option is available for suitability maps, it is limited to "suitable" or "unsuitable" [18].

Weighted overlay analysis adopts the quantitative scale of the case of study. Prioritization of hazards is viable in this method by assigning weights, generally in terms of percentage. Raster cell values from each hazard map are summed, multiplied, or averaged to produce a final suitability or cost surface map.

Fuzzy Logic overlay analysis scale ranges from 0 to 1. In contrast to Weighted overlay that is based on linear combinations, Fuzzy overlay is based on set theory. Fuzzy overlay determines the likelihood of a phenomenon to belong to multiple sets or criteria by analyzing their relationships [17].

Efforts to improve pipeline routing criteria for a consistent rating scale, and criteria prioritization in LCP approach have been performed by using mathematical models, such as Berry [19] research who implemented Delphi and Analytical Hierarchy Process (AHP) technique to calibrate cost surfaces. Nithin Nonis, Varghese, & S Suresh [20] modified AHP by incorporating expert's judgement and computed the LCP algorithm on the calibrated weighted surface in an onshore case of study.

Moghaddam & Delavar [21] studied statistical and fuzzy logic models for Hazard Overlapping Analysis to generate cost surfaces. Balogun, Matori, & Hamid-Mosaku [22] developed a "hybrid multi-criteria decision support system" by integrating fuzzy logic and AHP for routing criteria prioritization. Yildirim et al. [23] compared AHP, technique for order of preference by similarity to ideal solution (TOPSIS), and simple additive weighting (SAW) methods for criteria prioritization.

The LCP last step is the assessment of the pipeline route. Cost Distance and Cost path tools from ESRI ArcGIS Spatial Analyst Toolbox are the most used algorithms to determine the route. The Cost Distance tool generates an output where each raster cell value represents the least accumulative impedance or "cost" per unit distance to move through that cell [18]. Figure 3 describes the Cost Distance tool process.

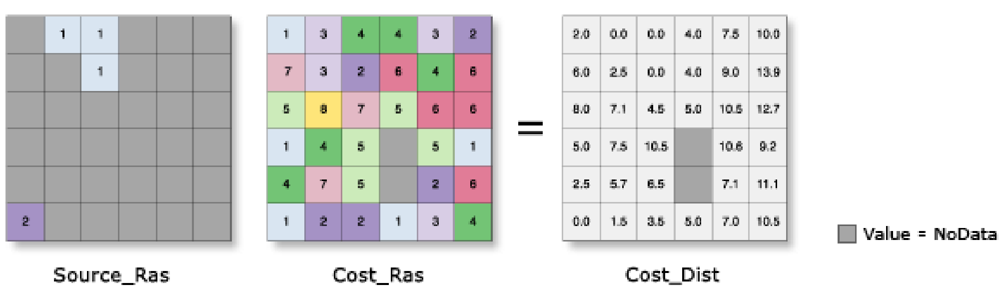

Figure 3 Cost Distance Tool Process Reprinted From [18].

An optional, but necessary output from Cost Distance tool is the Cost Back Link. This output is required as an input for Cost Path tool to determine the LCP. The Cost Back Link raster has values from 0 to 8 (Figure 4), where each value represents the direction of the next neighboring cell with the least accumulative cost from a cell to its least-cost source [18].

6	7	8
5	0	1
4	3	2

Figure 4 Cost Back Link Direction Value Where "0" Represents The Cell Source. Adapted From [18].

The Cost Path tool requires both Cost Distance and Back Link outputs, and the destination to assess the LCP. The output raster displays a one cell wide LCP or paths between the source and destination. The expected route or routes aim to be the "cheapest" ones.

Optimization Method

A different approach to solve the pipeline routing issue has been investigated by developing “objective functions” based on structural integrity analysis employing Ultimate Limit State (ULS) and Serviceability Limit State (SLS) design methods, and penalty-based criteria to manage project constraints. The objective function is minimized using optimization algorithms, and the penalty-based criteria is limited to assess the pipeline route.

The following Figure 5 describes the method process:

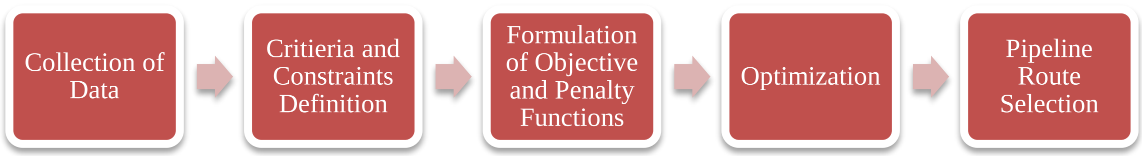

Figure 5 Optimization Method Flowchart.

Collection of data is same as the Least-Cost Path method. For the subsequent steps, different approaches has been found in literature:

Shamir [24] developed an onshore pipeline route optimization tool that incorporates a two-phase flow global constraint, and local constraints such as pipe length and hills. An objective function was formulated to evaluate the cost of pipeline segment. The function was minimized while satisfying the global and local constraints using Dynamic Programming optimization technique.

Hove, Olsen, & Meisingset [25] applied Simulated Annealing (SA) optimization algorithm to minimize an offshore pipeline routing “cost function” which includes material, free span, horizontal radius of curvature, vertical curvature, and lateral stability cost terms.

Marcoulaki et al. [26] developed a different pipeline system optimization framework (Figure 6) using stochastic optimization, GIS, design characteristics of pipeline components and their locations, and construction, operation, maintenance issues. An objective function was defined in terms of “cost” by considering geotechnical studies, pipeline route surveys, material studies, hydraulic modeling, and geographical information. Markov process was computed to execute iterations at constant SA temperature (Simulated Annealing control parameter) to encounter the “global optimum” objective function for two cases of study: case A considers geological information only, and case B considers further information such as population, land use, and infrastructure.

Marcoulaki et al. [27] improved the previous framework by adding Norsok M-506 [28] internal corrosion rate model, and by upgrading equipment design and cost functions. Seven design cases were performed by varying corrosion model parameters: acidity (pH) and CO2. Marcoulaki et al. [27] concluded that the total pipeline cost and optimal route are sensitive to the presence of corrosion agents.

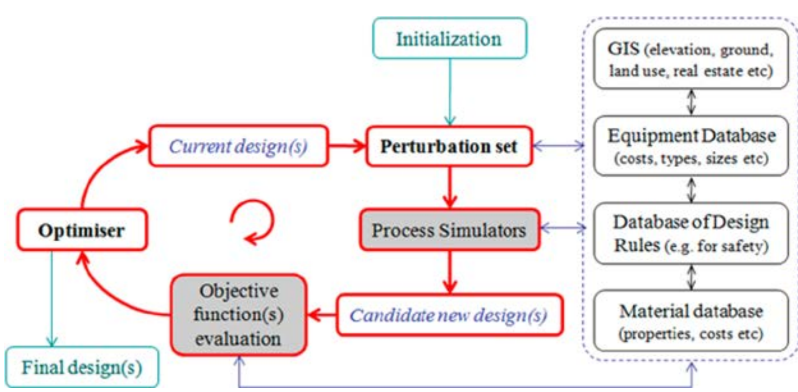

Figure 6 Pipeline System Optimization Framework Reprinted From [27].

Other optimizer algorithms that have been extensively used for pipeline routing are Genetic Algorithms (GA). Vieira et al. [29] developed a computer tool for optimization of submarine pipeline routes using Genetic Algorithms (GA). Geometric representation of pipeline route, objective function, and penalties based on physical obstacles, pipe self-crossing, minimum length of straight sections, topographic constraints such as longitudinal and transversal declivity, and on-bottom stability following DNV-RP-F109 [30] are described in [29].

Lima, Jr., Mauro Henrique Alves et al. [31] employed Vieira et al. tool in two hypothetical bathymetry scenarios, and added minimum radius of curvature and on-bottom stability criteria based on Absolute Static and Generalized Stability methods [30] to the objective function penalties. The study claims that stability criteria has a substantial influence on the evaluation of the optimum route.

Baioco et al. [32] followed the previous works by introducing "soft" and "hard" project constraints for feasibility analysis, and Fatigue Induced by Vortex Induced Vibrations (VIV) and wave loads based on screening criteria recommended by DNV-RP-F105 [33]. The study concluded that the screening criteria cost term is sensitive to pipeline length. Baioco et al. [34] extended the previous study by incorporating pressure drop criterion for multiphase fluid flow, and required ballast weight factor to reach minimum lateral safety factor.

Lucena et al. [35] calibrated the "hard" criteria of Baioco et al. method by employing advanced constraint-handling techniques such as Adaptive Penalty Method (APM), the e-Constrained method, and the Ho-Shimizu ranking technique. Rocha et al.

[36] study based on Baioco et al [34], and Lucena et al. [35] research, investigates the influence of submarine slope stability and safety factor criteria using one-dimensional infinite slope method. The study argues that the optimization process for the most reliable pipeline route is largely influenced by slope stability criteria.

Recently, Baioco et al. [37] integrated ballast weight term in the optimization process to minimize mitigation cost for on-bottom stability of the pipeline, and evaluated environmental loading combinations employing 100-year and 10-year return wave parameters with 10-year extreme near-bottom current velocities.

Other optimization algorithms have been implemented for submarine pipeline routing, such as the work done by:

- Lucena et al. [38] compared CLONALG Nature Inspired Algorithm (NIA) and GA optimizers using Lima, Jr., and Mauro Henrique Alves et al. [31] pipeline routing tool. Static penalty and APM constraint-handling techniques were performed for both clonalg and GA.
- Baioco, Albrech, Jacob, & Rocha [39] developed a multi-objective optimization tool using Artificial Immune System with Pareto External Memory (SIAMEP) algorithm. The route parameterization and constraints were supported by previous research [34].

Figure 7 summarize the LCP and Optimization methodologies:

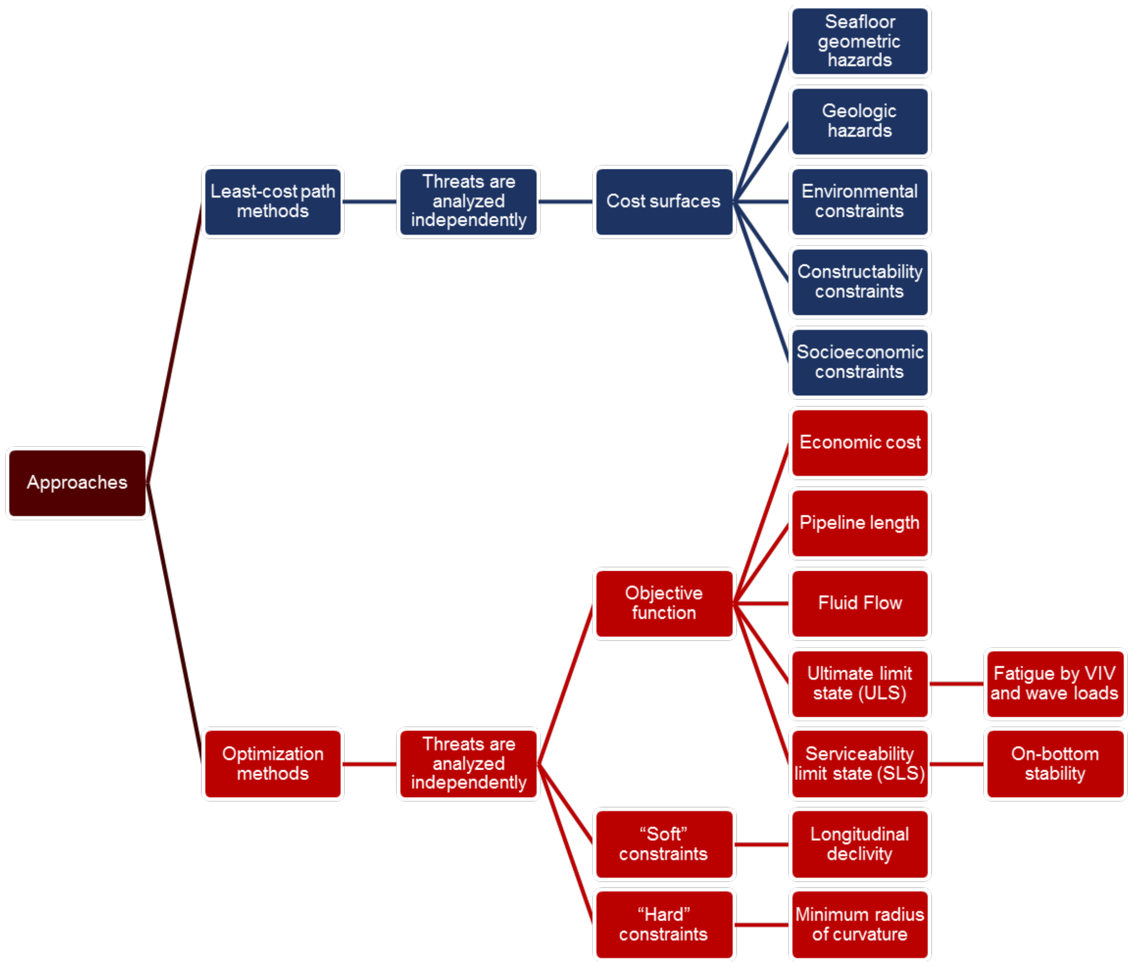

Figure 7 Pipeline Routing Methods In Literature Review.

Pipeline Route Validation

Although previous methodologies intend to minimize the hazards that the integrity of a pipeline may confront, there is no full certainty that all hazards will be addressed. Decision-makers usually validates the route through Risk Assessment, or Feasibility and Sensitivity Analysis.

Risk Assessment

Devine et al. [13] developed the following Risk Assessment framework (Figure 8) for route validation.

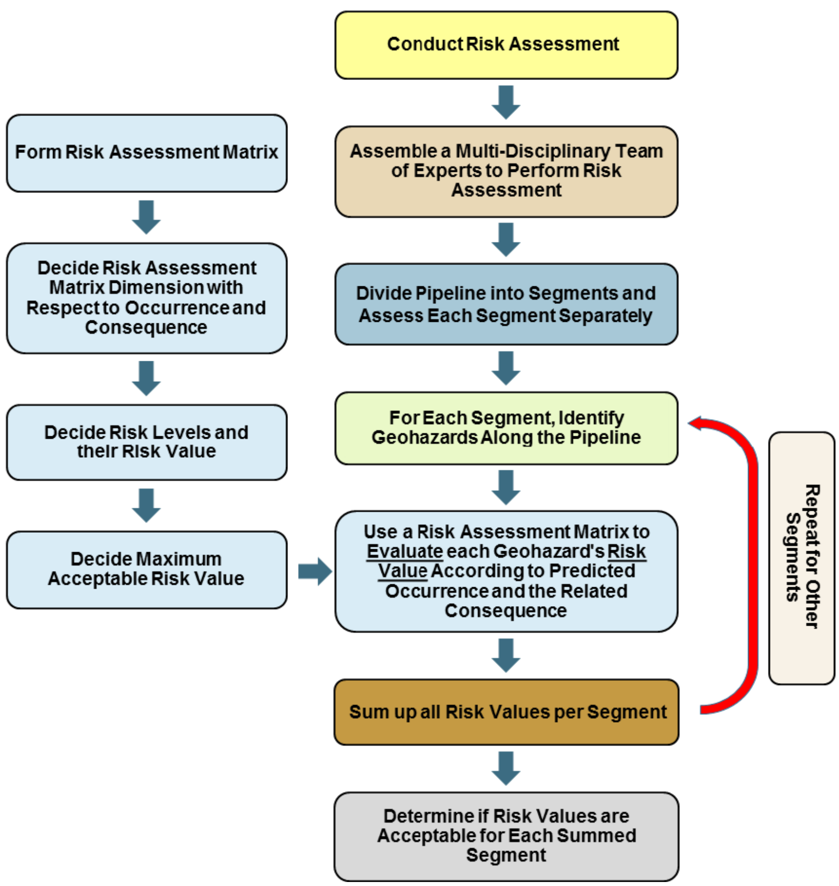

Figure 8 Risk Assessment Framework Reprinted From [13].

From Figure 8, multi-disciplinary team of experts might include specialists in marine engineering geology, geotechnical engineering, pipeline engineering, marine ecology, marine archeology, health/safety/environmental, project management, among others [13]. The Risk Assessment matrix (Table 3) should identify the potential hazards, their likelihoods, and consequences [13].

Table 3 Example Of "Industry Standard" Risk Matrix Reprinted From [13].

Risk Likelihood

Risk Consequence

		Rare	**Very Unlikely**	**Unlikely**	**Possible**	**Occasionally**	**Likely**
		Has not occurred in the industry	Has occurred in the industry	Has occurred on a similar project	Likely to occur in 10% of similar projects	Likely to occur 1-2 times on this project	Likely to occur repeatedly on this project
Infrastructure Damage and Environmental Impact	**Qualification**	**$< 10^{-5}$/yr**	**10^{-5} - 10^{-4} / yr**	**10^{-4} - 10^{-3}/ yr**	**10^{-3} - 10^{-2} /yr**	**10^{-2} - 10^{-1} /yr**	**$> 10^{-1}$/yr**
Catastrophic pipeline rupture and oil spill (500,000 US gallons)	**Catastrophic**	50	100	250	500	1000	2000
Severe pipeline rupture and oil spill (250,000 US gallons)	**Severe**	25	50	100	250	500	1000
Major pipeline damage and oil spill (100,000 US gallons)	**Major**	10	25	50	100	250	500
Moderate pipeline damage and oil spill (50,000 gallons)	**Moderate**	5	10	25	50	100	250
Minor pipeline damage and oil leakage (1,000 gallons)	**Minor**	2	5	10	25	50	100
Minor pipeline damage – no leakage	**Negligible**	1	2	5	10	25	50

A maximum acceptable Risk value is defined by the project team to evaluate the resulting sum of each segment Risk values in order to determine if the Risk is acceptable. Unacceptable Risk might imply mitigation of the hazard, or re-routing the pipeline [13].

Feasibility and Sensitivity Analysis

Dey & Gupta [40] provided a Decision Support System (DSS) using AHP for onshore pipeline route selection. Pipeline length, operability, maintainability, approachability, constructability, and environmental friendliness factors were taking into account, and a 1 to 9 ranking scale was established for constructing comparison matrices to determine weights for factors and sub factors.

Dey [41] expanded previous research by adding new maintainability sub factors such as construction and material defect, operational defect, and natural hazards, environmental impact and socio-economic assessment to the feasibility analysis framework (Figures 9, 10).

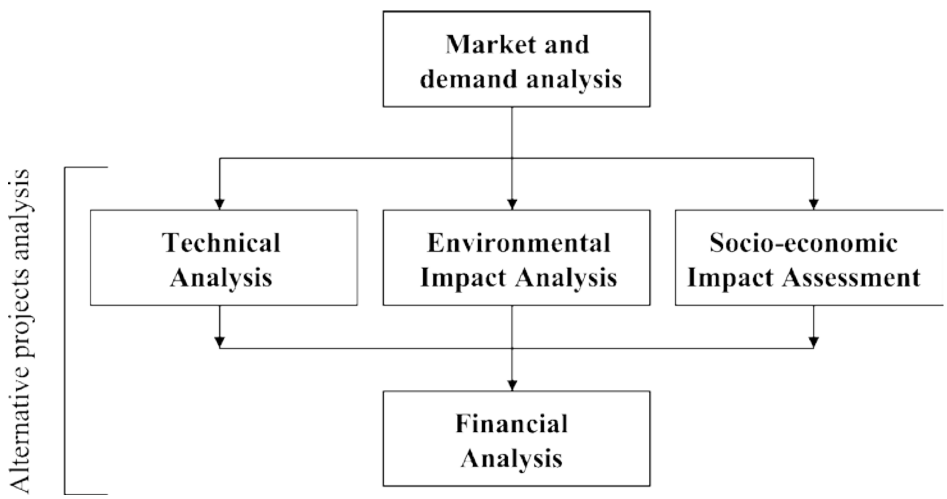

Figure 9 Project Selection Model Of Pipelines Reprinted From [41].

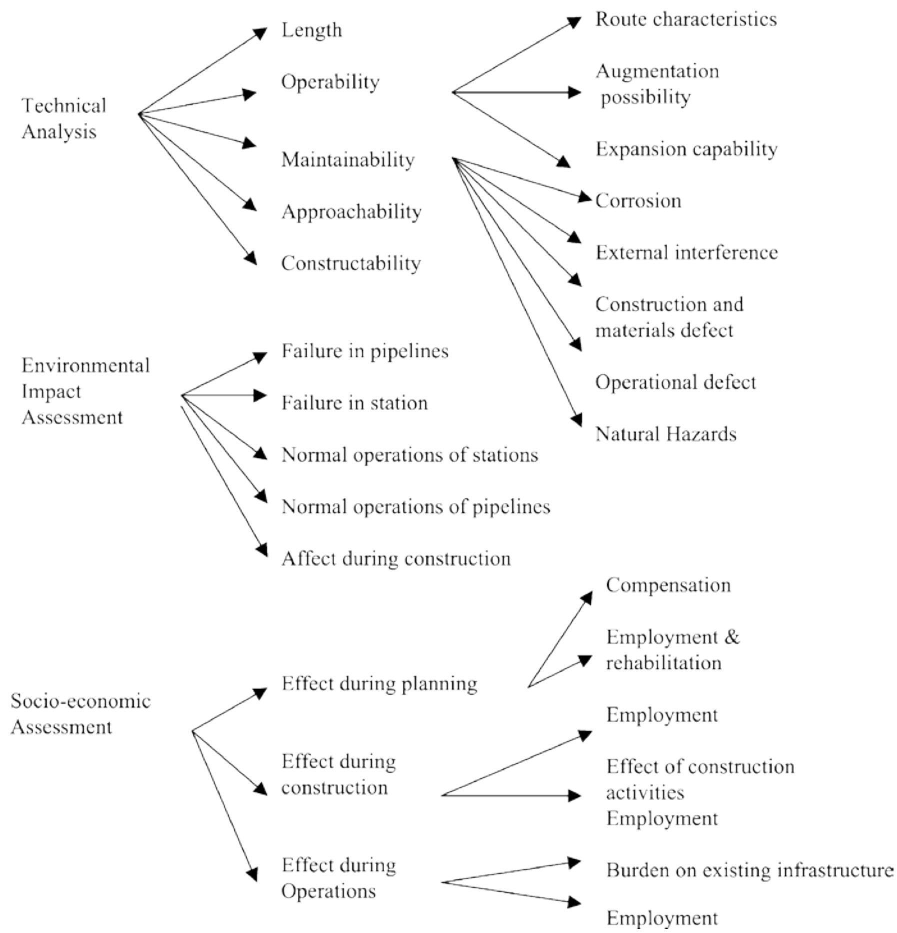

Figure 10 Factor And Subfactors For Project Selection Reprinted From [41].

Least-Cost Path + Feasibility & Sensitivity Analysis

Wasi & Bender [42] improved previous onshore pipeline routing frameworks by adding feasibility and sensitivity analysis. The following steps describe the approach:

1. Collection and conversion of spatial data using GIS tools.
2. Production of cost/friction maps using ranking criterion, and total cost surface to compute the least-cost path in three route scenarios (Figure 11).
3. Overlay of each route scenario with all considered map variables such as slopes, rivers, lakes, wetlands, public and private lands, to construct a decision matrix.
4. Integration of decision matrix with AHP to rank pipeline route scenarios.
5. Sensitivity analysis, quantification of risk, and stability analysis of the route optimization result.

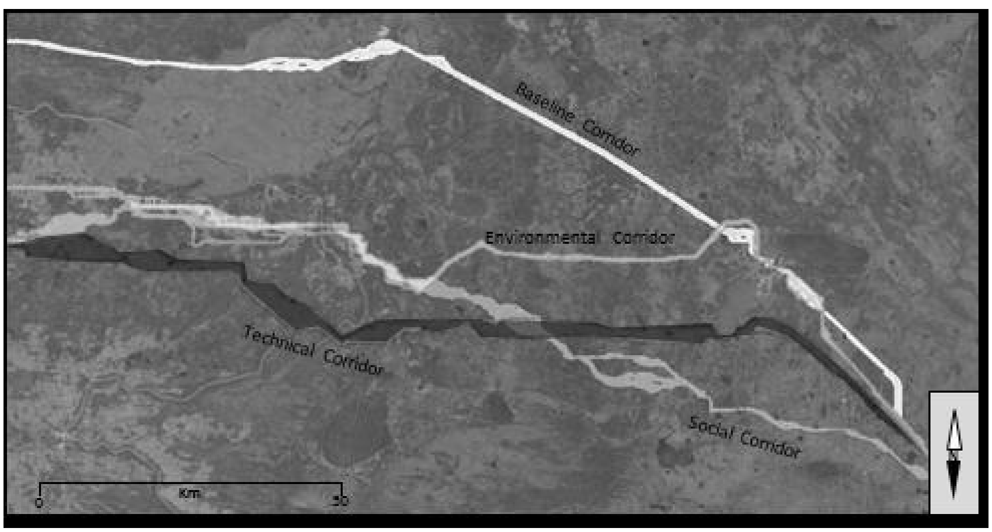

Figure 11 Simulated Thematic Route Corridors Reprinted From [42].

Least-Cost Path + Risk Assessment

Scott Byron [43] generated "Risk score maps" that include Risk factors associated with construction, operational, socioeconomic, and environmental issues in the Persian Gulf. Risk scores for each Risk issue were calculated by using the following formula 1:

$$RS = \frac{PO}{2} + PI \quad (1)$$

Where:

RS = risk score with 1.5 to 4.5 scale range (0.5 increments).

PO = probability of occurrence.

PI = potential impact scores: 1 (low), 2 (medium), or 3 (high).

Three weighting or criteria prioritization methods were applied in this research: Simple Weighted Index (SWI), Brown and Peterson (BP) and AHP pair-based comparison methods. A raster data layer was generated for each "high priority" Risk factor such as seismic Risk, steep slopes, commercial shipping dragging, landslides, crossing through hydrologic features, pipelines, roads, and railroads, coral reefs, and spill windows. Data values were weighted according to each weighting method.

The derived layers were added together and normalized to create three final maps (Figure 12):

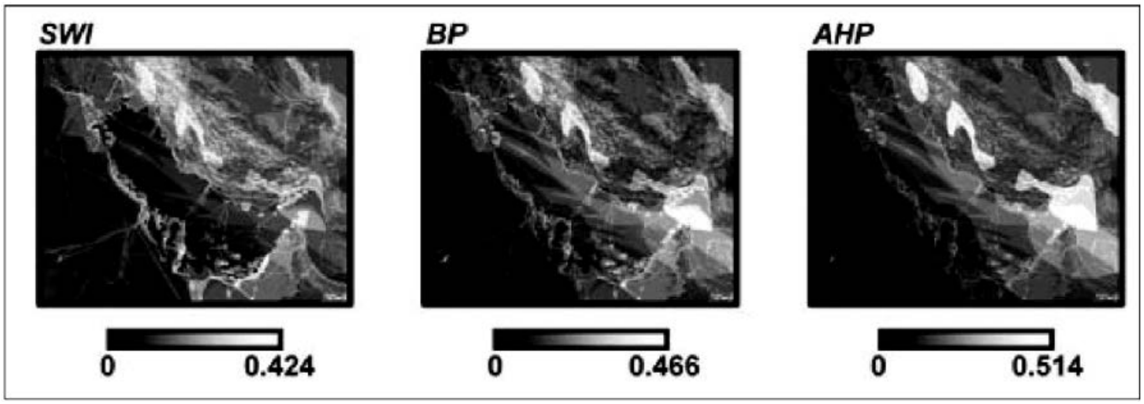

Figure 12 SWI, BP, And AHP Risk Maps. High Numbers Represent High Risk. Reprinted From [43].

Results were compared with IGAT 4, and Dolphin existing pipelines to validate the analysis (Figure 13, 14):

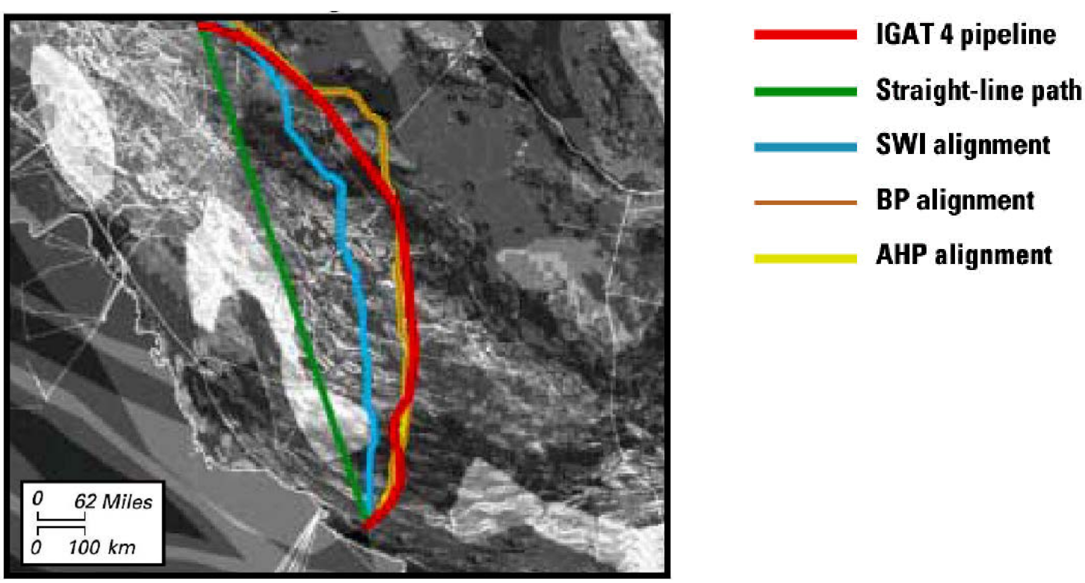

Figure 13 Comparison Between IGAT4, Straight-Line And SWI, BP, AHP Paths Reprinted From [43].

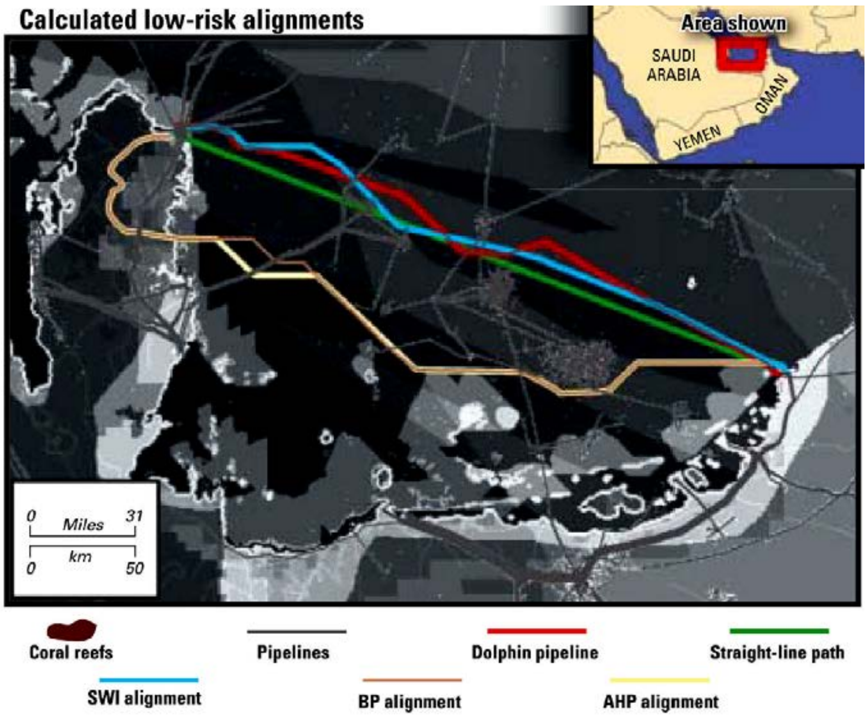

Figure 14 Comparison Between Dolphin, Straight-Line, SWI, BP, AHP Paths Reprinted From [43].

Devine et al. [13] propose a subsea pipeline route determination approach depicted by the following Figure 15:

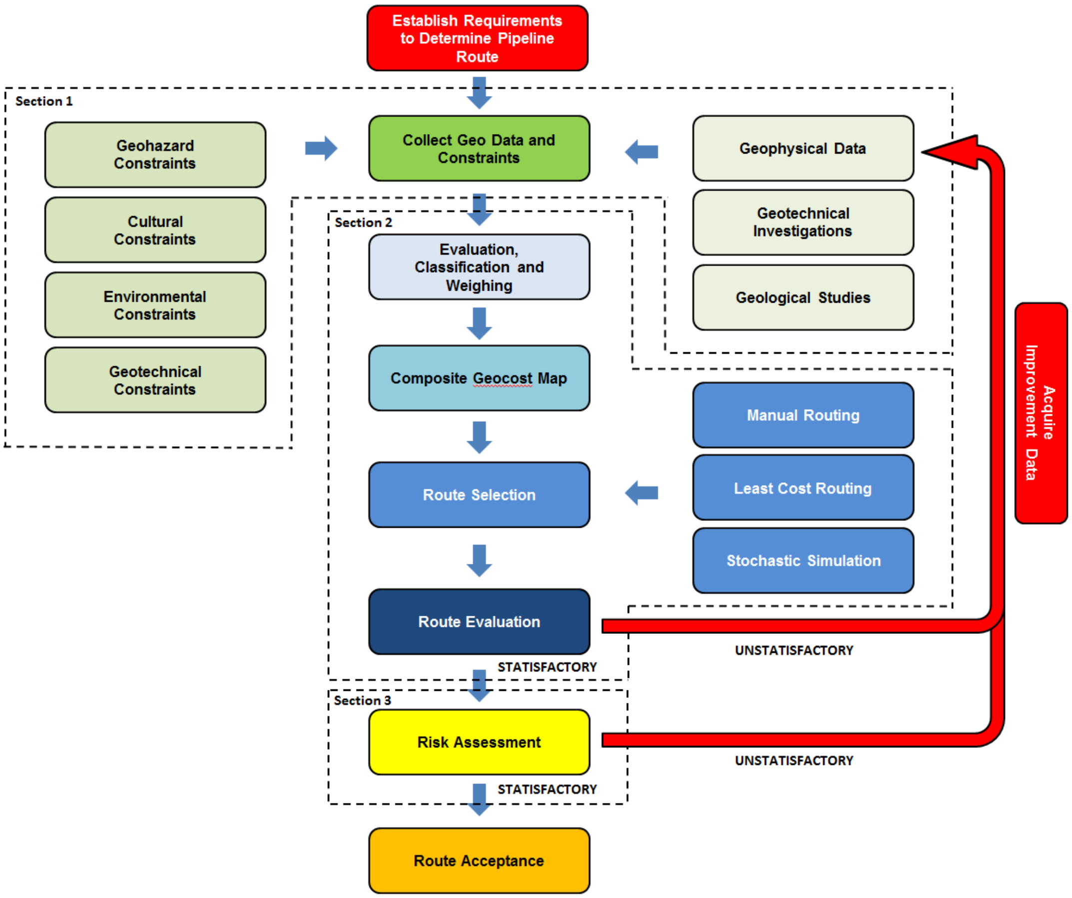

Figure 15 Pipeline Route Determination Flowchart Reprinted From [13].

The methodology is based on Least-Cost Path analysis where collection of data, identification of hazards, classification, weighting, and route selection takes place. Stochastic simulation was introduced as a solution for “composite geocost” map uncertainties such as human judgement, and data resolution. The final step is to validate the route through project team evaluation and Risk Assessment as described in *Risk Assessment* section.

Spatial Assessment of Risk and Routing

Although the purpose of this research is not to represent the state of Risk in spatial domain, this will be the latter task in the development of the Risk-based methodology for offshore pipeline routing. Therefore, it is important to document the state of the art regarding spatial Risk Assessment.

Medina-Cetina & Varela [57] developed an algorithm using Python 2.6 to communicate Bayesian Networks in GeNIe software with ArcGIS software in order to generate Risk maps. The algorithm extracts the spatial information contained in the GIS data of the case of study, which works as an input to proceed with Bayesian Reasoning while the output map is generated with the Risk values.

The tool named as *Bayesian Network and GIS* (BN+GIS) is capable to compute forward modelling (prognosis) and inverse modelling (diagnosis). The following Figures 16, 17, 18, and 19 describe the methodology process and case of study of [57], and illustrate the application of Bayesian Networks and GIS in prognosis and diagnosis Bayesian Reasoning.

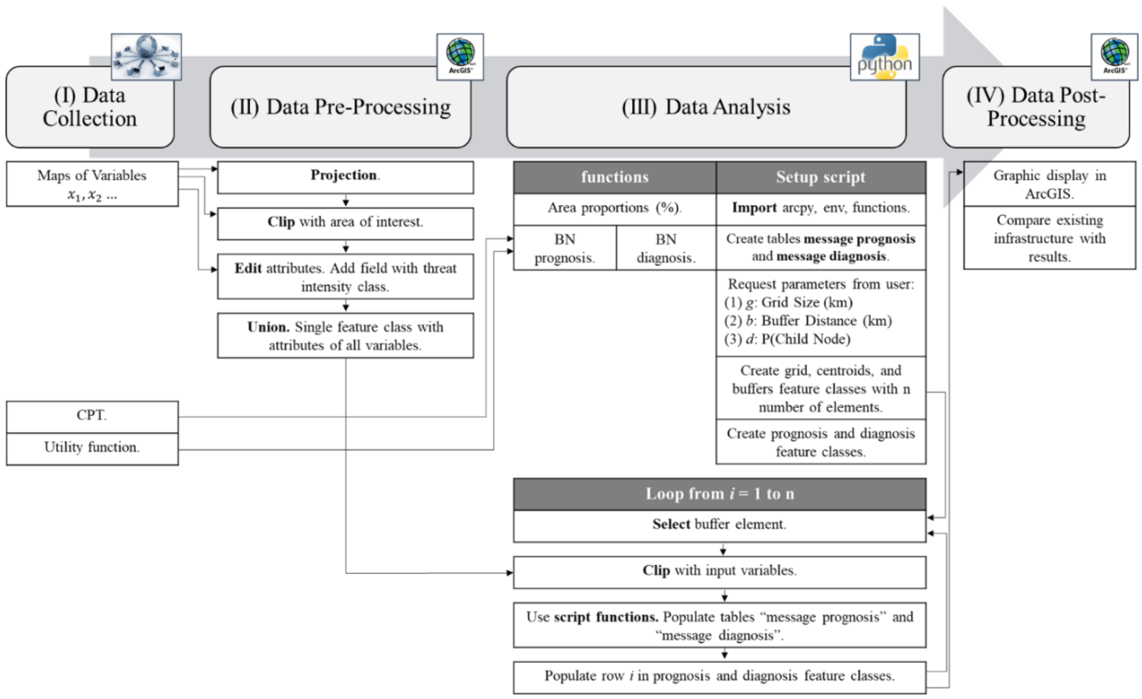

Figure 16 BN+GIS Tool Data Processing Sequence Reprinted From [57].

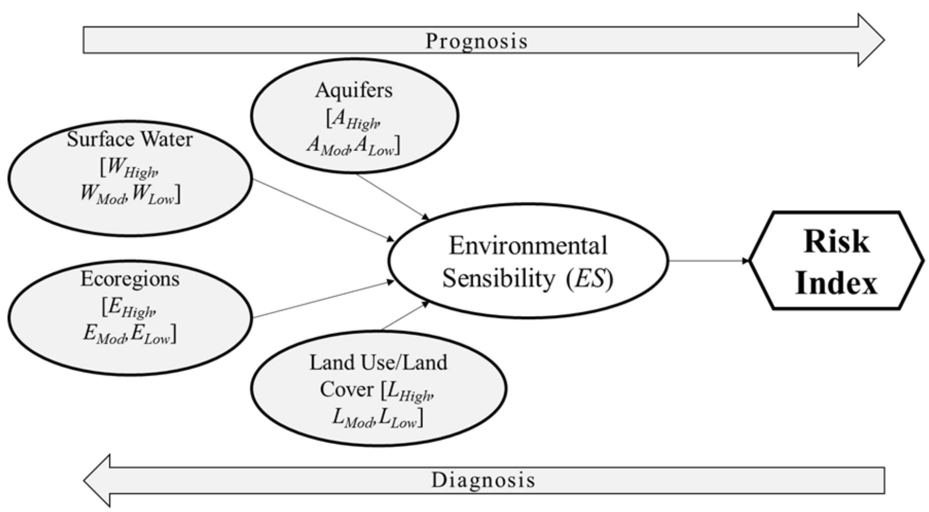

Figure 17 Bayesian Network Case Of Study Reprinted From [57].

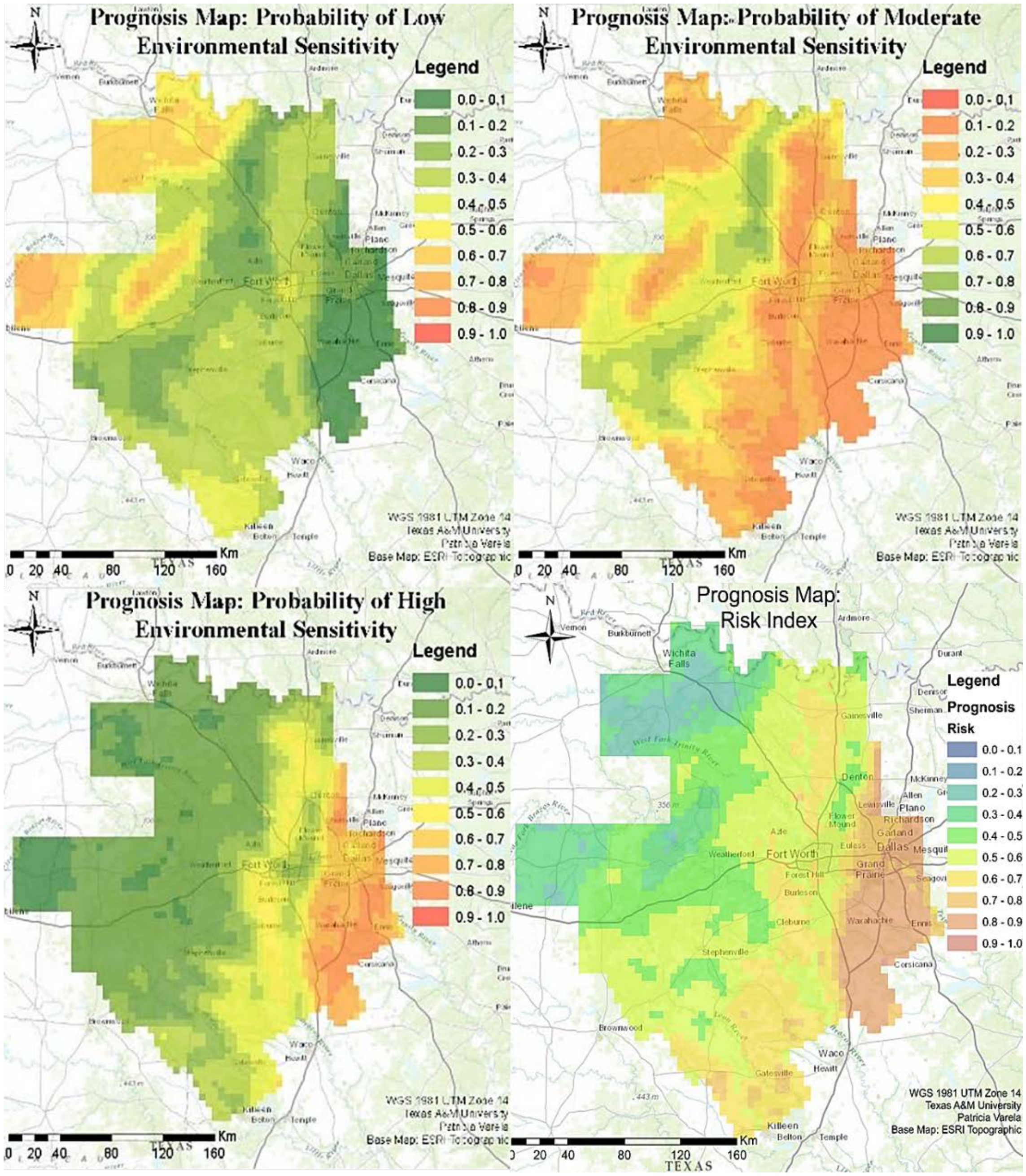

Figure 18 Prognosis Analysis Output Maps Reprinted From [57].

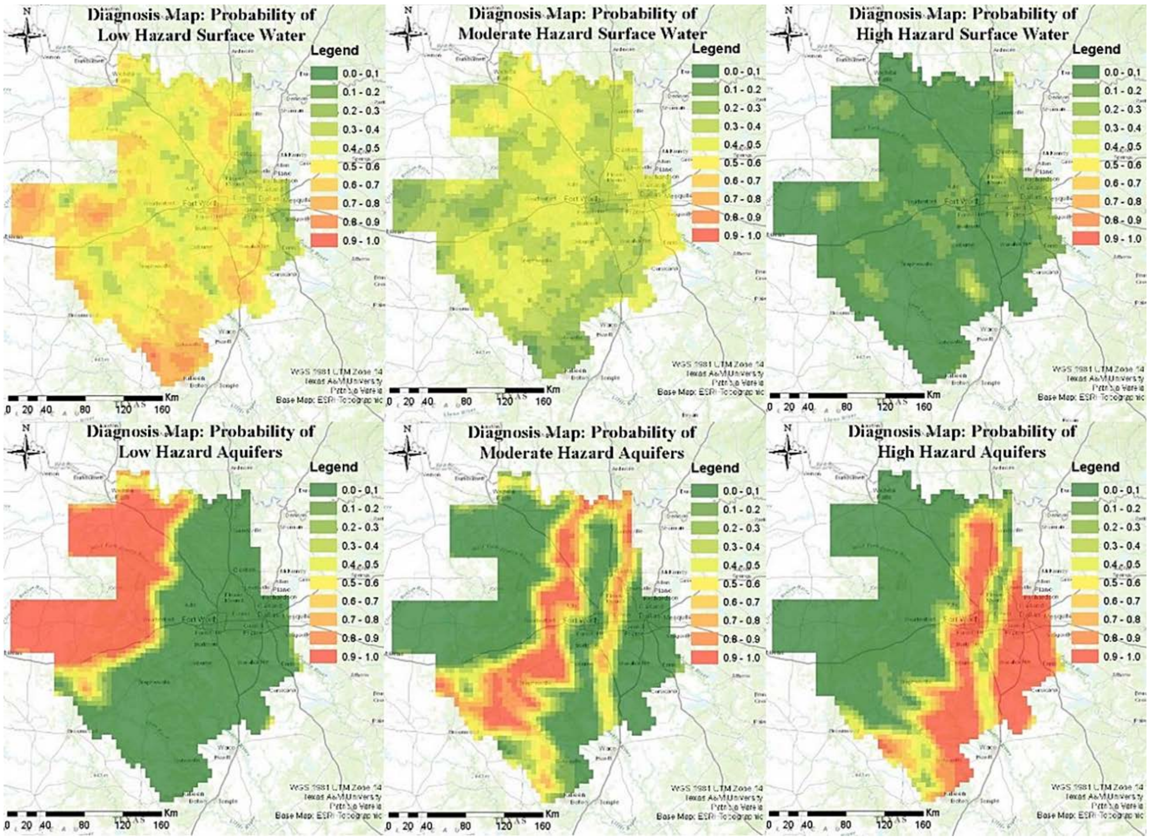

Figure 19 Diagnosis Analysis Output Maps Reprinted From [57]. The Probabilities Of Surface Water And Aquifers Control Variables Were Updated In Three States: Low, Moderate, And High For The Diagnosis Assessment.

The BN+GIS tool has potential to map the state of Risk by incorporating the Bayesian Network model presented in Chapter III, for offshore/deepwater environments. Once the Risk maps are produced, Cost Distance and Cost Path ArcGIS geoprocessing tools can be adopted to compute the Lowest-Risk Path. Optimization algorithms such as Genetic Algorithms or Simulated Annealing can also be employed to determine the optimum path or paths.

Risk Assessment of Offshore Pipelines by Segments

The Probabilistic Risk-based methodology described in Chapter II, and represented in Bayesian Networks in Chapter III has also the potential to conduct Risk Assessment for existing offshore pipelines. The pipeline can be analyzed as a whole, or by segments of the pipeline. Figure 20 illustrates how Risk Assessment is conducted by dividing a pipeline into five segment areas with 10 km x 10 km size [15].

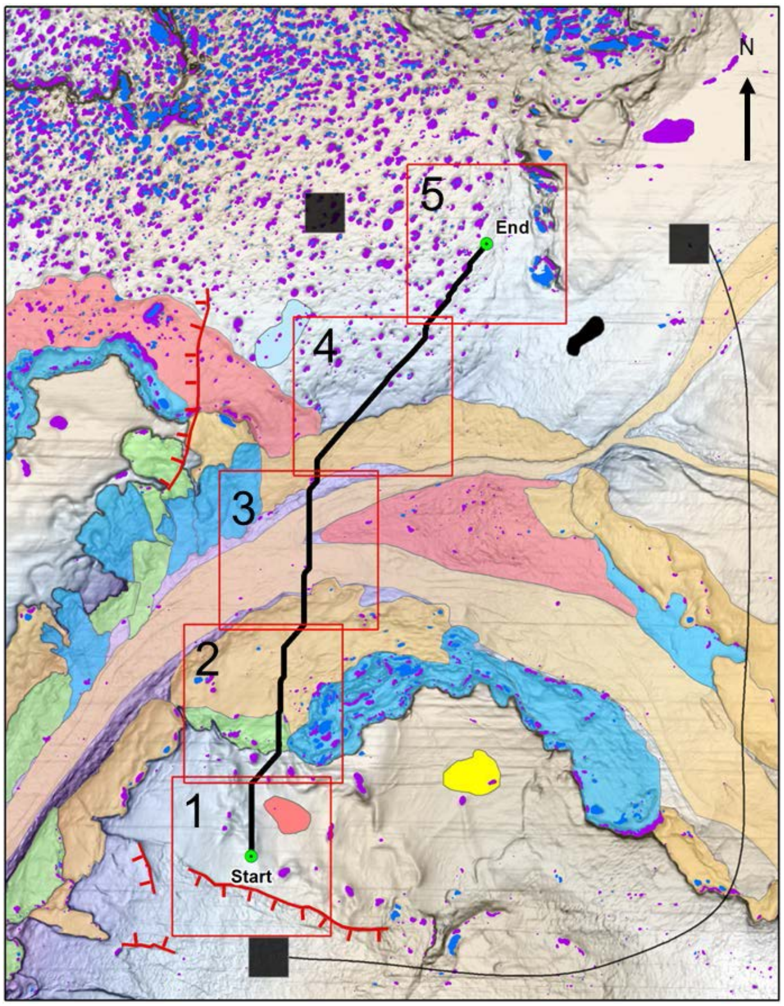

Figure 20 Risk Assessment Areas Along Pipeline Reprinted From [15].

Reliability and Risk Assessment

Fenton & Griffiths [61] describe two definitions of Risk:

- The probability of failure or Reliability.
- The product of the probability of failure and its respective cost or consequence value.

Probability of failure associated with design criteria (Reliability of design) is computed by different approaches such as analytical formulations, approximate analytical methods (First Order Second Moment), or simulation methods (Markov Chain Monte Carlo) [61]. Cost of failure is difficult to quantify according to [61], and most practitioners consider only the probability of failure (Reliability).

The Risk framework adopted for this research is defined as Risk = Hazard x Vulnerability x Consequences [44], where Hazard is the probability of occurrence of the threat, Vulnerability is the conditional probability of the consequence given the threat, and the Consequences are the value of the consequences in terms of economic, environmental, social losses.

It is important to contrast that the Risk framework from [44] might be associated with design criteria, but can also be associated with different criteria such as the case of spatial constraints (e.g. crossing prohibited areas), or expert’s beliefs where no physically-based models exist. Furthermore, the value of the consequences is an important asset to measure the state of Risk, and should be taken under consideration.

CHAPTER II

METHODOLOGY

Develop a Bayesian Network (BN) conceptual model to represent Medina-Cetina and Nadim [44] Risk Assessment framework for decision-making with application to offshore pipeline routing.

Bayesian Networks

Bayesian Networks are graphical representations of causal dependencies between variables (discrete or continuous) of a process, where nodes represent random variables, and arcs represent direct connections between variables [45]. Figure 21 illustrates the elemental structure of a BN, where “E” is the evidence, “H” the hypothesis, and P( ) is probability.

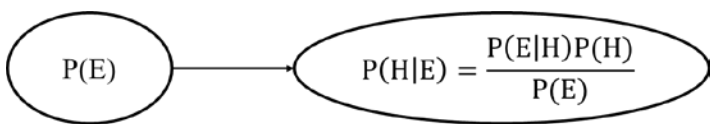

Figure 21 Bayesian Network Elemental Structure Reprinted From [45].

Korb & Nicholson [45] recommend the following steps (Figure 22) to construct a BN model:

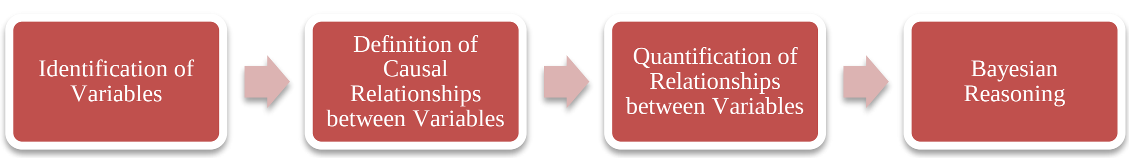

Figure 22 Building A Bayesian Network Adapted From [45].

The focus of this research is to identify the control variables of the decision-making process, and define their causal relationships.

Definition of Risk

Medina-Cetina and Nadim [44] defines Risk as:

$$Risk = Hazard \cdot Vulnerability \cdot Consequences \ (2)$$

$$R = P(T) \cdot P(C|T) \cdot u(C) \quad (3)$$

Where:

R = Risk.

P(T) = probability of occurrence of the threat or threats (hazards).

P(C|T) = probability of the consequences given the threats (vulnerability).

u(C) = value of the consequences (environmental, economic, life losses, etc.).

Bayesian Network Representation of Risk Framework

The following Figure 23 describes the most basic representation of Medina-Cetina and Nadim [44] Risk framework. "T" represents the threat, "C" the consequences, and "R" the state of Risk.

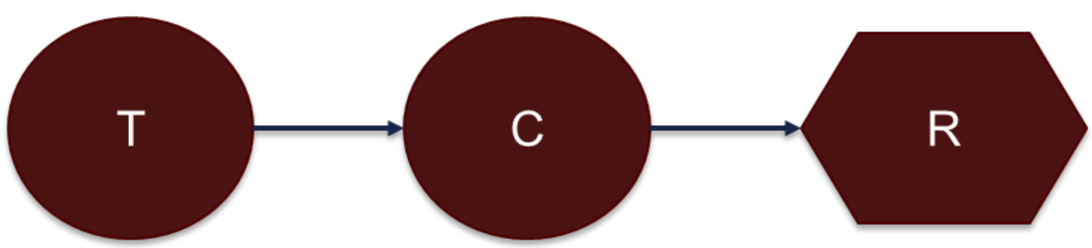

Figure 23 Bayesian Network Representation Of Risk Framework Adapted From [44].

Identification of Control Variables for Bayesian Network Modeling

The variables for BN modeling are based on Load and Resistance Factor Design (LRFD) format, mitigation criteria for construction restrictions, and pressure loss calculations for fluid flow assurance. The LRFD method evaluates design load effects L_{Sd} over design resistance R_{Rd} for the considered failure mechanisms (limit states) in different load scenarios i [46]:

$$f\left(\left(\frac{L_{Sd}}{R_{Rd}}\right)_i\right) \leq 1 \quad (4)$$

A load effect is defined as *"the resulting cross-sectional loads arising as response to applied loads"* [46]. The design resistance is equal to the characteristic resistance over resistance factors [46]. The limit states considered in this investigation are Ultimate Limit State (ULS) and Serviceability Limit State (SLS).

The proposed Integrated Risk-Based Assessment is illustrated in Figure 24.

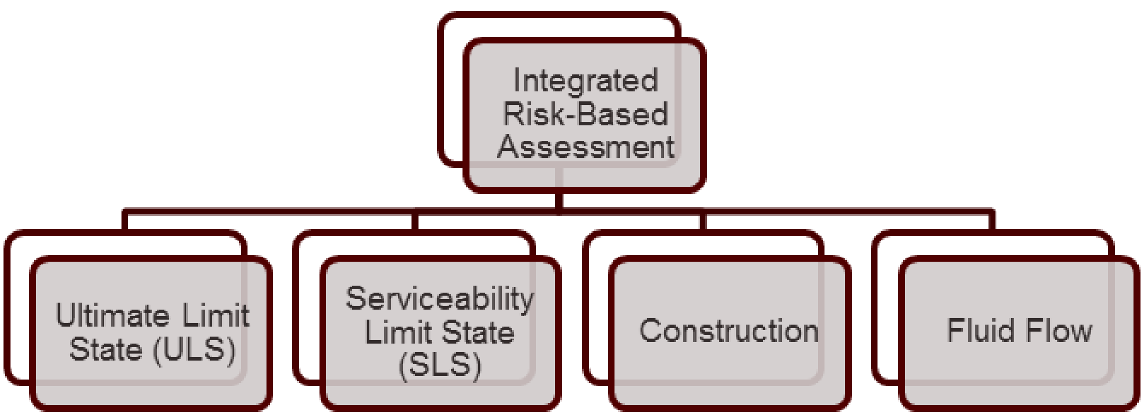

Figure 24 Proposed Methodology.

Figure 25 lists all the limit states considered in this study, plus the construction constraints that typically an offshore pipeline project may confront, lateral global buckling, free span, and pressure drop calculations [48] for fluid flow assurance:

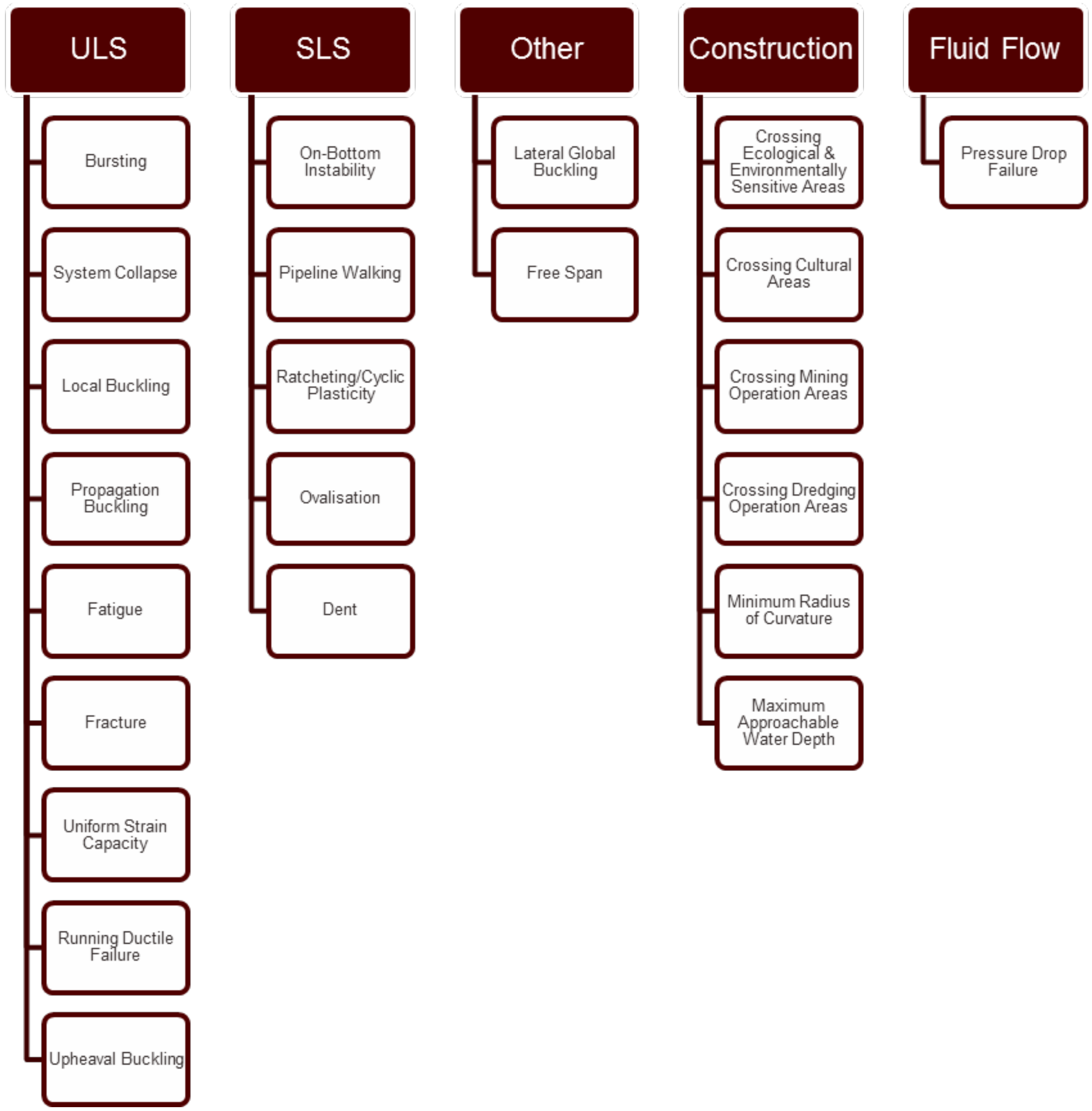

Figure 25 Limit States Adapted From [46, 47], Construction Criteria Adapted From [15] And Fluid Flow Criteria Adapted From [48].

Ultimate Limit States

An Ultimate Limit State (ULS) is a design condition that when exceed, the structural integrity of the pipeline will be affected [46]. In this section, each ULS listed on Figure 25 are discussed.

Bursting

Bursting failure occurs when tearing of the pipeline is not controlled, and consequently the pipeline fails by rupture [49]. The limit state equations proposed by DNVGL-ST-F101 [46] code are:

$$p_{li} - p_e \leq Min\left(\frac{p_b(t_1)}{\gamma_m \cdot \gamma_{SC,PC}};\ \frac{p_{lt}}{\alpha_{spt}} - p_e;\ \frac{p_{mpt} \cdot \alpha_U}{\alpha_{mpt}}\right) \quad (5)$$

$$p_{lt} - p_e \leq Min\left(\frac{p_b(t_1)}{\gamma_m \cdot \gamma_{SC,PC}};\ p_{mpt}\right) \quad (6)$$

Where:

p_{li} - local incidental pressure.

p_{lt} - local system test pressure.

p_b - pressure containment resistance.

p_{mpt} - Mill pressure test.

p_e - external hydrostatic pressure.

t_1 - nominal wall thickness of pipe.

α_{mpt} - Mill pressure test factor.

α_{spt} - system pressure test factor.

α_U - material strength factor.

γ_m - material resistance factor.

γ_{SC} - safety class resistance factor.

System Collapse

System Collapse failure occurs in the weakest point of the pipeline due to external over pressure [46]. Ovalisation of the pipeline during installation, construction or third-party impact should be considered [46]. The limit state equation proposed by DNVGL-ST-F101 [46] code is:

$$p_e - p_{min} \leq \frac{p_c(t_1)}{\gamma_m \cdot \gamma_{SC,LB}} \quad (7)$$

Where:

p_e - external hydrostatic pressure.

p_{min} - minimum internal pressure.

p_c - resistance for external pressure.

γ_m - material resistance factor.

γ_{SC} - safety class resistance factor.

Local Buckling

Local Buckling may occur in pipe members that are subjected to bending moment, effective axial force, and internal or external over pressure. The failure mode can be a yielding of the cross section or a buckling on the compressive side of the pipe [49]. All relevant loads described in DNVGL-ST-F101 [46] such as Functional, Environmental, Interference, and Accidental should be considered in following equations 8 and 9.

Bending moment + effective axial force + internal over pressure:

$$\left[\gamma_m \cdot \gamma_{SC,LB} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t_2)} + \left(\gamma_m \cdot \gamma_{SC,LB} \cdot \frac{S_{Sd}(p_d)}{\alpha_c \cdot S_p(t_2)}\right)^2\right]^2 + \left[\gamma_p \cdot \frac{p_d - p_e}{\alpha_c \cdot p_b(t_2)}\right]^2 \leq 1 \quad (8)$$

Bending moment + effective axial force + external over pressure:

$$\left[\gamma_m \cdot \gamma_{SC,LB} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t_2)} + \left(\gamma_m \cdot \gamma_{SC,LB} \cdot \frac{S_{Sd}(p_d)}{\alpha_c \cdot S_p(t_2)}\right)^2\right]^2 + \left[\gamma_m \cdot \gamma_{SC,LB} \cdot \frac{p_e - p_{min}}{p_c(t_2)}\right]^2 \leq 1 \quad (9)$$

Where:

p_d - design internal pressure.

p_e - external hydrostatic pressure.

p_b - pressure containment resistance.

p_{min} - minimum internal pressure.

p_c - resistance for external pressure.

γ_m - material resistance factor.

γ_{SC} - safety class resistance factor.

α_c - flow stress parameter.

S_{Sd} - design effective axial force load effect.

S_p - effective axial force load plastic capacity.

M_{Sd} - design moment load effect.

M_p - moment load plastic capacity.

It is important to point that this limit state takes into consideration the earthquake dynamic load effects (current & wave loads) that shall be classified as environmental or accidental loads, depending on the probability of occurrence. An accidental load is a load effect to the pipeline with a probability of occurrence less than 10^{-2} within a year [46].

Propagation Buckling

Buckling propagation may initiate when a Local Buckling has occurred. Buckle arrestors need to be installed if the following limit state (equation 10) is not fulfilled [46].

$$p_e - p_{min} \leq \frac{p_{pr}(t_2)}{\gamma_m \cdot \gamma_{SC,LB}} \quad (10)$$

Where:

p_e - external hydrostatic pressure.

p_{min} - minimum internal pressure.

p_{pr} - propagation pressure.

γ_m - material resistance factor.

γ_{SC} - safety class resistance factor.

Fatigue

Fatigue effects on pipelines due to stress fluctuations (cyclic loading) that can initiate cracks in girth welds are the main concern for pipeline engineers. Two analyses are described in DNVGL-ST-F101 [46]:

- Fatigue tests (S-N curves).
- Methods based on fracture mechanics.

S-N curves or stress range (S) versus number of cycles to failure (N) strongly depends on the girth weld classification proposed by DNVGL-ST-F101 [46]. The characteristic resistance to fatigue effects can be found using S-N curves. An example of S-N curves is illustrated in Figure 26.

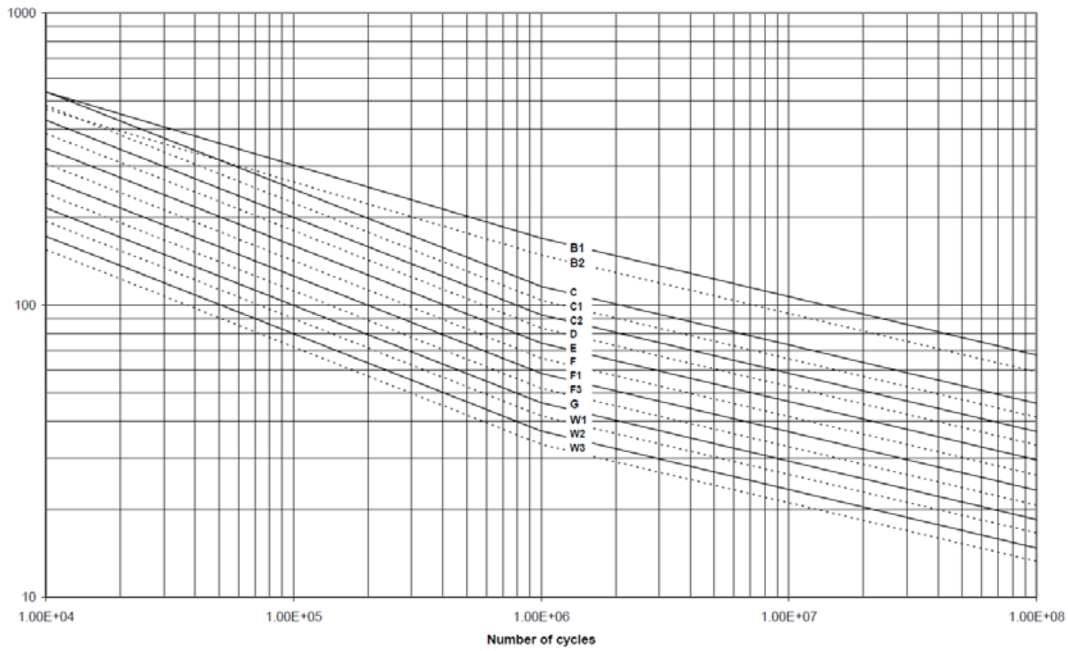

Figure 26 S-N Curves In Seawater With Cathodic Protection Reprinted From [50].

If the pipeline is loaded below the stress range limit (Figure 26), it is considered safe, and it will not fail.

Fracture

Fracture assessment through fracture mechanics analysis consist on determining the limit crack size in which the crack is stable [50]. In this research, a Tensile Stain Capacity (TSC) model [51] was adopted instead, for longitudinal strain capacity assessment of pipelines. Exceedance of the strain capacity triggers to ductile fracture failure of a girth weld defect [51].

The equations proposed by Fairchild et al. [51] are the following:

$$\varepsilon_c = 0.53 \cdot PF \cdot \frac{\left[\phi\left(N, \kappa, \lambda, \frac{e}{t}\right)\frac{\delta}{t} + \beta_7\right]\left(\beta_1 \frac{D}{t} + \beta_2\right)}{\beta_6 + \beta_8\left(\frac{\frac{a}{t}}{1 - \frac{a}{t}}\right)^{\beta_3} \tanh\left(\beta_4\left(\frac{2C}{t}\right)^{\beta_5}\right)} \quad (11)$$

$$\varepsilon_c = \begin{cases} \varepsilon_c & if\ \varepsilon_c < 2/3UEL \\ 2/3UEL & if\ \varepsilon_c \geq 2/3UEL \end{cases} \quad (12)$$

Where:

ε_c - longitudinal/tensile strain capacity.

e - high-low misalignment.

a - imperfection height.

2C - imperfection length.

δ - weld metal toughness.

λ - weld strength overmatch.

t - nominal wall thickness of pipe.

D - nominal outsider diameter.

PF - pressure factor.

N - strain hardening coefficient.

κ - relative strength coefficient.

β_i - fitting coefficients.

Uniform Strain Capacity

The maximum longitudinal strain due to buckling is limited to the Uniform Strain Capacity of the material (Ultimate Tensile Strength). According to DNVGL-RP-F110 [47], the following criteria should be fulfilled:

$$\varepsilon_{eq} \leq \frac{\varepsilon_{US}}{\gamma_{US}} \quad (13)$$

Where:

ε_{eq} - equivalent strain.

ε_{US} - equivalent strain capacity.

γ_{US} - uniform strain safety factor.

Running Ductile Failure

Pipelines with multiphase flow are designed to resist Running Ductile fractures due to presence of CO_2 in the liquid dense phase [46]. When CO_2 changes from liquid to gas, the decompression behavior is different in comparison with natural gas, and this behavior can trigger a Running Ductile Failure [46]. In order to mitigate this issue, Charpy V-Notch test is conducted to measure the material toughness, and it should meet the values described in the following Table 4.

Table 4 Charpy V-Notch Impact Test Requirements For Fracture Arrest Properties (Joules) Reprinted From [46].

Wall thickness	≤30 mm [3)]		
	D (mm)		
SMYS	≤610	≤820	≤1120
245	40	40	40
290	40	43	52
360	50	61	75
415	64	77	95
450	73	89	109
485	82	100	124
555[4)]	103	126	155

Upheaval Buckling

Upheaval Buckling may occur due to axial loading and cover soil failure in buried pipelines. Unacceptable local plastic deformations or collapse of the pipeline will occur if the limit state criteria is not fulfilled. Axial loading limit state [47] is defined by equation 14:

$$|\varepsilon_{Sd}| \leq \left|\frac{\varepsilon_{ca}}{\gamma_{ax}}\right| \quad (14)$$

Where:

ε_{Sd} - design strain.

ε_{ca} - characteristic axial strain capacity.

γ_{ax} - uniform strain safety factor.

Global and local cover soil failure may occur if soil resistance is surpassed by uplift forces. Global and local soil limit states [53] are defined in equations 15 and 16:

$$F_{uplift,local,u} = N_c \cdot \overline{s_u} \cdot D - \gamma' \cdot A_p \quad (15)$$

$$F_{uplift,global,u} = \gamma' \cdot H \cdot D + \gamma' \cdot D^2 \left(\frac{1}{2} - \frac{\pi}{8}\right) + 2 \cdot \bar{s_u} \cdot \left(H + \frac{D}{2}\right) \quad (16)$$

Where:

$F_{uplift,local,u}$ - uplift resistance in undrained conditions (local failure mode).

$F_{uplift,global,u}$ - uplift resistance in undrained conditions (global failure mode).

γ' - submerged unit weight.

H - cover height.

D - nominal outsider diameter.

A_p – cross-sectional area of the pipe.

N_c - bearing capacity factor.

$\bar{s_u}$ - average undrained shear strength.

Serviceability Limit States

A Serviceability Limit State (SLS) is a design condition that when exceed, the pipeline normal operation will be compromised [46]. In this section, each SLS listed on Figure 25 will be discussed.

On-Bottom Stability

On-Bottom Stability limit state takes into account the vertical and lateral stability of pipelines due to hydrodynamic loads. The vertical stability limit state [54] is expressed in equation (17).

$$\gamma_W \cdot \frac{b}{w_s + b} = \frac{\gamma_W}{S_g} \leq 1 \quad (17)$$

Where:

γ_W – factor of safety.

b - pipe buoyancy per unit length.

w_s - pipe submerged weight per unit length.

Floatation and sinking shall be considered for pipelines that are intended to be buried [54]. Pipe specific density should be larger than cover soil specific density and liquefied cover soil specific density if liquefaction of the soil is probable, to avoid floatation. Sinking will not occur if the pipe specific density is less than soil specific density, and liquefied soil specific density [55].

Two design methods were included for lateral stability:

- Generalized Lateral Stability, which is based on Dynamic Lateral Stability Analysis [54].
- Absolute Lateral Static Stability (Quasi-Static Analysis) [54].

Generalized Lateral Stability allows lateral displacement from less than half a pipe diameter (virtually stable pipe) to 10 diameters. The following condition needs to be fulfilled for stability:

$$L > L_{stable} \;\&\; L_{10} \quad (18)$$

Where:

L - significant weight parameter.

L_{stable} - weight required for virtually stable pipe.

L_{10} - weight required for obtaining a 10 pipe diameter displacement.

L_{stable} and L_{10} are obtained from empirical expressions and design curves. Full description of the calculations of these parameters can be found in [54]. The significant weight parameter can be computed using equation 19:

$$L = \frac{w_s}{0.5 \cdot \rho_w \cdot D \cdot U_s^2} \quad (19)$$

Where:

w_s - pipe submerged weight per unit length.

ρ_w - mass density of water.

D - pipe outer diameter including all coating.

U_s - significant wave velocity.

Note: L_{stable}, L_{10}, and L need to take into account the earthquake induced current and wave velocities in their parameter calculations.

Absolute Lateral Static Stability does not allow lateral displacement. The criteria consists in vertical and horizontal load combinations as expressed in equation 20 and 21:

$$\gamma_{SC} \cdot \frac{F_Y^* + \mu \cdot F_Z^*}{\mu \cdot w_s + F_R} \leq 1.0 \ (20)$$

$$\gamma_{SC} \cdot \frac{F_Z^*}{w_s} \leq 1 \ \ (21)$$

Where:

γ_{SC} - safety class resistance factor.

F^*_Y - peak horizontal hydrodynamic (drag and inertia) load.

F^*_Z - peak vertical hydrodynamic (lift) load.

w_s - pipe submerged weight per unit length.

μ - coefficient of friction.

F_R - passive soil resistance.

Note: The hydrodynamic load calculations should consider the earthquake induced current and wave velocities in their parameters.

Pipeline Walking

Accumulated axial displacement or “Pipeline Walking” shall be considered in the design process. Steel catenary riser (SCR) tension, seabed slope, thermal transients, and liquid hold-up effect are the main sources of axial displacement. Details of Pipeline

Walking calculations can be found in [49]. Large accumulated axial displacements can potentially damage jumpers, spools, and fixed structures [47].

Ratcheting/Cyclic Plasticity

Ratcheting phenomenon is defined as the increment of plastic deformation due to cyclic loading in pipelines with high pressure and high temperature operations. Ratcheting or Cyclic Plasticity is avoided by restricting the axial stress range [47]:

$$\frac{\sigma_R}{f_y} \leq 2 \cdot \alpha_B \cdot \sqrt{1 - \frac{3}{4} \cdot \left(\frac{\sigma_h}{f_y}\right)^2} \quad (22)$$

Where:

σ_R - the maximum axial stress range.

f_y - yield stress.

α_B - Bauschinger factor.

σ_h - the maximum absolute value of hoop stress that could occur during operation.

Ovalisation

Pipeline Ovalisation (out-of-roundness) caused by trawl interference, dragged anchor interference, vessel collision and dropped object impact, point loads such as artificial supports, free span shoulders, and support settlement should not be more than 3% [46]:

$$O_0 = \frac{D_{max} - D_{min}}{D} \leq 0.03 \quad (23)$$

Where:

O_0 - ovality.

D_{max} - greatest measured inside or outside diameter.

D_{min} - smallest measured inside or outside diameter.

Dent

Dent damage generated by trawl gear impact, vessel collision impact, and dropped object impact shall fulfill the following criterion [46]:

$$\frac{H_p}{D} \leq 0.05\eta \quad (24)$$

Where:

H_p - permanent plastic dent depth.

η - usage factor.

D - nominal outsider diameter.

Other Criteria

Lateral Global Buckling

Lateral Global Buckling is not considered a limit state but a structural response governed by the compressive effective axial force in the pipeline [47]. The pipeline section response is similar to a column in pure compression. Lateral Global Buckling might be initiated by:

- Vertical imperfections (uneven seabed).
- Lateral imperfections in even seabed.
- Trawl interference.

DNVGL-RP-F110 [47] categorize Lateral Global Buckling susceptibility in:

- Buckling
- No buckling.
- Maybe buckling (for trawling).

Lateral Global Buckling in uneven seabed will not be initiated if:

$$S(p_{li}, T_{l,max}) \leq \frac{\pi^2 \cdot EI}{(L_{uplift}(S))^2} \quad (25)$$

Lateral Global Buckling in uneven seabed will be initiated if:

$$S(p_{li}, T_{l,max}) > \frac{4 \cdot \pi^2 \cdot EI}{(L_{uplift}(S))^2} \quad (26)$$

Where:

p_{li} - local incidental pressure.

$T_{l,max}$ - local maximum design temperature.

EI - bending stiffness of the pipe.

L_{uplift} - length of the pipeline lifted off at the free span crests depending on the effective axial force.

Lateral Global Buckling in even seabed (Dynamic Analysis) will not be initiated if:

$$|S(op)| < 0.65 \cdot |S_{\infty}(100\ year)| \quad (27)$$

$$|S(des)| < 0.65 \cdot |S_{\infty}(1\ year)| \quad (28)$$

Where:

S(op) - effective axial force based on operational pressure and temperature.

S(des) - effective axial force based on incidental pressure and design temperature.

S∞(100 year) - effective axial force for the infinite buckling mode corresponding to 100-year return period environmental condition.

S∞(1 year) - effective axial force for the infinite buckling mode corresponding to 1-year return period environmental condition.

Note: Calculations for the effective axial forces in the infinite buckling mode shall consider the earthquake induced current and wave velocities.

Lateral Global Buckling initiated by trawl interference will depend on trawl load and lateral pipe soil resistance load combinations [47]:

- No buckling - Global Buckling is not initiated by F^{UE}_{T}, f^{LE}_{L}.
- No buckling - Global Buckling is not initiated by F^{BE}_{T}, f^{LE}_{L} and F^{UE}_{T}, f^{BE}_{L}.
- Maybe buckling - Global Buckling is initiated by F^{BE}_{T}, f^{LE}_{L} and F^{UE}_{T}, f^{BE}_{L} and single check is required.

- Buckling - Global Buckling is initiated by F^{BE}_{T}, f^{LE}_{L} and F^{UE}_{T}, f^{BE}_{L} and check with full soil matrix is required.

Where:

F^{UE}_{T} - upper estimate of trawl pullover load.

F^{BE}_{T} - best estimate of trawl pullover load.

f^{LE}_{L} - the lower estimate lateral break-out pipe-soil resistance force.

f^{BE}_{L} - the best estimate lateral break-out pipe-soil resistance.

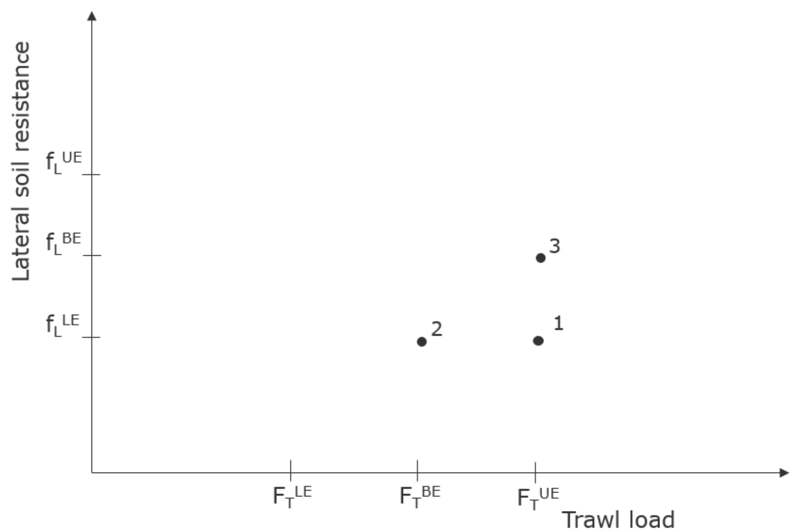

Figure 27 Soil-Trawl Matrix Reprinted From [47].

If buckling is not initiated, the following limit states need to be considered:

- Local Buckling.
- Fatigue.
- Fracture.
- Pipeline Walking

If buckling is initiated, the following limit states need to be considered:

- Local Buckling.
- Uniform Strain Capacity.
- Fatigue.
- Fracture.
- Pipeline Walking
- Ratcheting.
- Free span.

Free Span

DNVGL-RP-105 [52] free spanning for fatigue analysis induced by VIV and wave loads suggest two criteria:

- VIV avoidance (Dynamic Analysis).
- Screening fatigue (Dynamic Analysis).

The VIV avoidance criteria determines if VIV needs to be addressed in the ULS calculations [52]. If equations 29 are 30 are violated, then either Screening fatigue or Fatigue analysis [46] shall be checked.

$$f_{IL,1} > \frac{U_{extreme} \cdot \gamma_{f,IL}}{V_{R,onset}^{IL} \cdot D} \quad (29)$$

$$f_{CF,1} > \frac{U_{extreme} \cdot \gamma_{f,CF}}{2D} \quad (30)$$

Where:

$f_{IL,1}$ - natural frequency in in-line direction for a given free span.

$f_{CF,1}$ - natural frequency in cross-flow direction for a given free span.

$U_{extreme}$ - extreme flow condition.

$V^{IL}_{R,\ onset}$ - in-line onset value for the reduced velocity.

D - nominal outsider diameter.

$\gamma_{f,\ IL}$ - safety factor on in-line frequency.

$\gamma_{f,\ CF}$ - safety factor on cross-flow frequency.

The screening fatigue criteria considers a fatigue life of more than fifty years. Spans with a response dominated by the first symmetric mode are the only ones applicable for this analysis [52]. Equations 31 and 32 should be fulfilled to satisfy the screening fatigue criteria:

$$\frac{f_{IL,j}}{\gamma_{IL}} > \frac{U_{c,100-year}}{V^{IL}_{R,onset} \cdot D} \cdot \left(1 - \frac{L_{Free}/D}{250}\right) \cdot \frac{1}{\bar{\alpha}} \quad (31)$$

$$\frac{f_{CF,j}}{\gamma_{CF}} > \frac{U_{c,100-year} + U_{w,1-year}}{V^{CF}_{R,onset} \cdot D} \quad (32)$$

Where:

$f_{IL,j}$ - natural frequency in in-line direction for the j-th single span mode.

$f_{CF,j}$ - natural frequency in cross-flow direction for the j-th single span mode.

U_c - return period value for the perpendicular current component at pipe level.

U_w - return period value for the perpendicular component of the significant wave induced flow velocity at pipe level.

$V^{IL}_{R,\ onset}$ - in-line onset value for the reduced velocity.

$V^{CF}_{R,\ onset}$ - cross-flow onset value for the reduced velocity.

D - nominal outsider diameter.

L_{free} - free span length (apparent, visual) or mode shape length.

γ_{IL} - screening factor for in-line.

γ_{CF} - screening factor for cross-flow.

$\bar{\alpha}$ - current flow ratio.

Note: current and wave flow condition calculations for both VIV avoidance and Screening criteria should take into account the earthquake effects.

Seismic/Earthquake Design

Bai & Bai [49] reviewed many earthquake events and their effect on buried steel pipelines, and concluded that the impact of ground waves on long, straight pipelines is not significant. However, for unburied pipelines, special considerations are required for earthquake-induced ground waves and permanent ground deformation due to soil failures [49]. Criteria for the main soil failures is discussed as follows:

Surface faulting is *"the earth surface displacement associated with relative displacement of adjacent parts of the surface crust"* [49]. Bonilla [60] propose an equation to compute the maximum displacement at ground surface:

$$logL = -6.35 + 0.93 \cdot M_s \quad (33)$$

Where:

L - the maximum surface displacement in meters.

M_S - the earthquake surface wave magnitude.

Plastic range deformation due to tension of the pipeline can help to avoid rupture at fault crossing, but if compression of the pipeline is unavoidable, a compressive load effect shall be considered in the Local Buckling criteria as an accidental load [49].

Earthquake-induced landslide impact load and direction to pipelines needs to be taking into account in the calculation of the accidental loads if necessary. Landslides can induce Local Buckling, Fracture, Uniform Strain Capacity Failure, and Total Rupture of pipelines.

Soil liquefaction due to earthquake can cause sinking and floatation of the pipeline. Considerations for the pipe specific density vs liquefied soil specific density were described in the On-Bottom Stability section to avoid floatation and sinking.

In buried pipelines, longitudinal strain generated by earthquake-induced ground movements should be considered in the longitudinal strain calculations to prevent Fracture, Uniform Strain Capacity exceedance, and Upheaval Buckling failures.

Finally, earthquake-induced current and wave load effects and velocities shall be addressed in Local Buckling, Fatigue, Fracture, Uniform Strain Capacity, On-Bottom Stability, Lateral Global Buckling, and Free Span criteria.

Construction Criteria

Offshore pipeline projects often present spatial constraints such as Crossing Ecological and Environmentally Sensitive Areas, and Maximum Approachable Water Depth. These issues are mitigated by establishing a range of distances from where the pipeline is allowed to be installed.

Other construction project criteria such as the minimum radius of curvature to avoid pipelines to slide sideways due to residual tension and lateral friction force is required [37]:

$$R_{min} = \frac{T_{residual}}{\mu \cdot w_s} \quad (34)$$

Where:

R_{min} - minimum radius of curvature.

$T_{residual}$ - residual pipe tension from launching operation.

μ - coefficient of friction.

w_s - pipe submerged weight per unit length.

Fluid Flow Criteria

Fluid flow assurance calculations are based on the operating pressure versus pressure losses due to Wall Friction, Hydrostatic Pressure, and pipeline Fittings and Components. The Wall Friction and Hydrostatic pressure losses can be calculated using Beggs and Brill correlation [48], which is applicable for any flow situation such as uphill, downhill, horizontal, inclined, and vertical flow.

Pipeline Fittings and Components pressure losses are often provided by the manufacturer handbook or empirical curves. Depending on the size, type, and liquid flow, the pressure loss can be easily obtained.

CHAPTER III

BAYESIAN NETOWRK MODELING

In this Chapter, the Bayesian Network (BN) complete model and sub-models for offshore pipeline routing through Risk Assessment are introduced. The Chapter is subdivided in Ultimate Limit States, Serviceability Limit States, Other Criteria, Construction Criteria, and Fluid Flow Criteria in order to illustrate each Bayesian Network sub-model comprehended in the full detailed BN model.

The BN complete model, and sub-models for each limit state and criteria were constructed following the methodologies presented in Chapter II. The design loads, design resistances, constructions constraints, operation pressure, and pressure losses are represented as the threats (in green color), the pipeline failure mechanisms are the vulnerabilities of the system colored in red, and the value of the consequences are represented as the Risk (yellow).

Three qualitative states (low, moderate, and high) were assigned to the threats and vulnerabilities in this model. Other criteria such as Lateral Global Buckling and Screening Fatigue, both colored in blue, were assigned yes/no-qualitative states to represent their binary nature. E.g. if the pipeline does not fulfill the Lateral Global Buckling criteria, then relevant ULS shall be checked as described in Chapter II.

In some cases, threats depends on the effect of other threats such as the Vertical and Horizontal Hydrodynamic Loads. The Hydrodynamic Loads and their respective dependency threats were also assigned three states meaning that magnitude of the threats will directly influence the magnitude of the loads. Appendix A contains tables with full description of the cause-effect dependencies between variables.

The following sections present Bayesian Network representations of each ULS, SLS, and the criteria studied in this research, ending with the complete BN model with all variables and their dependencies. The models were constructed using GeNIe 2.2 Academic software.

Ultimate Limit State Bayesian Network Sub-Models

Bursting Bayesian Network

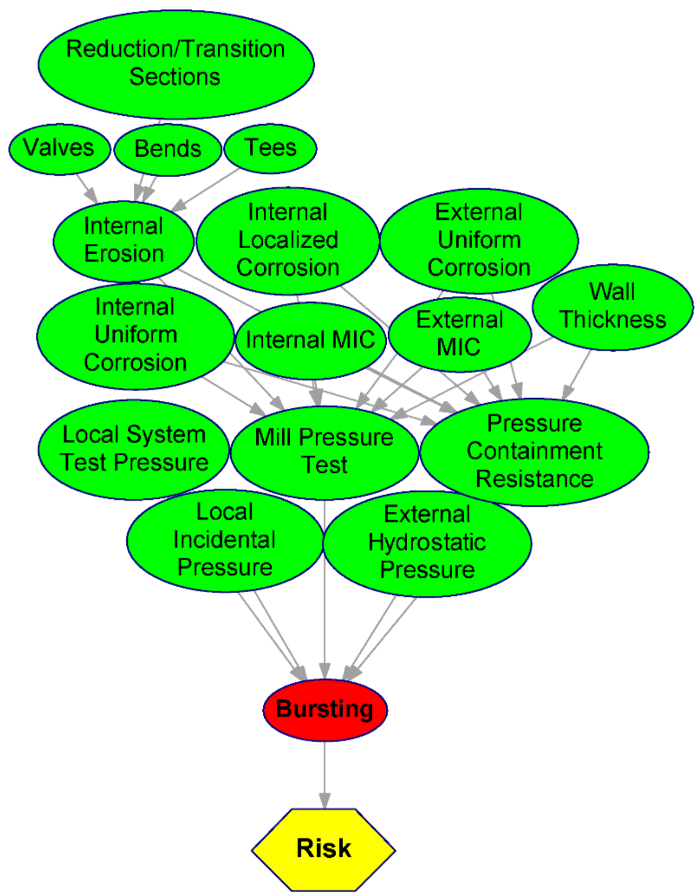

Figure 28 Bursting Bayesian Network Representation.

It is important to point that for building the Bursting BN model, the effects of internal and external corrosion to the wall thickness of the pipe were considered. Ayello et al. [56] developed a probabilistic quantitative assessment of internal and external corrosion for crude oil transportation pipelines using Bayesian Networks. Sources of internal corrosion such as uniform corrosion and internal erosion, and external corrosion sources like microbiologically induced corrosion (MIC) identified in [56], were adopted in this research.

System Collapse Bayesian Network

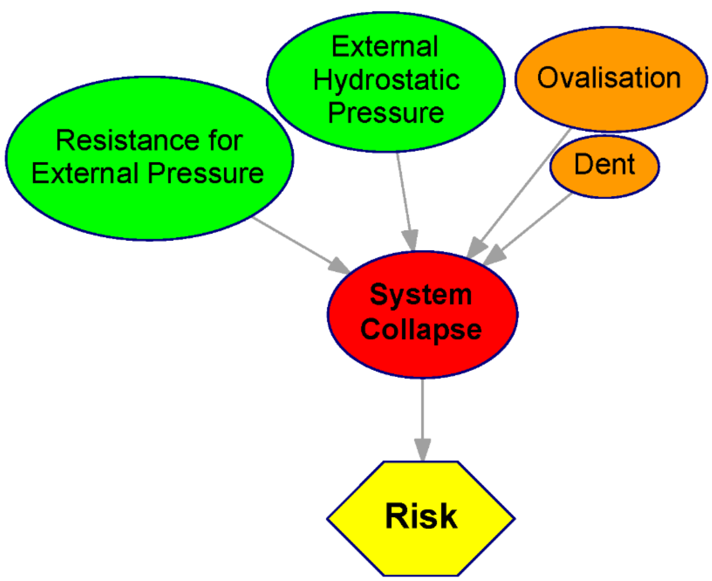

Figure 29 System Collapse Bayesian Network Representation.

Local Buckling and Propagation Buckling Bayesian Network

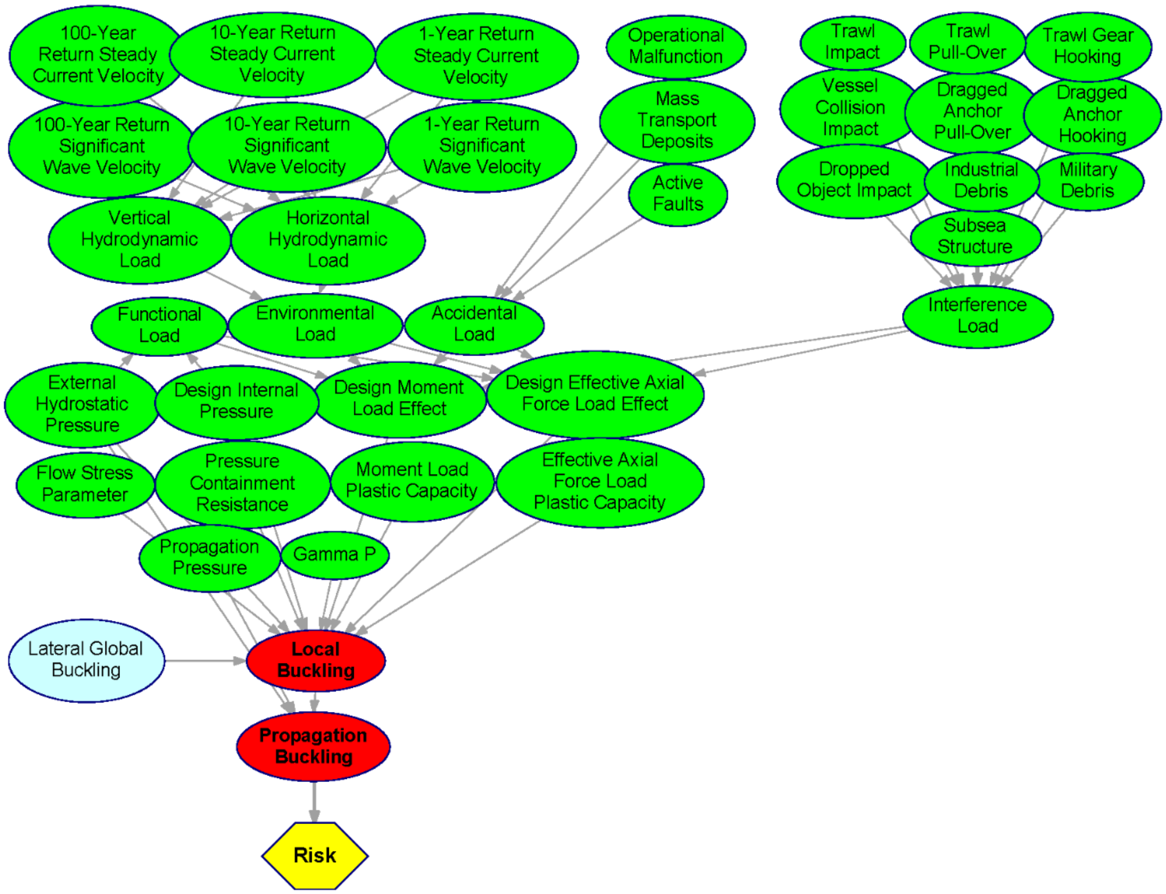

Figure 30 Local Buckling and Propagation Buckling Bayesian Network Representation.

Fatigue Bayesian Network

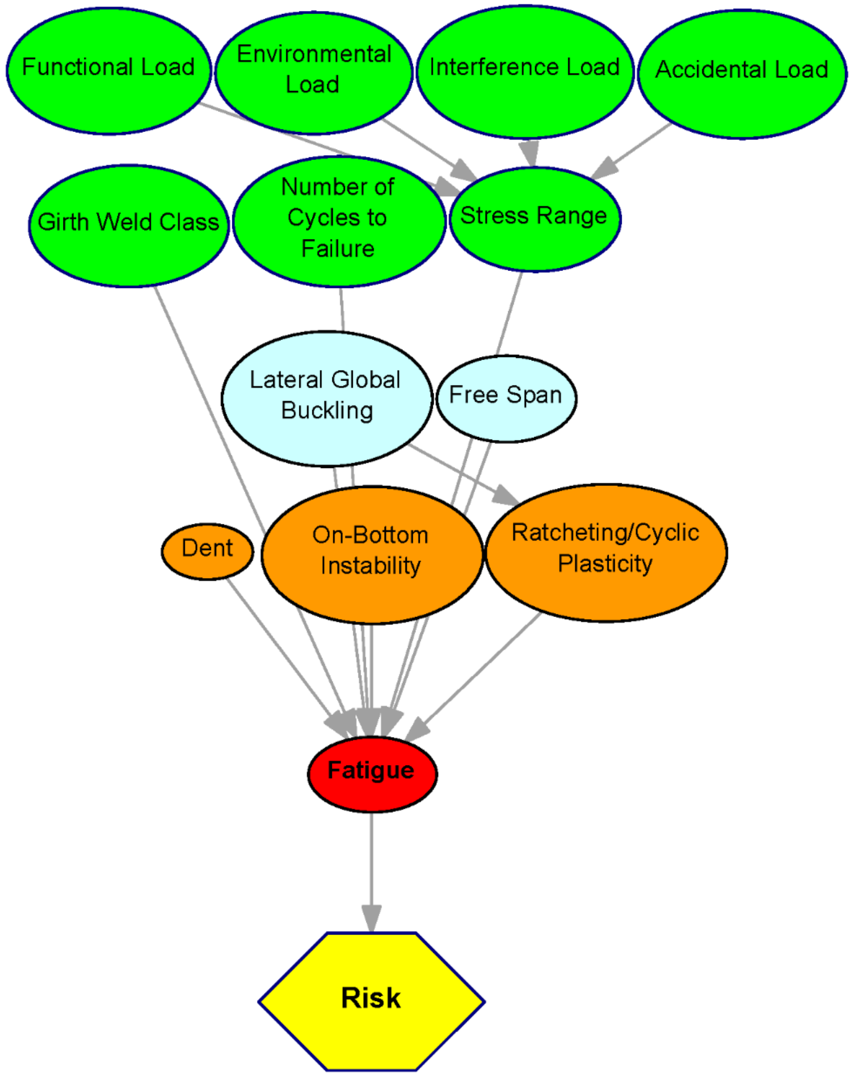

Figure 31 Fatigue Bayesian Network Representation.

Fracture Bayesian Network

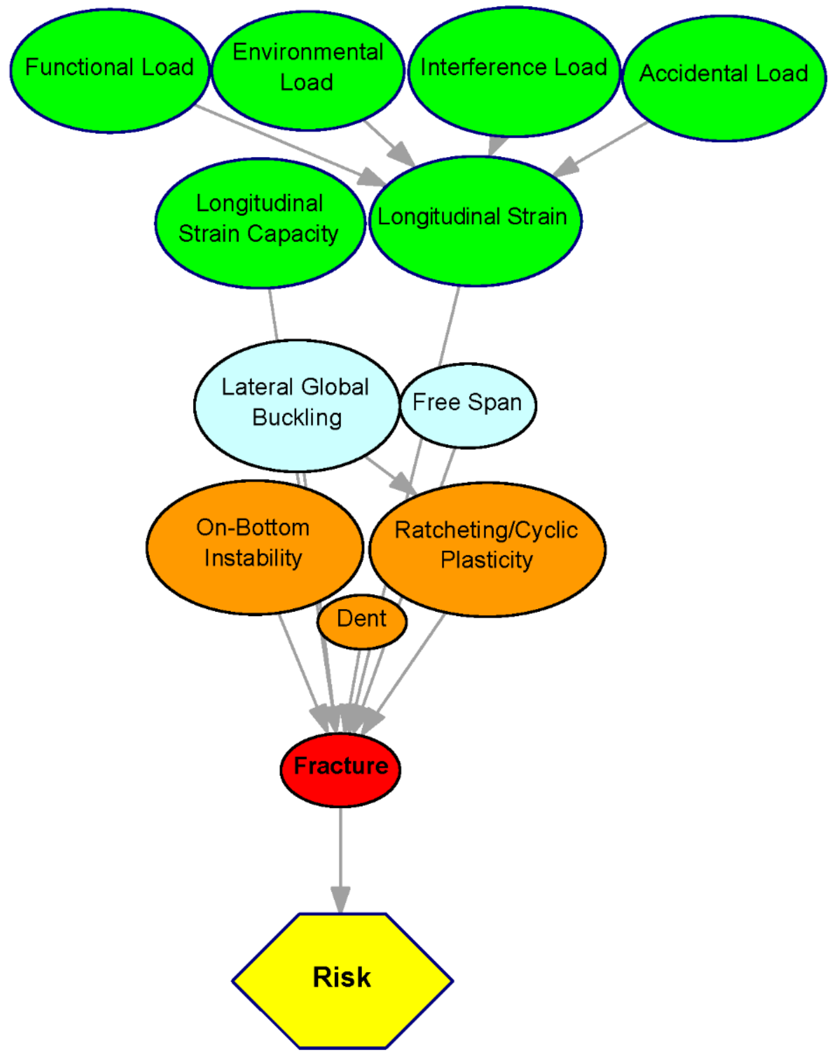

Figure 32 Fracture Bayesian Network Representation.

Uniform Strain Capacity Bayesian Network

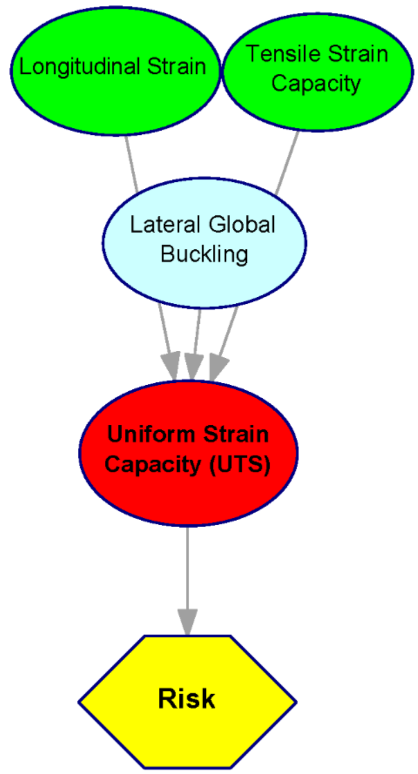

Figure 33 Uniform Strain Capacity Bayesian Network Representation.

Running Ductile Failure Bayesian Network

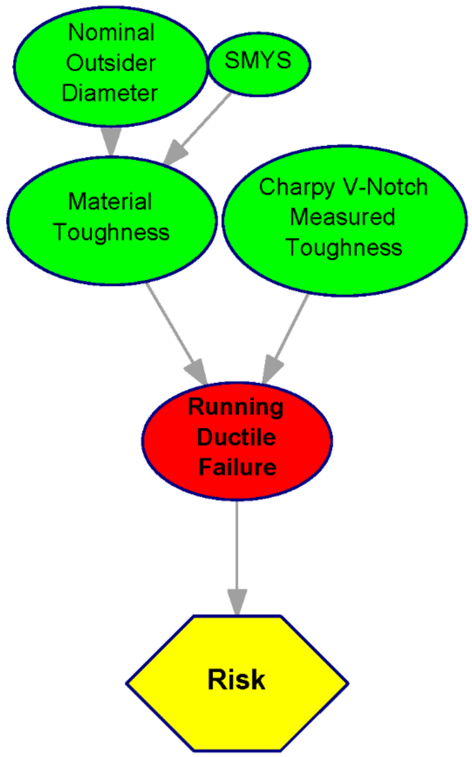

Figure 34 Running Ductile Failure Bayesian Network Representation.

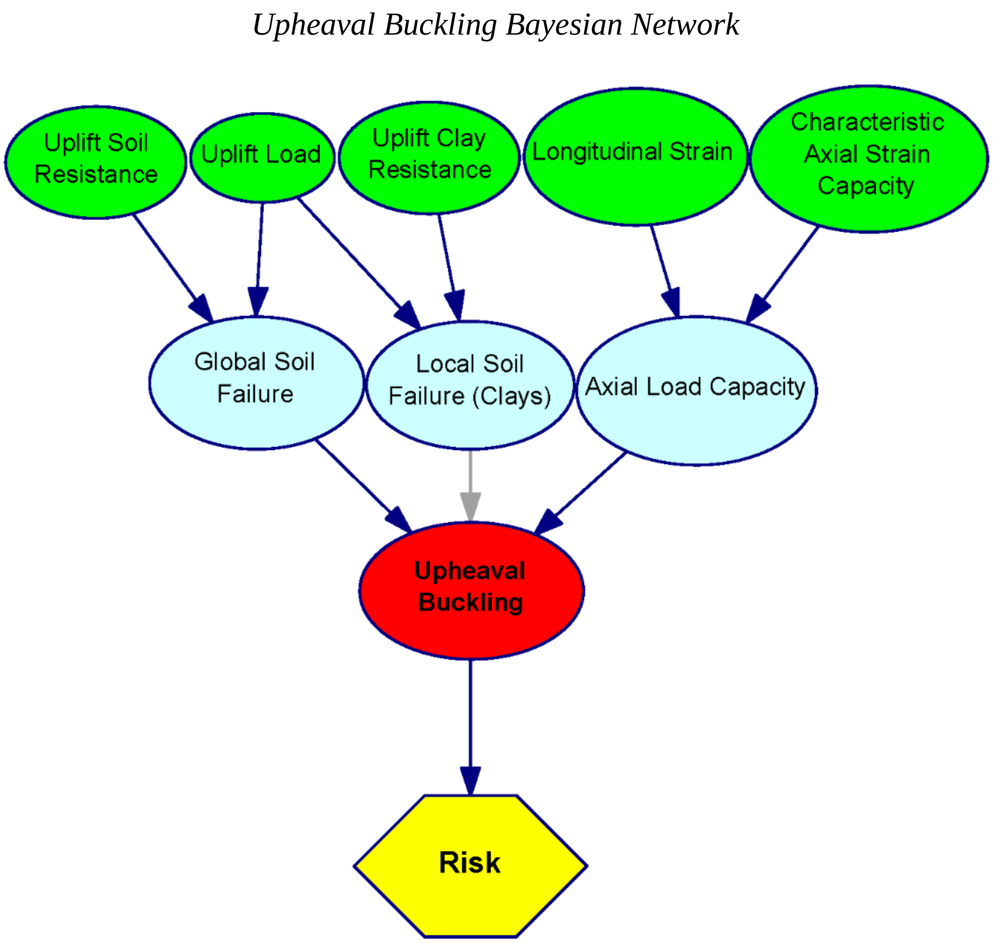

Figure 35 Upheaval Buckling Bayesian Network Representation.

Serviceability Limit State Bayesian Network Sub-Models

On-Bottom Instability Bayesian Network

Figure 36 On-Bottom Instability Bayesian Network Representation.

Pipeline Walking Bayesian Network

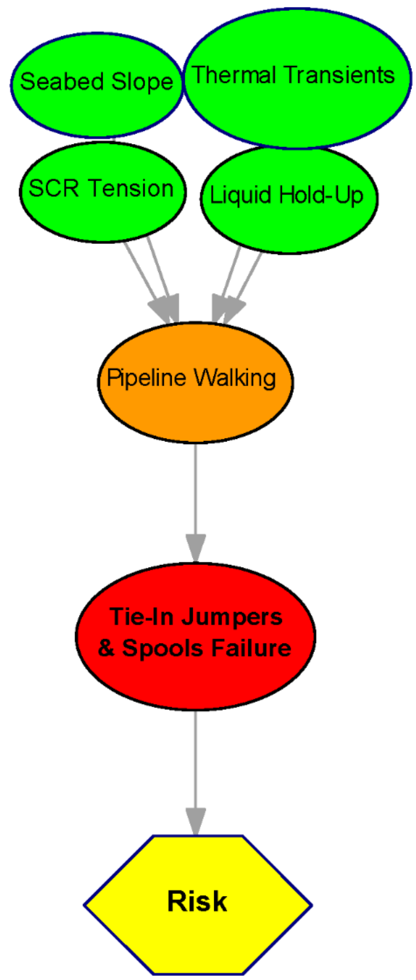

Figure 37 Pipeline Walking Bayesian Network Representation.

Ratcheting/Cyclic Plasticity Bayesian Network

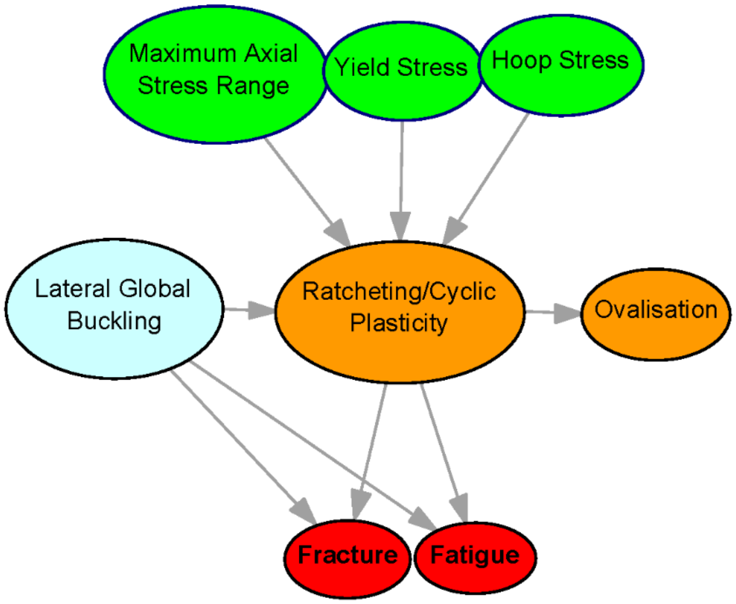

Figure 38 Ratcheting/Cyclic Plasticity Bayesian Network Representation.

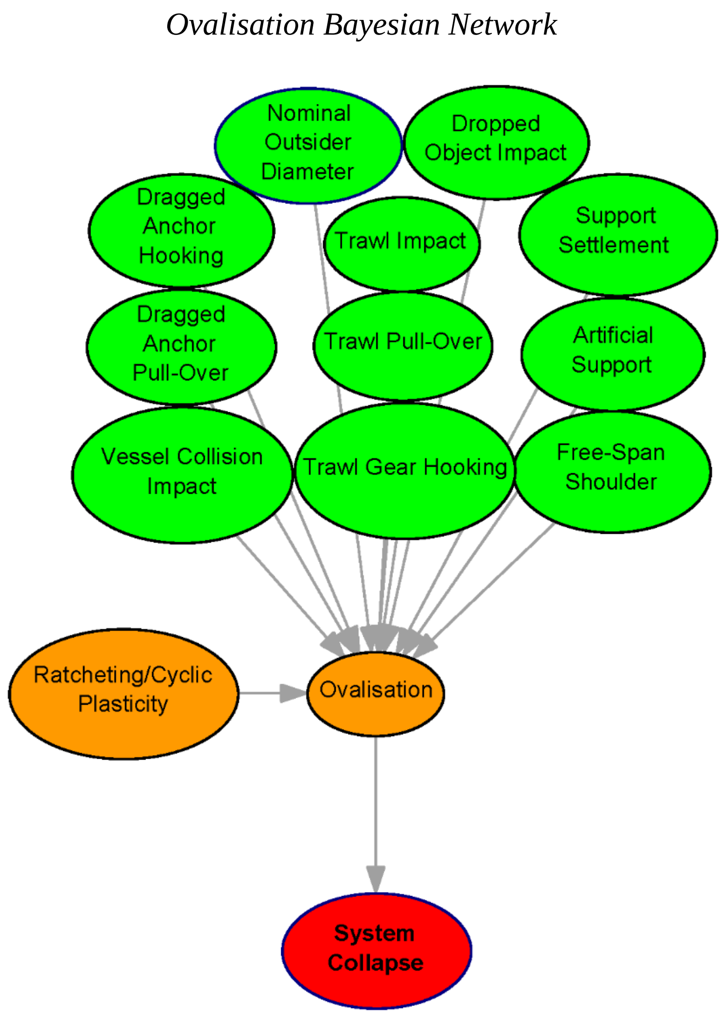

Figure 39 Ovalisation Bayesian Network Representation.

Dent Bayesian Network

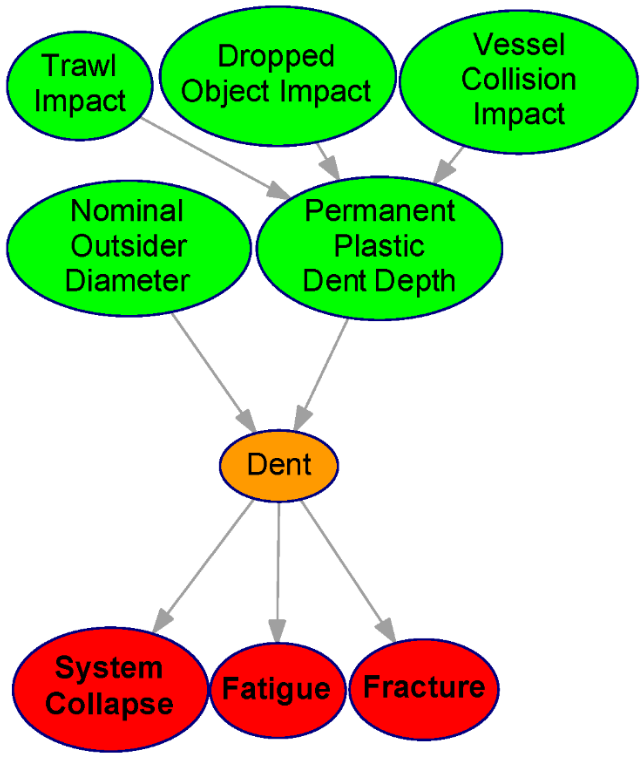

Figure 40 Dent Bayesian Network Representation.

Other Criteria Bayesian Network Sub-Models

Lateral Global Buckling Bayesian Network

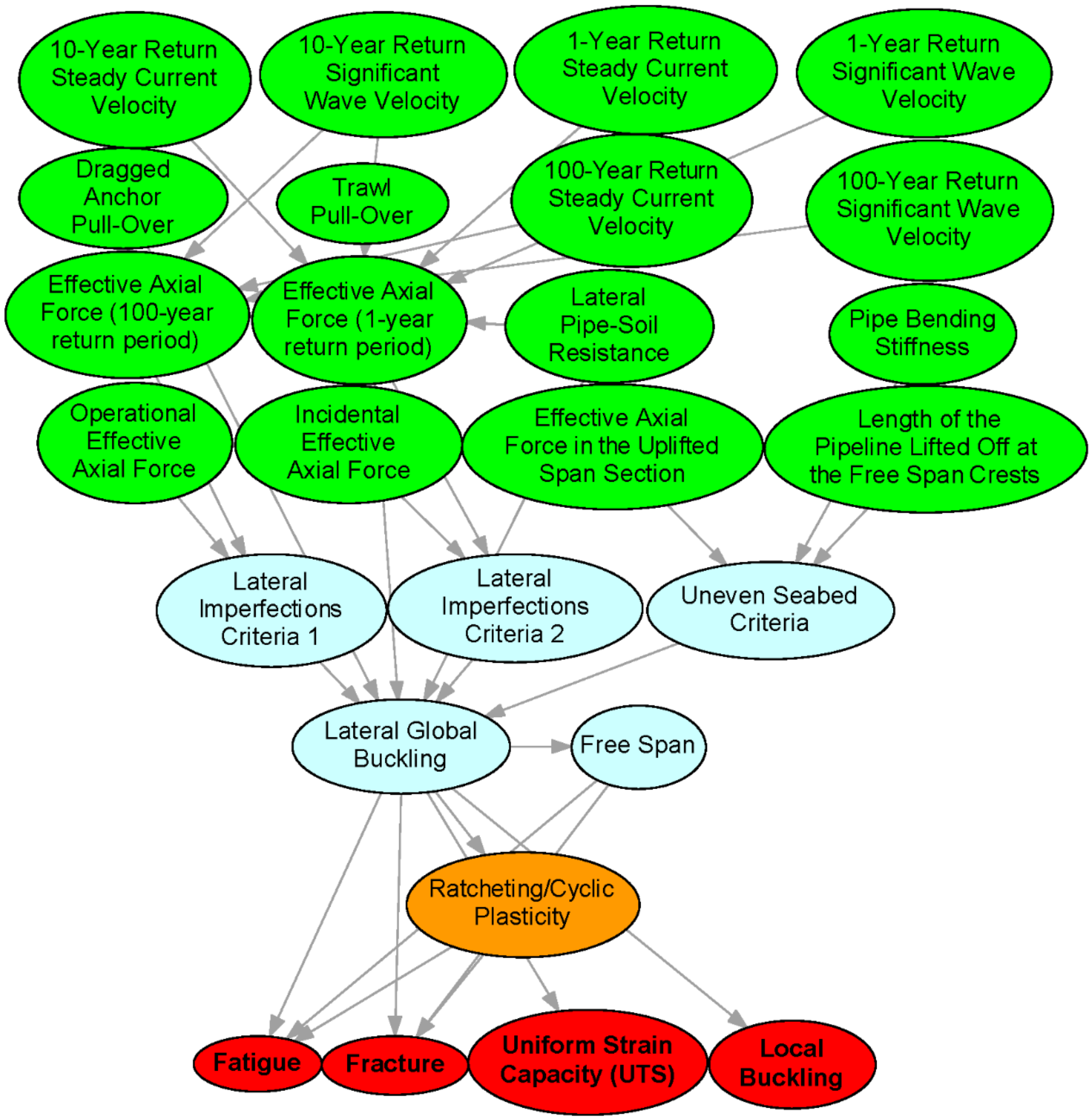

Figure 41 Lateral Global Buckling Bayesian Network Representation.

Free Span Bayesian Network

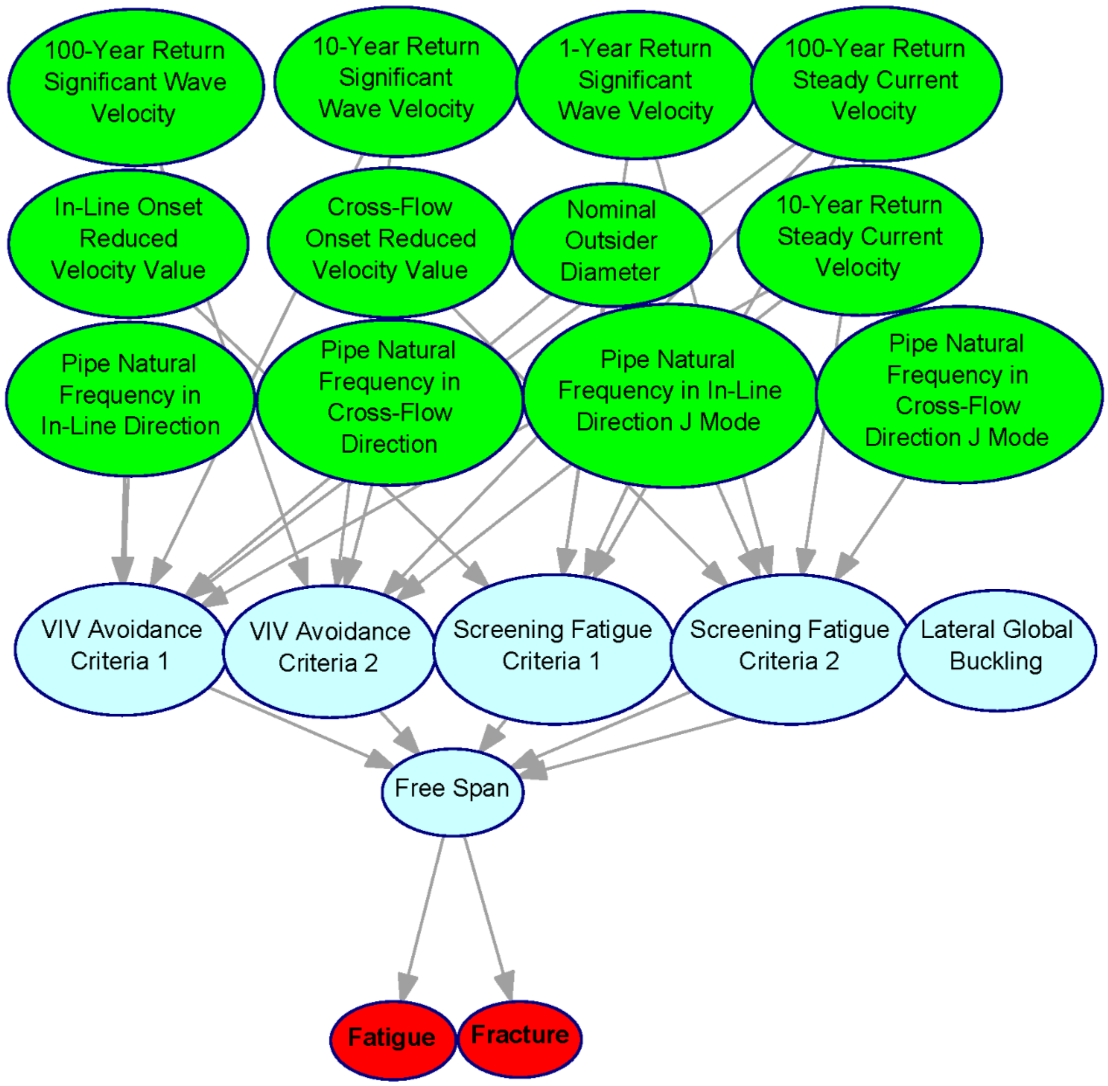

Figure 42 Free Span Bayesian Network Representation.

Construction Criteria Bayesian Network Sub-Model

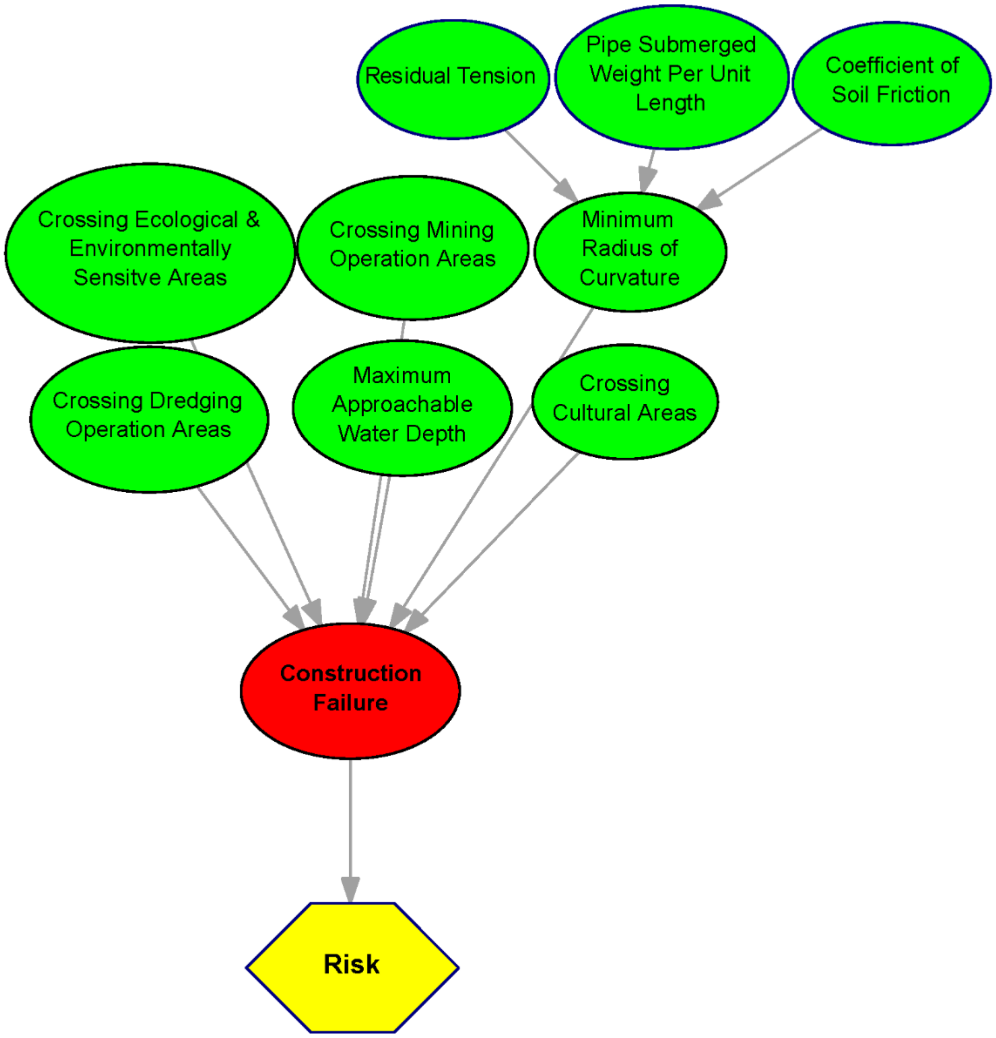

Figure 43 Construction Criteria Bayesian Network Representation.

Fluid Flow Criteria Bayesian Network Sub-Model

Figure 44 Fluid Flow Criteria Bayesian Network Representation.

Bayesian Network Complete Model

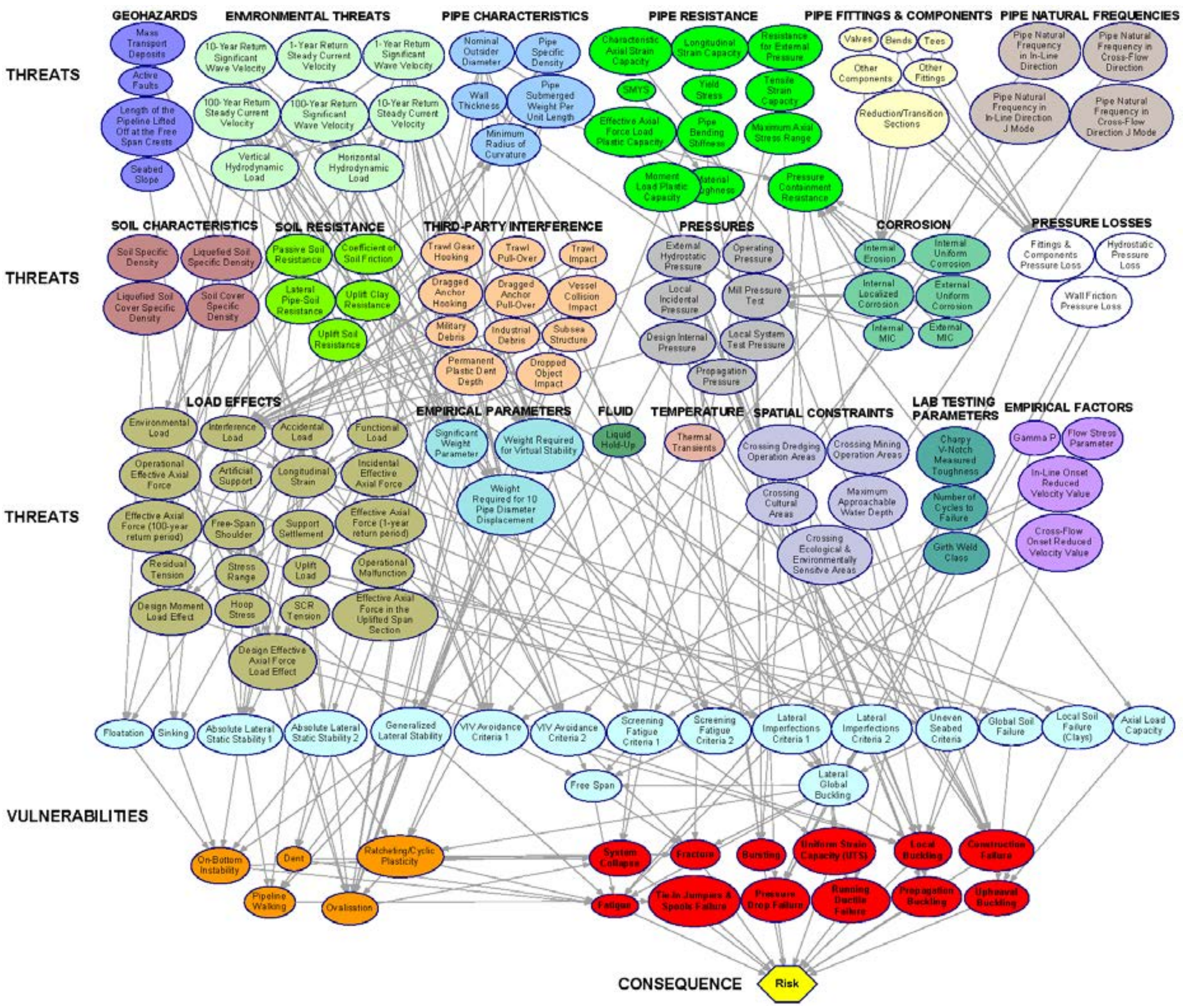

Figure 45 Offshore Pipeline Routing Bayesian Network Model.

CHAPTER IV

CONCLUSIONS

Bayesian Networks were adopted to successfully represent a Risk Assessment framework for offshore pipeline route selection. All the relevant Dynamic, Quasi-Static, and Static design limit states, construction, and fluid flow assurance criteria were integrated in one model to better represent the state of Risk of the pipeline. Multiple threats, multiple vulnerabilities, and the value of consequences were taking into account in the conceptualization of the BN model.

Cause-effect dependencies between in common control variables of physically-based models, and failure mechanisms are well represented in the Bayesian Network model using existing methodologies and theory. Additionally, cause-effect relationships between SLS, Free Span, Lateral Global Buckling, and ULS are displayed in the Bayesian Network.

Mitigation criteria for spatial constraints of offshore projects, and sources of pressure loss to fluid flow assurance were also represented in the Risk-based methodology proposed in this research.

The model is capable to quantify the variability corresponding to the control variables of the physically-based models, and the uncertainties regarding experts beliefs if needed.

Future work is to conduct the quantification of the dependency relationships stated in this research by performing Hazard Assessment, Vulnerability Assessment, and value of Consequences Assessment. Bayesian Reasoning such as prognosis and diagnosis is intended to be computed to represent the state of Risk in spatial domain to equip decision-makers with “Risk Maps” for offshore pipeline routing purposes. The latter of this research project is to adopt either geoprocessing tools of GIS software or optimization algorithms to determine the Lowest-Risk Path of the offshore pipeline in study.

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APPENDIX A

CAUSE-EFFECT DEPENDENCIES OF BAYESIAN NETWORK MODEL

Table 5 Bursting Dependencies.

Nodes	Description	States	Causes	Effects
Internal Uniform Corrosion	Wall loss	Low	CO_2	Pressure Containment Resistance
		Moderate	pH	Mill Pressure Test
		High	H_2S	
			Temperature	
			Fe^{2+}	
			O_2	
			Water Wet	
Internal Localized Corrosion	Wall loss	Low	Wax Deposits	Pressure Containment Resistance
		Moderate	Asphaltenes Deposits	Mill Pressure Test
		High	Sand Deposits	
			Water Layer	
Internal Erosion	Wall loss	Low	Valve	Pressure Containment Resistance
		Moderate	Bend	Mill Pressure Test
		High	Tee	
			Reducer/transition section	
			Sand	
			Liquid velocity	

Table 5 Continued.

Nodes	Description	States	Causes	Effects
Internal Microbiologically Influenced Corrosion (MIC)	Wall loss	Low	Sulfate-reducing bacteria (SRB)	Pressure Containment Resistance
		Moderate		Mill Pressure Test
		High		
External Uniform Corrosion	Thickness loss	Low	pH	Pressure Containment Resistance
		Moderate	HCO3	Mill Pressure Test
		High	Chlorides/Salinity	
			Sulfates	
			Microbiologically Influenced Corrosion (MIC)	
External Microbiologically Influenced Corrosion (MIC)	Thickness loss	Low	Sulfate-reducing bacteria (SRB)	Pressure Containment Resistance
		Moderate		Mill Pressure Test
		High		
Wall Thickness	Thickness	Low		Pressure Containment Resistance
		Moderate		Mill Pressure Test
		High		

Table 5 Continued.

Nodes	Description	States	Causes	Effects
Pressure Containment Resistance	Pressure	Low	Internal Uniform Corrosion	Bursting (ULS)
		Moderate	Internal Localized Corrosion	Local Buckling (ULS)
		High	Internal Erosion	
			Internal MIC	
			External Uniform Corrosion	
			External MIC	
			Wall Thickness	
Mill Pressure Test	Pressure	Low	Internal Uniform Corrosion	Bursting (ULS)
		Moderate	Internal Localized Corrosion	
		High	Internal Erosion	
			Internal MIC	
			External Uniform Corrosion	
			External MIC	
			Wall Thickness	

Table 5 Continued.

Nodes	Description	States	Causes	Effects
Local Incidental Pressure	Pressure	Low		Bursting (ULS)
		Moderate		
		High		
Local System Test Pressure	Pressure	Low		Bursting (ULS)
		Moderate		
		High		
External Hydrostatic Pressure	Pressure	Low		Bursting (ULS)
		Moderate		System Collapse (ULS)
		High		Functional Load
				Propagation Buckling (ULS)
Bursting (ULS)	Vulnerability	Low	Pressure Containment Resistance	Risk
		Moderate	Mill Pressure Test	
		High	Local Incidental Pressure	
			Local System Test Pressure	
			External Hydrostatic Pressure	

Table 6 System Collapse Dependencies.

Nodes	Description	States	Causes	Effects
Resistance for External Pressure	Resistance	Low		System Collapse (ULS)
		Moderate		
		High		
System Collapse (ULS)	Vulnerability	Low	External Hydrostatic Pressure	Risk
		Moderate	Resistance for External Pressure	
		High	Dent (SLS)	
			Ovalisation (SLS)	

Table 7 Local Buckling Dependencies.

Nodes	Description	States	Causes	Effects
Design Internal Pressure	Pressure	Low		Functional Load
		Moderate		Local Buckling (ULS)
		High		
Functional Load	Moment Load	Low	External Hydrostatic Pressure	Design Moment Load Effect
		Moderate	Design Internal Pressure	Stress Range
		High		Longitudinal Stain
Environmental Load	Moment Load	Low	Horizontal Hydrodynamic Load	Design Moment Load Effect
		Moderate	Vertical Hydrodynamic Load	Stress Range
		High		Longitudinal Stain
Subsea Structure	Load	Low		Interference Load
		Moderate		
		High		
Military Debris	Load	Low		Interference Load
		Moderate		
		High		
Industrial Debris	Load	Low		Interference Load
		Moderate		
		High		

Table 7 Continued.

Nodes	Description	States	Causes	Effects
Interference Load	Moment Load	Low	Dragged Anchor Pull-Over	Design Moment Load Effect
		Moderate	Trawl Pull-Over	Stress Range
		High	Dragged Anchor Hooking	Longitudinal Stain
			Trawl Gear Hooking	
			Trawl Gear Impact	
			Vessel Collision Impact	
			Dropped Object Impact	
			Subsea Structure	
			Military Debris	
			Industrial Debris	
Mass Transport Deposits	Load	Low	Active Volcanism	Accidental Load
		Moderate	Shear Strength	
		High	Tectonic Uplift	
			Pipe-Laying	
			Slope Angle	
			Manmade Drag Scars	
			Seismicity	
			Current Loads	
			Wave Loads	

Table 7 Continued.

Nodes	Description	States	Causes	Effects
Active Faults	Load	Low		Accidental Load
		Moderate		
		High		
Operational Malfunction	Load	Low		Accidental Load
		Moderate		
		High		
Accidental Load	Moment Load	Low	Mass Transport Deposits	Design Moment Load Effect
		Moderate	Active Faults	Stress Range
		High	Operational Malfunction	Longitudinal Stain
Design Moment Load Effect	Moment Load	Low	Functional Load	Local Buckling (ULS)
		Moderate	Environmental Load	
		High	Interference Load	
			Accidental Load	
Flow Stress Parameter	Flow Stress	Low		Local Buckling (ULS)
		Moderate		
		High		
Moment Load Plastic Capacity	Capacity	Low		Local Buckling (ULS)
		Moderate		
		High		

Table 7 Continued.

Nodes	Description	States	Causes	Effects
Design Effective Axial Force Load Effect	Axial Force	Low	Functional Load	Local Buckling (ULS)
		Moderate	Environmental Load	
		High	Interference Load	
			Accidental Load	
Effective Axial Force Load Plastic Capacity	Capacity	Low		Local Buckling (ULS)
		Moderate		
		High		
Gamma P	Factor	Low		Local Buckling (ULS)
		Moderate		
		High		
Local Buckling (ULS)	Vulnerability	Low	External Hydrostatic Pressure	Propagation Buckling (ULS)
		Moderate	Flow Stress Parameter	Risk
		High	Design Moment Load Effect	
			Moment Load Plastic Capacity	
			Design Effective Axial Force Load Effect	
			Effective Axial Force Load Plastic Capacity	
			Gamma P	
			Design Internal Pressure	
			Pressure Containment Resistance	

Table 8 Propagation Buckling Dependencies.

Nodes	Description	States	Causes	Effects
Propagation Pressure	Pressure	Low		Propagation Buckling (ULS)
		Moderate		
		High		
Propagation Buckling (ULS)	Vulnerability	Low	Local Buckling (ULS)	Risk
		Moderate	External Hydrostatic Pressure	
		High	Propagation Pressure	

Table 9 Fatigue Dependencies.

Nodes	Description	States	Causes	Effects
Girth Weld Class	Class	Class 1		Fatigue (ULS)
		Class 2		
		Class 3		
Stress Range	Stress	Low	Functional Load	Fatigue (ULS)
		Moderate	Environmental Load	
		High	Interference Load	
			Accidental Load	
Number of Cycles to Failure	Cycles	Low		Fatigue (ULS)
		Moderate		
		High		
Fatigue (ULS)	Vulnerability	Low	Dent (SLS)	Risk
		Moderate	Ratcheting/Cyclic Plasticity (SLS)	
		High	Free Span (ULS)	
			On-Bottom Instability (SLS)	
			Lateral Global Buckling	
			Stress Range	
			Number of Cycles	
			Girth Weld Class	

Table 10 Fracture Dependencies.

Nodes	Description	States	Causes	Effects
Longitudinal Strain	Strain	Low	Functional Load	Fracture (ULS)
		Moderate	Environmental Load	Uniform Strain Capacity [Ultimate Tensile Strength] (ULS)
		High	Interference Load	
			Accidental Load	Axial Loading Criteria
Longitudinal Strain Capacity	Strain	Low		Fracture (ULS)
		Moderate		
		High		
Fracture (ULS)	Vulnerability	Low	Dent (SLS)	Risk
		Moderate	Ratcheting/Cyclic Plasticity (SLS)	
		High	Free Span (ULS)	
			On-Bottom Instability (SLS)	
			Lateral Global Buckling	
			Longitudinal Strain Capacity	
			Longitudinal Strain	

Table 11 Uniform Strain Capacity Dependencies.

Nodes	Description	States	Causes	Effects
Tensile Strain Capacity	Strain	Low		Uniform Strain Capacity [Ultimate Tensile Strength] (ULS)
		Moderate		
		High		
Uniform Strain Capacity [Ultimate Tensile Strength] (ULS)	Vulnerability	Low	Longitudinal Strain	Risk
		Moderate	Tensile Strain Capacity	
		High	Lateral Global Buckling	

Table 12 Running Ductile Failure Dependencies.

Nodes	Description	States	Causes	Effects
SMYS - Specified Minimum Yield Stress	Stress	Low		Material Toughness
		Moderate		
		High		
Charpy V-Notch Measured Toughness	Toughness	Low		Running Ductile Failure (ULS)
		Moderate		
		High		
Material Toughness	Toughness	Low	Nominal Outsider Diameter	Running Ductile Failure (ULS)
		Moderate	SMYS	
		High		
Running Ductile Failure (ULS)	Vulnerability	Low	Charpy V-Notch Measured Toughness	Risk
		Moderate		
		High	Material Toughness	

Table 13 Upheaval Buckling Dependencies.

Nodes	Description	States	Causes	Effects
Characteristic Axial Strain Capacity	Strain	Low		Axial Loading Criteria
		Moderate		
		High		
Axial Loading Criteria	Criteria Satisfied?	Yes	Longitudinal Strain	Upheaval Buckling (ULS)
		No	Characteristic Axial Strain Capacity	
Uplift Load	Load	Low		Global Soil Failure
		Moderate		Local Soil Failure (Clays)
		High		
Uplift Soil Resistance	Resistance	Low		Global Soil Failure
		Moderate		
		High		
Global Soil Failure	Criteria Satisfied?	Yes	Uplift Load	Upheaval Buckling (ULS)
		No	Uplift Soil Resistance	
Uplift Clay Resistance	Resistance	Low		Local Soil Failure (Clays)
		Moderate		
		High		
Local Soil Failure (Clays)	Criteria Satisfied?	Yes	Uplift Load	Upheaval Buckling (ULS)
		No	Uplift Clay Resistance	
Upheaval Buckling (ULS)	Vulnerability	Low	Axial Load Capacity	Risk
		Moderate	Global Soil Failure	
		High	Local Soil Failure (Clays)	

Table 14 On-Bottom Instability Dependencies.

Nodes	Description	States	Causes	Effects
100-Year Return Significant Wave Velocity	Velocity	Low		Significant Weight Parameter
		Moderate		Weight Required for Virtual Stability
		High		Weight Required for 10 Pipe Diameter Displacement
				Horizontal Hydrodynamic Load
				Vetical Hydrodynamic Load
				VIV Avoidance Criteria 1
				VIV Avoidance Criteria 2
				Effective Axial Force (100-year return period)
10-Year Return Significant Wave Velocity	Velocity	Low		Significant Weight Parameter
		Moderate		Weight Required for Virtual Stability
		High		Weight Required for 10 Pipe Diameter Displacement
				Horizontal Hydrodynamic Load
				Vetical Hydrodynamic Load
				VIV Avoidance Criteria 1
				VIV Avoidance Criteria 2
				Effective Axial Force (100-year return period)
				Effective Axial Force (1-year return period)

Table 14 Continued.

Nodes	Description	States	Causes	Effects
1-Year Return Significant Wave Velocity	Velocity	Low		Significant Weight Parameter
		Moderate		Weight Required for Virtual Stability
		High		Weight Required for 10 Pipe Diameter Displacement
				Horizontal Hydrodynamic Load
				Vertical Hydrodynamic Load
				Screening Fatigue Criteria 1
				Screening Fatigue Criteria 2
				Effective Axial Force (1-year return period)
100-Year Return Steady Current Velocity	Velocity	Low		Weight Required for Virtual Stability
		Moderate		Weight Required for 10 Pipe Diameter Displacement
		High		Horizontal Hydrodynamic Load
				Vertical Hydrodynamic Load
				VIV Avoidance Criteria 1
				VIV Avoidance Criteria 2
				Screening Fatigue Criteria 1
				Screening Fatigue Criteria 2
				Effective Axial Force (100-year return period)

Table 14 Continued.

Nodes	Description	States	Causes	Effects
10-Year Return Steady Current Velocity	Velocity	Low		Weight Required for Virtual Stability
		Moderate		Weight Required for 10 Pipe Diameter Displacement
		High		
				Horizontal Hydrodynamic Load
				Vertical Hydrodynamic Load
				VIV Avoidance Criteria 1
				VIV Avoidance Criteria 2
				Effective Axial Force (100-year return period)
				Effective Axial Force (1-year return period)
1-Year Return Steady Current Velocity	Velocity	Low		Weight Required for Virtual Stability
		Moderate		Weight Required for 10 Pipe Diameter Displacement
		High		
				Horizontal Hydrodynamic Load
				Vertical Hydrodynamic Load
				Effective Axial Force (1-year return period)

Table 14 Continued.

Nodes	Description	States	Causes	Effects
Significant Weight Parameter	Weight	Low	100-Year Return Significant Wave Velocity	Generalized Lateral Stability
		Moderate		
		High	10-Year Return Significant Wave Velocity	
			1-Year Return Significant Wave Velocity	
Weight Required for Virtual Stability	Weight	Low	100-Year Return Significant Wave Velocity	Generalized Lateral Stability
		Moderate		
		High	10-Year Return Significant Wave Velocity	
			1-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			10-Year Return Steady Current Velocity	
			1-Year Return Steady Current Velocity	

Table 14 Continued.

Nodes	Description	States	Causes	Effects
Weight Required for 10 Pipe Diameter Displacement	Weight	Low	100-Year Return Significant Wave Velocity	Generalized Lateral Stability
		Moderate		
		High	10-Year Return Significant Wave Velocity	
			1-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			10-Year Return Steady Current Velocity	
			1-Year Return Steady Current Velocity	
Generalized Lateral Stability	Criteria Satisfied?	Yes	Significant Weight Parameter	On-Bottom Instability (SLS)
		No	Weight Required for Virtual Stability	
			Weight Required for 10 Pipe Diameter Displacement	

Table 14 Continued.

Nodes	Description	States	Causes	Effects
Horizontal Hydrodynamic Load	Load	Low	100-Year Return Significant Wave Velocity	Absolute Lateral Static Stability 1
		Moderate		Absolute Lateral Static Stability 2
		High	10-Year Return Significant Wave Velocity	Environmental Load
			1-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			10-Year Return Steady Current Velocity	
			1-Year Return Steady Current Velocity	
Vertical Hydrodynamic Load	Load	Low	100-Year Return Significant Wave Velocity	Absolute Lateral Static Stability 1
		Moderate		Absolute Lateral Static Stability 2
		High	10-Year Return Significant Wave Velocity	Environmental Load
			1-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			10-Year Return Steady Current Velocity	
			1-Year Return Steady Current Velocity	

Table 14 Continued.

Nodes	Description	States	Causes	Effects
Passive Soil Resistance	Soil Resistance	Low		Absolute Lateral Static Stability 1
		Moderate		
		High		
Absolute Lateral Static Stability 1	Criteria Satisfied?	Yes	Horizontal Hydrodynamic Load	On-Bottom Instability (SLS)
		No	Vertical Hydrodynamic Load	
			Coefficient of Soil Friction	
			Passive Soil Resistance	
			Pipe Submerged Weight Per Unit Length	
Absolute Lateral Static Stability 2	Criteria Satisfied?	Yes	Vertical Hydrodynamic Load	On-Bottom Instability (SLS)
		No	Pipe Submerged Weight Per Unit Length	
Pipe Specific Density	Density	Low		Floatation
		Moderate		Sinking
		High		
Soil Cover Specific Density	Density	Low		Floatation
		Moderate		
		High		

Table 14 Continued.

Nodes	Description	States	Causes	Effects
Liquefied Soil Cover Specific Density	Density	Low		Floatation
		Moderate		
		High		
Floatation	Criteria Satisfied?	Yes	Pipe Specific Density	On-Bottom Instability (SLS)
		No	Soil Cover Specific Density	
			Liquefied Soil Cover Specific Density	
Soil Specific Density	Density	Low		Sinking
		Moderate		
		High		
Liquefied Soil Specific Density	Density	Low		Sinking
		Moderate		
		High		
Sinking	Criteria Satisfied?	Yes	Pipe Specific Density	On-Bottom Instability (SLS)
		No	Soil Specific Density	
			Liquefied Soil Specific Density	
On-Bottom Instability (SLS)	Vulnerability	Low	Generalized Lateral Stability	Fatigue (ULS)
		Moderate	Absolute Lateral Static Stability 1	Fracture (ULS)
		High	Absolute Lateral Static Stability 2	
			Floatation	
			Sinking	

Table 15 Pipeline Walking Dependencies.

Nodes	Description	States	Causes	Effects
Seabed Slope	Longitudinal Displacement	Low		Pipeline Walking (SLS)
		Moderate		
		High		
Thermal Transients	Longitudinal Displacement	Low		Pipeline Walking (SLS)
		Moderate		
		High		
SCR Tension	Longitudinal Displacement	Low		Pipeline Walking (SLS)
		Moderate		
		High		
Liquid Hold-Up	Longitudinal Displacement	Low		Pipeline Walking (SLS)
		Moderate		
		High		
Pipeline Walking (SLS)	Total Longitudinal Displacement	Low	Seabed Slope	Tie-In Jumpers & Spools Failure
		Moderate	Thermal Transients	
		High	SCR Tension	
			Liquid Hold-Up	

Table 15 Continued.

Nodes	Description	States	Causes	Effects
Tie-In Jumpers & Spools Failure	Vulnerability	Low	Pipeline Walking (SLS)	Risk
		Moderate		
		High		

Table 16 Ratcheting/Cyclic Plasticity Dependencies.

Nodes	Description	States	Causes	Effects
Maximum Axial Stress Range	Axial Stress	Low		Ratcheting/Cyclic Plasticity (SLS)
		Moderate		
		High		
Yield Stress	Yield Stress	Low		Ratcheting/Cyclic Plasticity (SLS)
		Moderate		
		High		
Hoop Stress	Hoop Stress	Low		Ratcheting/Cyclic Plasticity (SLS)
		Moderate		
		High		
Ratcheting/Cyclic Plasticity (SLS)	Vulnerability	Low	Lateral Global Buckling	Ovalisation (SLS)
		Moderate	Maximum Axial Stress Range	Fatigue (ULS)
		High	Yield Stress	Fracture (ULS)
			Hoop Stress	

Table 17 Ovalisation Dependencies.

Nodes	Description	States	Causes	Effects
Dragged Anchor Hooking	Load	Low		Ovalisation (SLS)
		Moderate		Local Buckling (ULS)
		High		Interference Moment Load
Trawl Gear Hooking	Load	Low		Ovalisation (SLS)
		Moderate		Local Buckling (ULS)
		High		Interference Moment Load
Trawl Gear Impact	Load	Low		Ovalisation (SLS)
		Moderate		Dent (SLS)
		High		Local Buckling (ULS)
				Interference Moment Load
Vessel Collision Impact	Load	Low		Ovalisation (SLS)
		Moderate		Dent (SLS)
		High		Local Buckling (ULS)
				Interference Moment Load
Dropped Object Impact	Load	Low		Ovalisation (SLS)
		Moderate		Dent (SLS)
		High		Local Buckling (ULS)
				Interference Moment Load
Artificial Support	Load	Low		Ovalisation (SLS)
		Moderate		
		High		

Table 17 Continued.

Nodes	Description	States	Causes	Effects
Free-Span Shoulder	Load	Low		Ovalisation (SLS)
		Moderate		
		High		
Support Settlement	Load	Low		Ovalisation (SLS)
		Moderate		
		High		
Nominal Outsider Diameter	Diameter	Low		Ovalisation (SLS)
		Moderate		Dent (SLS)
		High		VIV Avoidance Criteria 1
				VIV Avoidance Criteria 2
				Screening Fatigue Criteria 1
				Screening Fatigue Criteria 2
				Material Toughness

Table 17 Continued.

Nodes	Description	States	Causes	Effects
Ovalisation (SLS)	Ovality	Low	Dragged Anchor Pull-Over	System Collapse (ULS)
		Moderate	Trawl Pull-Over	
		High	Dragged Anchor Hooking	
			Trawl Gear Hooking	
			Trawl Gear Impact	
			Vessel Collision Impact	
			Dropped Object Impact	
			Artificial Support	
			Free-Span Shoulder	
			Support Settlement	
			Ratcheting/Cyclic Plasticity (SLS)	
			Nominal Outsider Diameter	

Table 18 Dent Dependencies.

Nodes	Description	States	Causes	Effects
Permanent Plastic Dent Depth	Depth	Low	Trawl Gear Impact	Dent (SLS)
		Moderate	Vessel Collision Impact	
		High	Dropped Object Impact	
Dent (SLS)	Percentage	Low	Nominal Outsider Diameter	System Collapse (ULS)
		Moderate	Permanent Plastic Dent Depth	Fatigue (ULS)
		High		Fracture (ULS)

Table 19 Lateral Global Buckling Dependencies.

Nodes	Description	States	Causes	Effects
Effective Axial Force in the Uplifted Span Section	Axial Force	Low		Uneven Seabed Criteria
		Moderate		
		High		
Pipe Bending Stiffness	Bending Stiffness	Low		Uneven Seabed Criteria
		Moderate		
		High		
Length of the Pipeline Lifted Off at the Free Span Crests	Length	Low		Uneven Seabed Criteria
		Moderate		
		High		
Uneven Seabed Criteria	Criteria Satisfied?	Yes	Effective Axial Force in the Uplifted Span Section	Lateral Global Buckling
		No		
			Pipe Bending Stiffness	
			Length of the Pipeline Lifted Off at the Free Span Crests	
Operational Effective Axial Force	Axial Force	Low		Lateral Imperfections Criteria 1
		Moderate		
		High		
Lateral Pipe-Soil Resistance	Resistance	Low		Lateral Global Buckling
		Moderate		Effective Axial Force (100-year return period)
		High		Effective Axial Force (1-year return period)

Table 19 Continued.

Nodes	Description	States	Causes	Effects
Effective Axial Force (100-year return period)	Axial Force	Low	100-Year Return Significant Wave Velocity	Lateral Imperfections Criteria 1
		Moderate		
		High	10-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			10-Year Return Steady Current Velocity	
			Lateral Pipe-Soil Resistance	
Lateral Imperfections Criteria 1	Criteria Satisfied?	Yes	Operational Effective Axial Force	Lateral Global Buckling
		No	Effective Axial Force (100-year return period)	
Incidental Effective Axial Force	Axial Force	Low		Lateral Imperfections Criteria 2
		Moderate		
		High		

Table 19 Continued.

Nodes	Description	States	Causes	Effects
Effective Axial Force (1-year return period)	Axial Force	Low	10-Year Return Significant Wave Velocity	Lateral Imperfections Criteria 2
		Moderate		
		High	1-Year Return Significant Wave Velocity	
			10-Year Return Steady Current Velocity	
			1-Year Return Steady Current Velocity	
			Lateral Pipe-Soil Resistance	
Lateral Imperfections Criteria 2	Criteria Satisfied?	Yes	Incidental Effective Axial Force	Lateral Global Buckling
		No	Effective Axial Force (1-year return period)	
Dragged Anchor Pull-Over	Load	Low		Lateral Global Buckling
		Moderate		Ovalisation (SLS)
		High		Local Buckling (ULS)
				Interference Moment Load
Trawl Pull-Over	Load	Low		Lateral Global Buckling
		Moderate		Ovalisation (SLS)
		High		Local Buckling (ULS)
				Interference Moment Load

Table 19 Continued.

Nodes	Description	States	Causes	Effects
Lateral Global Buckling	Buckling?	Yes	Uneven Seabed Criteria	Ratcheting/Cyclic Plasticity (SLS)
		No	Lateral Imperfections Criteria 1	Fatigue (ULS)
			Lateral Imperfections Criteria 2	Fracture (ULS)
			Dragged Anchor Pull-Over	Uniform Strain Capacity (ULS)
			Trawl Pull-Over	
			Lateral Pipe-Soil Resistance	

Table 20 Free Span Dependencies.

Nodes	Description	States	Causes	Effects
Pipe Natural Frequency in In-Line Direction	Frequency	Low		VIV Avoidance Criteria 1
		Moderate		
		High		
Pipe Natural Frequency in Cross-Flow Direction	Frequency	Low		VIV Avoidance Criteria 2
		Moderate		
		High		
In-Line Onset Reduced Velocity Value	Factor	Low		VIV Avoidance Criteria 1
		Moderate		Screening Fatigue Criteria 1
		High		

Table 20 Continued.

Nodes	Description	States	Causes	Effects
VIV Avoidance Criteria 1	Criteria Satisfied?	Yes	Pipe Natural Frequency in In-Line Direction	Free Span (ULS)
		No	100-Year Return Significant Wave Velocity	
			10-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			10-Year Return Steady Current Velocity	
			In-Line Onset Reduced Velocity Value	
			Nominal Outsider Diameter	

Table 20 Continued.

Nodes	Description	States	Causes	Effects
VIV Avoidance Criteria 2	Criteria Satisfied?	Yes	Pipe Natural Frequency in Cross-Flow Direction	Free Span (ULS)
		No		
			100-Year Return Significant Wave Velocity	
			10-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			10-Year Return Steady Current Velocity	
			Nominal Outsider Diameter	
Pipe Natural Frequency in In-Line Direction J Mode	Frequency	Low		Screening Fatigue Criteria 1
		Moderate		
		High		
Pipe Natural Frequency in Cross-Flow Direction J Mode	Frequency	Low		Screening Fatigue Criteria 2
		Moderate		
		High		
Free Span Length	Length	Low		Screening Fatigue Criteria 1
		Moderate		
		High		

Table 20 Continued.

Nodes	Description	States	Causes	Effects
Cross-Flow Onset Reduced Velocity Value	Factor	Low		Screening Fatigue Criteria 2
		Moderate		
		High		
Screening Fatigue Criteria 1	Criteria Satisfied?	Yes	Pipe Natural Frequency in In-Line Direction J Mode	Free Span (ULS)
		No		
			1-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			In-Line Onset Reduced Velocity Value	
			Nominal Outsider Diameter	
Screening Fatigue Criteria 2	Criteria Satisfied?	Yes	Pipe Natural Frequency in Cross-Flow Direction J Mode	Free Span (ULS)
		No		
			1-Year Return Significant Wave Velocity	
			100-Year Return Steady Current Velocity	
			Cross-Flow Onset Reduced Velocity Value	
			Nominal Outsider Diameter	

Table 20 Continued.

Nodes	Description	States	Causes	Effects
Free Span	Vulnerability	Low	VIV Avoidance Criteria 1	Fatigue (ULS)
		Moderate	VIV Avoidance Criteria 2	Fracture (ULS)
		High	Screening Fatigue Criteria 1	
			Screening Fatigue Criteria 2	

Table 21 Construction Criteria Dependencies.

Nodes	Description	States	Causes	Effects
Crossing Ecological & Environmentally Sensitive Areas	Distance from Ecological & Environmentally Sensitive Areas	Low		Construction Failure
		Moderate		
		High		
Crossing Cultural Areas	Distance from Cultural Areas	Low		Construction Failure
		Moderate		
		High		
Crossing Mining Operation Areas	Distance from Mining Operation Areas	Low		Construction Failure
		Moderate		
		High		
Crossing Dredging Operation Areas	Distance from Dredging Operation Areas	Low		Construction Failure
		Moderate		
		High		
Residual Tension	Tension	Low		Minimum Radius of Curvature
		Moderate		
		High		
Coefficient of Soil Friction	Coefficient	Low		Minimum Radius of Curvature
		Moderate		Absolute Lateral Static Stability 1
		High		

Table 21 Continued.

Nodes	Description	States	Causes	Effects
Pipe Submerged Weight Per Unit Length	Submerged Weight Per Unit Length	Low		Minimum Radius of Curvature
		Moderate		Absolute Lateral Static Stability 1
		High		Absolute Lateral Static Stability 2
Minimum Radius of Curvature	Criteria Satisfied?	Yes	Residual Tension	Construction Failure
		No	Coefficient of Soil Friction	
			Pipe Submerged Weight Per Unit Length	
Maximum Approachable Water Depth	Distance from Deeper Waters	Low		Construction Failure
		Moderate		
		High		
Construction Failure	Vulnerability	Low	Crossing Ecological & Environmentally Sensitive Areas	Risk
		Moderate		
		High	Crossing Cultural Areas	
			Crossing Mining Operation Areas	
			Crossing Dredging Operation Areas	
			Minimum Radius of Curvature	
			Maximum Approachable Water Depth	

Table 22 Fluid Flow Criteria Dependencies.

Nodes	Description	States	Causes	Effects
Wall Friction Pressure Loss	Pressure Loss	Low		Pressure Drop Failure
		Moderate		
		High		
Hydrostatic Pressure Loss	Pressure Loss	Low		Pressure Drop Failure
		Moderate		
		High		
Valves	Number of Valves	Low		Fittings & Components Pressure Loss
		Moderate		
		High		Internal Erosion
Bends	Number of Bends	Low		Fittings & Components Pressure Loss
		Moderate		
		High		Internal Erosion
Tees	Number of Tees	Low		Fittings & Components Pressure Loss
		Moderate		
		High		Internal Erosion
Reduction/Transition Sections	Number of Reduction/Transition Sections	Low		Fittings & Components Pressure Loss
		Moderate		
		High		Internal Erosion

Table 22 Continued.

Nodes	Description	States	Causes	Effects
Other Fittings including:	Number of Other Fittings	Low		Fittings & Components Pressure Loss
Elbow		Moderate		
Cap		High		
Wye				
Single/multiple extruded headers				
Other Components including:	Number of Other Components	Low		Pressure Loss
		Moderate		
Flange		High		
Mechanical connectors				
Cathodic protection (CP) isolation joint				
Anchor flange				
Pig trap				
Fittings & Components Pressure Loss	Pressure Loss	Low	Valves	Pressure Drop Failure
		Moderate	Bends	
		High	Tees	
			Reduction/Transition Sections	
			Other Fittings	
			Other Components	

Table 22 Continued.

Nodes	Description	States	Causes	Effects
Operating Pressure	Pressure	Low		Pressure Drop Failure
		Moderate		
		High		
Pressure Drop Failure	Vulnerability	Low	Wall Friction Pressure Loss	Risk
		Moderate	Hydrostatic Pressure Loss	
		High	Fittings & Components Pressure Loss	
			Operating Pressure	

Table 23 Risk Dependencies.

Nodes	Description	States	Causes	Effects
Risk	Value of Consequences	Low	Construction Failure	
		Moderate	Pressure Drop Failure	
		High	Tie-In Jumpers & Spools Failure	
			Bursting (ULS)	
			System Collapse (ULS)	
			Local Buckling (ULS)	
			Propagation Buckling (ULS)	
			Fatigue (ULS)	
			Fracture (ULS)	
			Uniform Strain Capacity [Ultimate Tensile Strength] (ULS)	
			Running Ductile Failure (ULS)	
			Upheaval Buckling (ULS)	