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Optimization of Preventative Maintenance for Mechanical Damage of Offshore Pipelines

PIRAMID Technical Reference Manual No. 9.0

Confidential to C-FER's Pipeline Program Participants

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NOTICE

Restriction on Disclosure

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1. INTRODUCTION

1.1 Background

This document constitutes one of the deliverables associated with C-FER's joint industry program on risk-based optimization of pipeline integrity maintenance activities. The goal of this program is to develop models and software tools that can assist pipeline operators in making optimal decisions regarding integrity maintenance activities for a pipeline or pipeline segment. The software resulting from this joint industry program is called PIRAMID (Pipeline Risk Analysis for Maintenance and Inspection Decisions). This document is part of the technical reference manual for the program.

Implementation of the risk-based approach developed in this program requires quantitative estimates of both the frequency of line failure and the adverse consequences associated with failure should it occur. There is considerable uncertainty associated with the assessment of both the frequency and consequences of line failure. To find the optimal set of integrity maintenance actions in the presence of this uncertainty, a probabilistic optimization methodology based on decision influence diagrams has been adopted. A description of this approach and the reasons for its selection are given in PIRAMID Technical Reference Manual No. 1.2 (Stephens *et al.* 1995).

PIRAMID is developed as a series of individual modules. The first offshore module developed was a consequence assessment module that estimates the impact of a pipeline failure on cost, public safety, and the environment (see PIRAMID Technical Reference Manual No. 5.1 by Stephens *et al.* 1996). The consequence assessment module can be used to carry out a risk assessment or a decision analysis of different maintenance options, provided that the user inputs the probability of failure of the pipeline, both in its original state and after implementation of each of the candidate integrity maintenance actions.

The probability analysis modules of PIRAMID are developed individually for each failure cause. This is consistent with the fact that most integrity maintenance methods address individual failure causes (*e.g.*, magnetic flux leakage in-line inspection for metal loss corrosion, or cover depth surveys for mechanical damage). The major exception to this is hydrostatic testing, which mitigates against in-service failures caused by many types of defects, and should therefore be assessed with respect to its cumulative benefits for different failure causes (*i.e.*, metal loss corrosion, cracks, or dents). It is recognized that other minor exceptions exist for which a given inspection method can detect more than one failure cause (for example, high resolution magnetic flux leakage tools detect girth weld cracks in addition to metal loss corrosion), but these secondary benefits are assumed not to play a major role in integrity maintenance planning.

When the PIRAMID probability module for a given failure cause is integrated with the consequence module, a decision analysis can be carried out for integrity maintenance choices aimed at reducing the chance of failures due to that cause. In this case PIRAMID would compute the probabilities of failure from more basic pipeline attributes. For the mechanical damage case, for example, the failure probability is computed from impact frequency and the likelihood of a pipe body failure given impact.

1.2 Objective and Scope

This document describes the PIRAMID model and influence diagram that have been developed to estimate the probability distribution of pipe performance (*i.e.*, the probabilities of safe performance, small leaks, large leaks, and ruptures) with respect to outside forces caused by mechanical interference and to quantify the effect of mechanical damage prevention activities on that probability. It also describes the approach developed to combine this performance analysis influence diagram with the consequence analysis influence diagram described in PIRAMID Technical Reference Manual No. 5.1 (Stephens *et al.* 1996) in an overall model that identifies the optimal mechanical damage prevention strategy. The choices addressed in this analysis reflect inspection and maintenance options available to the operator that are intended to promote awareness of the location of a pipeline or to prevent line impact given subsea activity, such as cover monitoring, line reburial, and the introduction of mechanical protection.

2. THE DECISION ANALYSIS INFLUENCE DIAGRAM

2.1 Review of Diagram Representation and Terminology

A decision influence diagram is a graphical representation of a decision problem that shows the interdependence between the uncertain quantities that influence the decision(s) considered. A diagram consists of a network of *chance nodes* (circles) that represent uncertain parameters and *decision nodes* (squares) that represent choices to be made. A decision influence diagram will also contain a *value node* (rounded square) that represents the objective or value function that is to be maximized to determine the optimal set of choice(s) associated with the required decision(s).

All of these nodes are interconnected by directed arcs or arrows that represent dependent relationships between node parameters. Chance nodes that receive solid line arrows are *conditional nodes* meaning that the node parameter is conditionally dependent upon the values of the nodes from which the arrows emanate (*i.e.*, direct predecessor nodes). Chance nodes that receive dashed line arrows are *functional nodes* meaning that the node parameter is defined as a deterministic function of the values of its direct predecessor nodes. The difference between these two types is that conditional node parameters must be defined explicitly for all possible combinations of the values associated with their direct conditional predecessor nodes, whereas functional node parameters are calculated directly from the values of preceding nodes. The symbolic notation adopted in drawing the influence diagrams presented in this report and a summary of diagram terminology are given in Figure 2.1.

A detailed discussion of the steps involved in defining and solving decision influence diagrams, and a more thorough and rigorous set of node parameter and dependence relationship definitions, is presented in PIRAMID Technical Reference Manual No. 2.1 (Nessim and Hong 1995). Subsequent discussions assume that the reader is familiar with the concepts described in that document.

2.2 Structure of the Influence Diagram Solution

2.2.1 Overview

An optimization analysis of mechanical damage prevention activities involves a failure probability analysis that estimates the expected pipeline performance for different preventative maintenance options and a consequence analysis that defines the expected outcomes in the event of failure. The consequence analysis part of the solution was developed as a stand-alone module as part of a previous PIRAMID Project (Stephens *et al.* 1996). The approach adopted in developing a complete influence diagram solution for the optimization of mechanical damage prevention activities was to develop a separate influence diagram to calculate the probability of failure for different preventative maintenance options and link it to the already existing consequence analysis influence diagram. The purpose of Sections 2.2.2 to 2.2.4 is to give an overview of the mechanical damage influence diagram and describe how it is integrated with the consequence analysis influence diagram. Details of the relationships between different diagram nodes are explained in more detail in the remainder of this report.

2.2.2 The Mechanical Damage Influence Diagram

The mechanical damage influence diagram is shown in Figure 2.2. This diagram includes a decision node that describes the set of choices associated with mechanical damage prevention and chance nodes that link the choice to pipe performance with respect to mechanical damage. The diagram shows that the performance is calculated from a series of nodes describing the magnitude of the interference event (i.e., the energy associated with object impact or vessel grounding) and relevant mechanical properties of the pipe (*i.e.*, the yield strength). The diagram also implies that the impact of preventative maintenance activities is taken into account by updating the parameter that reflects the likelihood of occurrence of an interference event (*i.e.*, the damage section node).

The end nodes in the influence diagram shown in Figure 2.2 are Performance Given Impact and Pipe Performance Given Grounding. These nodes contain the information necessary to link the mechanical damage influence diagram to the consequence analysis influence diagram. Performance Given Impact represents the pipe performance at a randomly occurring mechanical interference event caused by an object that is either intentionally deployed from or unintentionally dragged by a vessel. Performance Given Grounding represents the pipe performance at a randomly occurring mechanical interference event caused by vessel grounding. Each of these nodes has four possible states: safe, small leak, large leak, or rupture. The purpose of the influence diagram in Figure 2.2 is to calculate the probability distributions associated with Performance Given Impact (and Grounding) for all specified choices. The linkage between the mechanical damage influence diagram nodes and the consequence analysis influence diagram is discussed in Section 2.2.3.

2.2.3 Connections between the Mechanical Damage and Consequence Analysis Influence Diagrams

Once the probability distributions of the Performance Given Impact (and Grounding) are calculated from the influence diagram in Figure 2.2, they can be used as input to the consequence analysis influence diagram shown in Figure 2.3, which is derived by introducing minor modifications to the original consequence analysis influence diagram described in PIRAMID Technical Reference Manual 5.1 (Stephens *et al.* 1996) and shown in Figure 2.4. By solving the consequence analysis diagram in Figure 2.3, using the inputs provided by the solution to the mechanical damage influence diagram in Figure 2.2, the solution to the complete mechanical damage prevention decision analysis problem is reached.

Connections between the two influence diagrams occur through the nodes highlighted in Figures 2.2 and 2.3, where the nodes highlighted in Figure 2.2 provide input to the nodes highlighted in Figure 2.3. The relationships between the two diagrams are as follows:

- *Choices.* The Choices node (node 1) consists of the set of choices specified for consideration and is common to both the consequence analysis influence diagram and the mechanical damage influence diagram.
- *Segment Performance.* The probability distribution of the Segment Performance node (node 3.3) in the consequence analysis influence diagram is calculated from the probability distribution of the Performance Given Impact (and Grounding) nodes (node 3.1 and 3.2) in the mechanical damage influence diagram. This calculation involves converting the probability of failure given interference (node 3.1 and 3.2) to the probability of failure for the whole pipeline segment, using the average number of interference events per unit length along the line from node 12.1 (see Section 7.3 for details). As such, calculation of Segment Performance (node 3.3) requires information from nodes 3.1, 3.2 and 12.1, which belong to the mechanical damage influence diagram.

2.2.4 Modifications to the Consequence Analysis Influence Diagram

A number of modifications were introduced to the consequence analysis influence diagram in Figure 2.3 in order to link it to the newly developed mechanical damage influence diagram. For comparison, Figure 2.4 gives the original influence diagram as defined in PIRAMID Technical Reference Manual No. 5.1. The modifications are as follows:

- The *Pipe Performance* node (node 3) in the original diagram was renamed to Segment Performance and renumbered to node 3.3 in order to distinguish it from the Performance Given Impact nodes (node 3.1 and 3.2). The probability distribution associated with the parameter of this node is no longer defined directly by the user, but is calculated by the program as described in Section 7.3.
- A conditional arrow was added from Segment Performance (node 3.3) to *Failure Section* (node 2.6). This arrow indicates that the probability distribution of the Failure Section is conditional on the parameter of the Segment Performance node (*i.e.*, the probability that a certain failure will occur on a given Section depends on the failure mode). This dependence can be understood by considering the probabilities of different failure modes for specific sections of the pipeline. Because mechanical damage-related attributes are allowed to vary freely from one section to another, the relative probabilities of different failure modes (*i.e.*, small leaks, large leaks, or ruptures) can also vary between sections. It therefore follows that if a failure occurs, the probability of it being on a given section depends on the failure mode. This means that the probability distribution of Failure Section is conditional on the parameter of the Pipe Performance node. In addition to the new arrow, the node calculation for the Failure Section node was also modified as discussed in Section 8.0.

- A conditional arrow was added from the Choice node (node 1) to the *Failure Section* node (node 2.6). This arrow accounts for the fact that a given choice may affect the line impact frequency and hence the relative failure frequencies for different pipeline sections.

2.3 Compound Node Influence Diagram and Organization of this Manual

As previously discussed in the consequence analysis influence diagram (Technical Reference Manual No. 5.1), each node in the influence diagrams in Figures 2.2 and 2.3 represents a single parameter that influences the decision problem being analyzed. This manual describes the methods used to define each node parameter for later use in solving the diagram and identifying the optimal choices.

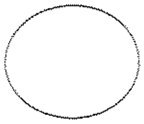
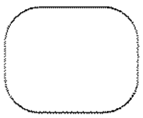
To facilitate understanding of the influence diagrams in Figures 2.2 and 2.3, nodes have been collected into logical groupings, resulting in the compound node influence diagram shown in Figure 2.5. Nodes 1 through 11 in the compound influence diagram existed in the consequence analysis compound influence diagram. Nodes 12, 13 and 14 have been added to accommodate the basic nodes in the new mechanical damage influence diagram (Figure 2.2). Figure 2.5 highlights compound nodes that were added for mechanical damage analysis, as well as compound nodes that existed in the original consequence analysis influence diagram but involved some modifications to establish the connection between the mechanical damage and consequence analysis influence diagrams (see Section 2.2.3).

This manual describes node calculations for the new mechanical damage influence diagram and the modifications made to the original consequence analysis influence diagram. The new models or modification associated with each compound node are described in a separate section in the following order:

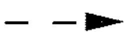
Section	Node group
3.0	Choices (node group 1)
4.0	Damage Potential (node group 12)
5.0	Damage Characteristics (node group 13)
6.0	Mechanical Properties (node group 14)
7.0	Pipe Performance (node group 3)
8.0	Conditions at Failure (node group 2)
9.0	Repair and Interruption Costs (node group 8)
10.0	Value (node group 11)

Figures

Node Notation

	Decision node:	Indicates a choice to be made
	Chance node:	Indicates uncertain parameter or event (discrete or continuous)
	Value node:	Indicates the criterion used to evaluate consequences

Arrow Notation

	Solid Line Arrow:	Indicates probabilistic dependence
	Dashed Line Arrow:	Indicates functional dependence

Other Terminology

Predecessor to node A :	Node from which a path leading to A begins
Successor to node A:	Node to which a path leading to A begins
Functional predecessor:	Predecessor node from which a functional arrow emanates
Conditional predecessor:	Predecessor node from which a conditional arrow emanates
Direct predecessor to A:	Predecessor node that immediately precedes A (i.e. the path from it to A does not contain any other nodes)
Direct successor to A:	Successor node that immediately succeeds A (i.e. the path from A to it does not contain any other nodes)
Direct conditional predecessor to A: (A must be a functional node)	A predecessor node from which the path to node A contains only one conditional arrow (may contain functional arrows)
Functional node:	A chance node that receives only functional arrows
Conditional node:	A chance node that receives only conditional arrows
Orphan node:	A node that does not have any predecessors

Figure 2.1 Influence diagram notation and terminology

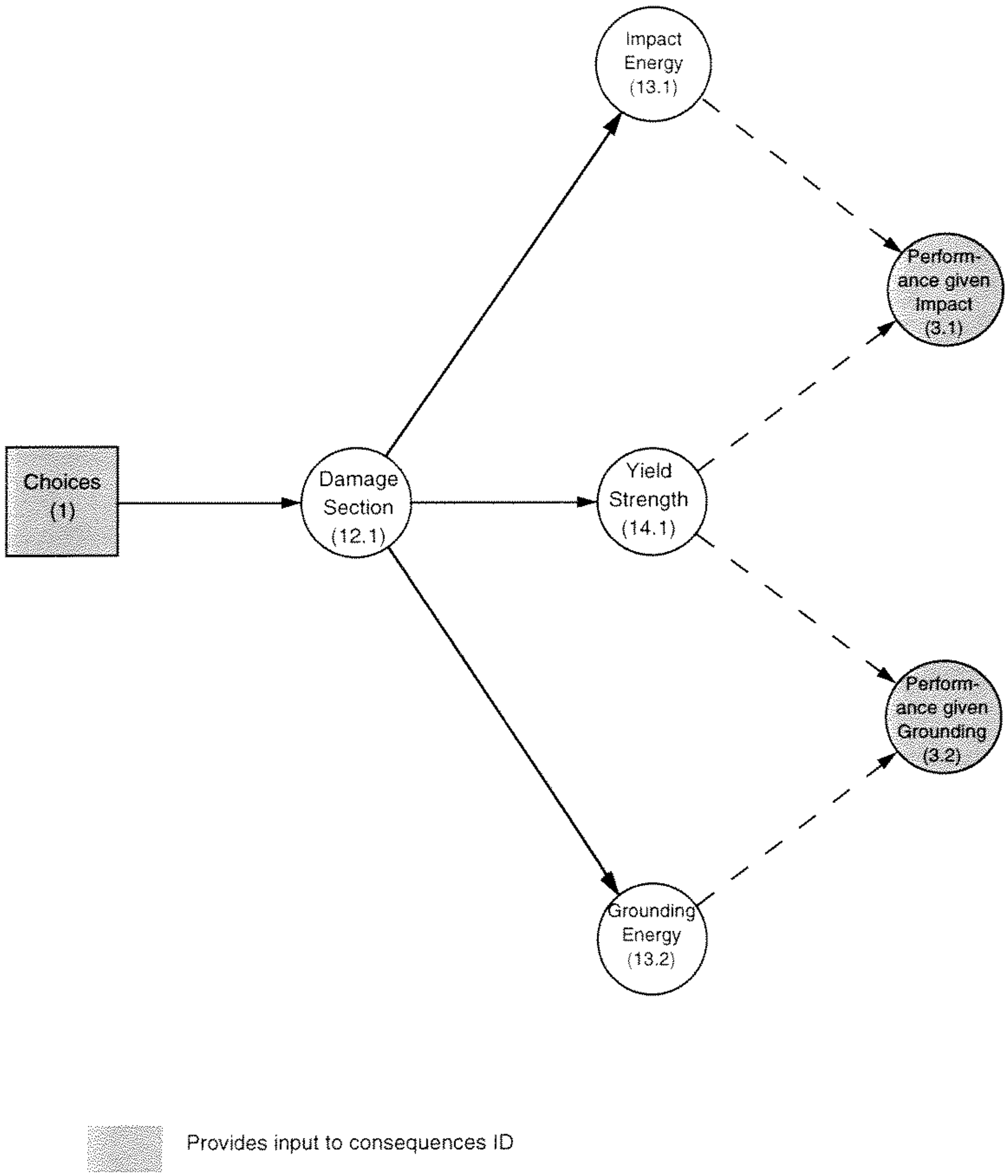


Figure 2.2 Influence diagram for mechanical damage failure probability estimation.

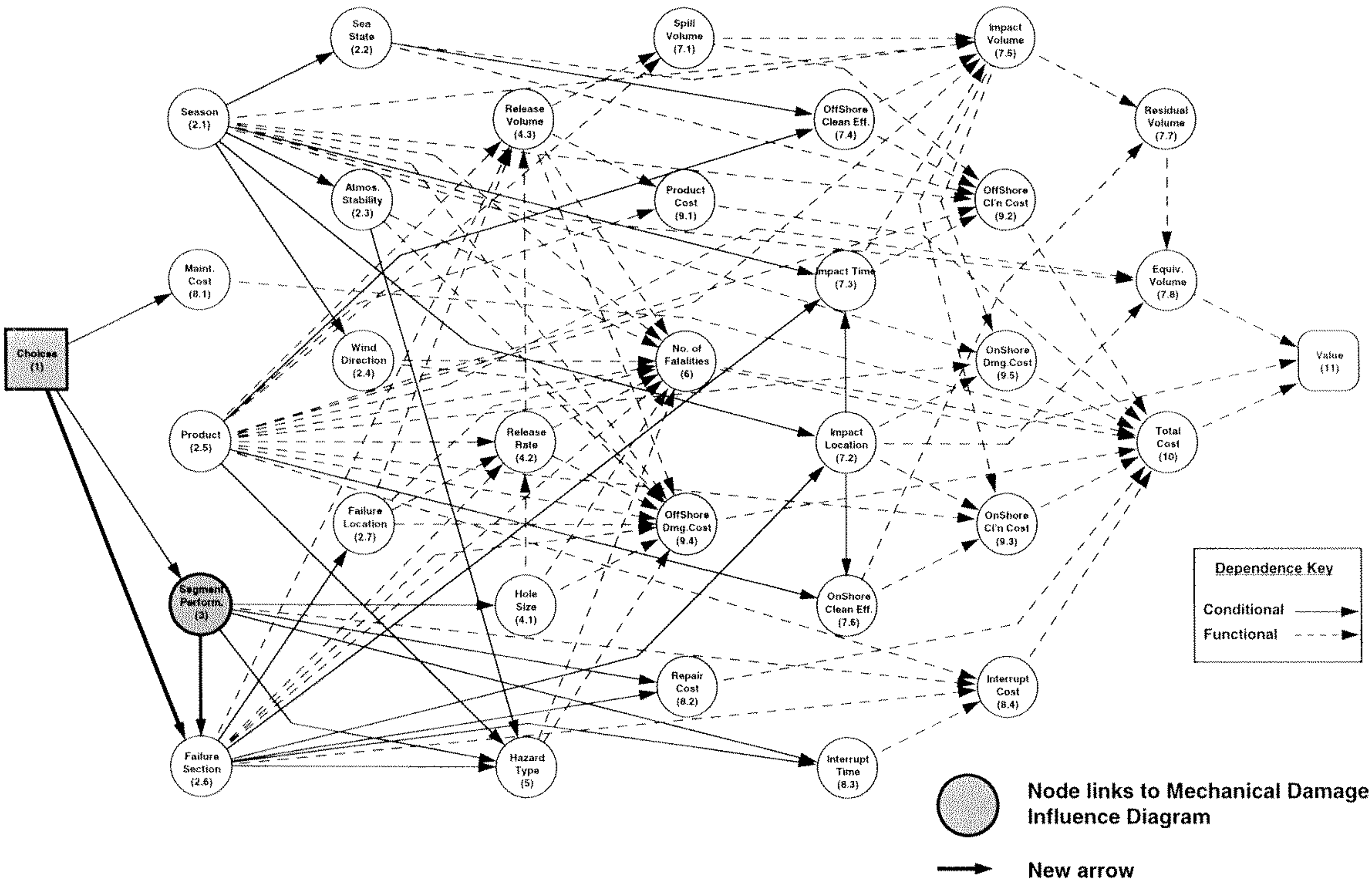


Figure 2.3 Decision influence diagram for consequence analysis and integrity maintenance optimization

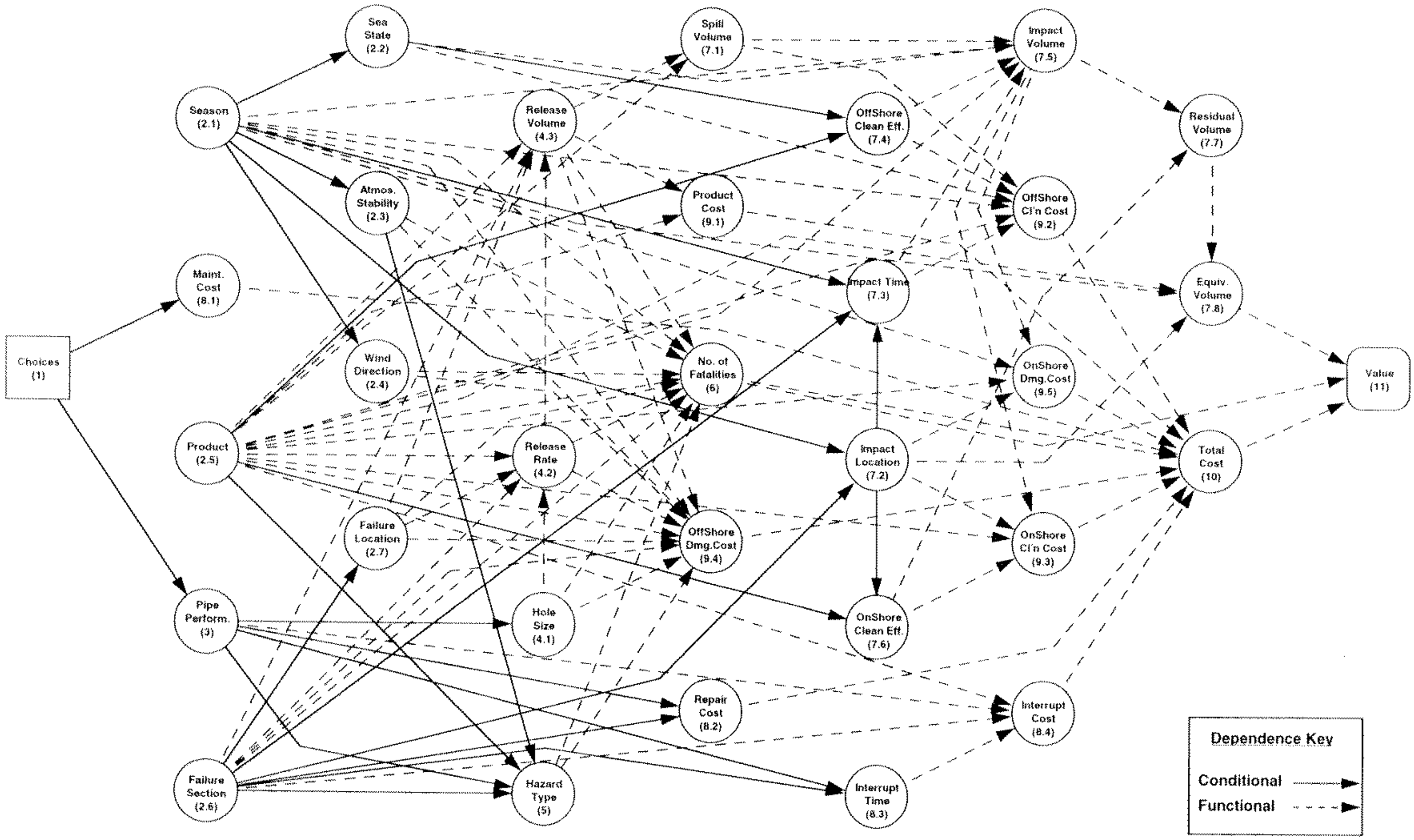


Figure 2.4 Decision influence diagram for integrity maintenance optimization of offshore pipeline systems (Stephens et al. 1996)

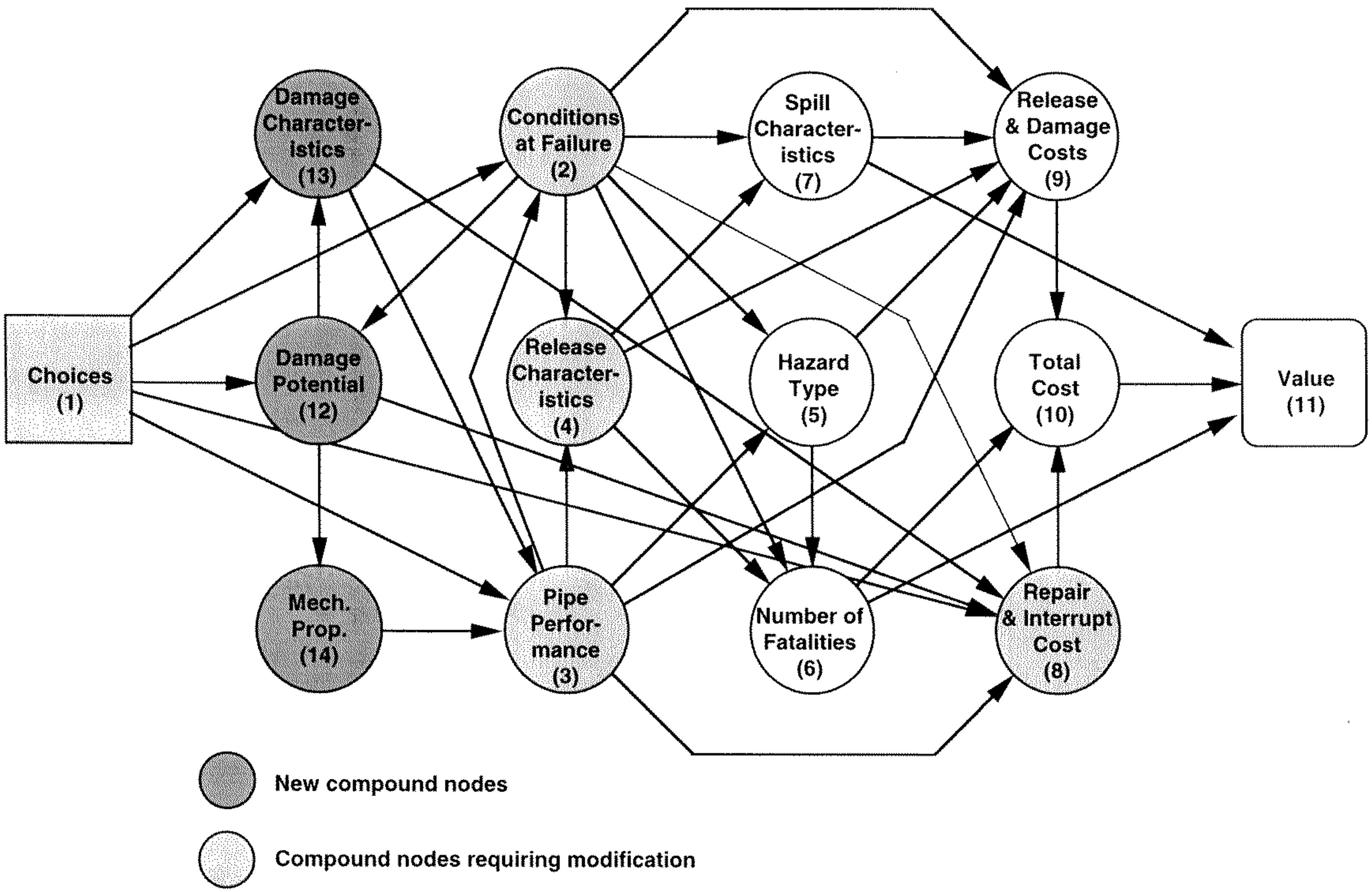


Figure 2.5 Compound node influence diagram for optimization of mechanical damage prevention

3. CHOICES

3.1 Node Parameter

The Choices node group (group 1) is highlighted in the version of the compound node influence diagram shown in Figure 3.1. This node group consists of a single Choices node that represents the preventative maintenance decision to be considered. The Choices node (node 1) is highlighted in the version of the basic node mechanical damage influence diagram shown in Figure 3.2. The specific decision parameter is the discrete set of integrity maintenance choices, as defined by the decision maker, that are to be evaluated using the influence diagram.

3.2 Available Preventative Maintenance Actions

In the context of the decision analysis model that has been developed for mechanical damage prevention, each maintenance choice is assumed to consist of a set of one or more distinct preventative maintenance actions. This approach implies that each choice will reflect the combined impact of each of the associated individual maintenance actions (*i.e.*, the combined benefits in terms of failure probability reduction and the combined costs in terms of initial and annual implementation costs).

A literature review was undertaken to develop a list of physical and operational attributes associated with the pipeline, the seabed corridor, and the sea surface corridor that are considered to have a discernible effect on the potential for failure of an existing subsea pipeline due to mechanical interference. The identified attributes, sorted by category of effect, are as follows:

1. Attributes that affect the awareness of the existence and specific location of a subsea pipeline:
    - level of vessel operator awareness.
2. Attributes that affect the potential for interference resulting from uncontrolled subsea activity.
    - reference cover (i.e., burial depth at time of construction, or at start of maintenance cycle);
    - cover erosion potential (i.e., potential for seabed degradation along pipeline corridor);
    - cover monitoring action (i.e., frequency of cover depth inspection);
    - response to cover monitoring (i.e., criteria for line reburial); and
    - mechanical protection (i.e., existence of armoured jacket or engineered backfill).

A set of candidate preventative maintenance activities was developed from this attribute list by assuming that actions could be undertaken by the operator to alter the state of specific line attributes (excluding cover erosion potential, which is assumed to be an unalterable characteristic of the seabed). These candidate maintenance activities are summarized in Table 3.1.

Figures and Tables

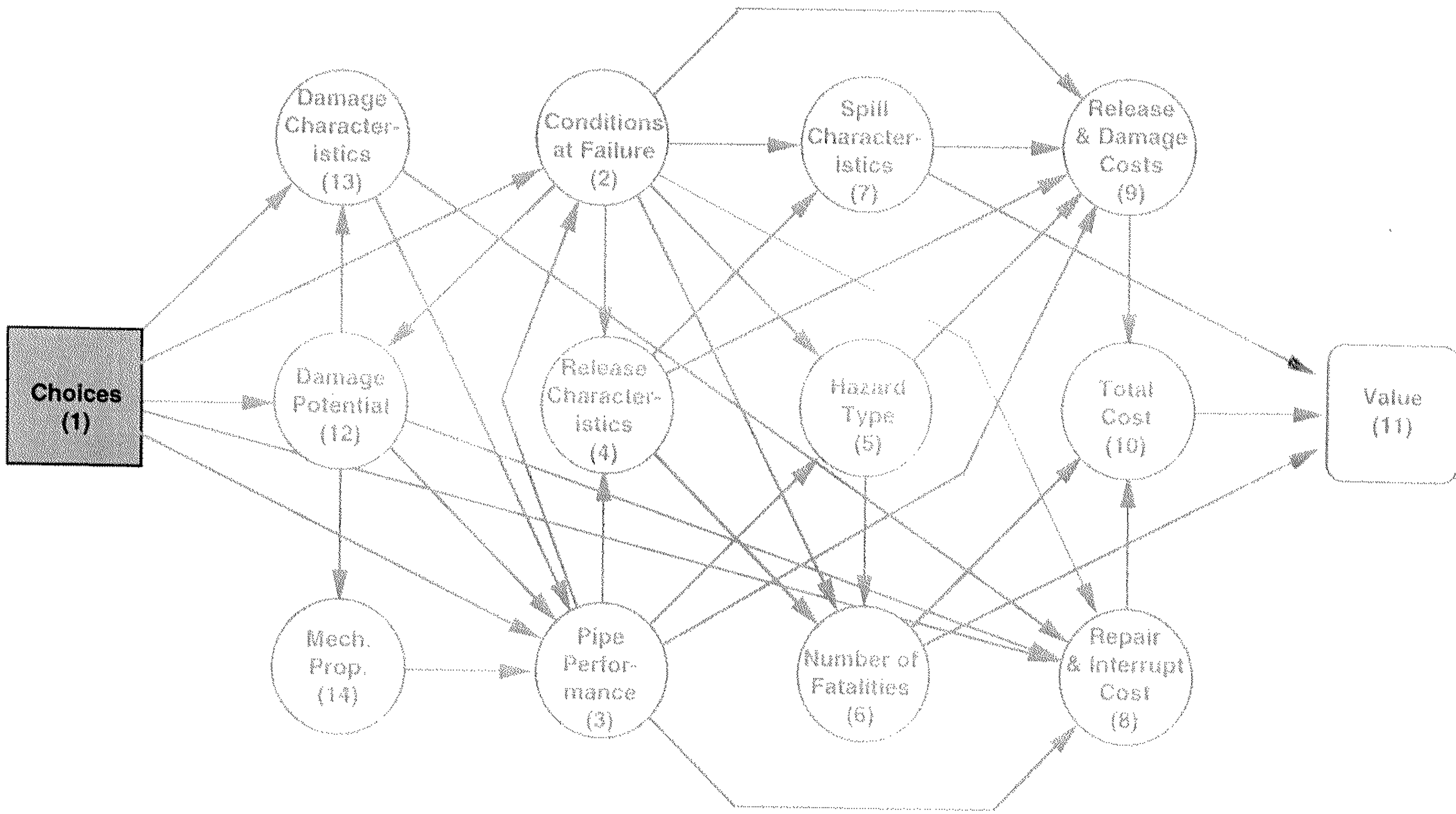


Figure 3.1 Compound node influence diagram highlighting Choices node group.

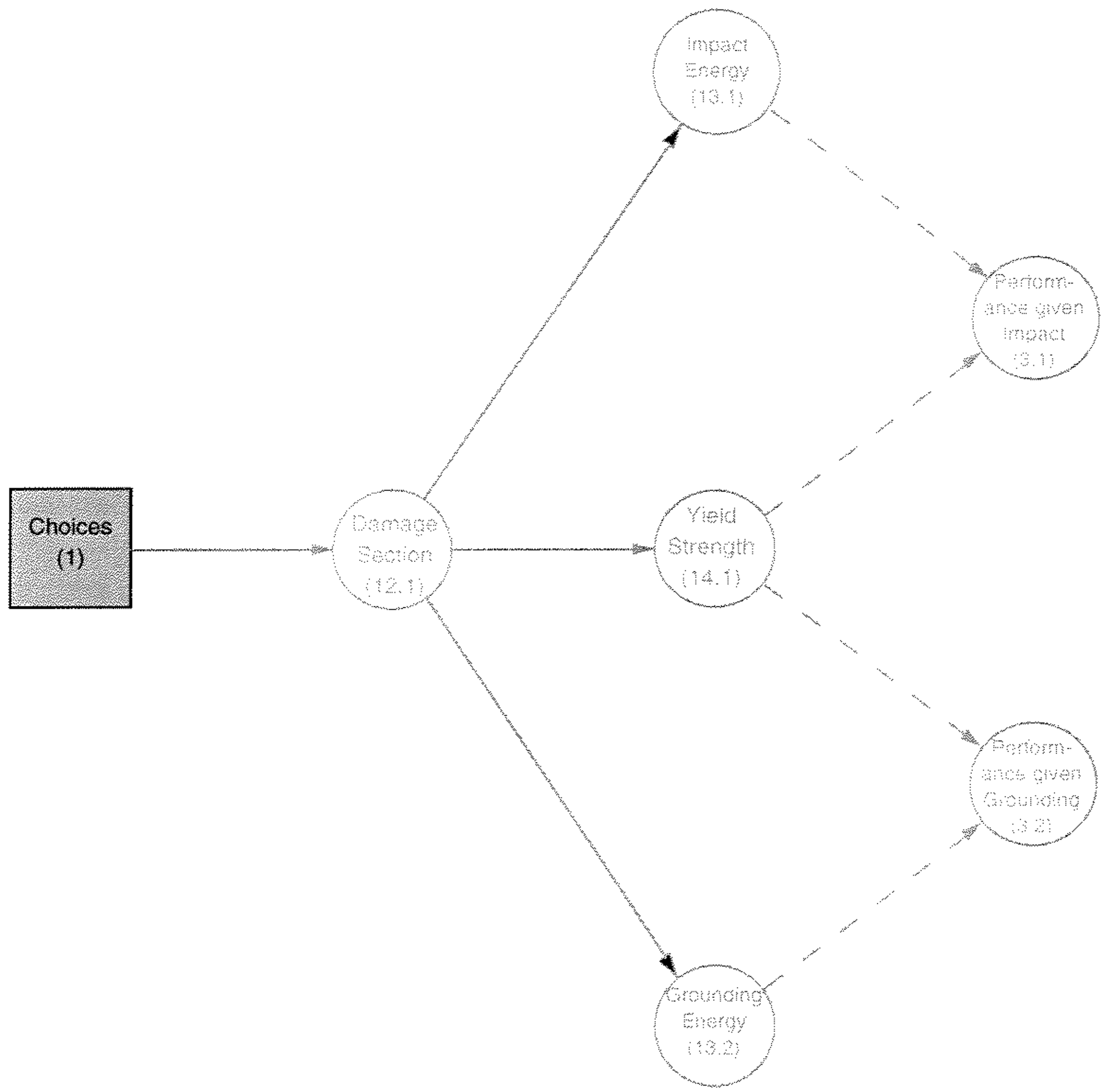


Figure 3.2 Basic node mechanical damage influence diagram highlighting Choices node.

Preventative Maintenance Action	Effect of Action on Factors Contributing to Probability of Failure	
	Awareness of Existence and Location of Line	Potential for Interference given Activity
Enhance level of awareness (of vessel operators)	X	
Modify reference cover (cover at start of maintenance cycle)		X
Modify cover monitoring action (frequency of cover depth inspection)		X
Modify response to cover monitoring (pipeline operator criteria for reburial)		X
Introduce mechanical protection (armoured jacket / engineered backfill)		X

Table 3.1 Choices available for preventative maintenance with regard to mechanical damage

4. DAMAGE POTENTIAL

4.1 Overview

The Damage Potential node group (group 12) is highlighted in the version of the compound influence diagram in Figure 4.1. This node group consists of a single Damage Section node that represents the relative likelihood of occurrence of a mechanical interference event at different locations along the length of the pipeline segment. This node parameter is discussed in Section 4.2.

4.2 Damage Section

4.2.1 Node Parameter

The Damage Section node (node 12.1) and its direct predecessor node are highlighted in the version of the basic node mechanical damage influence diagram shown in Figure 4.2. The Damage Section node parameter is a discrete probability distribution that defines the probability that a randomly occurring mechanical interference event (resulting either from pipeline contact with an object towed from a vessel or from direct pipeline contact with a vessel hull) will occur within a particular portion of the pipeline segment. The predecessor node arrow indicates that Damage Section is a conditional node meaning that the value of the node parameter is conditionally dependent upon the value of its direct predecessor node, which is Choices. The Damage Section node parameter must therefore be defined explicitly for each set of preventative maintenance actions identified at the Choices node.

The node parameter is calculated, for each choice, based on algorithms that have been developed to predict the frequency of pipeline interference events as a function of selected relevant line attributes, recognizing that available preventative maintenance choices effectively serve to modify the existing value of specific line attributes. The number of values associated with the Damage Section node parameter is equal to the number of distinct sections within the pipeline segment being considered, where a section is defined as a length of pipeline over which the line attributes relevant to mechanical damage are constant. Definition of the node parameter therefore requires the specification of all relevant pipeline attributes along the entire length of the pipeline segment. From this information the pipeline segment is sub-divided into distinct damage sections, each section having a common set of attribute values. The frequency of interference events is then estimated for each section of the line segment and these hit frequency estimates are then used to calculate the node parameter (*i.e.*, the relative probability of mechanical interference associated with each section).

Damage Potential

The set of line attributes that are assumed to have an effect on the probability of pipeline failure due to mechanical damage, and are therefore used to define distinct damage sections, are described in Section 4.2.2. The algorithms developed for estimating the line section hit frequency from these attributes is described in Section 4.2.3. Finally, calculation of the discrete probability distribution for the Damage Section parameter from the section hit frequency estimates is described in Section 4.2.4.

4.2.2 Damage Section Attributes

The set of line attributes that must be specified to define a damage section is listed in Table 4.1. These attributes reflect the following considerations:

- The type and density of sea surface vessel traffic crossing the pipeline corridor.
- Activities by the pipeline operator or associated agencies intended to promote vessel operator awareness of the existence and specific location of the pipeline.
- The potential for loss of pipeline cover due to erosion susceptibility of the seabed.
- The pipeline burial depth and measures taken to monitor and maintain the target burial depth.
- Preventative measures, in the form of mechanical protection of the pipe body, intended to limit the potential for mechanical interference resulting from uncontrolled activity.
- Physical and operational characteristics of the pipeline that affect the penetration resistance of the pipe body.

The table contains a complete list of line attributes that are considered to have an impact on the probability of pipeline failure due to mechanical damage. It is noted that subdivision of the pipeline segment into damage sections with consistent probability-related attributes is done independently of subdivision into failure sections with consistent consequence-related attributes. Attributes that affect both mechanical damage potential and failure consequences (as indicated in Table 4.1) are used independently in the two cases.

4.2.3 Estimation of the Frequency of Mechanical Interference Events

As outlined above, calculation of the Damage Section node parameter requires a model that can estimate the frequency of pipeline interference events as a function of the damage section attributes (see Table 4.1). Implicit in the modeling approach is the recognition that available preventative maintenance choices (see Table 3.1) effectively serve to modify the base-case values of selected line attributes. A model that reflects the impact of changes in the values of the line attributes that affect the interference frequency can therefore be used to estimate the impact of preventative maintenance actions on the probability of line failure and the associated level of operating risk.

Damage Potential

4.2.3.1 Analysis Approach

The modeling approach adopted to estimate interference frequency is based on the so-called *fault tree analysis* method. This method was developed in the aerospace industry in the early 1960's (Barlow and Lambert 1975) and has since been utilized for many applications including nuclear facilities, chemical plants, offshore oil and gas systems, and pipelines. A fault tree is a deductive model that identifies the logical combinations of *basic events* leading to the main accidental event being analyzed (referred to as the *top event*). In the present application, the top event is defined as "mechanical interference", which is assumed to result either from pipeline contact with an object towed from a vessel or direct contact between the pipeline and a vessel hull.

Construction of a fault tree is a top down process in which the top event is identified and related to the events that contribute directly to its occurrence (called intermediate events). Each intermediate event is then related to its direct contributors until the basic events are reached at the bottom of the tree. In constructing a fault tree, two main types of event relationships are considered: the AND relationship, which means that a number of events must coexist for the output event to occur; and the OR relationship, which means that any one (or more) of a number of events could cause the output event to occur.

4.2.3.2 Mechanical Interference Fault Trees

The fault trees developed to model mechanical interference, one for towed object impact and another for vessel hull grounding, are shown in Figure 4.3. The different shapes used in the figures follow standard fault tree notation. Branching points are called *gates* and are characterized by different shapes representing the AND and OR relationships defined earlier (see legend in Figure 4.3). An event that is defined as the result of other event combinations is called an output event and is placed in a rectangle. At the bottom of each branch of the tree the basic events are placed in circles.

The fault tree in Figure 4.3a models the top event of a pipeline hit by an object that is towed from behind a surface vessel. It is assumed that the object is either intentionally deployed (i.e., net gear) in the case of a commercial fishing vessel, or unintentionally dragged (i.e., an anchor) in the case of shipping. The first level of branching states that a line hit occurs if: the towed object comes in contact with the seabed over the alignment (intermediate event E2a) and the protective measures in place fail to prevent direct contact between the object and the pipe body (intermediate event E3a). Both of these events must be true for a hit to occur and therefore they are connected with an AND gate (gate 1a). At the second branch level, gate 2a states that object contact with the seabed will occur if there is a vessel crossing the alignment (basic event B1) AND the vessel happens to have net gear deployed if the area is a designated fishing zone, or is dragging an anchor if the area is a designated shipping corridor (basic event B2a). Gate 3a indicates that on-bottom protective measures will fail if both the depth of seabed disturbance associated with the towed object exceeds the cover depth (basic event B3a) AND the mechanical protection, if present, fails to prevent the object from contacting the pipe body (basic event B4a).

Damage Potential

The fault tree in Figure 4.3b models the top event of a pipeline hit by the hull of a grounding vessel. The first level of branching states that a line hit occurs if: there is vessel hull contact with the seabed over the alignment (intermediate event E2b) and the protective measures in place fail to prevent direct contact between the vessel hull and the pipe body (intermediate event E3b). Both of these events must be true for a hit to occur and therefore they are connected with an AND gate (gate 1b). At the second branch level, gate 2b states that vessel hull contact with the seabed will occur if there is a vessel crossing the alignment (basic event B1) AND the vessel draft exceeds the water depth (basic event B2b). Gate 3b indicates that on-bottom protective measures will fail if both the depth of seabed disturbance associated with vessel grounding exceeds the cover depth (basic event B3b) AND the mechanical protection, if present, fails to prevent the vessel hull from contacting the pipe body (basic event B4b).

4.2.3.3 Frequency Estimation based on the Mechanical Interference Fault Trees

The fault trees shown in Figure 4.3 can be used to estimate the probability (or frequency) of mechanical interference from the probabilities (or frequencies) of the basic events where each basic event probability is assumed to be a function of the value of selected Damage Section line attributes. In general, the complexity and accuracy of the calculation procedure depends on the characteristics of the fault tree (see McCormick 1981 for more details). For the trees shown, which assume independence between all basic events, output event probabilities can be calculated directly from the basic principles of probability theory.

Based on these principals, the probability associated with the outcome, p_O, of an AND gate can be calculated from:

$$p_O = p_{I1} \cdot p_{I2} \cdot p_{I3} \cdots\cdots \qquad [4.1]$$

where p_{I1}, p_{I2}, p_{I3}, are the probabilities of the input events to the associated gate. For an OR gate the outcome probability is given by:

$$p_O = 1 - [(1 - p_{I1}).(1 - p_{I2}).(1 - p_{I3}).......] \qquad [4.2]$$

The quantity in the square brackets in Equation [4.2] gives the probability that none of the input events will occur. Subtracted from 1, the result represents the probability that at least one of these events will occur, which is a sufficient condition for the output event to take place.

For the fault trees developed for mechanical interference, note that the basic event associated with sea surface vessel activity on the alignment (event B1) is defined by a crossing rate, r_{B1}, in units of crossing events per unit line length per year. Because the surface activity level is defined by a crossing frequency, the top event in the tree (event E1), therefore becomes a probability weighted frequency estimate characterizing the rate of occurrence of mechanical interference events, r, also in units of events per unit line length per year.

Damage Potential

The interference frequency estimation algorithm implicit in both fault trees takes the form:

$$r = r_{B1}\, p_{B2}\, p_{B3}\, p_{B4} \qquad [4.3]$$

where p_{B_i} is the probability of occurrence of basic event *Bi*. The basis for an estimate of the basic event probabilities required to solve Equation [4.3] is given in Section 4.2.3.4.

4.2.3.4 Basic Event Characterization Models

The probability (or frequency) of occurrence for each basic event associated with the fault trees shown in Figure 4.3 is assumed to be a function of the values of a sub-set of the Damage Section line attributes. The following is a description of the models that have been developed to estimate basic event probabilities from line attribute values.

Note that for many of the basic events considered herein, the relationships between relevant line attributes and the event probability are both subtle and complex. Where these underlying relationships are not well understood, or where a clear and simple analytical model could not express them, an empirical approach was adopted, provided that historical data was available to support model development. Where the current lack of understanding of underlying relationships, or the lack of historical data, precluded the use of either analytical or empirical models, a subjective approach based on engineering judgement was adopted. Note, also, that in some instances the probability estimation models developed reflect a combined approach where, for example, an analytical model was used to define basic relationships or trends and historical data and/or judgement was then used to benchmark the probability estimate for a representative set of attribute values.

4.2.3.4.1 Surface Vessel Activity on Alignment

Surface vessel activity over the pipeline corridor (basic event B1 in both the towed object and grounding vessel fault trees shown in Figures 4.3a and 4.3b), as defined by a rate or frequency of pipeline crossing events, is assumed to depend on whether or not the alignment intersects designated commercial fishing zones, shipping corridors, or platform safety zones. It is also assumed to depend on the density of vessel traffic within each of the traffic zone types. The set of values associated with the section attributes Vessel Traffic and Adjacent Platform can therefore be used to define a matrix of attribute value combinations, each of which is potentially associated with a different crossing rate estimate. The crossing rate matrix is shown in Table 4.2.

Note that the format of the crossing rate matrix shown in Table 4.2 implies that in the vicinity of fixed offshore platforms the activity level is independent of the type and density of surrounding fishing or shipping traffic. This assumption is based on the premise that a traffic exclusion area will always be maintained in the safety zone surrounding a platform. Note also that the crossing rate within the platform safety zone is assumed to be a direct function of platform type (i.e., manned vs. unmanned, major vs. minor).

A generally accepted set of offshore pipeline crossing rate estimates, as a function of vessel traffic type (and density) or platform type, is not currently available in the public domain. Representative crossing rate estimates were therefore developed based on selected historical data and judgement. The adopted reference values are summarized in Table 4.2. The basis for the tabulated values is given below.

For shipping traffic, a heavily used traffic lane can be assumed to involve between 10,000 and 100,000 annual vessel passages (e.g., Fujii et al. 1974, Macduff 1974, and Pederson 1995). In 1985 it was estimated that there were as many as three million vessels trips through 24 major waterways in the Gulf of Mexico (Reed 1987), which averages to 12,500 trips per waterway. Assuming a representative high-end annual traffic volume of 50,000 passages and a corridor width of five kilometres gives a crossing rate of 10,000 events per km yr. Adopting this crossing rate for high density traffic areas and progressively reducing this rate by one and then two orders of magnitude for medium and low traffic density areas, respectively, gives the shipping traffic crossing rates shown in the table.

For commercial fishing traffic, a crossing rate model reported by Bilderbeck et al. (1995) takes the form:

$$r = \frac{2}{\pi}\frac{T\,v}{L^2} \qquad [4.4]$$

where T is the number of hours fished per year at trawl speed v in an area approximated as a square of side length L.

Based on the above model a representative crossing rate of 4.4 events per km yr is sited by Bilderbeck et al. for an actively fished area in the UK sector of the North Sea. Rounding this rate estimate up to ten events per km yr, adopting this as a representative crossing rate for high density traffic areas, and reducing this rate by first one and then two orders of magnitude for medium and low traffic density areas, respectively, gives the fishing traffic crossing rates shown in the table.

For vessels operating within the platform safety zone, it can be assumed that the pipeline crossing rate is proportional to the number of trips made to the platform by service vessels. It is also reasonable to assume that major and minor manned platforms are serviced by supply vessels on the order of once per day and once every other day, respectively, and major and minor unmanned platforms are serviced by supply vessels on the order of twice per week and once per week, respectively. Making a final conservative assumption that each round trip to the platform will involve one crossing of a pipeline that falls within the platform safety zone yields (to one significant figure) the tabulated platform service traffic crossing rate estimates.

4.2.3.4.2 Towed Object Deployment

The probability that a vessel crossing the pipeline alignment will be towing an intentionally deployed object or an unintentionally dragged object, that is in contact with the seabed (basic event B2a in the fault tree shown in Figure 4.3a), is assumed to depend on: the type of vessel traffic, the water depth, and the general level of vessel operator awareness of the presence and significance of subsea pipelines in the area. The set of values associated with the damage section attributes: Vessel Traffic, Water Depth Range (as calculated from the pipeline elevation profile), and Level of Awareness can therefore be used to define a matrix of attribute value combinations each of which is associated with a potentially different event probability. The corresponding event probability matrix is shown in Table 4.3.

Development of event probability estimates for this basic event involved establishing representative event probabilities for all possible combinations of Vessel Traffic Type and Water Depth, taking into account the potential effect of vessel operator awareness on the overall event probability. The adopted event probability estimates are summarized in Table 4.3 and the basis for the adopted values is given below.

For areas designated as shipping corridors, it is assumed that in water depths that permit anchoring (typically less than 150 m) there is a general likelihood of approximately 1×10^{-7} that an emergency or accident scenario will develop during a crossing event resulting in anchor drag across a pipeline. The basis for this reference deployment probability is as follows. A reasonable estimate of the likelihood that a vessel will experience a loss of control incident requiring anchoring is on the order of 1×10^{-3} per trip. Assuming that a typical trip covers a distance of 1000 km, and assuming further that typical anchor drag distances range from 50 m in hard clay to 200 m in mud (Colquhoun 1985), it follows that the likelihood that the drag path of an anchor deployed at some time during the trip will intersect a randomly selected point on the vessel path is equal to the drag distance divided by the trip distance, which is on the order of 1×10^{-4}. Given the assumed likelihood of anchor deployment of 1×10^{-3} and a likelihood of drag path conflict given deployment of about 1×10^{-4}, the resulting total probability of anchor drag conflict is on the order of 1×10^{-7}.

In deeper water, specifically water depths ranging from 150 m to 300 m, the above anchor deployment probability is thought to be reduced by an order of magnitude to 1×10^{-8}, since only a small fraction of the total vessel traffic with have anchor chains of sufficient length to make an attempt at anchoring worthwhile. In water deeper than 300 m, it is assumed that no anchor contact with the seabed is possible (i.e., the deployment probability is 0).

Operator awareness level is assumed to have a relatively small effect (i.e., ± 10%) on the anchor deployment probability in shipping corridors since vessel operators responding to emergency situations tend to be distracted by the situation at hand and therefore may not take into consideration knowledge that they may have of the presence of and potential for damage to subsea pipelines in the area.

Damage Potential

For areas designated as commercial fishing zones, it is conservatively assumed that net gear is always deployed and in contact with the seabed (i.e., probability of towed object deployment is 1.0) in water depths not exceeding 150 m. The 150 m water depth is taken to be the practical limit for typical net gear and it is therefore assumed that no gear will be deployed and in contact with the seabed in deeper water (i.e., the probability of towed object deployment is 0.0).

Operator awareness level is assumed to have no effect on the net gear deployment probability since fishing vessel operators typically assume that subsea pipelines located in designated fishing areas are protected from net gear damage through burial or other means.

Finally, within platform safety zones, it is assumed that there is a general likelihood of approximately 1×10^{-5} that an emergency or accident scenario will develop during service vessel anchoring resulting in anchor drag across a pipeline. The basis for this reference deployment probability is as follows. Based on work by Macduff (1974) on historical vessel accident *causation probabilities* a representative estimate of the likelihood that a vessel will experience a loss of control incident on approach to a platform is on the order of 1×10^{-4} per trip. Assuming that a typical platform supply trip covers a distance of 1 km (i.e., twice the standard 500 m safety zone radius) and assuming further that a typical anchor set distance is on the order of 100 m, it follows that the likelihood that the drag path of an anchor deployed at some time during passage through the safety zone will intersect a randomly selected point on the vessel path is equal to the drag distance divided by the trip distance, which is on the order of 1×10^{-1}. Given the assumed likelihood of anchor deployment of 1×10^{-4} and a likelihood of drag path conflict, given deployment of about 1×10^{-1}, the resulting total probability of anchor drag conflict is on the order of 1×10^{-5}.

The above deployment probability is considered to apply to the safety zone for all platforms in water depths up to 300 m on the assumption that all vessels servicing a platform will have chain lengths sufficient to permit anchoring. In water deeper than 300 m, it is assumed that supply vessels will anchor to a permanent floating mooring installation and no anchor contact with the seabed will therefore occur (i.e., the deployment probability is 0).

Operator awareness level is assumed to have a significant effect (i.e., ± 50%) on the anchor deployment probability in platform safety zones because vessel operators are well aware of the presence of and potential for damage to subsea pipelines in the area.

4.2.3.4.3 Seabed Disturbance Depth Due to Towed Object Exceeds Cover

The probability that the depth of seabed disturbance caused by a towed object in contact with the seabed will exceed the cover depth (basic event B3a in the fault tree shown in Figure 4.3a) is assumed to depend on the type of vessel towing the object and by inference the likely type of object being towed (i.e., fishing net gear vs. anchor) as well as the effective pipeline cover depth at the time of the event. The effective cover depth is assumed to depend on the depth of pipeline cover at the time of construction (or at the start of the current inspection and maintenance cycle), the potential for cover depth reduction due to seabed erosion, the frequency of cover depth inspection, and the operators response to the findings of a cover depth inspection. The set of values associated with the damage section attributes Vessel Traffic, Reference Cover, Cover Erosion Potential, Cover Monitoring Action, Response to Cover Monitoring, and Water Depth Range (as calculated from pipeline elevation profile) can therefore be used to define a matrix of attribute value combinations, each of which is associated with a potentially different event probability. The event probability matrix is shown in Table 4.4.

Note that this event probability matrix shown in Table 4.4 references three distinct *effective cover depth* categories. The effective cover depth is not a damage section attribute but rather a characterization of the likely pipeline cover depth at a future point in time as inferred from the value of the damage section attributes: Reference Cover, Cover Erosion Potential, Cover Monitoring Action, Response to Cover Monitoring, and Water Depth Range. The assumed relationships between the various line attributes associated with pipe cover and the effective cover depth is shown in Table 4.5.

The basic assumptions underlying the relationships implied by Table 4.5 are as follows:

- a non-eroding seabed will maintain pipeline cover except in the case of storm disturbance;
- an eroding seabed will eventually eliminate pipeline cover unless it is maintained;
- severe storms can eliminate pipeline cover in water depths less than 5 m;
- severe storms can reduce pipeline cover in water depths between 5 and 20 m;
- periodic cover monitoring is more effective than inspection only after severe storms;
- line reburial if the line is exposed is equivalent to maintaining limited or variable cover; and
- line reburial if cover falls below design minimum is equivalent to maintaining design cover.

With effective cover depths established as per Table 4.5, development of event probability estimates for the basic event of seabed disturbance depth exceeding cover depth involved establishing representative event probabilities for all possible combinations of Vessel Traffic and Effective Cover Depth. The adopted event probability estimates are summarized in Table 4.4. The basis for the adopted values is the assumption that the depth of seabed disturbance associated with fishing net gear is negligible whereas the corresponding disturbance depth associated with dragging anchors is typically always greater than the depth of cover for pipelines buried according to industry standard practice (Colquhoun 1985).

The above implies that in commercial fishing areas, the probability that the disturbance depth will exceed the pipeline cover depth is 1.0 for lines with no cover and 0.0 for lines with cover to minimum requirements. For lines having intermittent or variable cover the event probability is set to an intermediate value of 0.5.

For shipping corridors and platform safety zones, where anchor drag is the issue, the probability that the disturbance depth will exceed the pipeline cover is taken to be 1.0 regardless of the effective depth of pipeline cover.

4.2.3.4.4 Failure of Mechanical Means to Protect against Towed Objects

The probability that mechanical protection (i.e., armoured jacket or engineered backfill) will fail to protect the pipe body from interference damage caused by towed objects contacting the seabed (basic event B4a in the fault tree shown in Figure 4.3a) is assumed to depend on the type of vessel involved in the interference event and the type of mechanical protection. The set of values associated with the damage section attributes Vessel Traffic and Mechanical Protection can therefore be used to define a matrix of attribute value combinations, each of which is associated with a potentially different event probability. The event probability matrix is shown in Table 4.6.

Development of event probability estimates for this basic event involved establishing representative event probabilities for all possible combinations of Vessel Traffic and Mechanical Protection. The adopted event probability estimates are summarized in Table 4.6 and the basis for the adopted values is as follows. It is assumed that an armoured jacket will provide complete protection against failure due to net gear impact but no protection against failure due to anchor hooking, whereas engineered backfill will provide complete protection against failure due to both net gear impact and anchor hooking. The underlying assumption is that the flukes of an anchor can still hook a jacket-protected pipeline but engineered backfill will destabilize and turn an anchor preventing the flukes from hooking the pipeline (Hvam et al. 1990). Note that this assumption conservatively ignores the extra resistance to anchor induced local denting afforded by an armoured jacket.

4.2.3.4.5 Vessel Draft Exceeds Water Depth

The probability that the draft of a vessel attempting to cross the pipeline corridor will exceed the water depth, or the likelihood of a vessel grounding over the pipeline, (basic event B2b in the fault tree shown in Figure 4.3b) is assumed to depend on: the type (and by implication draft) of vessel, the water depth, and the general level of vessel operator awareness (of the presence and significance of subsea pipelines in the area). The set of values associated with the damage section attributes: Vessel Traffic, Water Depth Range (as calculated from the pipeline elevation profile), and Level of Awareness can therefore be used to define a matrix of attribute value combinations each of which is associated with a potentially different event probability. The corresponding event probability matrix is shown in Table 4.7.

Development of event probability estimates for this basic event involved establishing representative event probabilities for all possible combinations of Vessel Traffic Type and Water Depth, taking into account the potential effect of vessel operator awareness on the overall event probability. The adopted event probability estimates are summarized in Table 4.7 and the basis for the adopted values is given below.

For areas designated as shipping corridors, it is assumed that if a localized area of shallow water (i.e., a shoal) exists, there is a general likelihood of approximately 1×10^{-6} that a vessel with grounding potential, on a course that would traverse the shallow water hazard, will fail to steer clear and end up grounding on top of the pipeline. The basis for this reference grounding probability is as follows. Based on work by Fujii et al. (1974) on historical vessel *mismanoeuvre probabilities* a representative estimate of the likelihood that a vessel will fail to change course to avoid collision with a fixed hazard is on the order of 1×10^{-4} per hazard encounter. Assuming that failure to avoid the hazard will definitely lead to grounding if the vessel draft exceeds the depth of the water, it remains necessary to estimate the likelihood that a grounding event will actually involve the pipeline. Unfortunately, the nature of a specific grounding event is highly location specific because it depends on the relative location of the pipeline within the shallow water area, the topography of the seabed, and the direction of vessel travel. Given that the information necessary to characterize these parameters cannot readily be distilled into simple pipeline system attributes, it is assumed for simplicity that if grounding occurs there is a 1 in 100 chance that the path of the grounding vessel will actually intersect the pipeline alignment.

Given the assumed likelihood of grounding due to mismanoeuvre of 1×10^{-4} and a likelihood of grounding path conflict with the pipeline given grounding of about 1×10^{-2}, the resulting total probability of vessel grounding over the pipeline alignment is on the order of 1×10^{-6}. (Note that this conditional event probability, when multiplied by a moderate shipping traffic density of 1000 crossings per km yr, gives a vessel on pipeline grounding frequency of 1×10^{-4}, which is of the same order of magnitude as estimates reported by Colquhoun 1985 for shoal areas in the major shipping corridor through the Danish Great Belt.)

The above shipping traffic grounding probability applies only to a vessel with grounding potential (i.e., a vessel having a draft greater than the water depth). The fraction of shipping with grounding potential depends on the water depth. Based on displacement data reported by Rasmussen (1983) for shipping traffic in the Danish Great Belt, and draft vs. displacement relationships given by Larsen (1983), representative estimates of the percentage of shipping traffic with grounding potential as a function of water depth can be developed. For fully loaded vessels the percentage with grounding potential is estimated to be: 100 % in 5 m water, 40 % in 10 m water, 2 % in 15 m water, and 0.05 % in 20 m water. For vessels in ballast (i.e., empty) the percentage with grounding potential is estimated to be: 50 % in 5 m water, 0.4 % in 10 m water, and 0 % in 15 m water.

Based on the above estimates, and assuming that a grounding vessel is equally likely to be either fully loaded or in ballast, the following grounding potentials are assumed for discrete water depth ranges: 100 % for water depths of 0 to 5 m, 50 % for depths of 5 to 10 m, 10 % for depths of 10 to 15 m, 0.5 % for depths of 15 to 20 m, and 0 % for depths greater than 20 m. Multiplying these grounding potentials by the reference grounding probability of 1×10^{-6} gives the following event probability estimates: 1×10^{-6} for water depths of 0 to 5 m, 5×10^{-7} for depths of 5 to 10 m, 1 x 10^{-7} for depths of 10 to 15 m, 5 x 10^{-9} for depths of 15 to 20 m, and 0 for depths greater than 20 m.

Operator awareness level is assumed to have a significant effect (i.e., ± 50%) on the grounding probability in shipping traffic zones since vessel operator awareness of the presence a subsea pipeline can be assumed to imply a general familiarity with the seabed hazards in the area. This being the case, the assumed magnitude of the effect on grounding frequency is supported by Fujii et al. (1974) who have reported that the grounding frequency for domestic traffic (assumed to be familiar with the local hazards) is significantly less than half the frequency for foreign traffic (assumed to be less familiar with the local hazards).

For areas designated as commercial fishing zones, it is assumed that there is no chance of vessel grounding in water depths greater than 5 m; this being slightly greater than the maximum draft associated with virtually all commercial fishing vessels. In water less than 5 m deep, it is assumed that while vessel operators working the area are in general familiar with the seabed topography, there remains a finite potential for grounding due to mismanoeuvre. Starting with Fujii's basic mismanoeuvre probability of 1 x 10^{-4}, and assuming that the potential increase in mismanoeuvre probability for shallow water fishing vessels (due to the fact that they are constantly negotiating shallow areas) is offset by the fact that only a fraction of all vessels have a draft sufficient to cause grounding, leads to a grounding frequency estimate equal to the basic mismanoeuvre probability. Assuming further that a shallow water grounding event involving a fishing vessel will not necessarily stop the forward progress of the vessel (i.e., a grounding vessel will ultimately intersect the pipeline alignment), the resulting total probability of fishing vessel grounding over the pipeline alignment is estimated to be on the order of 1 x 10^{-4}.

Note that operator awareness level is assumed to have no effect on the fishing vessel grounding probability since vessel operators typically assume that subsea pipelines located in designated fishing areas are protected from damage through burial or other means.

Finally, within platform safety zones, it is assumed that there is virtually no chance of vessel grounding since the operators of all vessels servicing a platform are assumed to be aware of draft restrictions associated with the platform in question.

4.2.3.4.6 Seabed Disturbance Depth Due to Grounding Exceeds Cover

The probability that the depth of seabed disturbance resulting from a vessel grounding event will exceed the cover depth (basic event B3b in the fault tree shown in Figure 4.3b) is assumed to depend on the type (and, by implication, size) of vessel involved in the grounding event and the effective depth of pipeline cover at the time of the event. The effective cover depth is assumed to depend on the depth of pipeline cover at the time of construction (or at the start of the current inspection and maintenance cycle), the potential for cover depth reduction due to seabed erosion, the frequency of cover depth inspection, and the operators response to the findings of a cover depth inspection. The set of values associated with the damage section attributes Vessel Traffic,

Damage Potential

Reference Cover, Cover Erosion Potential, Cover Monitoring Action, Response to Cover Monitoring, and Water Depth Range (as calculated from pipeline elevation profile) can therefore be used to define a matrix of attribute value combinations, each of which is associated with a potentially different event probability. The event probability matrix is shown in Table 4.8.

Note that the event probability matrix shown in Table 4.8 references three distinct *effective cover depth* categories. The effective cover depth is not a damage section attribute but rather a characterization of the likely pipeline cover depth at a future point in time as inferred from the value of the damage section attributes: Reference Cover, Cover Erosion Potential, Cover Monitoring Action, Response to Cover Monitoring, and Water Depth Range. The assumed relationships between the various line attributes associated with pipe cover and the effective cover depth is shown in Table 4.5. See Section 4.2.3.4.3 for a discussion of the underlying basis for the assumed relationships.

Development of event probability estimates for this basic event involved establishing representative event probabilities for all possible combinations of Vessel Traffic and Effective Cover Depth. The adopted event probability estimates are summarized in Table 4.8 and the basis for the adopted values is as follows. It is assumed that the depth of seabed disturbance associated with fishing vessel grounding is finite but limited due to the relatively limited displacement of typical fishing vessels, whereas the corresponding disturbance depth associated with the grounding of shipping or platform service vessels is typically always greater than the depth of cover for pipelines buried according to industry standard practice.

Based on the above it is assumed that in commercial fishing areas, the probability that the disturbance depth will exceed the pipeline cover depth is 1.0 for lines with no cover and 0.1 for lines with cover to minimum requirements. For lines having intermittent or variable cover the event probability is set to an intermediate value of 0.5.

For shipping corridors and platform safety zones, where the displacement of grounding vessels is potentially very large, the probability that the disturbance depth will exceed the pipeline cover is conservatively taken to be 1.0 regardless of the effective depth of pipeline cover.

4.2.3.4.7 Failure of Mechanical Means to Protect against Vessel Grounding

The probability that mechanical protection (i.e., armoured jacket or engineered backfill) will fail to protect the pipe body from interference damage caused by vessel grounding (basic event B4b in the fault tree shown in Figure 4.3b) is assumed to depend on the type (and, by implication, size) of vessel involved in the grounding event and the type of mechanical protection. The set of values associated with the damage section attributes Vessel Traffic and Mechanical Protection can therefore be used to define a matrix of attribute value combinations, each of which is associated with a potentially different event probability. The event probability matrix is shown in Table 4.9.

Damage Potential

Development of event probability estimates for this basic event involved establishing representative event probabilities for all possible combinations of Vessel Traffic and Mechanical Protection. The adopted event probability estimates are summarized in Table 4.9 and the basis for the adopted values is the assumption that neither an armoured jacket nor engineered backfill will provide protection against pipeline failure due to vessel hull grounding. Note that this assumption conservatively ignores the extra resistance to local denting damage afforded by an armoured jacket and the load spreading effect of engineered backfill.

4.2.4 Damage Section Probability Distribution

The probability that a randomly selected mechanical interference event will fall within a given pipeline section, i, is proportional to the potential number of interference events on the section, which is equal to the product of the section line hit frequency, r_i, and the section length, l_i. Recall that r_i is calculated for each section using Equation [4.3] with the required basic event probabilities being estimated from the values of the associated Damage Section attributes. Based on this information, the probability associated with a given section, p_L can be calculated as the number of potential interference events divided by the total number of events for the whole pipeline segment. For offshore pipelines, which are assumed to be susceptible to damage resulting from two independent damage mechanisms (towed object impact and vessel grounding), this can be expressed as:

$$p_i = \frac{r_{ai} l_i + r_{bi} l_i}{\sum_{all\ i} \left(r_{ai} l_i + r_{bi} l_i \right)} \qquad [4.5]$$

where r_{ai} is the interference rate associated with towed object impact events and r_{bi} is the interference rate associated with vessel grounding events.

Figures and Tables

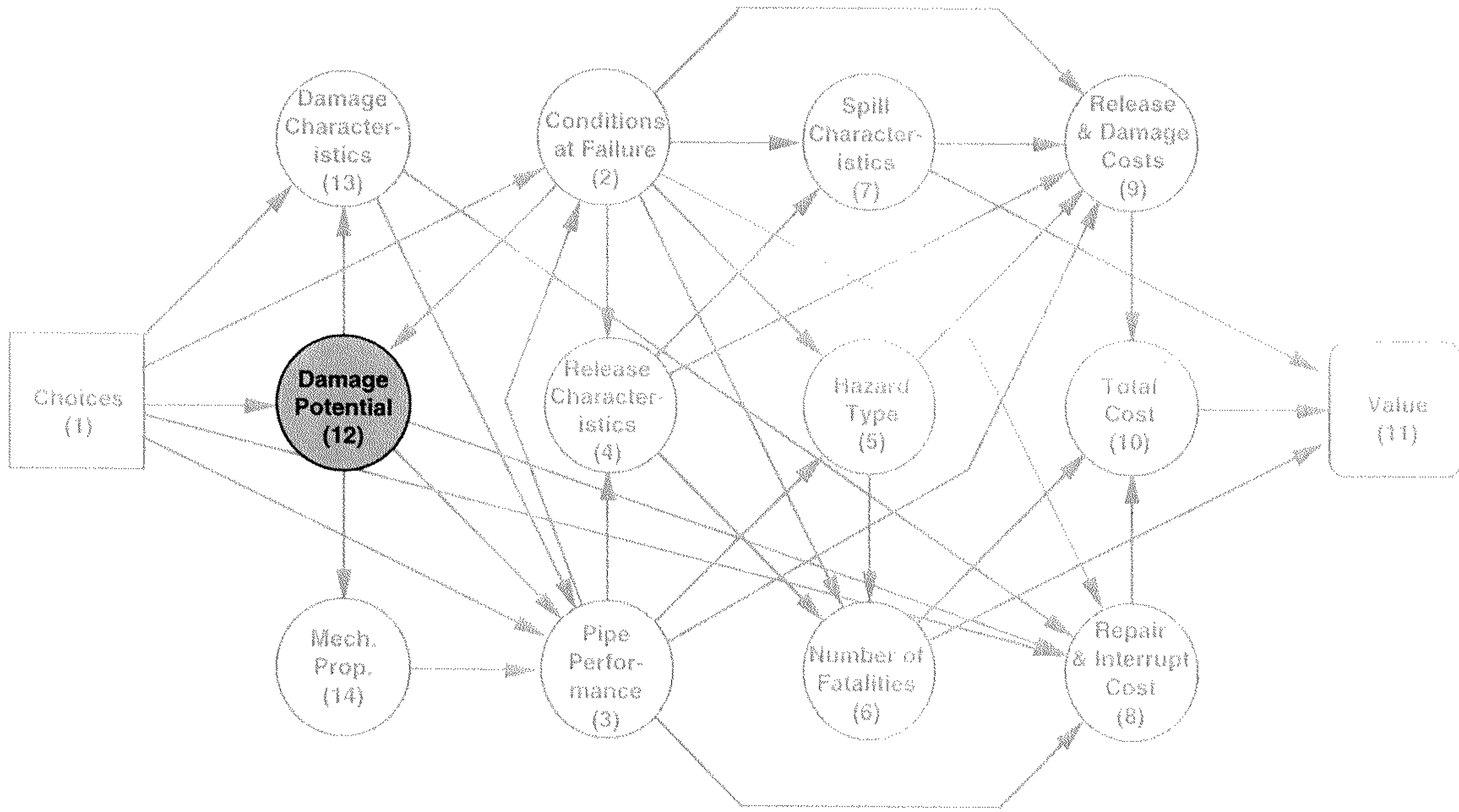


Figure 4.1 Compound node influence diagram highlighting Damage Potential node group.

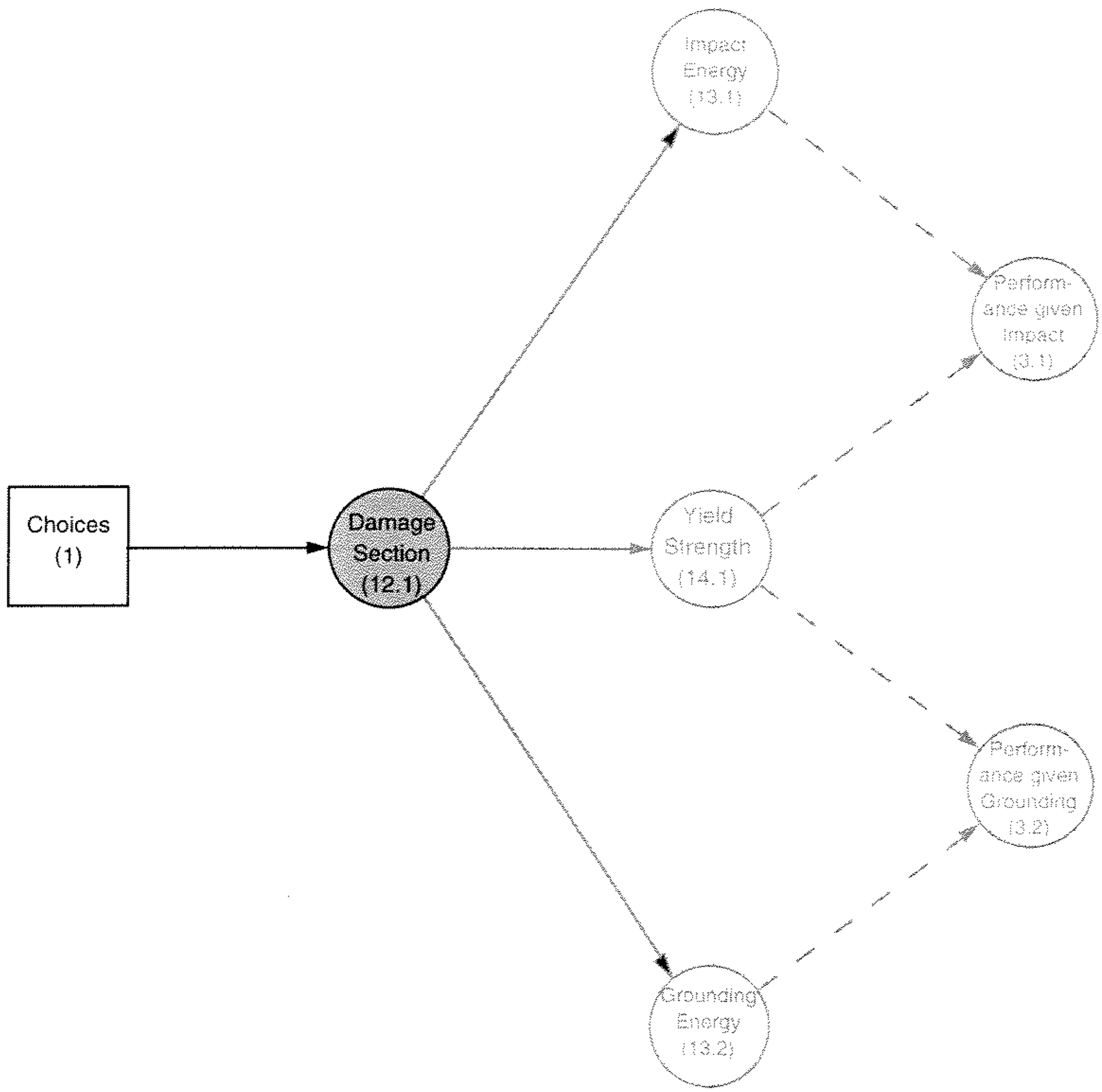
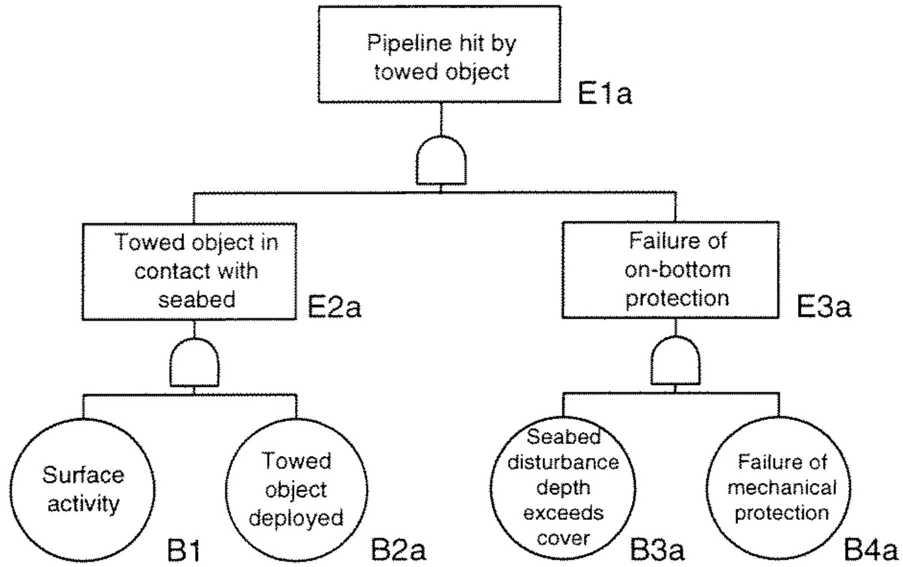
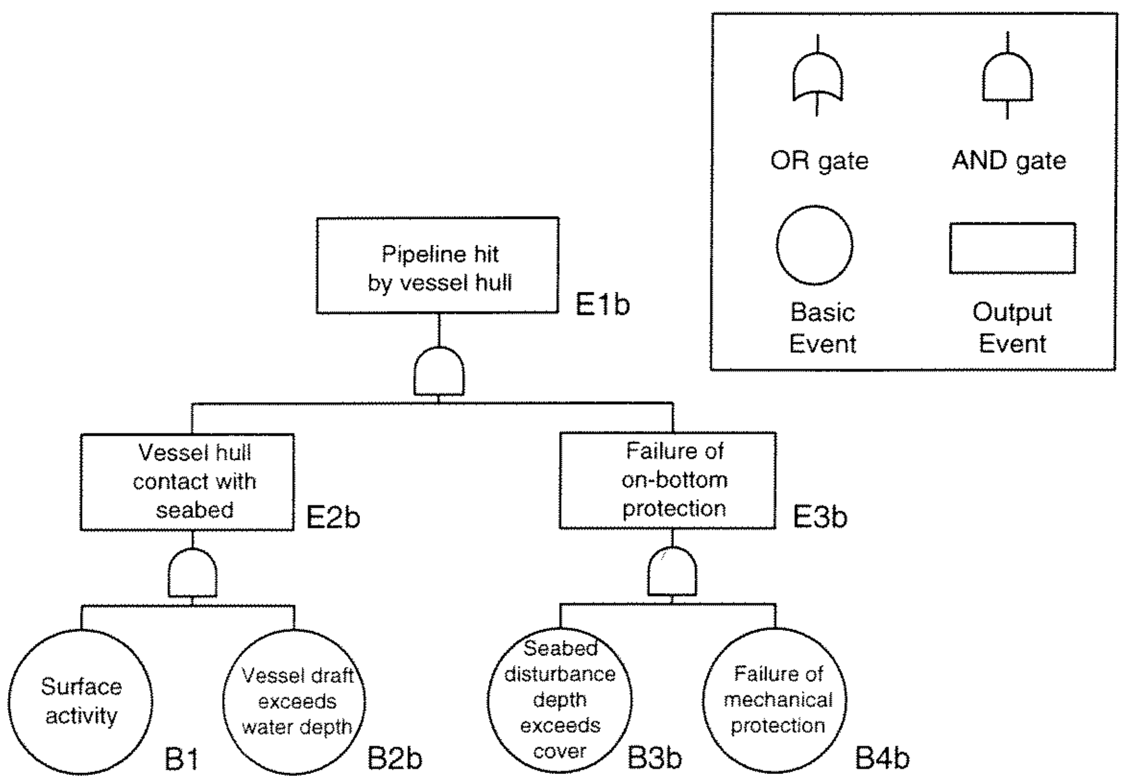


Figure 4.2 Basic node mechanical damage influence diagram highlighting Damage Section node and immediate predecessor node.



(b) Mechanical interference with towed object



(a) Mechanical interference with grounding vessel

Figure 4.3 Mechanical interference fault trees.

Pipeline Attribute	Definition	Affect Consequences ?
Pipe Diameter	Numerical value	Yes
Pipe Wall Thickness	Numerical value	Yes
Pipe Body Yield Strength	Numerical value	No
Elevation / Depth Profile	Numerical value	Yes
Water Depth Range (calculated from Elevation Profile)	Defined by numeric value but assigned to a range: 0 to < 5m 5 to < 10 m 10 to < 20 m 20 to < 60 m 60 to < 150 m 150 to < 300 m 300+ m	No
Adjacent Platform - Type	Major manned platform Minor manned platform Major unmanned platform Minor unmanned platform	Yes
Vessel Traffic **Internally assigned to platform sections (based on Adjacent Platform - type)*	No significant traffic Commercial Fishing - high density Commercial Fishing - medium density Commercial Fishing - low density Shipping - high density Shipping - medium density Shipping - low density *Platform Service - major manned platform** *Platform Service - minor manned platform** *Platform Service - major unmanned platform** *Platform Service - minor unmanned platform**	Yes
Level of Awareness	Above Average Average Below Average	No
Reference Cover	No Cover Finite Cover (limited or variable depth) Finite Cover (to minimum requirement)	No
Cover Erosion Potential	No Yes	No
Cover Monitoring Action	None After Storm (depth < 5 m) After Storm (depth < 20 m) Periodically* & After Storm (depth < 5 m) Periodically* & After Storm (depth < 20 m)	No
Response to Cover Monitoring	Rebury if line exposed Rebury if cover < design minimum	No
Mechanical Protection	None (other than weight coating) Armored Jacket Engineered Backfill	No

Table 4.1 Attributes affecting the probability of line failure due to mechanical damage

Vessel Traffic Characterization		Crossing Rate (events per km yr)
No Significant Traffic		0
Shipping:	- high density traffic	10,000
	- medium density traffic	1,000
	- low density traffic	100
Commercial Fishing:	- high density traffic	10
	- medium density traffic	1.0
	- low density traffic	0.1
Platform Service*:	- major manned platform	400
	- minor manned platform	200
	- major unmanned platform	100
	- minor unmanned platform	50

*Note: platform service crossing rate applies within platform safety zones only

Table 4.2 Crossing rate matrix for basic event B1 (surface activity)

Water Depth Range	Vessel Traffic Type								
	Commercial fishing			Shipping			Platform Service		
0 to < 5 m	1.0	1.0	1.0	1.1×10^{-7}	1×10^{-7}	0.9×10^{-7}	1.5×10^{-5}	1×10^{-5}	0.5×10^{-5}
5 to < 10 m	1.0	1.0	1.0	1.1×10^{-7}	1×10^{-7}	0.9×10^{-7}	1.5×10^{-5}	1×10^{-5}	0.5×10^{-5}
10 to < 15 m	1.0	1.0	1.0	1.1×10^{-7}	1×10^{-7}	0.9×10^{-7}	1.5×10^{-5}	1×10^{-5}	0.5×10^{-5}
15 t o< 20 m	1.0	1.0	1.0	1.1×10^{-7}	1×10^{-7}	0.9×10^{-7}	1.5×10^{-5}	1×10^{-5}	0.5×10^{-5}
20 to < 60 m	1.0	1.0	1.0	1.1×10^{-7}	1×10^{-7}	0.9×10^{-7}	1.5×10^{-5}	1×10^{-5}	0.5×10^{-5}
60 to < 150 m	1.0	1.0	1.0	1.1×10^{-7}	1×10^{-7}	0.9×10^{-7}	1.5×10^{-5}	1×10^{-5}	0.5×10^{-5}
150 to < 300 m	0.0	0.0	0.0	1.1×10^{-8}	1×10^{-8}	0.9×10^{-8}	1.5×10^{-6}	1×10^{-6}	0.5×10^{-6}
300+ m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Below	Average	Above	Below	Average	Above	Below	Average	Above
	Level of Vessel Operator Awareness								

Table 4.3 Event probability matrix for basic event B2a (towed object deployment)

Category of Effective Cover Depth[3]	Vessel Type		
	Commercial Fishing[1]	Shipping[2]	Platform Service[2]
1 – no effective cover	1.0	1.0	1.0
2 – intermittent/variable cover	0.5	1.0	1.0
3 – cover to min. requirement	0.0	1.0	1.0

Notes:
1) Towed object assumed to be fishing net gear
2) Towed object assumed to be vessel anchor
3) See Table 4.5 for attributes defining Effective Cover Depth categories

Table 4.4 Event probability matrix for basic event B3a
(seabed disturbance depth due to towed object exceeds cover depth)

Cover Monitoring Action		Reference Cover						
Action	Response	No Cover	Finite Cover					
			Eroding Seabed			Stable Seabed		
None	N/A	1	1	1	1	1	R* - 1	R*
After storm only (water depths < 5 m)	Rebury is line exposed	1	1	1	1	2	R* - 1	R*
	Rebury if cover < min. req'd	1	2	1	1	3	R* - 1	R*
After storm only (water depths < 20 m)	Rebury is line exposed	1	1	1	1	2	2	R*
	Rebury if cover < min. req'd	1	2	2	1	3	3	R*
Periodically & after Storm (water depths < 5 m)	Rebury is line exposed	1	2	1	2	2	R* - 1	R*
	Rebury if cover < min. req'd	1	3	2	3	3	R* - 1	R*
Periodically & after Storm (water depths < 20 m)	Rebury is line exposed	1	2	2	2	2	2	R*
	Rebury if cover < min. req'd	1	3	3	3	3	3	R*
*Note R = 2 if reference cover is 'limited or variable' R = 3 if reference cover is 'to minimum requirement'			0 to 5 m	5 to 20 m	20+ m	0 to 5 m	5 to 20 m	20+ m
			Water Depth Range					

Effective Cover Depth Category:
1 Effective cover = No cover
2 Effective cover = Intermittent or variable cover
3 Effective cover = Cover to minimum requirements

Table 4.5 Effective cover depth categorization

Type of Mechanical Protection	Vessel Type		
	Commercial Fishing[1]	**Shipping[2]**	**Platform Service[2]**
None[3]	1.0	1.0	1.0
Armoured Jacket	0.0	1.0	1.0
Engineered Backfill	0.0	0.0	0.0

Note:
1) Towed object assumed to be fishing net gear
2) Towed object assumed to be vessel anchor
3) Concrete weight coating is not considered to be an effective form of mechanical protection

Table 4.6 Event probability matrix for basic event B4a
(failure of mechanical measures to protect pipe from towed objects)

Water Depth Range	Vessel Traffic Type								
	Commercial fishing			Shipping			Platform Service		
0 to < 5 m	1×10^{-4}	1×10^{-4}	1×10^{-4}	1.5×10^{-6}	1×10^{-6}	0.5×10^{-6}	0.0	0.0	0.0
5 to < 10 m	0.0	0.0	0.0	7.5×10^{-7}	5×10^{-7}	2.5×10^{-7}	0.0	0.0	0.0
10 to < 15 m	0.0	0.0	0.0	1.5×10^{-7}	1×10^{-7}	0.5×10^{-7}	0.0	0.0	0.0
15 to < 20 m	0.0	0.0	0.0	7.5×10^{-9}	5×10^{-9}	2.5×10^{-9}	0.0	0.0	0.0
20 to < 60 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60 to < 150 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
150 to < 300 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300+ m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Below	Average	Above	Below	Average	Above	Below	Average	Above
	Level of Vessel Operator Awareness								

Table 4.7 Event probability matrix for basic event B2b (vessel draft exceeds water depth)

Category of Effective Cover Depth*	Vessel Type		
	Commercial Fishing	Shipping	Platform Service
1 – no effective cover	1.0	1.0	1.0
2 – intermittent/variable cover	0.5	1.0	1.0
3 – cover to min. requirement	0.1	1.0	1.0

*Note: See Table 4.5 for attributes defining Effective Cover Depth categories

Table 4.8 Event probability matrix for basic event B3b
(seabed disturbance depth due to grounding vessel exceeds cover depth)

Type of Mechanical Protection	Vessel Type		
	Commercial Fishing	Shipping	Platform Service
None[1]	1.0	1.0	1.0
Armoured Jacket	1.0	1.0	1.0
Engineered Backfill	1.0	1.0	1.0

Note:
1) Concrete weight coating is not considered to be an effective form of mechanical protection

Table 4.9 Event probability matrix for basic event B4b
(failure of mechanical measures to protect pipe from grounding vessels).

5. DAMAGE CHARACTERISTICS

5.1 Overview

The Damage Characteristics node group (group 13) is highlighted in the version of the compound node influence diagram in Figure 5.1. This node group includes parameters describing the dominant characteristic of a possible mechanical interference event. The relevant characteristic is the magnitude of the energy that could potentially be transferred to (and potentially absorbed by) the pipe body as a result of either towed object impact or vessel hull contact with the pipeline. The individual parameters associated with the Damage Characteristics node group are highlighted in the version of the basic node mechanical damage influence diagram shown in Figure 5.2. These node parameters are discussed in the following sections.

5.2 Damage Characteristics Node Parameters

5.2.1 Impact Energy

5.2.1.1 Node Parameter

The Impact Energy node (basic node 13.1) and its direct predecessor node are highlighted in the version of the basic node mechanical damage influence diagram in Figure 5.2. The parameter of this node represents the kinetic energy associated with a towed object in contact with the seabed that could potentially be transferred, in part or in total, to the pipe body during a randomly selected impact event in which it is assumed that the object (or, in the case of an anchor, potentially the vessel to which it is attached) will be brought to a complete stop. It is defined by a continuous probability distribution that can take any value within a defined range. The influence diagram indicates that the Impact Energy node is conditionally dependent on the Damage Section node, which means that a separate Impact Energy probability distribution must be defined for each Damage Section, or more specifically for each distinct combination of the pipeline damage section attributes that are thought to have an effect on the energy distribution.

For towed objects that are intentionally deployed (i.e., net gear associated with fishing vessels) randomness in the kinetic energy associated with a mechanical interference event results primarily from variations in the size and speed of the towed object that will have to be brought to a standstill during an impact event. For towed objects that are unintentionally dragged (i.e., anchors associated with shipping in emergency situations) randomness in the kinetic energy associated with a mechanical interference event results primarily from variations in the size and speed of the towing vessel that will have to be brought to a standstill during an impact event.

It is assumed that both the effective mass and velocity of the object (or object plus towing vessel) involved is dependent upon the type of vessel traffic associated with the area through which the pipeline corridor passes. It is further assumed that the size of object (or towing vessel) involved in an impact event can depend on the water depth (e.g., deep water net gear may differ from shallow water gear). The existing damage section attributes Vessel Traffic and Water Depth Range (as calculated from the pipeline elevation profile) can therefore be used to define a matrix of attribute combinations, each of which is potentially associated with a different impact energy distribution. The impact energy matrix is shown in Table 5.1.

Note that in the vicinity of fixed offshore platforms the impact energy is assumed to be independent of the type of surrounding fishing or shipping traffic. This assumption is based on the premise that a traffic exclusion area will always be maintained in the safety zone surrounding a platform and within the platform zone the impact energy will be associated solely with platform supply and service vessels.

5.2.1.2 Parameter Characterization

The development of a probabilistic characterization of the kinetic energy that must be dissipated during an object impact event, as a function of vessel traffic type and water depth, was beyond the scope of this project. However, representative impact energy distributions for shipping, commercial fishing, and platform service traffic have been developed and the parameter characterizations are given in Table 5.1. The basis for the tabulated energy values is as follows.

The total kinetic energy, E_T, associated with a floating system moving through the water is given by:

$$E_T = \frac{1}{2} m_e v^2 \qquad [5.1]$$

where m_e is the total effective mass of the system (which includes the added mass of entrapped and entrained water) and v is the speed of the system.

For shipping lanes and platform safety zones, where anchor drag is the contact mechanism, the system that can impart its energy to the pipeline is assumed to include the mass of both the anchor and the ship to which it is attached. The mass of the entire moving system is considered to have the potential to act on the pipe because a representative contact event is assumed to involve anchor hooking of the pipe body and a hooked anchor is assumed to exert force on the pipe body until the attached vessel is brought to rest.

The effective mass of a moving vessel is generally assumed to be equal to approximately 1.08 times the mass of the displaced water (Hvam et al. 1990) and the total vessel displacement is typically in the range of 1.1 to 1.15 times the so-called *dead weight tonnage* (DWT). The effective mass is therefore approximately equal to 1.2 times the DWT of the vessel. The total energy, in terms of vessel DWT expressed in mass units, is therefore given by:

$$E_T = 0.6(DWT)v^2 \qquad [5.2]$$

For significant vessels (i.e., DWT > 10,000) the speed at which an anchor will be deployed is usually in the range of 0.2 to 0.5 m/s (Hvam et al. 1990). If a speed of 0.35 m/s is taken to be a representative value, the probability distribution for the total kinetic energy of the ship and anchor system can be obtained by scaling the probability distribution of the DWT of typical shipping traffic.

The displacement distribution of vessels passing through a major shipping corridor in the Danish Great Belt, as presented by Rasmussen (1985), can be characterized as follows: 50 % of all traffic exceeded 15,000 DWT, 1% of traffic exceeded 130,000 DWT, and 0.1% of traffic exceeded 260,000 DWT. This vessel displacement variability can be approximated by a log normal distribution with a mean value of 23,000 DWT and a standard deviation of 27,000 DWT.

Based on the above, a representative estimate of the total kinetic energy kinetic energy associated with anchor drag in a major shipping corridor is given by a log normal distribution with a mean value of 1690 kJ and a standard deviation of 1990 kJ. In the absence of statistical data for platform service vessels, the same energy distribution can conservatively be assumed to apply to platform service vessels operating within the safety zone.

For fishing vessels, where net gear drag is the contact mechanism, the system that can impart its energy to the pipeline is assumed to be limited to the effective mass of the so-called fishing boards or trawl beams that hold the net open. Only the net gear mass is considered because a typical contact event is assumed to involve bringing the net gear to rest against the pipe body after which the gear will be dragged over the pipe with no significant chance of snagging.

A survey of representative North Sea fishing vessels and associated net gear, as reported by Bilderbeck et al. (1995), indicates that the effective kinetic energy for slow moving, lightweight board-type systems is in the range of 2 to 9 kJ. For faster moving and heavier beam-type systems the effective kinetic energy is reported to be significantly greater (i.e., in the range of 47 to 52 kJ). Excluding beam-type systems on the assumption that board-type systems are much more prevalent and, assuming further that the energy levels tabulated by Bilderbeck et al. for board-type systems are representative of the fishing vessel population as a whole, a reasonable characterization of the variability in net gear kinetic energy is given by a log normal distribution with a mean value of 4.8 kJ and a standard deviation of 3.0 kJ.

5.2.2 Grounding Energy

5.2.2.1 Node Parameter

The Grounding Energy node (basic node 13.2) and its direct predecessor node are highlighted in the version of the basic node mechanical damage influence diagram in Figure 5.2. The parameter of this node represents the kinetic energy associated with a moving vessel that could potentially be transferred, in part or in total, to the pipe body during a randomly selected vessel hull grounding event in which it is assumed that the vessel will be brought to a complete stop. It is defined by a continuous probability distribution that can take any value within a defined range. The influence diagram indicates that the Grounding Energy node is conditionally dependent on the Damage Section node, which means that a separate Grounding Energy probability distribution must be defined for each Damage Section, or more specifically for each distinct combination of the pipeline damage section attributes that are thought to have an effect on the energy distribution.

Randomness in the kinetic energy associated with a hull grounding mechanical interference event results primarily from variations in the size and speed of the vessel that will have to be brought to a standstill during a grounding event. It is assumed that both the effective mass and velocity of the vessel involved is dependent upon the type of vessel traffic associated with the area through which the pipeline corridor passes. It is further assumed that the size of vessel involved in a grounding event will depend on the water depth (i.e., larger vessels will only ground in deeper water). The existing damage section attributes Vessel Traffic and Water Depth Range (as calculated from the pipeline elevation profile) can therefore be used to define a matrix of attribute combinations, each of which is potentially associated with a different grounding energy distribution. The grounding energy matrix is shown in Table 5.2.

Note that in the vicinity of fixed offshore platforms the grounding energy is assumed to be independent of the type of surrounding fishing or shipping traffic. This assumption is based on the premise that a traffic exclusion area will always be maintained in the safety zone surrounding a platform and within the platform zone the grounding energy will be associated solely with platform supply and service vessels.

5.2.2.2 Parameter Characterization

The development of a probabilistic characterization of the kinetic energy that must be dissipated during a grounding event, as a function of vessel traffic type and water depth, was beyond the scope of this project. However, representative grounding energy distributions for shipping, commercial fishing, and platform service traffic have been developed and the parameter characterizations are given in Table 5.2. The basis for the tabulated energy values is as follows.

Damage Characteristics

For all grounding events, it is assumed that the energy to be dissipated is the total kinetic energy associated with the moving vessel (see Equation [5.2]).

Assuming a typical travel speed of approximately 6 m/s for shipping traffic, and using the vessel displacement distribution calculated from the data reported by Rasmussen (see Section 5.2.2.1), a representative estimate of the kinetic energy associated with vessel grounding in a shipping corridor is given by a log normal distribution with a mean value of 500,000 kJ and a standard deviation of 580,000 kJ. In the absence of statistical data for platform service vessels, the same energy distribution can conservatively be assumed to apply to platform service vessels operating within the safety zone.

For fishing vessels, a representative vessel displacement distribution is obtained by scaling the shipping traffic displacement distribution by a factor of 0.01. (This implies a vessel population with a mean displacement of 230 DWT and a displacement of 1300 DWT with an exceedance probability of 1%.). Combining this displacement distribution with a representative trawling speed of 2 m/s gives an estimate of the kinetic energy associated with vessel grounding in a designated fishing area that is described by a log normal distribution with a mean value of 550 kJ and a standard deviation of 650 kJ.

Figures and Tables

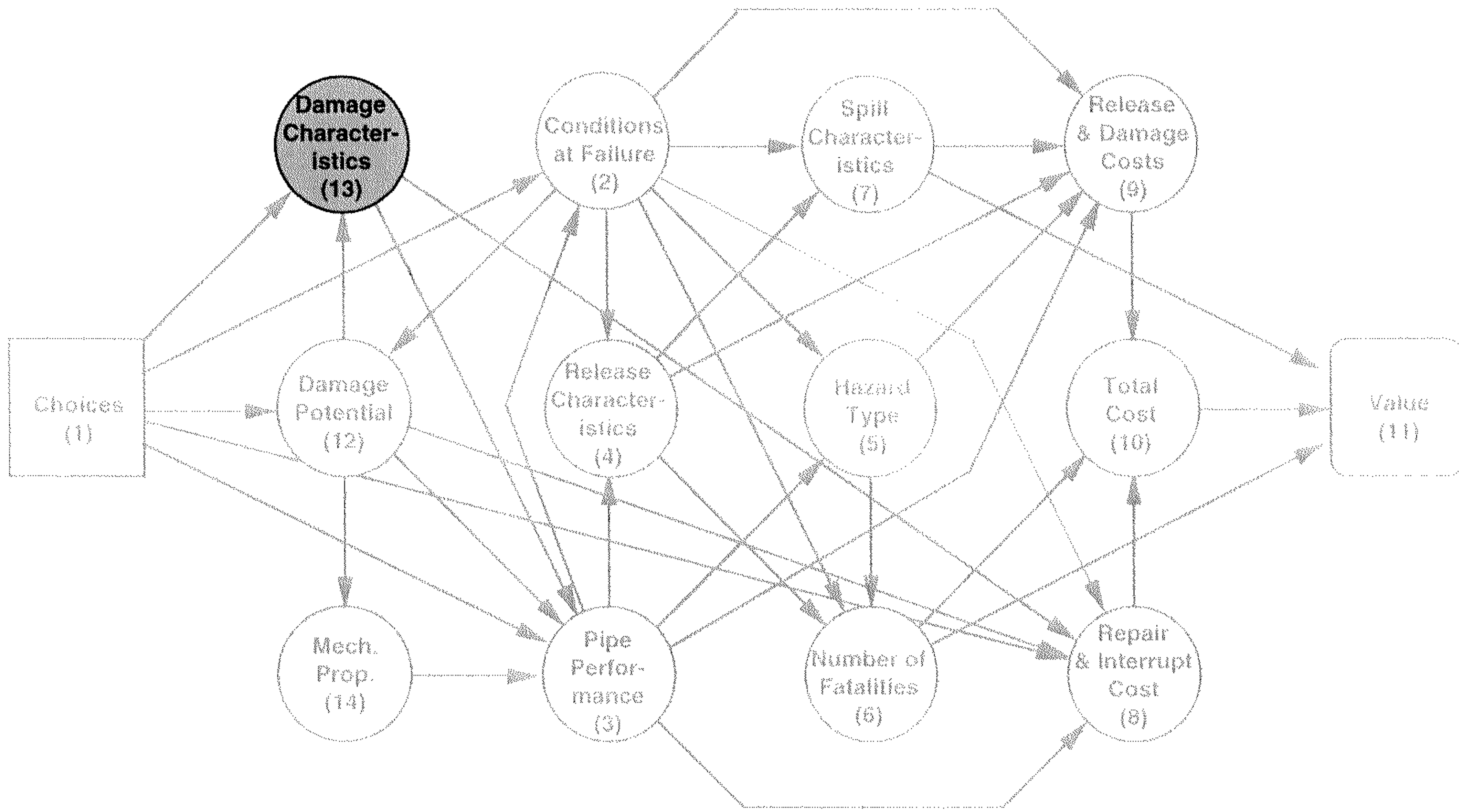


Figure 5.1 Compound node influence diagram highlighting Damage Characteristics node group.

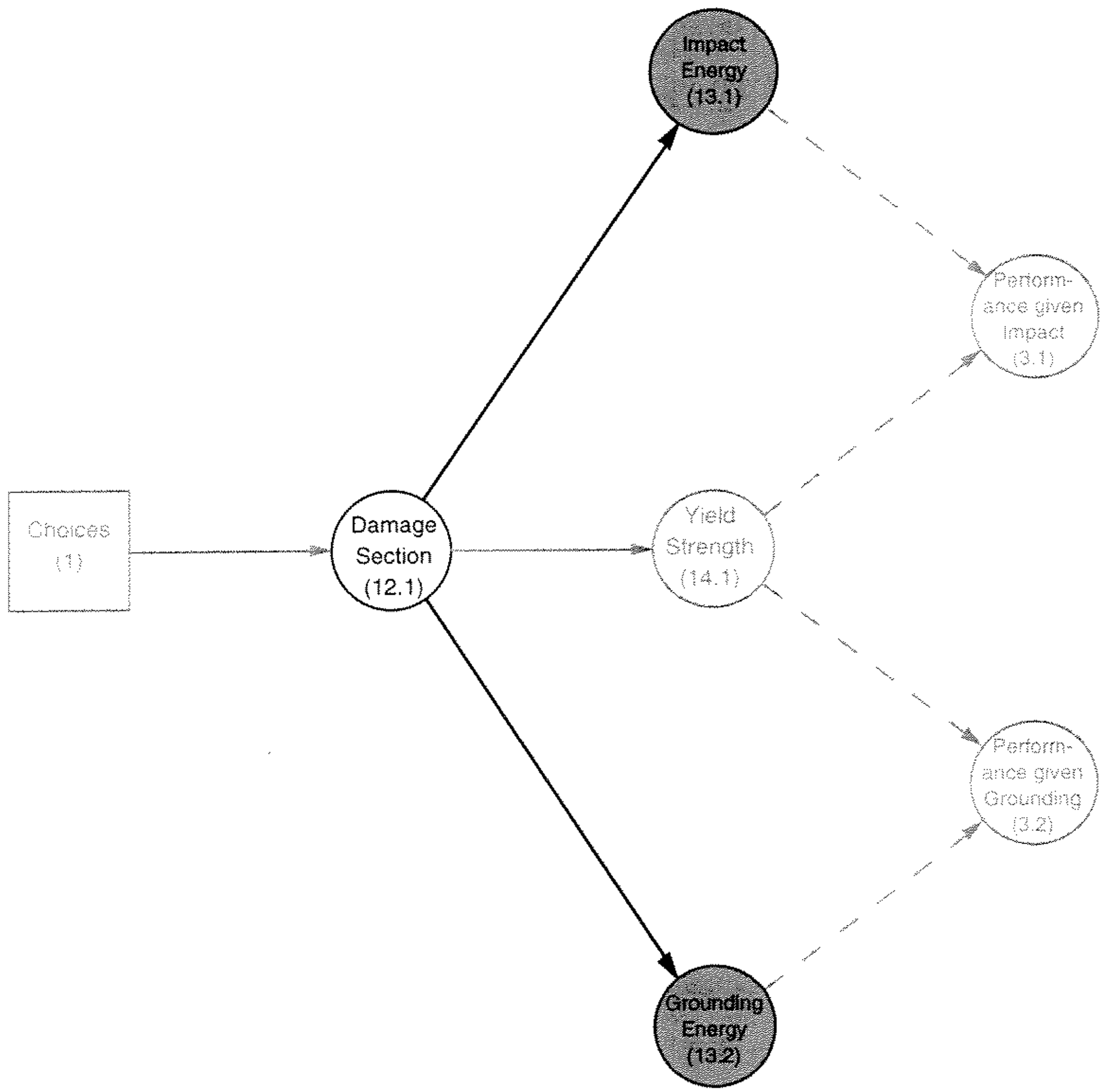


Figure 5.2 Basic node mechanical damage influence diagram highlighting the Damage Characteristics nodes and immediate predecessor node.

Water Depth Range	Vessel Traffic Type	
	Shipping	**Platform Service**
0 to < 5 m	Lognormal (μ = 1690 kJ, σ = 1990 kJ)	Lognormal (μ = 1690 kJ, σ = 1990 kJ)
5 to < 10 m	Lognormal (μ = 1690 kJ, σ = 1990 kJ)	Lognormal (μ = 1690 kJ, σ = 1990 kJ)
10 to < 15 m	Lognormal (μ = 1690 kJ, σ = 1990 kJ)	Lognormal (μ = 1690 kJ, σ = 1990 kJ)
15 to < 20 m	Lognormal (μ = 1690 kJ, σ = 1990 kJ)	Lognormal (μ = 1690 kJ, σ = 1990 kJ)
20 to < 60 m	Lognormal (μ = 1690 kJ, σ = 1990 kJ)	Lognormal (μ = 1690 kJ, σ = 1990 kJ)
60 to < 150 m	Lognormal (μ = 1690 kJ, σ = 1990 kJ)	Lognormal (μ = 1690 kJ, σ = 1990 kJ)
150 to < 300 m	Lognormal (μ = 1690 kJ, σ = 1990 kJ)	Lognormal (μ = 1690 kJ, σ = 1990 kJ)
300+ m	Lognormal (μ = 1690 kJ, σ = 1990 kJ)	Lognormal (μ = 1690 kJ, σ = 1990 kJ)

Table 5.1 Towed object impact energy attribute matrix.

Water Depth Range	Vessel Traffic Type		
	Commercial Fishing	**Shipping**	**Platform Service**
0 to < 5 m	Lognormal (μ = 550 kJ, σ = 650 kJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)
5 to < 10 m	Lognormal (μ = 550 kJ, σ = 650 kJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)
10 to < 15 m	Lognormal (μ = 550 kJ, σ = 650 kJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)
15 to < 20 m	Lognormal (μ = 550 kJ, σ = 650 kJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)
20 to < 60 m	Lognormal (μ = 550 kJ, σ = 650 kJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)
60 to < 150 m	Lognormal (μ = 550 kJ, σ = 650 kJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)
150 to < 300 m	Lognormal (μ = 550 kJ, σ = 650 kJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)
300+ m	Lognormal (μ = 550 kJ, σ = 650 kJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)	Lognormal (μ = 500 MJ, σ = 580 MJ)

Table 5.2 Vessel grounding energy attribute matrix

6. MECHANICAL PROPERTIES

6.1 Overview

The Mechanical Properties node group (group 14) is highlighted in the version of the compound node influence diagram in Figure 6.1. This node group includes parameters describing the pipe mechanical properties that are required to calculate the probability of a loss of containment type of failure (*i.e.*, pipe body penetration) and the mode of failure (*i.e.*, leak vs. rupture). In the context of the damage resistance model adopted herein, the relevant characteristic is the yield strength of the pipe body material. The parameter associated with the Mechanical Properties node group is highlighted in the version of the basic node mechanical damage influence diagram shown in Figure 6.2. This node parameter is discussed in the following section.

6.2 Mechanical Properties Node Parameters

6.2.1 Yield Strength

6.2.1.1 Node Parameter

The Yield Strength node (node 14.1) and its direct predecessor node are highlighted in the version of the basic node mechanical damage influence diagram shown in Figure 6.2. The node parameter represents the actual yield strength of the pipe steel at the location of a randomly occurring mechanical interference event. As indicated in Figure 6.2, this is a conditional node for which the probability distribution must be explicitly defined for each possible value of its predecessor node. Since the predecessor node represents the section of pipeline at which the interference event occurs, the yield strength distribution must be defined for each pipeline section defined at the Damage Section node.

Randomness in the yield strength results from variability in the manufacturing process. The actual pipe body yield strength will vary from joint-to-joint within a heat and from heat-to-heat within an order of line pipe. Ideally, for each order of line pipe, the joint-to-joint variability in yield strength can be defined by a probability distribution calculated from the mill test data provided by the pipe manufacturer. The appropriate strength distribution for each pipeline section defined at the Damage Section node can then be obtained by matching it with the strength distribution calculated for the corresponding pipe order. For existing pipelines, however, mill data is often unavailable or insufficient to facilitate the development of a representative yield strength distribution. Alternatively, analysis of historical mill test data indicates that a representative probability distribution for the actual yield strength of the pipe body steel can be derived from the specified minimum yield strength. (Note that specified minimum yield strength is a line attribute associated with the Damage Section node.)

6.2.1.2 Parameter Characterization

A representative relationship between the probability distribution of the actual yield strength and the specified minimum yield strength was determined from the information summarized in Table 6.1, which was collected directly from various line pipe manufacturers or found in the literature. The table reports the mean-to-specified strength ratio, γ, and the coefficient of variation (defined as the standard deviation divided by the mean value), v, of the yield strength data obtained from a number of sources. The value of γ is always greater than 1.0 because the specified yield strength is treated as a minimum allowable value and pipe manufacturers design their product to have a higher average yield strength than the minimum allowable in order to minimize the chance of producing steel that does not meet specifications. The data in the table indicate that representative values of γ and v are 1.1 and 0.035, respectively. The data also indicates that the yield strength can be represented by either a normal or lognormal distribution type.

Based on this information, it is assumed that a representative yield strength characterization is given by a normal distribution type with a mean, μ_s, and standard deviation, σ_s, calculated from the specified yield strength, s_n, using the following relationships:

$$\mu_S = \gamma s_n = 1.1 s_n \qquad [6.1a]$$

$$\sigma_S = v\mu_s = 0.035\mu_s \qquad [6.1b]$$

It is noted that this yield strength characterization is considered applicable to pipe manufactured in accordance with recent pipe manufacturing standards. It may not, however, be representative of the yield strength distribution for older line pipe.

Figures and Tables

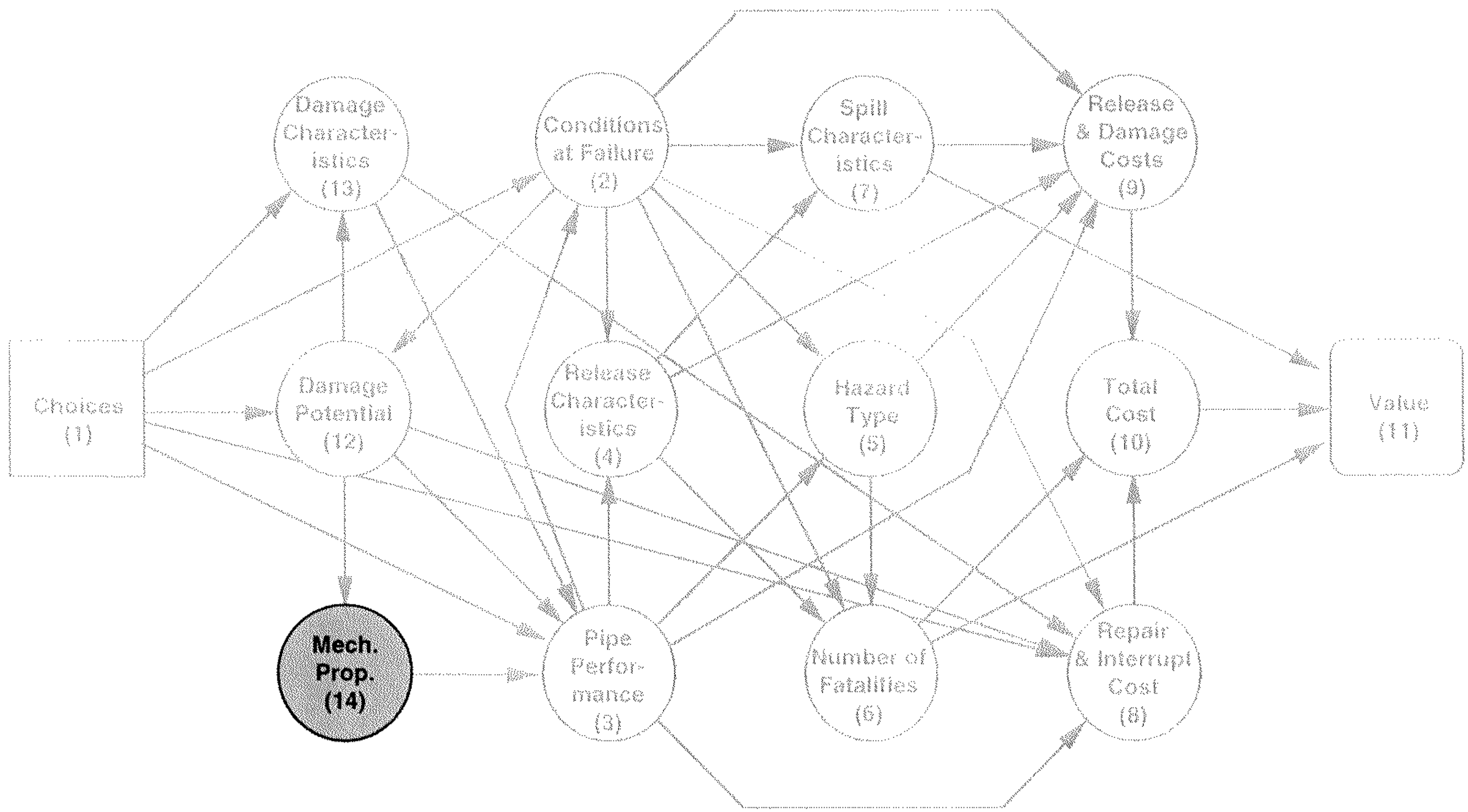


Figure 6.1 Compound node influence diagram highlighting Mechanical Properties node group.

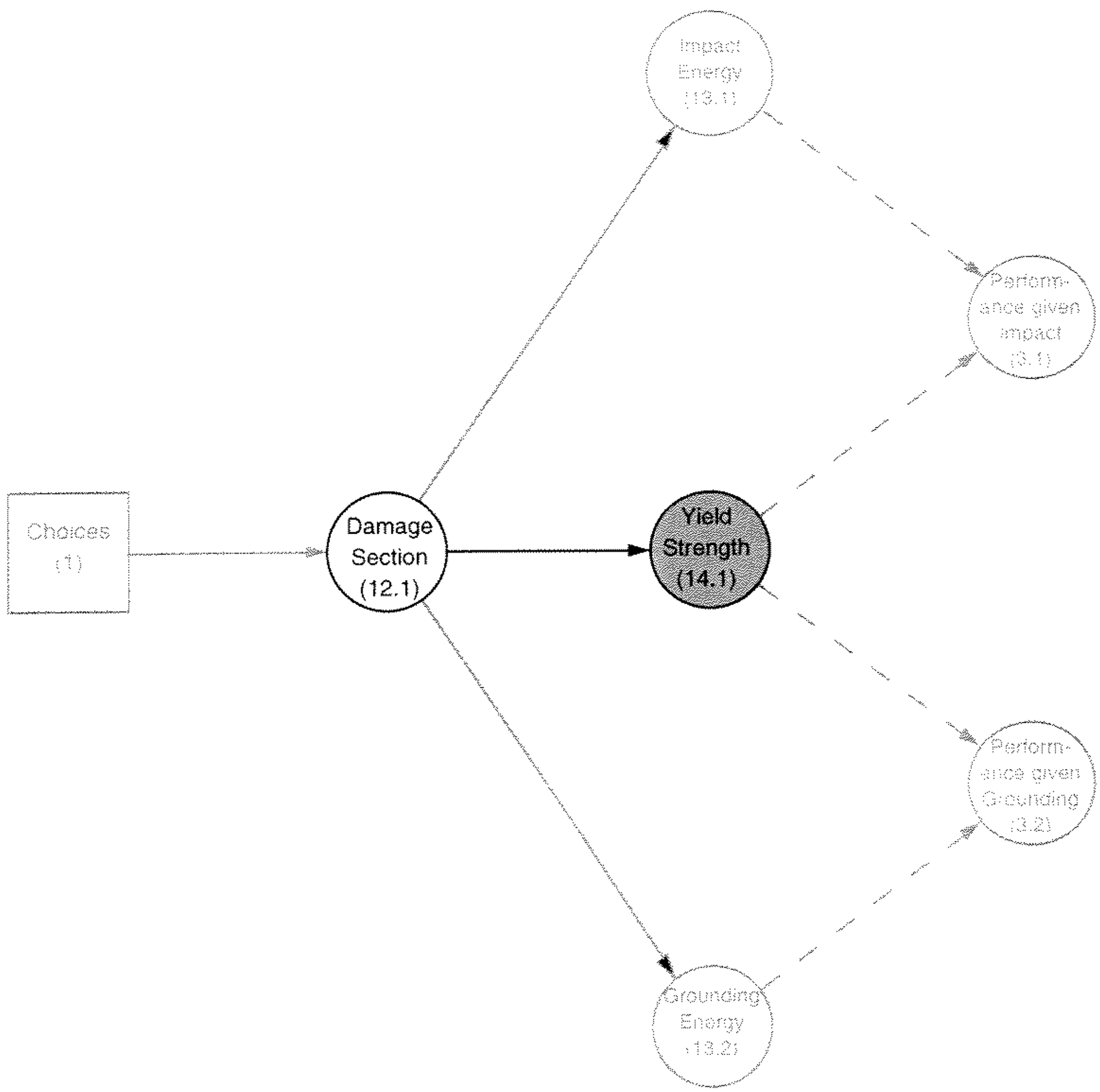


Figure 6.2 Basic node mechanical damage influence diagram highlighting Yield Strength node and immediate predecessor node.

Data Source	Pipe Information	Mean / Nominal	StDev / Nominal	COV (%)	Distribution Type
Mill data	spiral pipe, X60	1.11	0.0370	3.3	--
Mill data	spiral pipe, X65	1.09	0.0359	3.3	--
Mill data	spiral pipe, X70	1.06	0.0317	3.0	--
Mill data	U&O pipe, X70	1.15	0.0419	3.6	normal
Jiao *et al.* 1992	offshore pipelines	1.07	0.0428	4.0	lognormal
Abrams and Hansen 1984	U&O pipe, X70	1.09	0.0440	4.0	normal

Table 6.1 Pipe yield strength data

7. PIPE PERFORMANCE

7.1 Overview

The Pipe Performance node group (group 3) is highlighted in the version of the compound influence diagram in Figure 7.1. The node group includes three individual nodes. The first node (Performance Given Impact - node 3.1) represents the pipe performance in the event of pipeline contact with a towed object. Its probability distribution is evaluated from the mechanical damage portion of the influence diagram (Figure 7.2). . The second node (Performance Given Grounding - node 3.2) represents the pipe performance in the event of pipeline contact with a grounding vessel hull. Its probability distribution is also evaluated from the mechanical damage portion of the influence diagram (Figure 7.2). The third node (Segment Performance - node 3.3) represents the performance of the whole segment of pipeline. Its probability distribution is evaluated from the distributions of the Performance Given Impact and Grounding nodes (3.1 and 3.2) and the frequency of occurrence of mechanical interference events on the segment (from node 12.1 representing Damage Section). It is then used in the consequence analysis portion of the influence diagram (Figure 7.3) as described in PIRAMID Technical Reference Manual No. 5.1 (Stephens *et al.* 1996).

7.2 Performance Given Impact

7.2.1 Node Parameter

The Performance Given Impact and its direct predecessor nodes are highlighted in the version of the mechanical damage influence diagram shown in Figure 7.2. The specific node parameter is defined as the performance of the pipeline at the time of a randomly occurring mechanical interference event associated with an object towed from behind a surface vessel. As indicated in Figure 7.2, Performance Given Impact is a functional node meaning that the value of the node parameter is calculated directly from the values of its direct predecessor node parameters which include: impact energy and pipe body yield strength.

The node parameter is a discrete random variable that can assume one of four possible values or states:

- safe;
- small leak;
- large leak; and
- rupture.

A small leak corresponds to a small pin hole and a slow product release rate that does not result in a significant hazard. A large leak, involving an effective hole diameter of tens of millimeters, or a rupture, involving a hole size on the order of the pipe diameter, are assumed to result in high release rates and the potential for creating a significant hazard to people and property.

The probability distribution for this node is defined by estimates of the probabilities associated with each of the possible states of the node parameter. Probability estimates for each state: rupture, p_R, large leak, p_{LL}, small leak, p_{SL}, and safe, p_S can be calculated from:

$$p_R = p_{R|P}\, p_{P|I} \quad [7.1a]$$

$$p_{LL} = p_{LL|P}\, p_{P|I} \quad [7.1b]$$

$$p_{SL} = p_{SL|P}\, p_{P|I} \quad [7.1c]$$

$$p_S = 1 - (p_{SL} + p_{LL} + p_R) \quad [7.1d]$$

where $p_{P|I}$ is the probability of pipe body penetration given impact, and $p_{i|P}$ is the probability of failure in the i^{th} mode given wall penetration.

Calculation of the conditional event probabilities $p_{P|I}$ and $p_{i|P}$ involves the use of probability distributions characterizing the relevant uncertain parameters (*i.e.*, impact energy and pipe body yield strength) in deterministic response models that define the conditions leading to each possible mode of failure. The probabilistic model used to estimate the probability of line failure given impact is described in Section 7.2.2. The model used to estimate the probability of failure by leak or rupture given pipe body failure is described in Section 7.2.3.

7.2.2 Probability of Pipe Body Failure given Impact

The model used to estimate the probability of pipe body failure given impact assumes that a subsea pipeline absorbs the energy associated with impact primarily through local denting of the pipe wall. This model conservatively ignores the additional energy that can be absorbed through global bending of the pipeline in response to significant lateral loading. This simplification effectively precludes the need to take into account the complex interaction between a buried pipeline and the surrounding seabed sediment that tends to provide restraint against lateral pipe deformation and thereby affects the degree to which impact energy is absorbed by global bending.

Based on the above assumption, the probability of pipe body failure (i.e., wall penetration) given impact with a towed object, $p_{P|I}$, is taken to be equal to the probability that the effective kinetic energy associated with the towed object, E_i, will exceed the energy absorption capability (or resistance) of the pipe body in a local denting mode, R, at the impact location. This can be written as:

$$p_{PII} = p(E_I > R) = p(R - E_I < 0) \qquad [7.2]$$

The kinetic energy available to cause pipe body failure is assumed to vary from zero to 100% of the total kinetic energy associated with the towed object. This assumption follows from the fact that the fraction of the total available kinetic energy that can effectively be brought to bear on the pipe body will depend on the angle of incidence and the nature of the interaction event.

For example, with regard to intentionally deployed objects, such as net gear towed along the sea bottom by a fishing vessel, it can be shown that the effective kinetic energy available to cause pipe denting varies with the perpendicular closing velocity squared, where the closing velocity varies with the cosine of the angle of incidence. Assuming that the pipeline hit frequency estimate reflects all line crossing events, and assuming further that the line crossing angle (i.e., angle of incidence) is random, it follows that the effective impact energy can be approximated as being uniformly distributed over a range of 0.0 to 1.0 times the total available kinetic energy.

With regard to unintentionally dragged objects, such as an anchor deployed to bring a floundering vessel under control, it can be assumed that the anchor will drag for a finite distance before the vessel is brought to a stop and the energy transferred to a perpendicularly oriented pipeline in the path of the anchor will depend on the distance dragged prior to impact. Assuming that the pipeline hit frequency estimate reflects all drag events that could involve the pipeline (i.e., all drag paths that intersect the line) and assuming further that the energy dissipated per unit drag length is uniform, it follows that the effective impact energy is uniformly distributed over a range of 0.0 to 1.0 times the total available kinetic energy. If the potential for oblique impact is also acknowledged this assumption can be shown to be conservative.

The effective impact energy associated with all types of towed object interference events can therefore reasonably be given by:

$$E_I = C_E \, E_{T_I} \qquad [7.3]$$

where E_{TI} is the total available kinetic energy of the dragged object system and C_E is an effective impact energy multiplier taken as a uniformly distributed variable with a mean value of 0.5 and a standard deviation of 0.289.

The pipe body resistance to failure by local denting can be estimated using a semi-empirical model developed by Ellinas and Walker (1989) to predict the energy absorbed by a tubular element during the formation of a local dent caused by impact with a line indentor oriented perpendicular to the tube axis. According to this so-called *knife edge denting model* the energy absorbed by a pipe can be approximated by:

$$R_p = 25\sigma_s t^2 \left(\frac{d^3}{D}\right)^{0.5} \quad [7.4]$$

where D = pipe diameter;
t = pipe wall thickness;
d = dent depth; and
σ_s = pipe body yield strength.

This energy absorption model presumes unlimited material ductility. A finite ductility limit will impose an upper limit on the dent depth at the point of pipe wall material failure and thereby impose an upper limit on total energy absorption. Unfortunately, no experimental data currently exists to reliably establish the dent depth at the point of material failure for the assumed indentation model. For the purpose of establishing a reasonable upper limit on total energy absorption, and consistent with the approach suggested by Bilderbeck *et al.* (1995), it is assumed that pipe wall material failure will occur when the dent depth reaches 50% of the pipe diameter. This assumption leads to an estimate of the ultimate pipe body resistance given by:

$$R_p = 8.84\sigma_s t^2 D \quad [7.5]$$

In the most general sense, the uncertainty in estimating the ultimate resistance using Equation [7.4] can be taken into account by incorporating two model uncertainty factors in the final expression for the pipe body resistance, R, which is given by:

$$R = C_1 R_P + C_2 \quad [7.6]$$

where C_1 and C_2 are the multiplicative and additive components of the model error, respectively. However, in the absence of the test data necessary to accurately characterize these uncertainty parameters, it will be assumed that the pipe body resistance model is unbiased with a test-to-predicted ratio of unity (i.e., C_1 = 1.0 and C_2 = 0.0).

7.2.3 Failure Mode given Impact Induced Failure

Pipe body failure due to impact induced local denting is assumed to manifest itself as tensile tearing of the pipe wall due to excessive plastic straining. The mode of failure: small leak, large leak, or rupture; will depend on the length of the tear that develops when the tensile strain limit of the material is exceeded. The tear geometry will depend on depend on the size, shape, and orientation of the indentation resulting from the impact event.

A model for predicting the likely extent of a pipe body tear resulting from the plastic straining caused by local denting has yet to be developed. In the absence of a recognized model for estimating the effective tear area as a function of pipe damage attributes, a subjective approach has been adopted. Using this approach, the relative likelihood of small leak, large leak, and rupture failure modes is assigned to a set of predefined values.

In the current *PIRAMID* implementation of damage caused by towed object impact the following failure mode occurrence probabilities are assumed to apply: small leak (0%), large leak (50%), and rupture (50%). These occurrence probabilities reflect two basic assumptions: the first is that should pipe body failure occur, the effective tear area will likely be significant (thereby precluding the likelihood of a small leak); the second is that large leak and rupture type failures are both equally likely to develop. (It is recognized that the second assumption is a gross simplification of a complex failure mechanism, however, in the absence of a recognized model or relevant historical data it is considered to be the most reasonable approximation.)

7.3 Performance given Grounding

7.3.1 Node Parameter

The Performance Given Grounding and its direct predecessor nodes are highlighted in the version of the mechanical damage influence diagram shown in Figure 7.2. The specific node parameter is defined as the performance of the pipeline at the time of a randomly occurring mechanical interference event associated with vessel grounding. As indicated in Figure 7.2, Performance Given Impact is a functional node meaning that the value of the node parameter is calculated directly from the values of its direct predecessor node parameters which include: grounding energy and pipe body yield strength.

As with the Performance Given Impact node, this node parameter is a discrete random variable that can assume one of four possible states including safe, small leak, large leak and rupture.

The probability distribution for this node is defined by estimates of the probabilities associated with each of the possible states of the node parameter. Probability estimates for each state: rupture, p_R, large leak, p_{LL}, small leak, p_{SL}, and safe, p_S can be calculated from:

$$p_R = p_{R|P}\, p_{P|G} \qquad [7.7a]$$

$$p_{LL} = p_{LL|P}\, p_{P|G} \qquad [7.7b]$$

$$p_{SL} = p_{SL|P}\, p_{P|G} \qquad [7.7c]$$

$$p_S = 1-(p_{SL} + p_{LL} + p_R) \qquad [7.7d]$$

where $p_{P|G}$ is the probability of pipe body penetration given grounding, and $p_{i|P}$ is the probability of failure in the i^{th} mode given wall penetration.

Calculation of the conditional event probabilities $p_{P|G}$ and $p_{i|P}$ involves the use of probability distributions characterizing the relevant uncertain parameters (*i.e.*, grounding energy and pipe body yield strength) in deterministic response models that define the conditions leading to each possible mode of failure. The probabilistic model used to estimate the probability of line failure given grounding is described in Section 7.3.2. The model used to estimate the probability of failure by leak or rupture given pipe body failure is described in Section 7.3.3.

7.3.2 Probability of Pipe Body Failure given Grounding

The model used to estimate the probability of pipe body failure given vessel grounding is similar to the model adopted for estimating failure given towed object impact. It assumes that a subsea pipeline absorbs the energy associated with vessel hull contact primarily through local denting of the pipe wall. This model conservatively ignores the additional energy that can be absorbed through global bending of the pipeline in response to significant lateral loading. This simplification effectively precludes the need to take into account the complex interaction between a buried pipeline and the surrounding seabed sediment that tends to provide restraint against lateral pipe deformation and thereby affects the degree to which hull grounding energy is absorbed by global bending.

Based on the above assumption, the probability of pipe body failure (i.e., wall penetration) given contact with the hull of a grounding vessel, $p_{P|G}$, is taken to be equal to the probability that the effective kinetic energy associated with the grounding vessel, E_G, will exceed the energy absorption capability (or resistance) of the pipe body in a local denting mode, R, at the impact location. This can be written as:

$$p_{P|G} = p(E_G > R) = p(R - E_G < 0) \qquad [7.8]$$

The kinetic energy available to cause pipe body failure is assumed to vary from zero to 100% of the total kinetic energy associated with the grounding vessel. This assumption follows from the fact that the fraction of the total available kinetic energy that can effectively be brought to bear on the pipe body will depend on the nature of the grounding event. If it is assumed that a grounding vessel hull will deform and displace seabed sediment for a finite distance before it is brought to a stop, then the energy transferred to a pipeline in the path of the hull will depend on the distance ploughed prior to contact with the pipe. Assuming that the grounding frequency estimate reflects all events that could involve the pipeline (i.e., all plough paths that intersect the line) and assuming further that the energy dissipated per unit plough length is uniform, it follows that the effective grounding energy is uniformly distributed over a range of 0.0 to 1.0 times the total available kinetic energy.

The effective kinetic energy associated with grounding events can therefore reasonably be given by:

$$E_G = C_E \, E_{T_G} \qquad [7.9]$$

where E_{TG} is the total available kinetic energy of the grounding vessel and C_E is an effective impact energy multiplier taken as a uniformly distributed variable with a mean value of 0.5 and a standard deviation of 0.289.

The pipe body resistance to failure by grounding induced local denting, R, can be estimated using the model previously described for towed object impacts events (see Equations [7.5] and [7.6] in Section 7.2.2).

7.3.3 Failure Mode given Grounding Induced Failure

As was assumed for failures caused by towed object impact, pipe body failure due to grounding induced local denting is assumed to manifest itself as tensile tearing of the pipe wall due to excessive plastic straining. The mode of failure: small leak, large leak, or rupture; will depend on the length of the tear that develops when the tensile strain limit of the material is exceeded. The tear geometry will depend on the size, shape, and orientation of the indentation resulting from vessel hull.

As previously noted, a model for predicting the likely extent of a pipe body tear resulting from the plastic straining caused by local denting has yet to be developed and in the absence of a recognized model a subjective approach has been adopted. Using this approach, the relative likelihood of small leak, large leak, and rupture failure modes is assigned to the same set of predefined values that were chosen to characterize failures caused by towed object impact (i.e., 0% small leak, 50% large leak, and 50% rupture).

7.4 Segment Performance

7.4.1 Node Parameter

The Segment Performance node and its direct predecessor nodes are highlighted in the version of the consequence analysis influence diagram shown in Figure 7.3. The specific node parameter is defined as the annual performance of the pipeline segment. As discussed in Section 2.2.3, this node also requires information from three nodes in the mechanical damage influence diagram; the probability of failure for a towed object interference event from node 3.1, the probability of failure for a vessel grounding interference event from node 3.2, and the rate of occurrence of these interference events from node 12.1.

The node parameter is a discrete random variable that can assume one of four possible states:

- safe;
- small leak;

- large leak; and
- rupture.

A small leak corresponds to a small hole and a slow product release rate that does not result in a significant hazard. A large leak, involving a hole of significant size, or a rupture are assumed to result in high release rates and the potential for significant hazard to people and property.

7.4.2 Calculation of Node Probability Distribution

In general, the segment probability of failure due to mechanical interference can be calculated by multiplying the probability of failure associated with a single randomly occurring interference event by the potential number of events on the segment. Recalling that a segment will consist of different damage sections, i, each potentially having a different mechanical interference frequency for towed object impact, r_{Ii}, and vessel grounding, r_{Gi}, the annual segment failure probability due to mechanical damage, pms_j (where the subscript j represents the failure mode) can be calculated from:

$$pms_j = \sum_i pmd_{I_{ij}} r_{I_i} l_i + \sum_i pmd_{G_{ij}} r_{G_i} l_i \qquad [7.10]$$

where pmd_{Iij} is the probability of failure in the j^{th} failure mode for a single interference event resulting from towed object impact in the i^{th} damage section, pmd_{Gij} is the similar probability of failure for a single interference event resulting from vessel grounding, and l_i is the length of the i^{th} damage section.

In order to solve the consequence analysis influence diagram, the probabilities of failure due to other causes must be added to the probabilities of failure due to mechanical damage at this node. This ensures that maintenance decisions are based on the total risk associated with the line segment, not just the risk due to mechanical damage. In order to achieve this, the node requires definition of the probabilities of failure due to other causes. The required information includes

- the failure rate per unit length per year, λ_k, for each major failure cause, k, other than mechanical damage; and
- the relative frequency q_{jk} of different failure modes, j, for each failure cause, k.

The total annual probability of failure for the segment, ps_j, for each cause j can be calculated using:

$$ps_j = pms_j + l \sum_k \lambda_k \, q_{jk} \qquad [7.11]$$

where pms_j is the average annual probability of failure mode j for the segment due to mechanical damage and l is the total length of the segment. Equation [7.11] assumes that failure rates due to all causes other than mechanical damage are uniform along the length of the segment. The probability of safe performance for the segment can be calculated by subtracting the total segment failure probabilities due to all causes from 1.

It is noted that estimating the total annual probability of failure as the failure rate times the segment length is a valid approximation provided that the annual probability of more than one failure on the line segment is small (*i.e.*, less than 0.1). This condition is satisfied if the total failure probability from Equation [7.11] is less than 0.5. If this condition can not be satisfied, the pipeline must be analyzed in smaller segments.

7.4.3 Failure Rate Estimates for Other Causes

A review of historical pipeline failure rates was carried out as part of another project within the PIRAMID development program (PIRAMID Technical Reference Manual No. 7.1 - Stephens and Playdon 1998). This review produced baseline failure rates representing natural gas and hydrocarbon liquid pipelines that are considered to be average with respect to construction, operation, and maintenance practices. These rates are given in Table 7.1 and can be used as default failure probabilities in the absence of more line-specific data.

Note that it is not necessary to define the failure rates by failure cause as indicated in Table 7.1, since only the total failure rate per failure mode is used in the calculation. The input format in Table 7.1 is selected because it was believed that it is easier to define the relative frequency of different failure modes separately for different failure causes. An equivalent input would consist of the total failure rate due to all causes other than mechanical damage and the corresponding relative frequencies of different failure modes, defined in any row of Table 7.1, with zero inputs in all other rows.

Figures and Tables

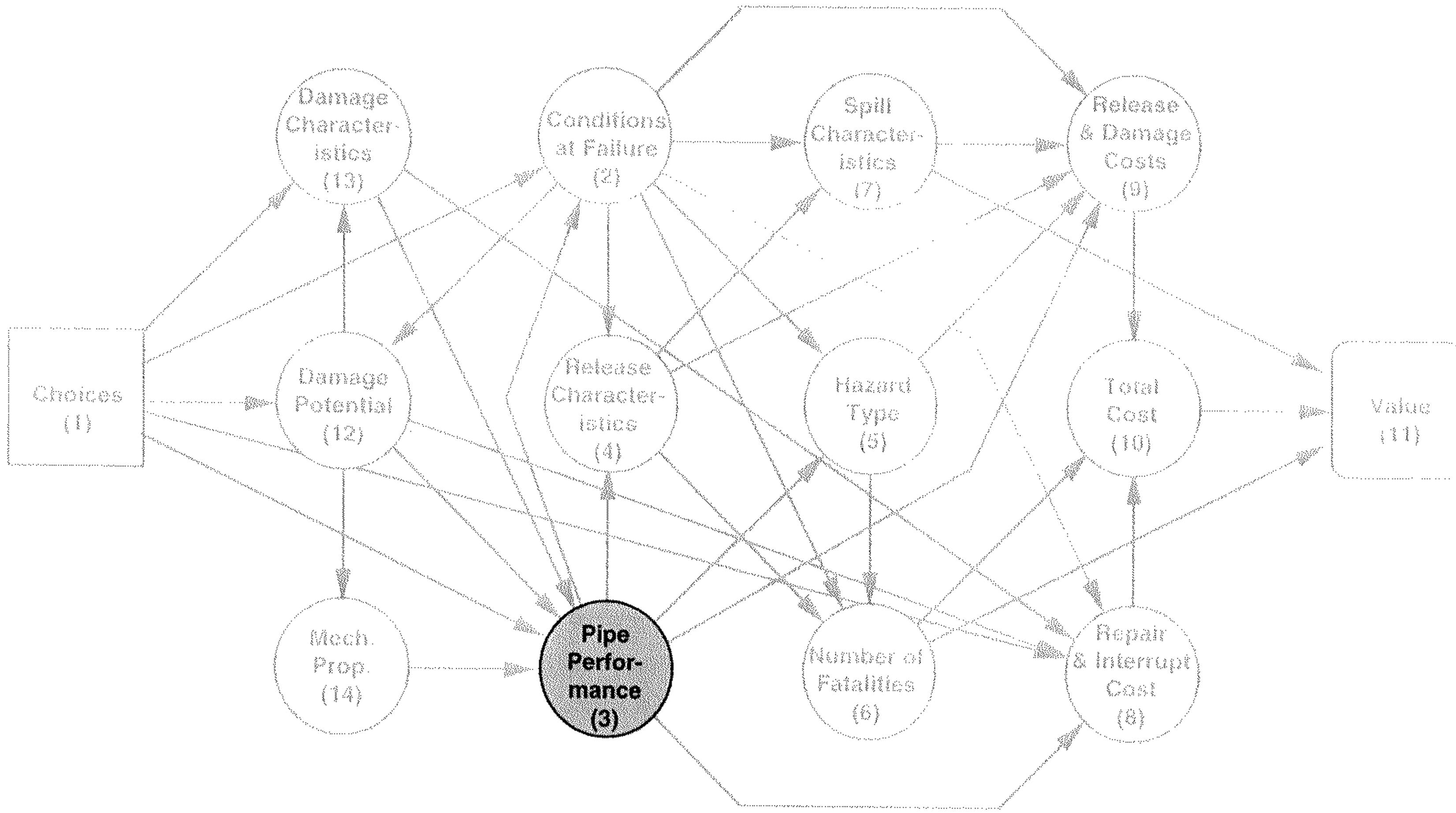


Figure 7.1 Compound node influence diagram highlighting Pipe Performance node group.

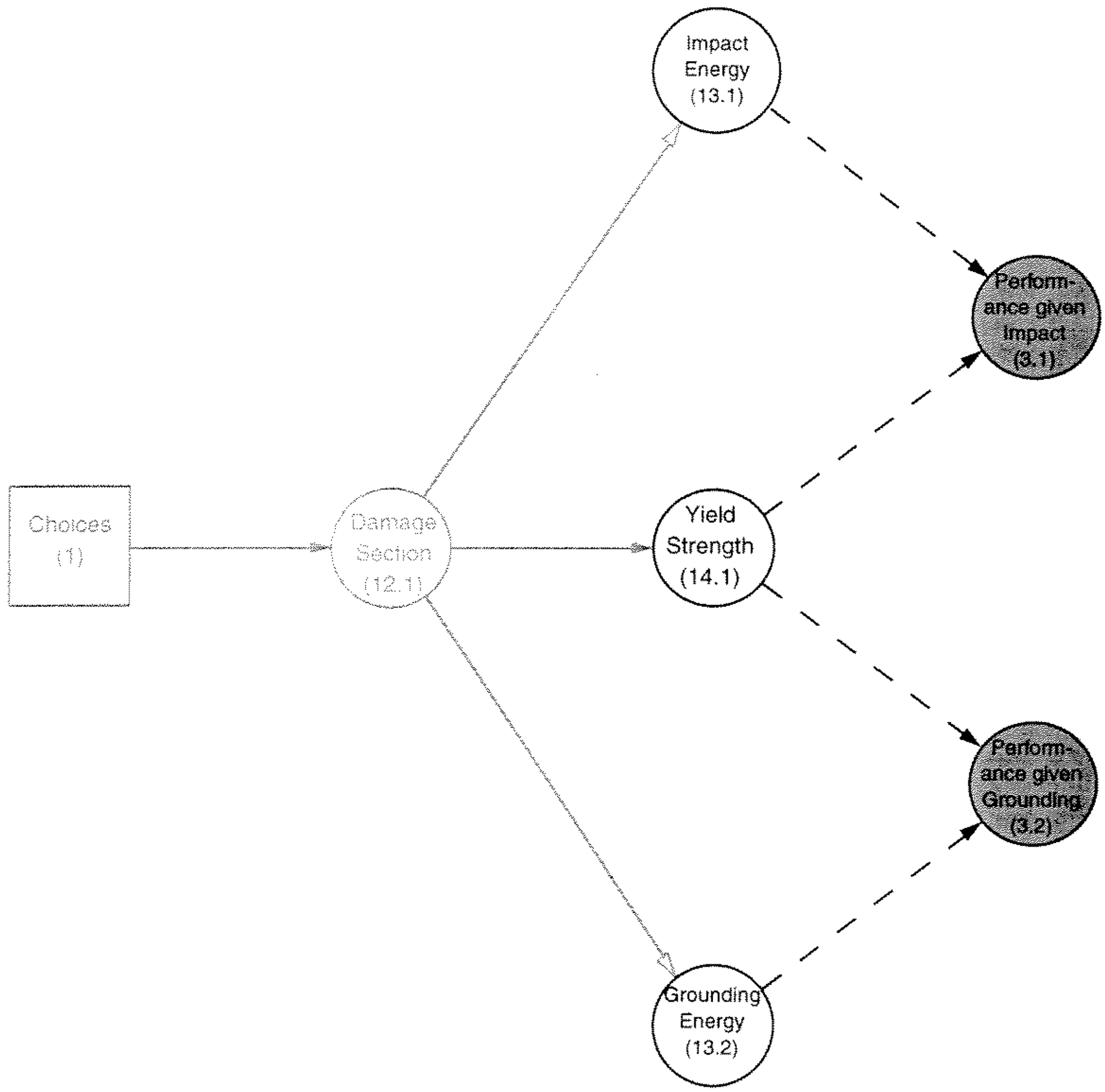


Figure 7.2 Basic node mechanical damage influence diagram highlighting the Performance given Damage node and immediate predecessor node.

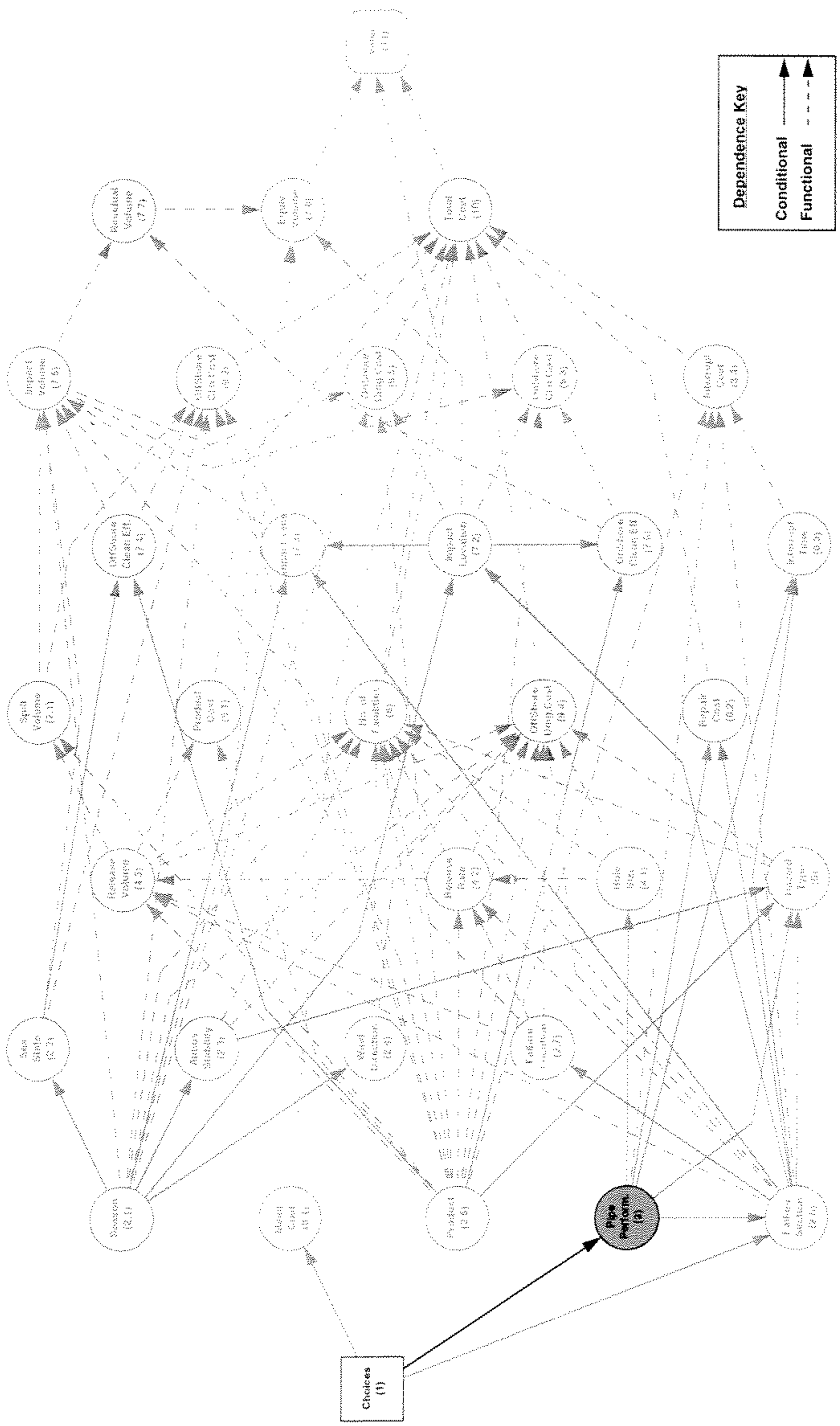


Figure 7.3 Basic node consequence influence diagram highlighting Segment Performance node and associated immediate predecessor node.

Failure Cause	Baseline Failure Rate (incidents/km yr)		Mode Factor		
	Gas Pipeline	Liquid Pipeline	small leak	large leak	rupture
External Metal Loss Corrosion	1.0×10^{-4}	2.6×10^{-4}	0.85	0.10	0.05
Internal Metal Loss corrosion	4.4×10^{-4}	5.4×10^{-4}	0.85	0.10	0.05
Natural Hazard Damage	0.8×10^{-4}	3.0×10^{-4}	0.25	0.50	0.25
Ground Movement	not applicable	not applicable	0.20	0.40	0.40
Environmental Cracks (SCC)	not applicable	not applicable	0.60	0.30	0.1
Mechanical Cracks (fatigue)	not applicable	not applicable	0.6	0.3	0.1
Other Causes	1.6×10^{-4}	2.8×10^{-4}	0.8	0.1	0.1

Table 7.1 Average pipeline failure rates by cause and failure mode

8. CONDITIONS AT FAILURE

8.1 Overview

The Conditions at Failure node group (group 2) is highlighted in the version of the compound node influence diagram in Figure 8.1. This node group includes parameters describing the conditions associated with a possible failure of the pipeline, including weather conditions (*i.e.*, season, sea state, atmospheric stability, and wind direction) and product in the line for the pipeline section at which the failure occurs, and the specific failure location within that section.

Nodes within this group are required by the consequence analysis portion of the influence diagram and were therefore discussed in detail in PIRAMID Technical Reference Manual No. 5.1 (Stephens *et al.* 1996). The node group is included in the present document because one of the nodes, namely node 2.6 representing the Failure Section, was modified as a consequence of incorporating the mechanical damage analysis portion of the influence diagram. This node is discussed in detail in Section 8.2.

8.2 Failure Section

The Failure Section node (node 2.6) and its direct predecessor node are highlighted in the version of the basic node consequence analysis influence diagram shown in Figure 8.2. The node parameter represents the pipeline section containing the failure location. It is noted that pipeline sections for this node correspond to lengths of the pipeline for which *the line attributes affecting failure consequences* are uniform (see PIRAMID Technical Reference Manual No. 5.1 for a detailed listing of these attributes). The sections corresponding to this node are therefore different than those corresponding to the Damage Section node for which sectioning is based on the attributes affecting failure probability due to mechanical damage. Some line attributes affect both probabilities and consequences and are therefore included in the sectioning criteria for both the Damage Section and Failure Section nodes. As shown in Table 4.1, these common attributes are pipe diameter, wall thickness, elevation profile, adjacent platform type and vessel traffic. Attributes that affect probability but not consequences include pipe body yield strength and reference cover, for instance, whereas examples of attributes that affect consequences but not probabilities are pipeline orientation and operating temperature.

It would have been possible to combine the Damage Section and Failure Section nodes into one node for which the individual sections are uniform with respect to all attribute parameters. This approach is simpler than the one adopted in PIRAMID, however it is not as computationally efficient. Figure 8.3 illustrates the difference between the two approaches. The figure shows a pipeline that has three Damage Sections (*i.e.*, sections with uniform probability-related attributes) and four Failure Sections (*i.e.*, sections with uniform consequence-related attributes). The approach adopted in PIRAMID requires the probability analysis to be carried out for the three

Damage Sections and the consequence analysis to be carried out for the four Failure Sections. If the pipeline were divided into uniform sections with respect to all attributes combined, it would have six different sections, requiring both probability and consequence analyses to be carried out six times.

An arrow was added to the consequence analysis influence diagram to account for conditional dependence of the Failure Section on Segment Performance. This dependence means that the probability of a failure event occurring on a specific section of the line depends on whether the failure occurs by rupture, large leak, or small leak. The reason for this new relationship is that, in this version of the program, the probabilities of different failure modes are calculated from the mechanical damage attributes corresponding to each individual section, and therefore the relative probabilities of small leak, large leak, and rupture will vary from section to section. Since the probability of a given failure mode depends on the section, it follows that the probability of a specific section given failure depends on the failure mode.

The probabilities associated with this node can be calculated using Bayes' theorem which, in the context of the present problem, states that the probability of a specific section, i, given failure is proportional to the probability of failure occurring on that section:

$$p(Sec_i | f_j) \propto p(f_j | Sec_i) \qquad [8.1]$$

where j indicates a specific failure mode. The probability of failure given a specific Failure Section can be calculated as the sum of the probabilities of failure of all interference events within that section. This leads to (refer to Figure 8.3):

$$p(f_j | Sec_i) = \sum pd_{jk}\, r_k\, l_{ik} \qquad [8.2]$$

where pd_{jk} is the probability of failure mode j for a randomly selected interference event on Damage Section k, r_k is the number of interference events per unit length on Damage Segment k, and l_{ik} is the length of the portion of Damage Section k that overlaps Failure Section l. The summation in Equation [8.2] is for all Damage Sections overlapping the Failure Section being considered. Once Equation [8.2] is evaluated for all Failure Sections, the probability distribution of the Failure Section can be calculated by using Equation [8.1] and normalizing the probabilities of all sections to add up to one. This leads to:

$$p(Sec_i | f_j) = \frac{p(f_j | Sec_i)}{\sum_i p(f_j | Sec_i)} \qquad [8.3]$$

Figures

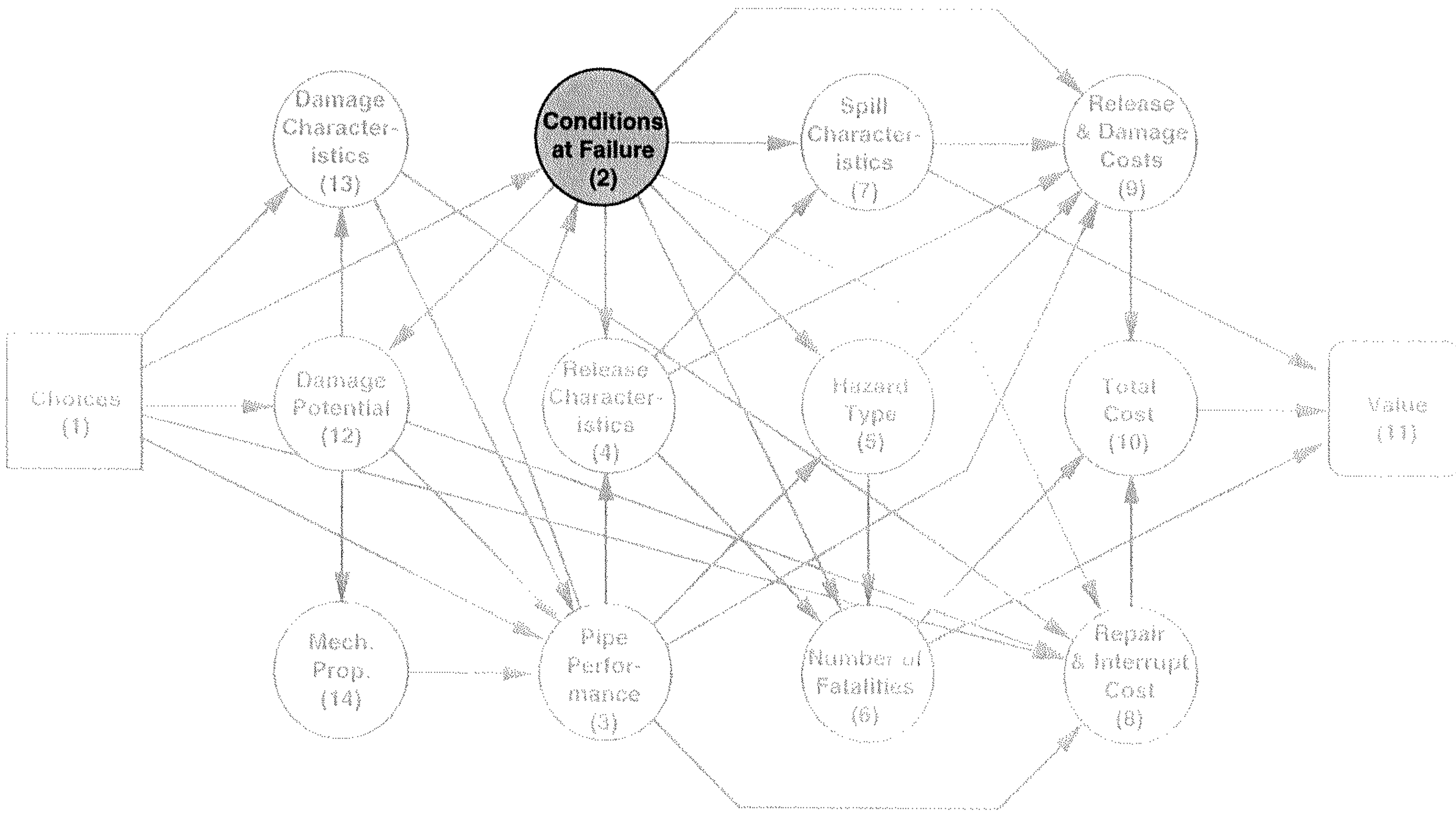


Figure 8.1 Compound node influence diagram highlighting Conditions at Failure node group.

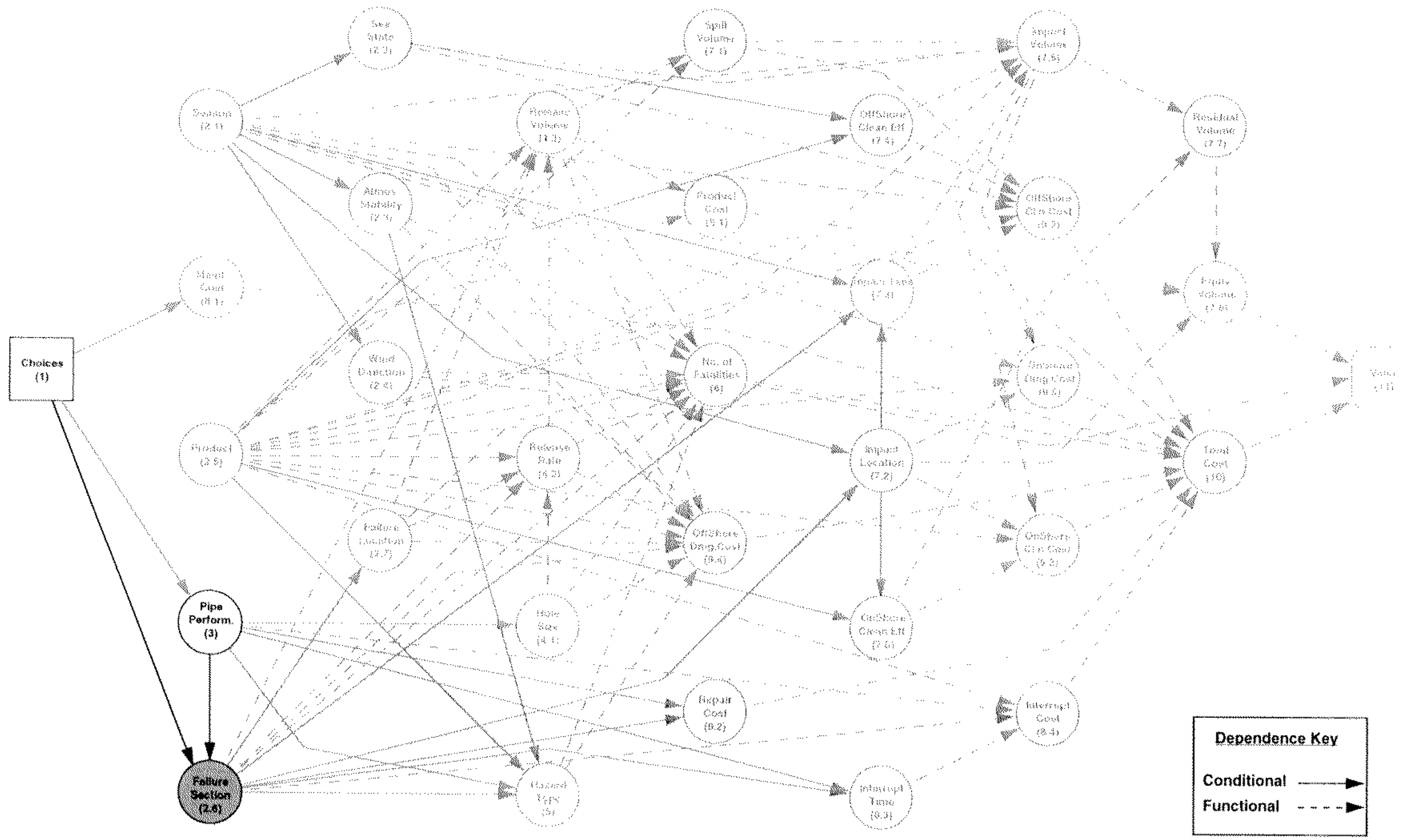


Figure 8.2 Basic node consequence influence diagram highlighting Failure Section node and associated immediate predecessor nodes.

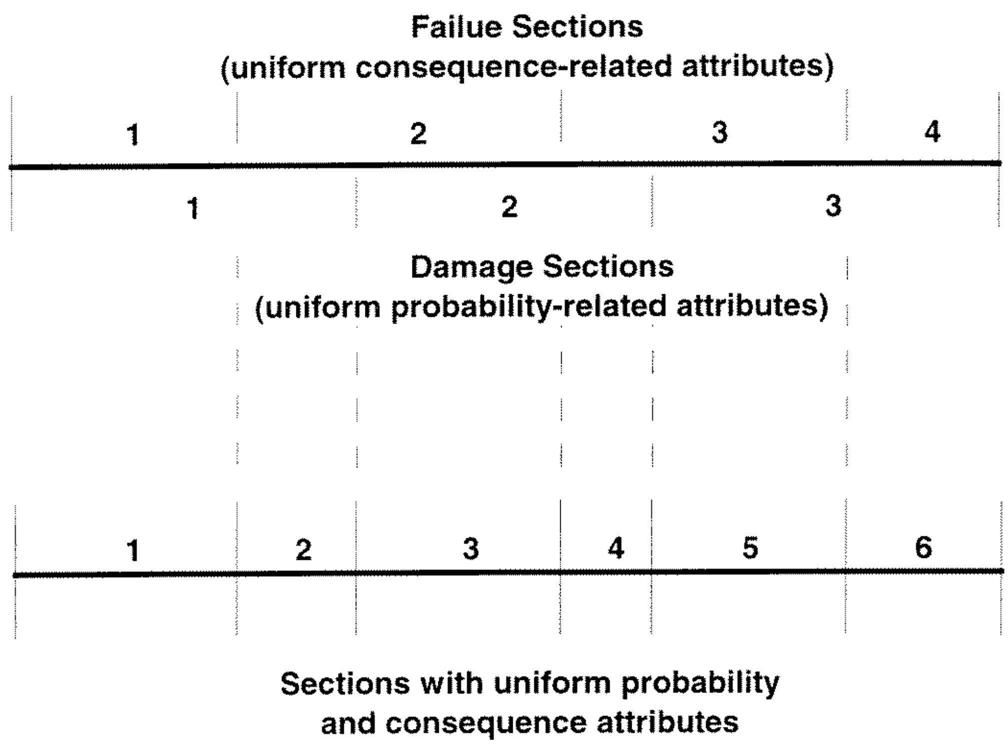


Figure 8.3 Illustration of pipeline segmentation with respect to probability-related and consequence-related attributes

9. REPAIR AND INTERRUPTION COST

9.1 Overview

The Repair and Interruption Cost node group (group 8) is highlighted in the version of the compound node influence diagram in Figure 9.1. This node group includes parameters describing the maintenance cost, failure repair cost, interruption time, and interruption cost. Nodes within this group belong to the consequence analysis portion of the influence diagram and were therefore discussed in detail in PIRAMID Technical Reference Manual No. 5.1 (Stephens *et al.* 1996). The node group is included in the present document because one of its nodes, namely node 8.1 representing the Maintenance Cost, was modified as a consequence of incorporating the mechanical damage analysis portion of the influence diagram. This node is discussed in detail in Section 9.2.

9.2 Maintenance Cost

The Maintenance Cost node (node 8.1) and its direct predecessor node are highlighted in the version of the basic node consequence analysis influence diagram shown in Figure 9.2. The node parameter represents the total annual maintenance cost for the whole pipeline segment in present value currency. The predecessor node arrow indicates that Maintenance Cost is a conditional node meaning that the value of the node parameter is conditionally dependent upon the value of its direct predecessor node, which is Choices. The Maintenance Cost node parameter must therefore be defined explicitly for all inspection and maintenance options identified at the Choices node.

The node parameter is calculated, for each choice, based on user defined specification of both the initial cost of implementing a particular set of maintenance actions, CM_{in}, and the expected annual cost associated with each action set, CM_{in}. Given that the total maintenance cost parameter is defined as an annual cost, the initial cost component must be converted into an equivalent annual cost before the two cost components are added together. The initial cost can be converted into and equivalent annual cost using a capitol recovery factor, F_{cr}, which effectively treats the initial cost as a loan that is amortized over a fixed period of time.

In the context developed herein, the capitol recovery factor is given by

$$F_{cr} = \frac{r}{[1-(1+r)^{-\tau}]} \qquad [9.1]$$

where, r, is the real interest rate defined as the actual interest rate less the inflation rate and, τ, is the expected remaining life of the pipeline segment.

Repair and Interruption Cost

The total annual maintenance cost, CM_t, is therefore

$$CM_t = CM_{an} + F_{cr}\, CM_{in} \qquad [9.2]$$

The cost information required to define the node parameter inputs is highly pipeline specific. The initial and annual costs for each set of candidate integrity maintenance actions identified at the Choices node should therefore be established for a given pipeline based on operating company experience and/or budget price estimates provided by contractors that provide pipeline inspection and maintenance services.

A reasonable estimate of the expected remaining life must also be made; however, the total annual cost is not highly sensitive to this quantity, particularly when the remaining life is on the order of 20 years or more. Finally, the real interest rate must be estimated and the appropriate value will depend on forecasted economic conditions, however, real interest rates have historically fallen in the three to five percent range and the total annual cost estimate is not highly sensitive to variations in the assumed interest rate within this range.

Figures

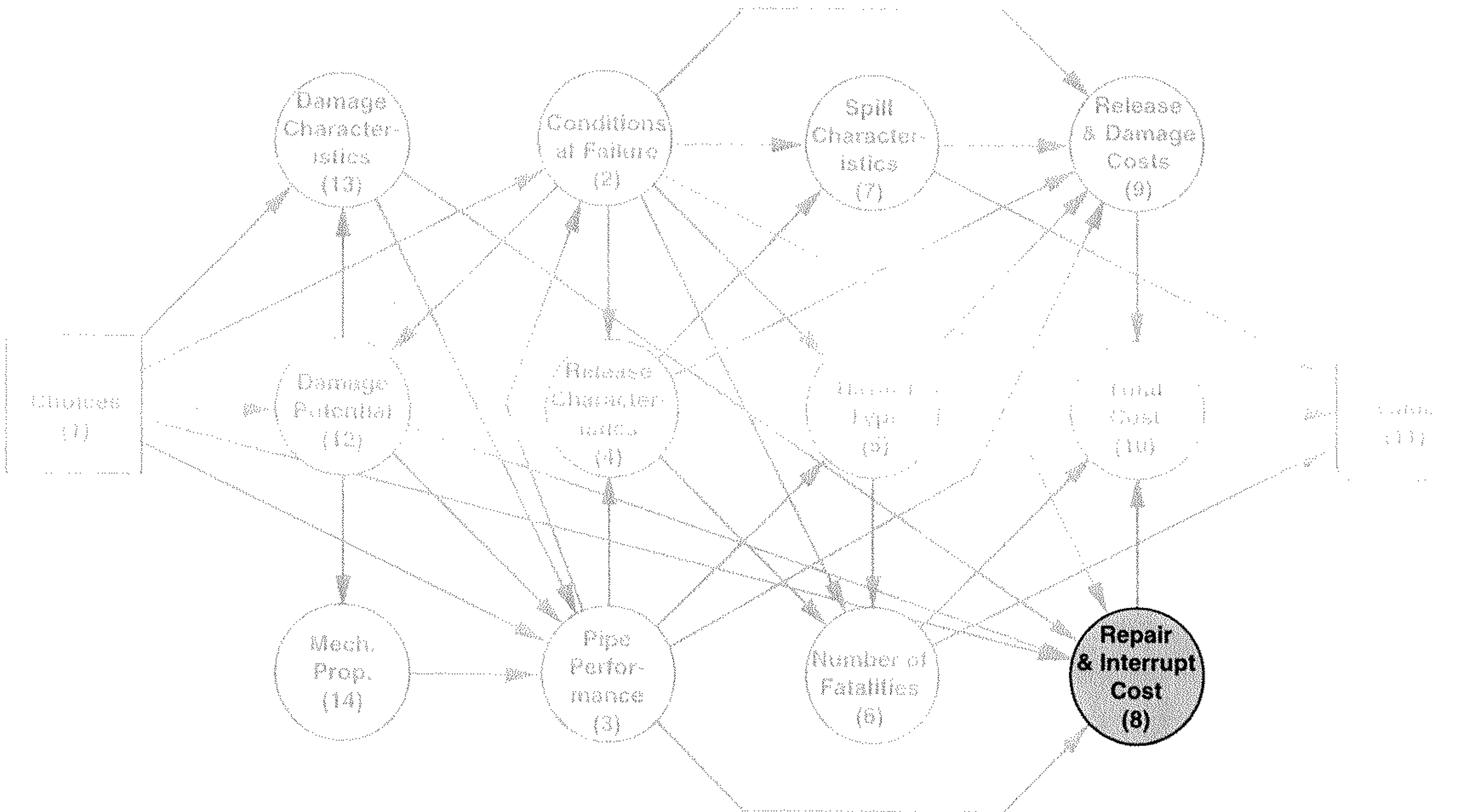


Figure 9.1 Compound node influence diagram highlighting Repair & Interrupt Cost node group.

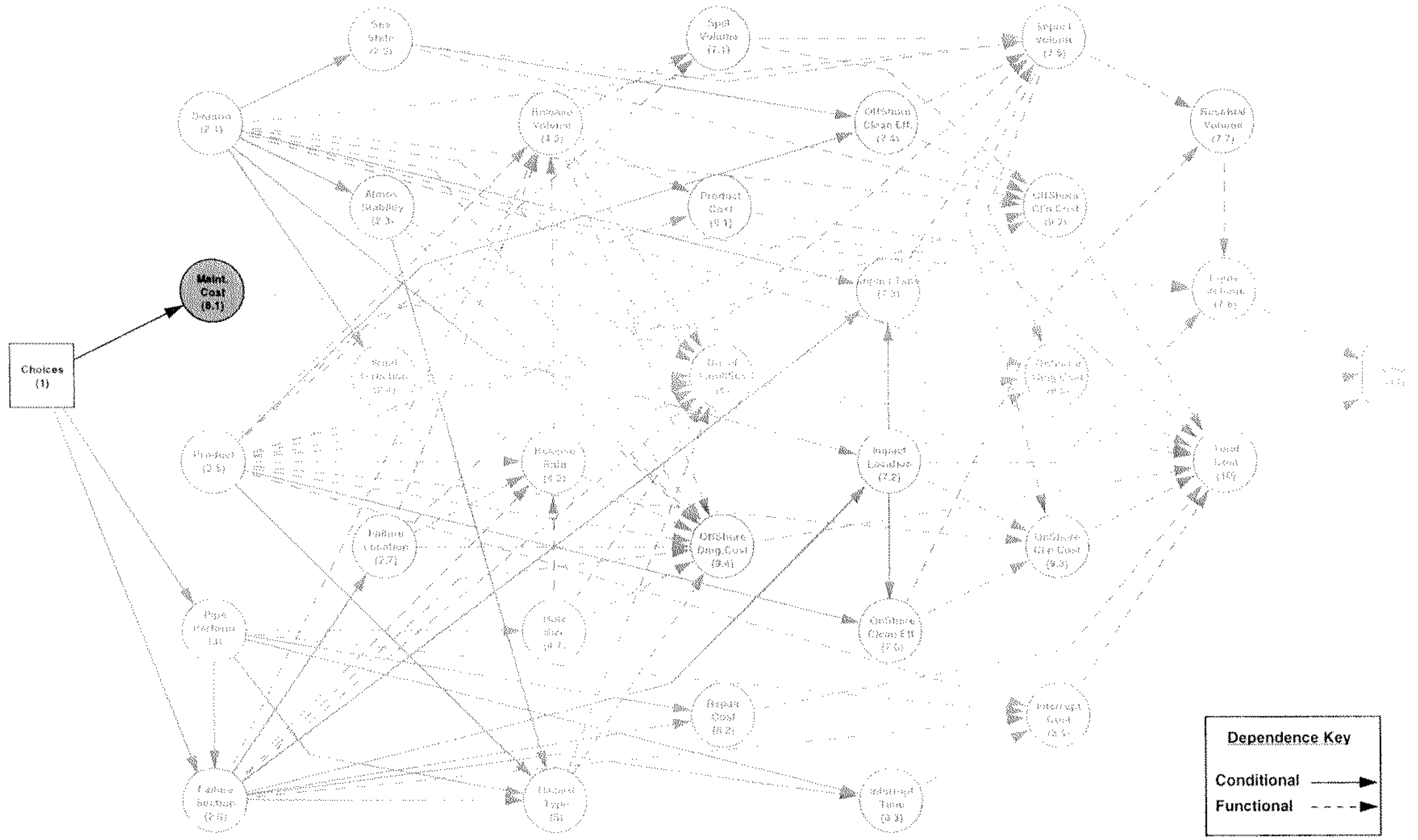


Figure 9.2 Basic node consequence influence diagram highlighting Maintenance Cost node and associated immediate predecessor node.

10. VALUE

The Value node (node 11) and its direct predecessor nodes are highlighted in the versions of the influence diagram shown in Figures 10.1 and 10.2. The value node defines the criterion used to evaluate maintenance choices taking into account the safety, environmental protection, and financial objectives of the decision-maker. Depending on the preferences of the user, the specific parameter of the node is either the utility or the total cost.

For the utility option, value is defined as a function of the number of fatalities, the equivalent spill volume, and the total cost, which are the three parameters measuring human safety, environmental protection, and financial objectives. The utility function is defined as an all-inclusive criterion for ranking different combinations of these three parameters, taking into account the decision-maker's attitudes toward risk and tradeoffs between life safety, environmental impact, and costs. The purpose of the influence diagram in this case is to maximize the expected utility.

For the total cost option, the node parameter is defined as the total cost. In this case, the influence diagram is used to identify the minimum cost choice subject to user-defined constraints regarding the maximum allowable level of environmental risk.

Details of the inputs and calculations associated with the value node are given in PIRAMID Technical Reference Manual No. 5.1 (Stephens *et al.* 1996). That document describes value optimization for a single choice node that includes a set of discrete options which is entirely consistent with the choice definition approach adopted for optimization analysis of mechanical damage prevention activities.

Figures

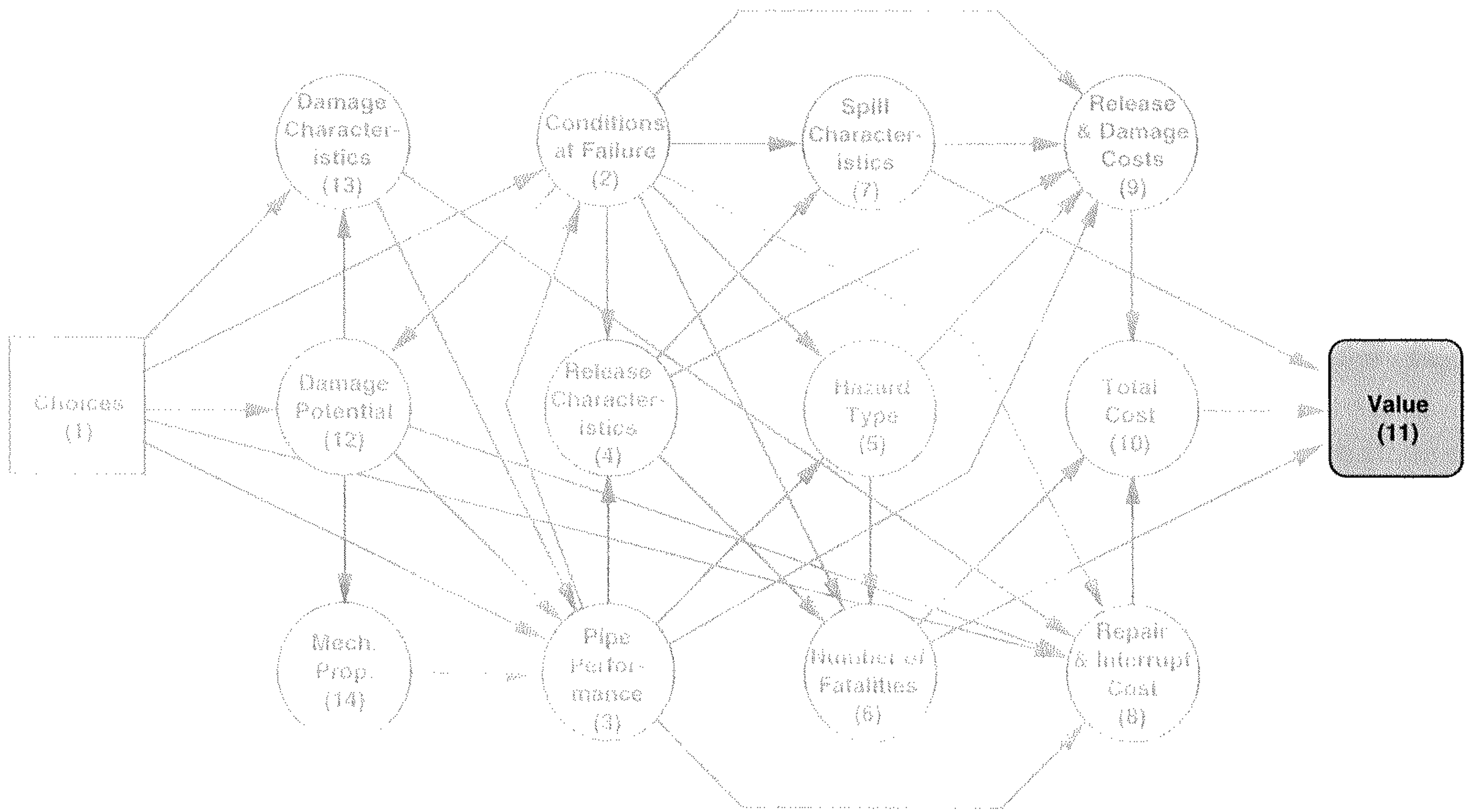


Figure 10.1 Compound node influence diagram highlighting value node group.

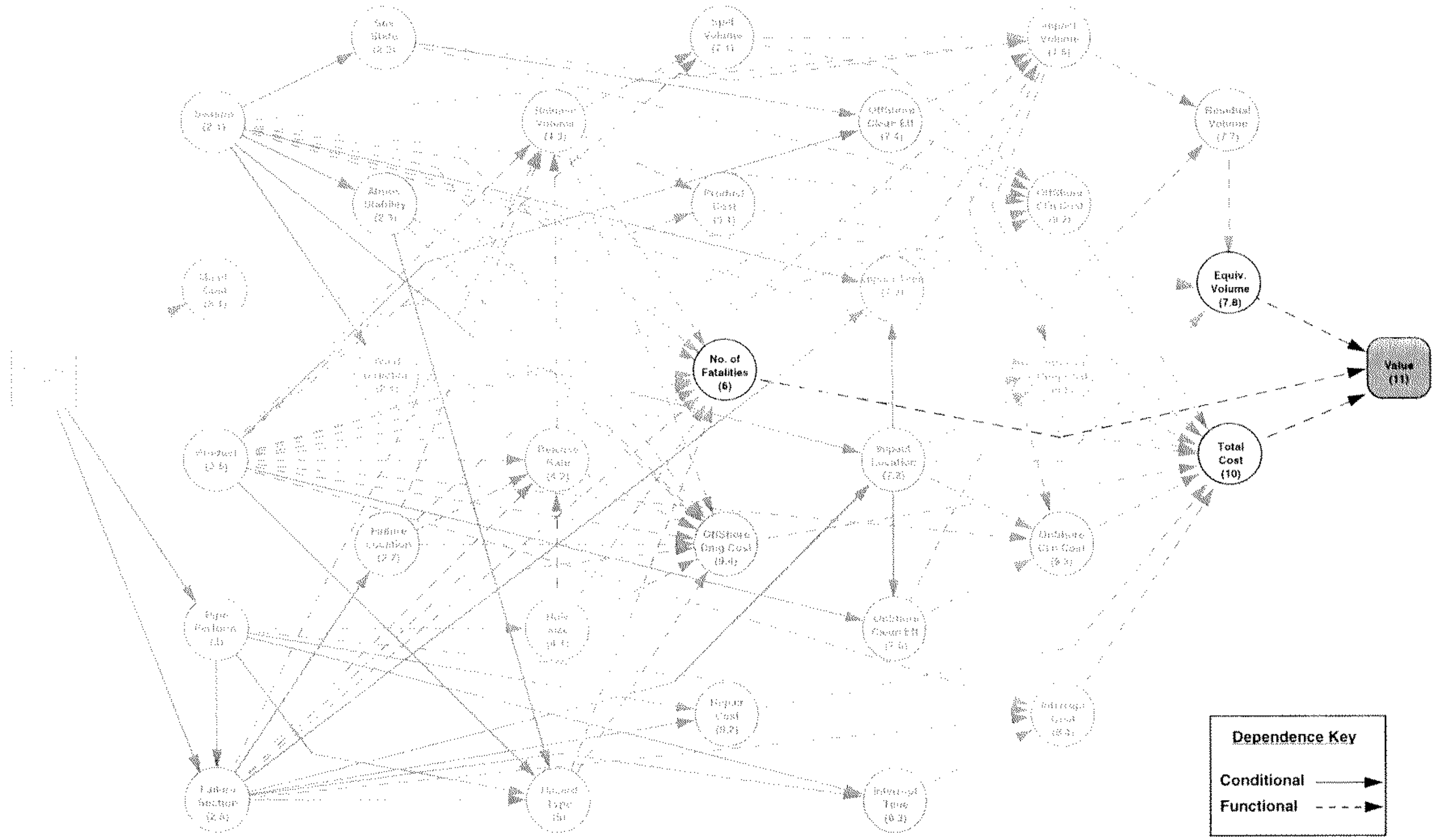


Figure 10.2 Basic node consequence influence diagram highlighting value node and associated immediate predecessor nodes.

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