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# Optimization of Preventative Maintenance for Mechanical Damage

## PIRAMID Technical Reference Manual No. 8.0

AK

**Confidential to C-FER's Pipeline Program Participants**

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## NOTICE

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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 module developed was a consequence assessment module that estimates the impact of a (onshore) pipeline failure on cost, public safety, and the environment (see PIRAMID Technical Reference Manual No. 3.2 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 right of way patrols 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 puncture 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. 3.2 (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; to encourage notification prior to the start of activity; to detect on going activity; and to enhance measures intended to prevent impact given activity.

# 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 dependence 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 impact force, the size of the indentor generating the force, and mechanical properties of the pipe (*i.e.*, yield strength and notch toughness). 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 node in the influence diagram shown in Figure 2.2 is Performance Given Damage. This node contains the information necessary to link the mechanical damage influence diagram to the consequence analysis influence diagram. Performance Given Damage represents the pipe performance at a randomly occurring mechanical interference event within a specific pipeline section. This node 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 Damage 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 Damage 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 3.2 (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.
- *Season.* The Season node (node 2.1) consists of the relative probability of summer or winter conditions at the time of an interference event. It is also 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 3.2) in the consequence analysis influence diagram is calculated from the probability distribution of the Performance Given Damage node (node 3.1) in the mechanical damage influence diagram. This calculation involves converting the probability of failure given impact (node 3.1) to the probability of failure for the whole pipeline segment, using the average number of impact events per unit length along the line from node 12.1 (see Section 7.3 for details). As such, calculation of Segment Performance (node 3.2) requires information from nodes 3.1 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. 3.2. The modifications are as follows:

- The *Pipe Performance* node (node 3) in the original diagram was renamed to Segment Performance and renumbered to node 3.2 in order to distinguish it from the Performance Given Damage node (node 3.1). 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 Season (node 2.1) to Segment Performance (node 3.2). This arrow indicates that the probability distribution of the Segment Performance is conditional on the Season node parameter (*i.e.*, the probability of line failure depends on the season at the time of failure). This dependence can be understood by considering that the probability of failure depends on the likelihood of impact which is assumed to be conditionally dependent on season (see Figure 2.2).
- A conditional arrow was added from Segment Performance (node 3.2) 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 Season (node 2.1) to *Failure Section* (node 2.6). This arrow accounts for the fact that the line impact frequency is assumed to vary with season. Because failure frequency depends on impact frequency, the relative failure frequencies for different pipeline sections will also potentially vary with the season.

- 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. 3.2), 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) |

The Decision Analysis Influence Diagram

6.0 Mechanical Properties (node group 14)

7.0 Pipe Performance (node group 3)

8.0 Conditions at Failure (node group 2)

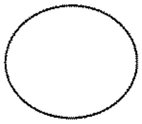
9.0 Repair and Interruption Costs (node group 8)

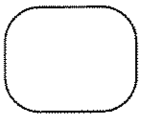
10.0 Value (node group 11)

Figures

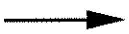
**Node Notation**

 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

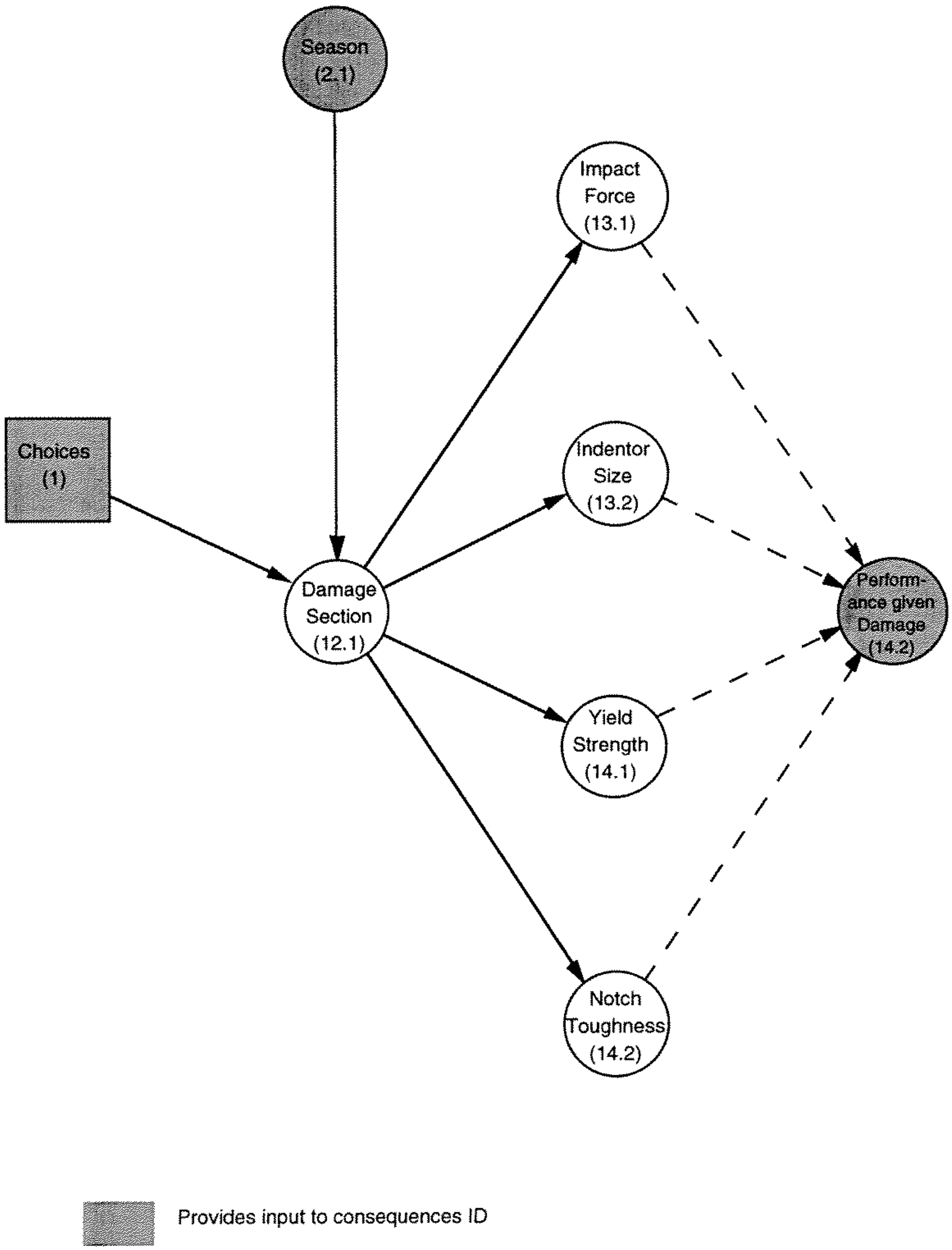
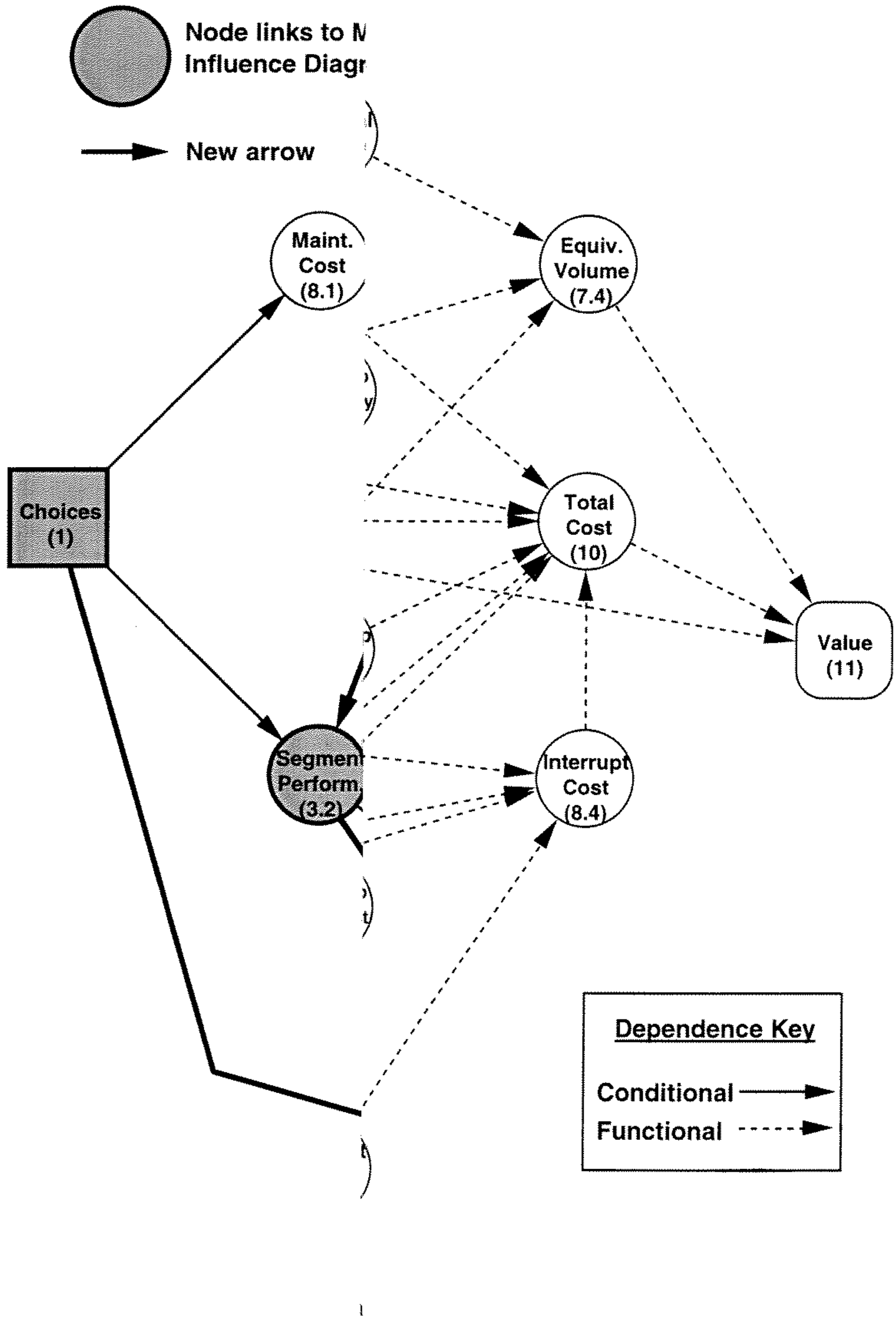
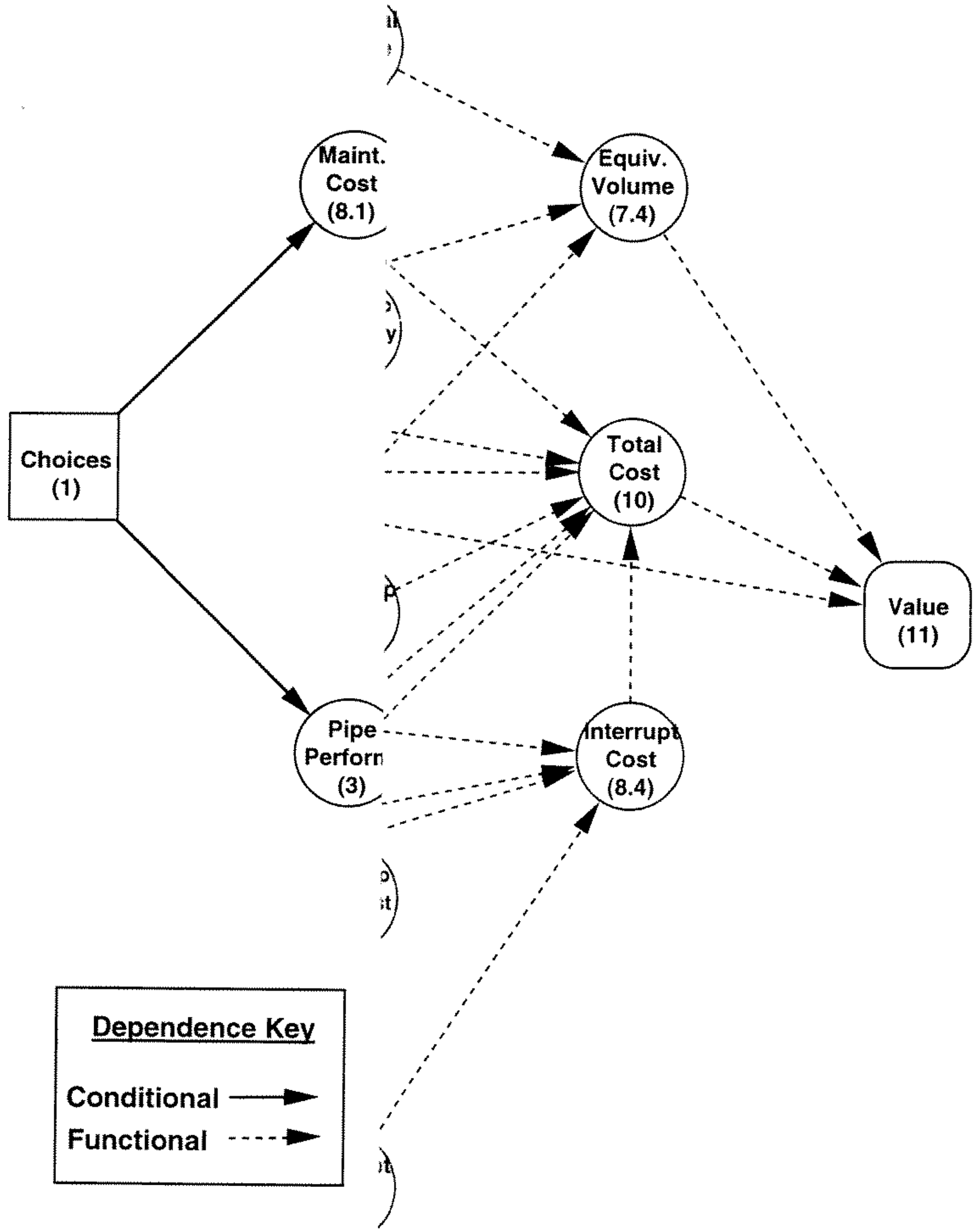



Figure 2.2 Influence diagram for mechanical damage failure probability estimation


Node links to M
Influence Diagr
New arrow
Maint. Cost (8.1)
Equiv. Volume (7.4)
Choices (1)
Total Cost (10)
Value (11)
Segment Perform. (3.2)
Interrupt Cost (8.4)
Dependence Key
Conditional
Functional




ɔhens *et al*. 1996)

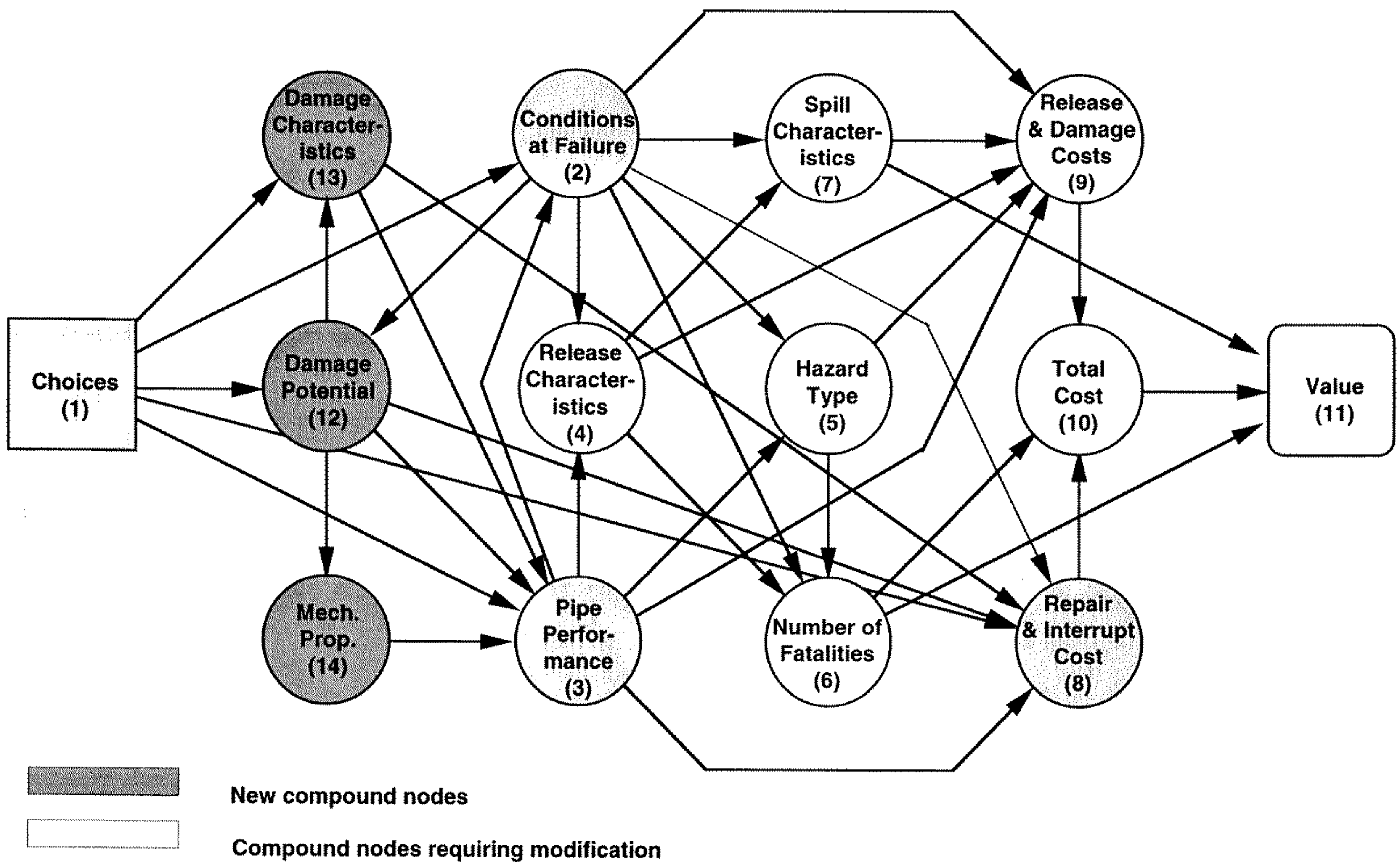



Figure 2.5 Compound node influence diagram for optimization of mechanical damage prevention

# 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 right-of-way, and the community at large that are considered to have a discernible effect on the potential for failure of an existing 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 pipeline.

    - right-of-way condition
    - explicit pipeline signage
    - permanent above-ground alignment marker
    - buried alignment markers
    - level of public awareness

2. Attributes that affect the use of, and effectiveness of, dig notification systems.

    - existence of one call system
    - type of one call system
    - operator response to notification
    - level of public awareness

Choices

3. Attributes that affect the likelihood of detecting on-going activity on the alignment.

    - right-of-way surveillance interval
    - right-of-way surveillance method

4. Attributes that affect the potential for interference resulting from uncontrolled activity.

    - line burial depth
    - mechanical protection

Attributes associated with the first three categories are thought to influence the probability of failure by affecting the likelihood of uncontrolled excavation or digging activity occurring directly on the pipeline alignment (where uncontrolled activity means activity by parties unaware of the exact location of the line). The last category is associated with attributes that are thought to influence the potential for line impact given uncontrolled activity directly on the alignment.

A list 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. These candidate maintenance activities are summarized in Table 3.1.

# Figures and Tables

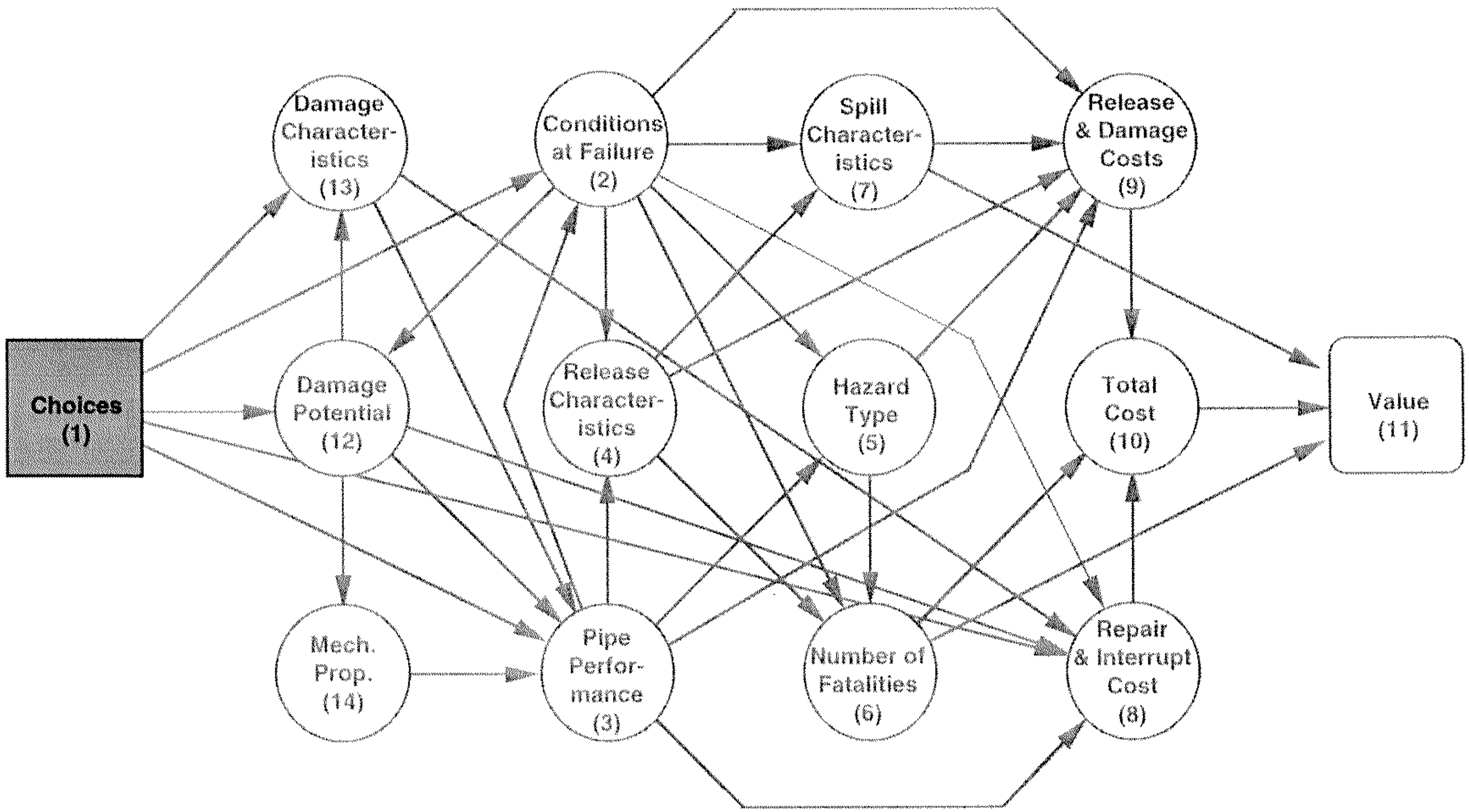



Figure 3.1 Compound node influence diagram highlighting Choices node group

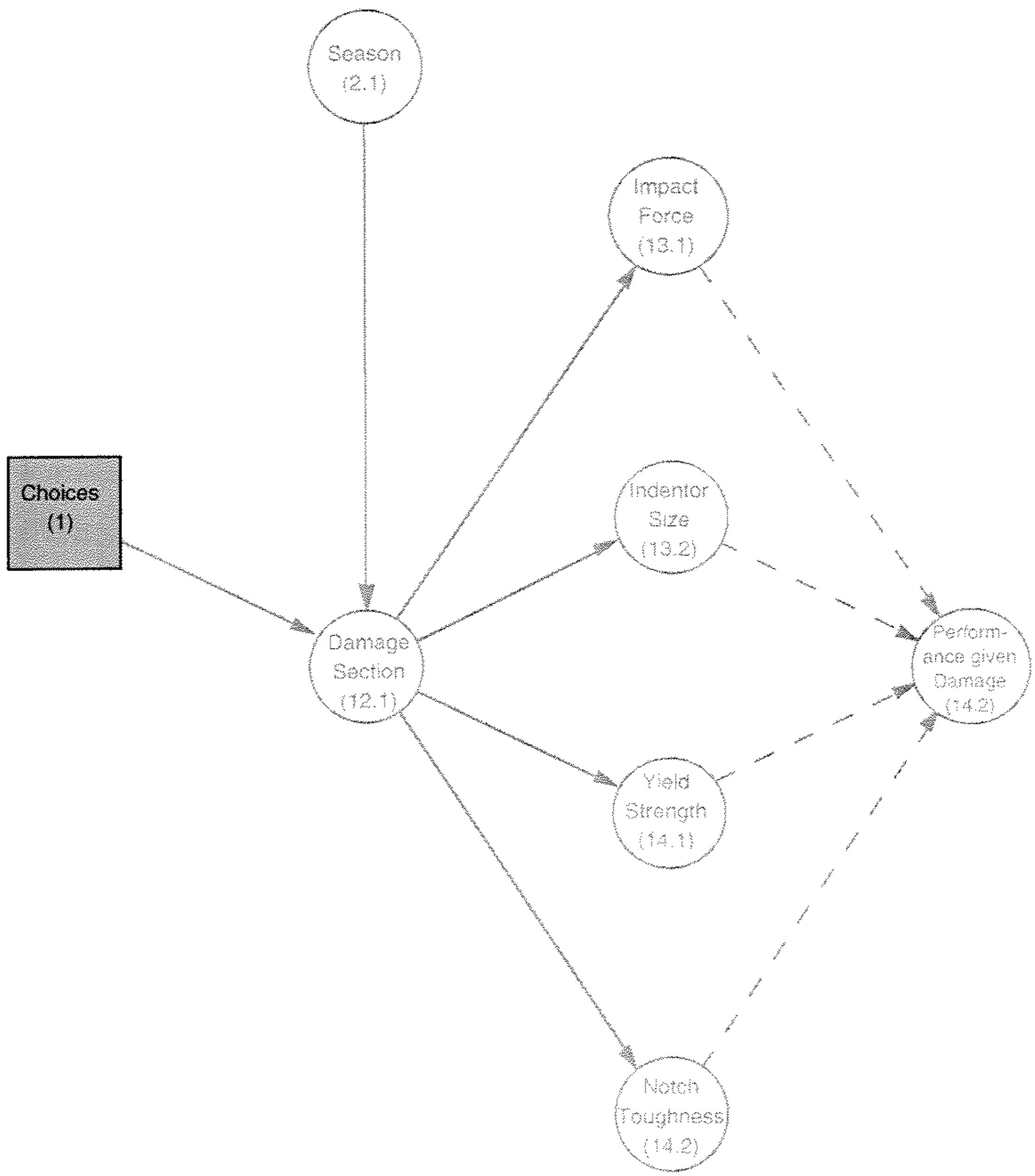



Figure 3.2 Basic node mechanical damage influence diagram highlighting Choices node

| Maintenance Action | Effect of Action on Factors Contributing to Probability of Failure | | | |
|---|---|---|---|---|
| | Awareness of Existence and Location of Pipeline | Effectiveness of Dig Notification Systems | Likelihood of Detecting Activity on Alignment | Potential for Interference given Activity |
| Enhance right-of-way condition | X | | | |
| Add explicit pipeline signage | X | | | |
| Add permenant above-ground markers | X | | | |
| Add buried alignment markers | X | | | |
| Enhance level of public awareness | X | X | | |
| Introduce or modify one call system | | X | | |
| Change dig notification response | | X | | |
| Modify right-of-way patrol frequency | | | X | |
| Modify right-of-way patrol method | | | X | |
| Increase pipeline burial depth | | | | X |
| Introduce mechanical protection | | | | 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 relatively 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 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).

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 are listed in Table 4.1. These attributes reflect the following considerations:

- Characteristics of the right-of-way that influence public awareness of the existence and specific location of the pipeline.
- Activities by the operator or associated agencies intended to promote the awareness, use, and effectiveness of dig notification (*i.e.*, one call) systems.
- Activities by the operator or their representatives intended to detect pending or on-going excavation or digging activity with the potential to cause mechanical interference.
- Preventative measures intended to limit the potential for mechanical interference resulting from uncontrolled activity.
- Physical and operational characteristics of the pipeline that affect the puncture resistance and/or fracture initiation susceptibility 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.

#### 4.2.3.1 Analysis Approach

The modeling approach adopted in this project 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". The events leading to the top event include the occurrence of excavation or digging activity on the alignment, events that result in the failure of measures intended to prevent activity on the alignment (*e.g.*, failure of one call systems to notify relevant operator and failure of right-of-way patrols to detect activity in time), and the failure of mechanical protection if present.

The two main types of event interactions considered in fault trees are:

- The AND relationship, which means that a number of events must coexist for the output event to occur. For example, construction activity AND lack of timely detection of the activity must coexist for mechanical interference to occur.
- The OR relationship, which means that any one (or more) of a number of events could cause the output event to occur. For example, either contractor's ignorance of the presence and location of a pipeline OR contractor's negligence in avoiding it could result in the pipeline being hit by excavation equipment.

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.

#### 4.2.3.2 Mechanical Damage Fault Tree

The fault tree developed to model mechanical interference is shown in Figure 4.3. The different shapes used in the figure 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 4.3 models the top event of a pipeline hit by an excavator. The first level of branching states that a line hit occurs if: there is excavation activity on the alignment (basic event B1), the preventative measures fail to stop uncontrolled activity (intermediate event E2), and the protective measures fail to prevent uncontrolled activity leading to line impact (intermediate event E3). These events must all be true for the hit to occur and therefore they are connected with an AND gate (gate 1).

Damage Potential

At the second branch level, Gate 2 states that preventative measures will fail if either the alignment is not correctly located (intermediate event E4) OR if the contractor accidentally hits the correctly located line (basic event 13). Gate 3 indicates that protective measures will fail if both the excavation depth exceeds the depth of cover (basic event B14) AND the mechanical protection, if present, fails to prevent the excavation tool from contacting the pipe (basic event B15).

This process of defining relationships between contributing events continues through progressively lower branch levels until all branches in the fault tree end with a basic event. (A full description of each branch in the tree is given in Appendix A.)

Note that the basic events associated with the fault tree described in Figure 4.3 are all assumed to be independent events and the event numbering sequence conveys the following loosely chronological sequence of causal events given activity on the alignment (event B1):

- parties fail to use one call system before moving onto alignment (event B2);
- right-of-way indicators not recognized by interested parties (event B3);
- if indicators recognized, parties ignore right-of-way indicators (event B4);
- one call system, if used, fails to notify relevant operator (event B5);
- explicit pipeline signage not seen by interested parties (event B6);
- if explicit signage seen, parties ignore pipeline signage and do not contact operator (event B7);
- no right-of-way patrol occurs during activity period (event B8);
- if patrol occurs during activity period, patrol personnel fail to detect activity (event B9);
- if operator is notified of pending activity, operator fails to correctly locate alignment (event B10);
- permanent above-ground markers, if they exist, fail to convey alignment location (event B11);
- buried alignment markers, if they exist, fail to convey alignment location (event B12);
- accidental activity occurs on located alignment (event B13);
- excavation depth exceeds cover depth (event B14); and
- mechanical protection, if it exists, fails to protect pipe (event B15).

#### 4.2.3.3 Frequency Estimation Based on the Mechanical Damage Fault Tree

The fault tree 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 depend on the characteristics of the fault tree (see McCormick 1981 for more details). For the tree shown, which assumes 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

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

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 tree developed for mechanical damage, note that the basic event associated with activity on the alignment (event B1) is defined by an occurrence rate, $r_a$, in units of events per unit line length per year. Because the activity level is defined by a frequency or rate of occurrence, 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.

The mechanical interference frequency estimation algorithm implicit in the fault tree takes the form

$$r = r_a \, f\left(p_{B2}, p_{B3}, \ldots p_{B15}\right) \qquad [4.3]$$

where $p_{Bi}$ is the probability of occurrence of basic event *Bi*. The frequency estimation algorithm is described in detail in Appendix A. The basis for an estimate of the basic event probabilities required to solve Equation [4.3] is described 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 tree 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 they could not be expressed by a clear and simple analytical model, 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 Activity on Alignment

Digging or excavation activity on the alignment (basic event B1 in Figure 4.3), as defined by a rate or frequency of occurrence, is assumed to depend on the adjacent land use and whether or not the alignment is intersected by crossings or passes through special terrain features. The set of values associated with the section attributes Adjacent Land Use and Crossings / Special Terrain can therefore be used to define a matrix of attribute value combinations each of which is potentially associated with a different activity rate estimate. It is further assumed that the rate of activity will vary with Season, particularly where there are distinct summer and winter seasons, with the winter season being associated with frozen ground and possible snow cover. Therefore, a different activity rate matrix is potentially applicable for each season. The activity rate matrix is shown in Table 4.2. Note that the format of the activity rate matrix shown in the table implies that at crossings and special terrain locations the activity level is assumed to be independent of the land use type.

A generally accepted set of activity rate estimates as a function of land use, season, etc. is not currently available in the public domain. However, based on reasonable assumptions and historical data that are considered valid for transmission line systems in North America, a representative set of values was developed as follows.

First, the rate of digging or excavation activity is assumed to be a function of the population density associated with the adjacent land use category. Specifically, the activity level is assumed to vary with the square root of the population density, based on the assumption that the potential for interaction between a linear system (*i.e.*, a pipeline) and a uniformly distributed population is proportional to the number of *tributary area blocks* intersected by the system, where a tributary area block is defined as the land area tributary to each person (see Figure 4.4). Second, for agricultural land use, it is assumed that an activity rate increase of 5 to 10 times that based solely on population density should be introduced to reflect the disproportionately large amount of digging activity associated with farming.

The above assumptions and the representative population density estimates developed for each land use category in a previous study (Stephens *et al.* 1995), lead to the relative activity factors shown in Table 4.3. To convert these relative activity factors into quantitative activity rate estimates reference is made to historical data cited by Meadows and Sage (1985) which indicates an average activity rate of approximately 0.2 jobs per year per kilometer for pipelines located in heavily populated Class 3 and Class 4 areas. Adopting this rate estimate for the urban residential land use category, a scale factor is obtained that can be used to estimate activity rates from the relative activity factors for all other land use types. The resulting land use related activity rates (in events per unit line length per year) are shown in Table 4.3.

With regard to seasonal effects, analysis of one call system data collected by Alberta One Call indicates that the activity level during summer months is approximately twice as high as during winter months. For climate zones having a distinct winter season (*e.g.*, lasting four or five months) involving frozen ground and snow cover it is therefore suggested that the yearly average activity rates for each land use category be multiplied by 1.3 and 0.65 for summer and winter seasons, respectively. The seasonally adjusted activity rates for each land use category are summarized in Table 4.2. Note that for locations where the winter season is shorter and/or milder, seasonal differences in activity rates will be less.

In the absence of historical data pertaining to activity levels on pipelines passing through special terrain features such as; bogs, muskegs, marshes, and swamps, or for lines crossing significant bodies of water (*i.e.*, lakes), it is suggested that, for all cases, the activity rate estimate developed for the remote land use category be adopted (see Table 4.2).

Finally, for pipelines at road/rail, river/stream, or aerial crossings an activity rate estimate in units of events per crossing per year (as opposed to events per kilometer per year) is proposed to reflect the assumption that activity will likely be concentrated at either end of the crossing making the rate estimate largely independent of crossing length. Again published historical data is not available to support specific activity rate estimates for crossings so the following order of magnitude values are proposed based on judgement: an activity rate estimate of 1.0 events per crossing per year at roadway and railway crossings; 0.1 events per crossing per year at significant river and stream crossings; and for aerial crossings, which are above ground and highly visible, 0.01 events per crossing per year. The seasonally adjusted activity rate estimates for crossings are summarized in Table 4.2.

#### 4.2.3.4.2 Failure of Parties to Call Before Moving onto Alignment

The probability that parties (*e.g.*, excavation contractors) will fail to make use of a one call system before moving onto the pipeline right-of-way (basic event B2 in Figure 4.3) is assumed to depend on: the type of one call system in place; the nature of the dig notification requirement; and the general level of public awareness as to the importance and benefit associated with using a dig notification system. The set of values associated with the damage section attributes: One Call System Type; Dig Notification Requirement; and Level of Public 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 4.4.

Damage Potential

Development of the event probability estimation model for this basic event involved defining representative probability estimates for all possible attribute value combinations. The approach taken was based on historical data supplemented by judgement. Historical data for gas transmission lines operating in the United States as compiled by the US DOT, indicates that approximately 54% of excavation jobs involve prior notification (Courtney *et al.* 1977). Analysis of pipeline data by the Transportation Research Board (TRB 1988) indicates that when the use of one call systems is mandatory and enforced through penalties for failure to participate, the number of notifications approximately doubles.

This information suggests that, where one call systems exists, failure-to-call probabilities of 0.7, 0.5, and 0.3 are representative where participation is, respectively: voluntary, required but not enforced, or both required and enforced. In the absence of supporting data, it is assumed that these event probabilities apply regardless of the type of system in place (*i.e.*, multiple possibly competing systems vs. single unified systems vs. unified systems operated according to minimum standards). Given that the level of public awareness must have an effect on the likelihood of one call participation, it is further assumed that a high level of awareness (relative to average conditions) will decrease the event probabilities by 0.1 whereas a low level of awareness will increase the event probabilities by the same amount. The basic event probability estimates based on these assumptions are summarized in Table 4.4. Note that where one call systems do not exist the event probability is taken to be 1.0.

#### 4.2.3.4.3 Right-of-Way Indicators Not Recognized

The probability that parties (*e.g.*, excavation contractors) will fail to recognize that they are on or adjacent to a pipeline right-of-way (basic event B3 in Figure 4.3) is assumed to depend on the condition of the right-of-way and the general level of public awareness regarding the possible existence of buried pipelines in the general area. The set of values associated with the damage section attributes Right-of-Way Indication and Level of Public Awareness can therefore be used to define a matrix of attribute value combinations each of which is associated with a potentially different event probability. It is further assumed that the probability of failing to recognize the right-of-way will vary with Season, particularly where there are distinct summer and winter seasons, with the winter season being associated with snow covered ground. Therefore, a different activity rate matrix is potentially applicable for each season. The event probability matrix is shown in Table 4.5.

Development of the event probability estimation model for this basic event involved defining representative probability estimates for all possible attribute value combinations. In the absence of historical data, the approach taken was based on judgement. The basic premise is that, regardless of the level of public awareness, if there are no indications (*i.e.*, if the right-of-way does not in any significant way look different from the surrounding area) the probability of failing to recognize will be 1.0. Conversely, if there are continuous and distinctive right-of-way indicators that can be seen and understood from any point on the alignment, the event probability will be 0.0. For an average level of public awareness, a probability of 0.65 is assumed for right-of-ways providing finite but limited indication of the presence of a pipeline, and an event probability of 0.35 (approximately half the preceding value) is assumed for right-of ways having distinct but intermittent or variable indication.

Given that the level of public awareness will have an effect on the likelihood of parties recognizing right-of-way indicators for intermediate levels of indication, it is further assumed that a high level of awareness (relative to average conditions) will decrease the event probabilities by 0.1 whereas a low level of awareness will increase the event probabilities by the same amount. Finally, to acknowledge a small but finite difference in recognition probabilities between summer and winter (snow covered) seasons, the preceding yearly average probability estimates are assumed to increase by 0.05 during summer months and decrease 0.05 during winter months. The basic event probability estimates based on these assumptions are summarized in Table 4.5.

#### 4.2.3.4.4 Right-of-Way Indicators Ignored

The probability that parties (*e.g.*, excavation contractors) will ignore right-of-way indications and not use the one call system (basic event B4 in Figure 4.3) is assumed to depend on whether or not a one call system exists and the general level of public awareness as to the importance and benefit associated with using a dig notification system. The set of values associated with the damage section attributes One Call System Type and Level of Public 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 4.6.

Development of the event probability estimation model for this basic event involved defining representative probability estimates for all possible attribute value combinations. Again, in the absence of historical data, the approach taken was based on judgement. The basic assumption is that for an average level of public awareness, there is a 0.3 chance that parties will ignore the right-of-way indications and fail to use the notification system, if one exists, regardless of the type of system in place. To acknowledge the effect of public awareness programs, the likelihood of parties ignoring indications is assumed to decrease or increase by 0.1 for high and low levels of public awareness, respectively. The basic event probability estimates based on these assumptions are summarized in Table 4.6. Note that where a one call system does not exist, the event probability is taken to be 1.0 (*i.e.*, the absence of a notification system has the same effect as ignoring an existing system).

#### 4.2.3.4.5 Failure of One Call System to Notify Relevant Operators

The probability that the one call system will fail to contact the relevant pipeline operator (basic event B5 in Figure 4.3) is assumed to depend on the type of system in place. The set of values associated with the One Call System Type damage section attribute therefore defines the array of event probabilities. The corresponding event probability array is shown in Table 4.7.

In the absence of data, development of the event probability estimates for this basic event was based on judgement. The basic assumption is that where a one call system exists, there is a 10% chance that the operator of the pipeline of interest will not be notified. To acknowledge the potentially detrimental effect of multiple, potentially competing, one call services operating in the same area, this reference event probability is assumed to double. Where a unified system, operating to minimum prescribed standards is in place the event probability is assumed to be half the reference value. The basic event probability estimates based on these assumptions are summarized in Table 4.7.

#### 4.2.3.4.6 Explicit Pipeline Signage Not Seen

The probability that parties (*e.g.*, excavation contractors) will fail to detect explicit signage posted by the pipeline operator (basic event B6 in Figure 4.3) is assumed to depend on the type and location of the explicit pipeline signage and the season of the year. The set of values associated with the Explicit Pipeline Signage damage section attribute therefore defines the array of event probabilities. The event probability array is shown in Table 4.8. Note that a different event probability array is potentially applicable for each season.

In the absence of specific data, development of the event probability estimates for this basic event was based on judgement. It is assumed that if there is explicit signage posted at closely spaced intervals, and the signage is clearly visible at any point along the right-of-way, then the event probability is 0.0. If the signage is posted at selected strategic locations only, the probability of not seeing it is assumed to be 0.5, and if no explicit signage exists then the event probability is taken to be 1.0. To acknowledge the impact of season on the detection probability, it is further assumed that summer and winter conditions will respectively increase and decrease the event probability estimate for the intermediate case by 0.1. The basic event probability estimates based on these assumptions are summarized in Table 4.8.

#### 4.2.3.4.7 Explicit Pipeline Signage Ignored

The probability that parties (*e.g.*, excavation contractors) will ignore explicit pipeline signage, and not contact operator directly (basic event B7 in Figure 4.3) is assumed to depend on the general level of public awareness as to the importance and benefit associated with using a dig notification system. The set of values associated with the Level of Public Awareness damage section attribute therefore defines the array of event probabilities. The event probability array is shown in Table 4.9.

Again, in the absence of specific data, development of the event probability estimates for this basic event was based on judgement. The basic assumption is that for an average level of public awareness, there is a 0.10 chance that parties will ignore the explicit signage and fail to notification the operator directly. To acknowledge the effect of public awareness programs, the likelihood of parties ignoring indications is assumed to decrease or increase by 0.05 for high and low levels of public awareness, respectively. The basic event probability estimates based on these assumptions are summarized in Table 4.9.

#### 4.2.3.4.8 No Right-of-Way Patrol during Activity Period

The probability that there will not be a right-of-way patrol during the on-site mobilization and activity time period (basic event B8 in Figure 4.3) is assumed to be solely dependent upon the patrol frequency. The set of time intervals associated with the Right-of-Way Surveillance Interval damage section attribute therefore defines the array of event probabilities. The event probability array is shown in Table 4.10.

Development of the event probability estimation model for this basic event was based on an analytical model that incorporates the following assumptions: 1) patrols are carried out at a fixed inspection interval; 2) mechanical interference events occur randomly in time; and 3) the time to impact for a randomly selected interference event is uncertain and best characterized by a probability distribution. Using this model, the probability of no patrol during an activity period is equal to the probability that an event having interference potential will be given sufficient time to develop into an interference event before the next right-of-way patrol occurs.

Assuming that the time to impact for a randomly selected interference event can be characterized by a triangular distribution with a mean time to impact of 1 day, and further assuming that, a week consists of six days during which activity is possible (*i.e.*, ignoring Sundays) it can be shown that the basic event probabilities are as shown in Table 4.10. The derivation of the tabulated detection probabilities is given in Appendix B.

#### 4.2.3.4.9 Failure of Right-of-Way Patrol Personnel to Detect Activity

The probability that right-of-way patrol personnel will fail to detect on-going activity (basic event B9 in Figure 4.3) is assumed to be solely dependent upon the patrol method. The set of values associated with the Right-of-Way Surveillance Method damage section attribute therefore defines the array of event probabilities. The event probability array is shown in Table 4.11.

Development of the event probability estimation model for this basic event was based on judgement influenced by the knowledge that the frequency of human errors associated with simple design tasks is on the order of 0.01 for single-step tasks (Melchers and Harrington 1982). Assuming that the act of searching for signs of pending or on-going excavation activity during an aerial patrol is analogous to a simple single-step task, the probability of not detecting the signs of activity through inattention is assumed to be 0.01. For ground-based patrols, the chance of missing activity due to inattention is thought to be less because progress down the right-of-way is slower, but this reduction is potentially more than offset by the potential that all of the right-of-way cannot be readily seen from the ground due to access restrictions. To reflect this consideration, the probability of not detecting activity during a ground-based patrol is assumed to be 0.05. These basic event probability estimates are summarized in Table 4.11.

#### 4.2.3.4.10 Failure of Operator to Ensure Correct Location of Alignment

The probability that the alignment will not be correctly located given operator notification (basic event B10 in Figure 4.3) is assumed to depend on the operators policy regarding response to dig notification. The set of values associated with the Dig Notification Response damage section attribute therefore defines the array of event probabilities. The event probability array is shown in Table 4.12.

In the absence of specific data, development of event probability estimates for this basic event was based on judgement. The reference assumption is that if the pipeline is located and marked by the operator, the probability of incorrect location will be approximately 0.1. This value assumes no site supervision by the operator during the activity period. The reference value is halved to 0.05 if, in addition to marking, the operator provides site supervision and it is reduced by an order of magnitude to 0.01 if excavation is carried out by the operator or their representative. At the other extreme, if the operator provides location information but does not mark the line, the probability of incorrect location is taken to be 0.5. These basic event probability estimates are summarized in Table 4.12.

#### 4.2.3.4.11 Failure of Permanent Alignment Markers to Convey Alignment Location

The probability that permanent alignment markers will fail to correctly convey the location of the pipeline alignment (basic event B11 in Figure 4.3) is assumed to depend solely on whether permanent above-ground markers exist (damage section attribute Permanent Markers). If permanent markers exist, it is assumed that they will convey the location with certainty (*i.e.*, event probability is 0.0). If they do not exist the event probability is 1.0. The event probability array and associated probability estimates are shown in Table 4.13.

#### 4.2.3.4.12 Failure of Buried Alignment Markers to Convey Alignment Location

The probability that buried alignment markers (*e.g.*, coloured tape) will fail to correctly convey the location of the pipeline alignment (basic event B12 in Figure 4.3) is assumed to depend on whether buried markers exist (damage section attribute Buried Markers). In the absence of data, it is assumed that if permanent markers exist, they stand a 50/50 chance of conveying the alignment location (*i.e.*, event probability is 0.5). If they do not exist the event probability is 1.0. The event probability array and associated probability estimates are shown in Table 4.14.

#### 4.2.3.4.13 Accidental Activity on Located Alignment

The probability that accidental activity, with the potential to cause impact, will occur on a correctly located alignment (basic event B13 in Figure 4.3) is assumed to depend on the operators policy regarding response to dig notification. The set of values associated with the Dig Notification Response damage section attribute therefore defines the array of event probabilities. The event probability array is shown in Table 4.15.

In the absence of specific data, development of event probability estimates for this basic event was based on judgement. The reference assumption is that if excavation activity is carried out by the excavation contractor based on line marking by the contractor or others, the probability of accidental activity on the alignment due to construction mishaps will be approximately 0.05. If, however, excavation is carried out by the operator or their representative, it is assumed that a more careful approach will be taken thereby effectively reducing the event probability to approximately 0.01. These basic event probability estimates are summarized in Table 4.15.

#### 4.2.3.4.14 Excavation Depth Exceeds Cover Depth

The probability that the depth of digging or excavation activity will exceed the depth of cover (basic event B14 in Figure 4.3) is assumed to be primarily dependent upon the pipeline burial depth. The cover depth intervals associated with the Depth of Cover damage section attribute therefore defines the array of event probabilities. The event probability array is shown in Table 4.16.

Development of the event probability estimation model for this basic event was based on historical data for gas transmission lines located in the United States and Europe. Data from the US DOT, analysed by Courtney *et al.* (1977), indicates that on average there is a 15% chance that the depth of excavation activity will exceed the depth of pipe cover. Data reported by the European Gas Pipeline Incident Group (EGIG 1993) suggests relative mechanical damage incident frequencies of approximately 4, 1, and 0.9 for cover depth ranges of 0 to 0.8 m, 0.8 to 1.0 m, and greater than 1.0 m, respectively. Assigning the U.S. average event probability estimate of 0.15 to lines with burial depths in what is assumed to be the most common depth range (*i.e.*, 0.8 to 1.0 m), leads to event probability estimates of 0.6 for cover depths less than 0.8 m and 0.135 for lines deeper than 1.0 m.

The event probabilities associated with the rather course EGIG cover depth ranges were then subjectively extrapolated to cover the additional burial depth ranges defined in Table 4.16 as follows. The shallow EGIG cover depth range was subdivided into a 0 to 0.6 m and a 0.6 to 0.8 m range and the associated probability estimate of 0.8 was conservatively assumed to apply to the deeper 0.6 to 0.8 m cover depth range. An event probability of 1.0 was then conservatively assigned to the shallower 0 to 0.6 m depth range. The deep EGIG cover depth range was subdivided into a 1.0 to 1.2 m and a 1.2+ m depth range and the associated 0.135 probability estimate was assigned to the 1.0 to 1.2 m cover depth range. A marginally lower probability estimate of 0.12 (*i.e.*, 90% of 0.135) was then assigned to the deeper range to acknowledge the beneficial effect of deeper burial. The resulting event probability array is summarized in Table 4.16.

#### 4.2.3.4.15 Failure of Mechanical Protection

The probability that mechanical protection (*e.g.*, buried concrete slabs or steel armor plates) will fail to protect the pipe body from interference damage (basic event B15 in Figure 4.3) is assumed to depend solely on whether mechanical protection of any sort exists (damage section attribute Mechanical Protection). If protection exists, it is assumed that they will prevent damage with certainty (*i.e.*, event probability is 0.0). If they do not exist the event probability is 1.0. The event probability array and associated probability estimates are shown in Table 4.17.

### 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, $p_i$, can be calculated as the number of potential interference events divided by the total number of events for the whole pipeline segment. This can be expressed as:

$$p_i = \frac{r_i\, l_i}{\sum_{all\, i} (r_i\, l_i)} \qquad [4.4]$$

Figures and Tables

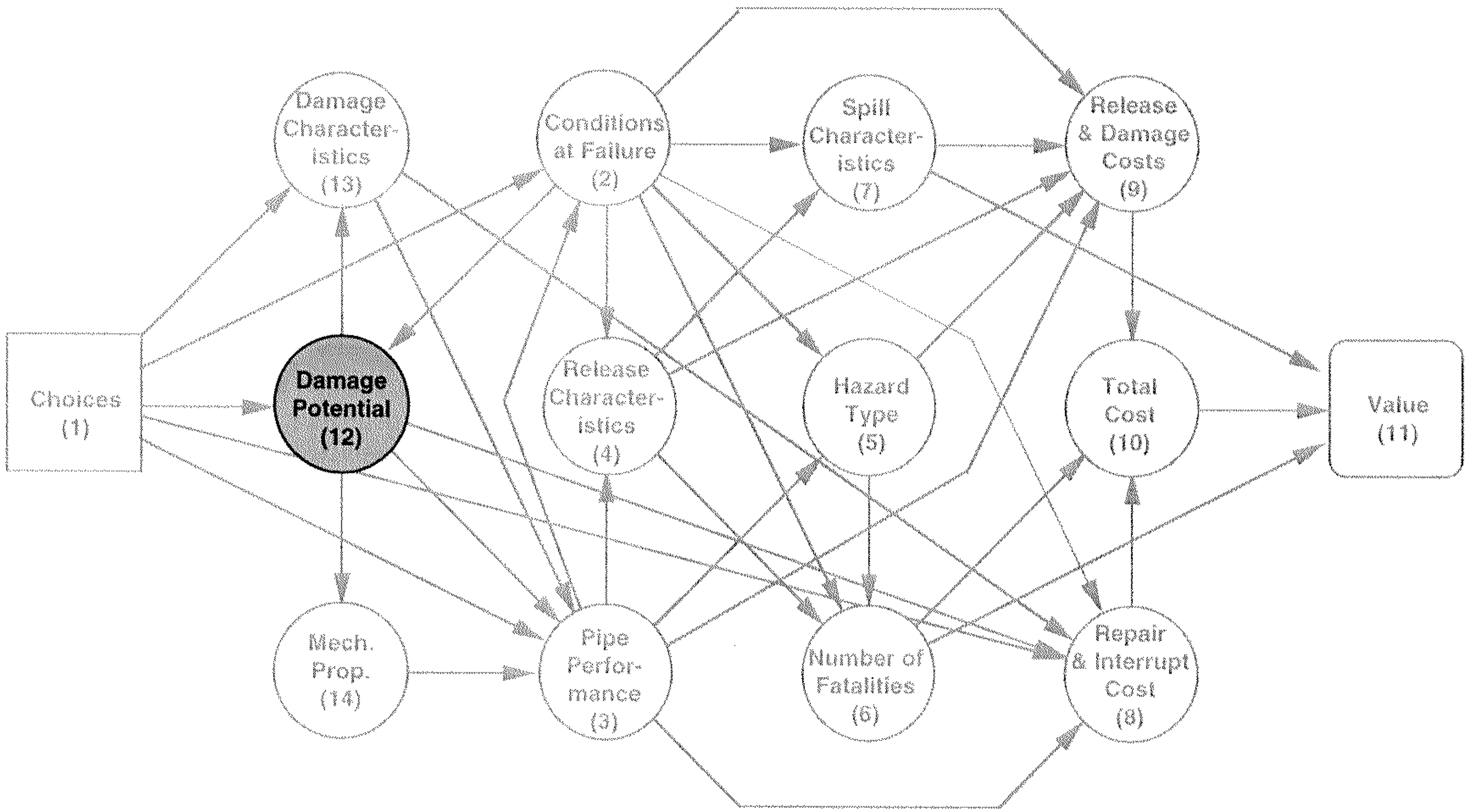



Figure 4.1 Compound node influence diagram highlighting Damage Potential node group

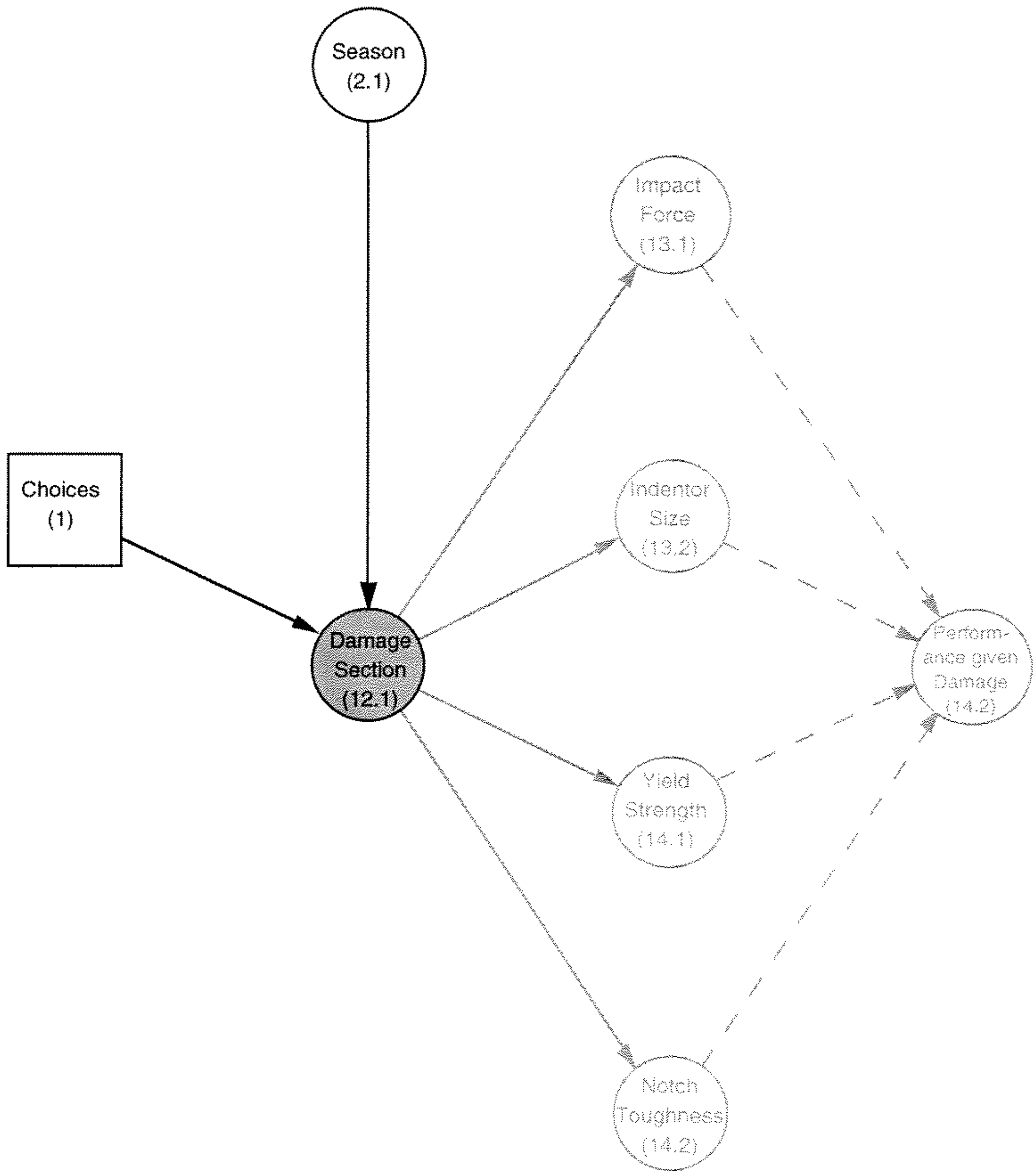



Figure 4.2 Basic node mechanical damage influence diagram highlighting Damage Section node and associated immediate predecessor nodes

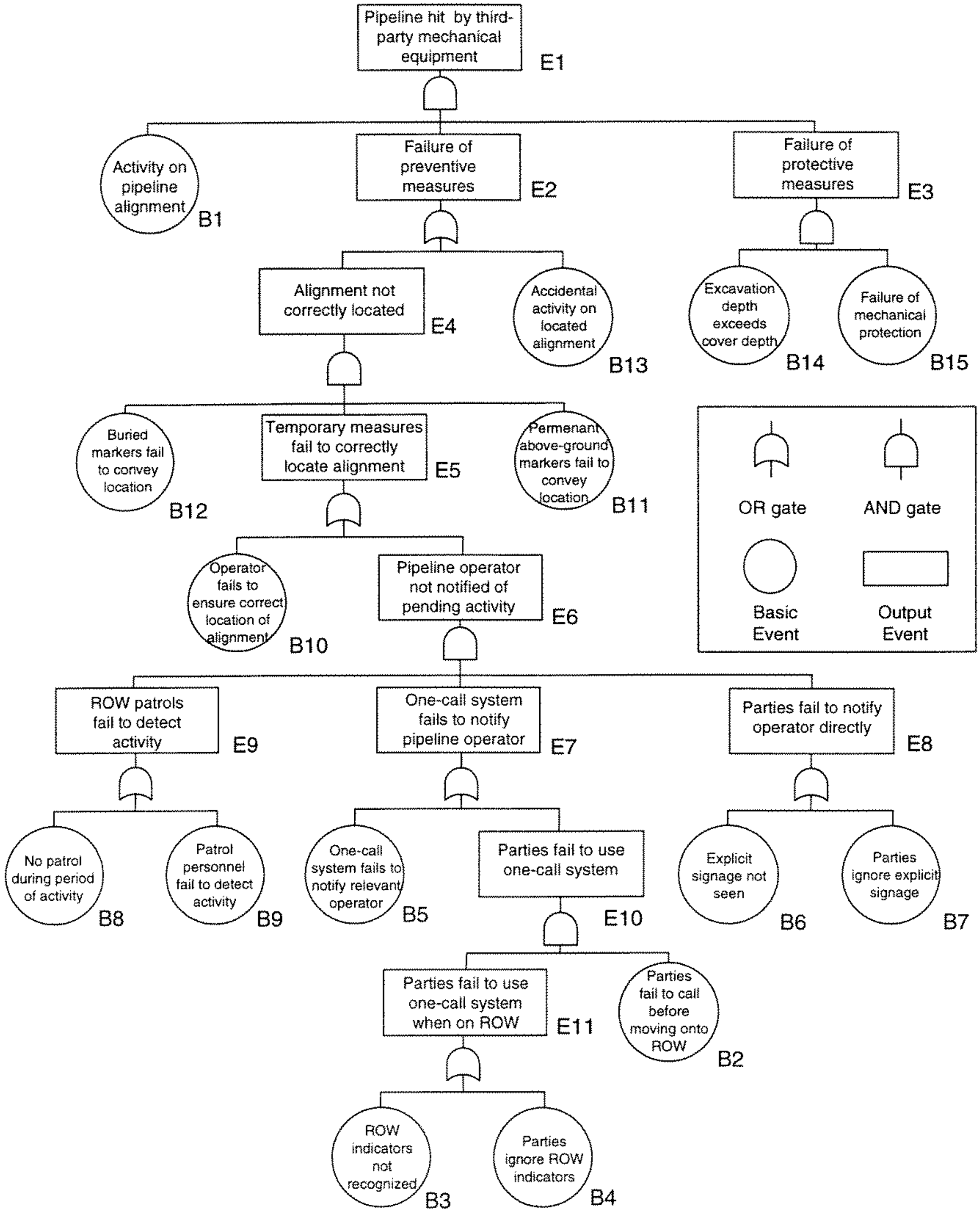



Figure 4.3 Fault tree for mechanical interference

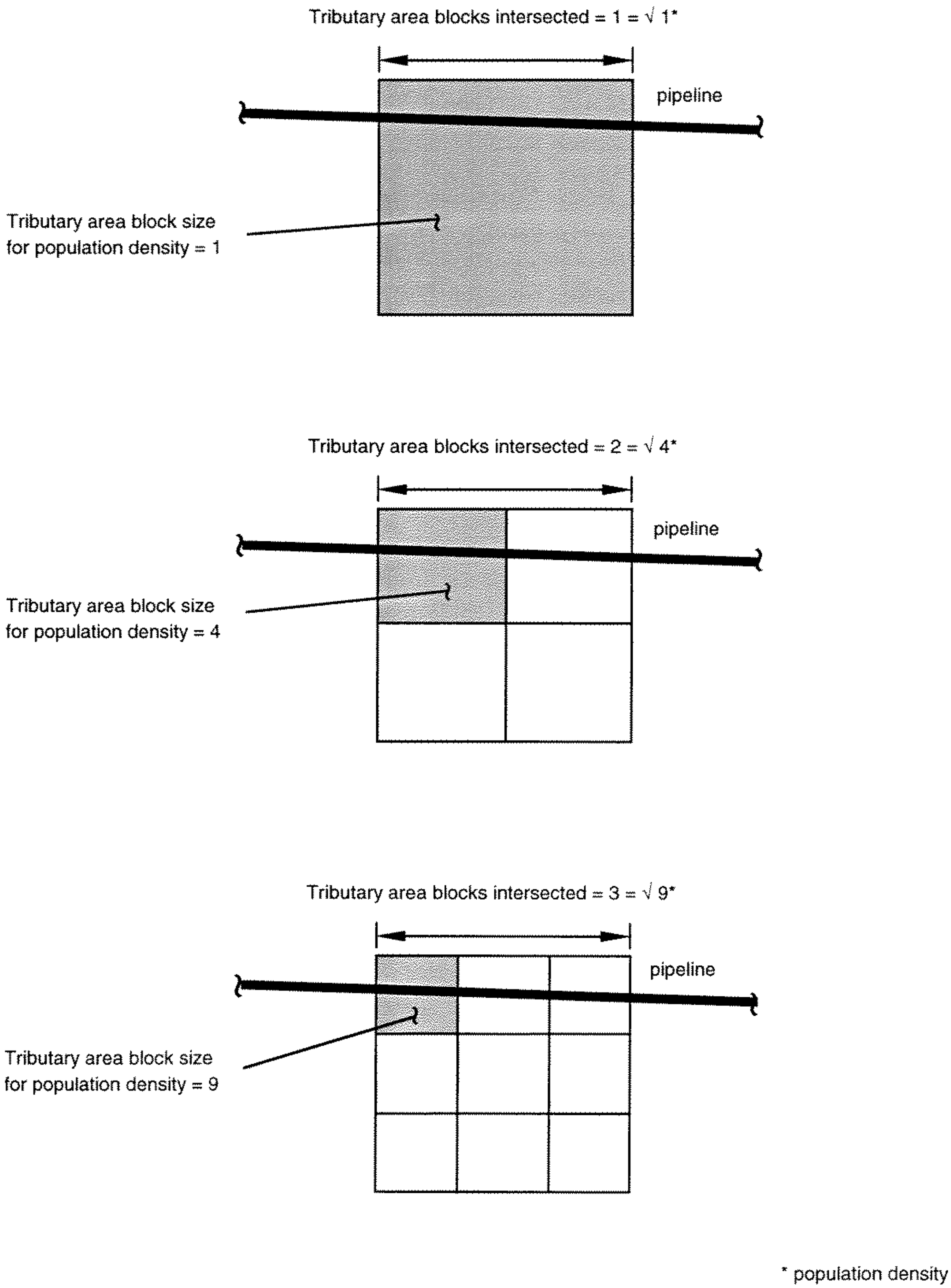



Figure 4.4 Basis for population density factor

| Pipeline Attribute | Definition | Affect Consequences ? |
|---|---|---|
| Pipe Diameter | Numerical value | Yes |
| Pipe Wall Thickness | Numerical value | Yes |
| Pipe Body Yield Strength | Numerical value | No |
| Pipe Body Notch Toughness | Numerical value | No |
| Operating Pressure | Numerical value | Yes |
| Depth of Cover | Defined by numeric value but assigned a depth range:<br>0.0 to 0.6 m<br>0.6 to 0.8 m<br>0.8 to 1.0 m<br>1.0 to 1.2 m<br>1.2+ m | No |
| Adjacent Land Use | Industrial<br>Commercial<br>Residential - urban<br>Residential - rural<br>Agricultural<br>Parkland - forested<br>Parkland - other<br>Remote - forested<br>Remote - other | Yes |
| Pipeline Crossings / Special Terrain | Typical X-country terrain<br>Roadway/Railway - uncased<br>Roadway/Railway - cased<br>River/Stream - unlined<br>River/Stream - lined<br>Bog/Muskeg<br>Marsh/Swamp<br>Lake<br>Aerial | Yes |
| One-call System Type | None<br>Multiple systems<br>Unified system<br>Unified system (to min. standards) | No |
| Dig Notification Requirement | Required and enforced<br>Required (not enforced)<br>Not required (voluntary) | No |
| Dig Notification Response | Provide location Information only<br>Locate and mark (no site supervision)<br>Locate and mark (with site supervision)<br>Excavation by operator | No |
| Level of Public Awareness | Above average<br>Average<br>Below average | No |
| Right-of-Way Indication | None<br>Limited<br>Intermittent or variable<br>Continuous and distinctive | No |
| Explicit Pipeline Signage | None<br>At selected strategic locations<br>Closely spaced and highly visible | No |
| Permanent Alignment Markers | No<br>Yes | No |
| Buried Alignment Markers | No<br>Yes | No |
| Right-of-Way Surveillance Interval | Daily<br>Every other day<br>Every third day<br>Weekly<br>Bi-weekly<br>Monthly<br>Bi-monthly or longer | No |
| Right-of-Way Surveillance Method | Aerial<br>Ground | No |
| Mechanical Protection | No<br>Yes | No |

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

| Crossings or Special Terrain | Adjacent Land Use | | | | | |
|---|---|---|---|---|---|---|
| | Urban - Residential | Commercial or Industrial | Rural - Residential | Agricultural | Parkland | Remote |
| Typical Cross-country | 0.13 I 0.26 (0.20) | 0.042 I 0.078 (0.06) | 0.013 I 0.026 (0.02) | 0.013 I 0.026 (0.02) | 0.0013 I 0.0026 (0.002) | 0.0002 I 0.00039 (0.0003) |
| Bog or Muskeg | 0.0002 I 0.00039 (0.0003) | | | | | |
| Marsh or Swamp | 0.0002 I 0.00039 (0.0003) | | | | | |
| Lake | 0.0002 I 0.00039 (0.0003) | | | | | |
| Road or Rail* | 0.65 I 1.3 (1.0) | | | | | |
| River or Stream* | 0.065 I 0.13 (0.1) | | | | | |
| Aerial Crossing* | 0.0065 I 0.013 (0.01) | | | | | |

Note:

1. numbers separated by I are seasonal values (*i.e.*, winter I summer)
2. numbers in parenthesis are yearly average values
3. activity level is defined in events per kilometre per year except at crossings (designated by *)
4. at crossings activity level is defined in units of events per crossing per year

Table 4.2 Activity rate matrix for basic event B1 (activity on alignment)

| **Land Use or Special Terrain** | **Reference Population Density** (people / sq km) | **Population Density Factor** (see note 1) | **Activity Adjustment Factor** | **Relative Activity Factor** (see note 2) | **Reference Activity Level** (events / km yr) |
|---|---|---|---|---|---|
| **Urban - Residential** | 50 | 7.1 | 1 | 7.1 | 0.2 |
| **Commercial or Industrial** | 5 | 2.2 | 1 | 2.2 | 0.06 |
| **Rural - Residential** | 0.5 | 0.71 | 1 | 0.71 | 0.02 |
| **Agricultural** | 0.01 | 0.10 | 5 to 10 | 0.50 to 1.0 (assume 0.75) | 0.02 |
| **Parkland** | 0.01 to 0.0001 (assume 0.005) | 0.071 | 1 | 0.071 | 0.002 |
| **Remote** | negligible (assume .0001) | 0.01 | 1 | 0.01 | 0.0003 |

Notes: 1. Population density factor = $\sqrt{}$ population density

2. Relative activity factor = Population density factor $\times$ Activity adjustment factor

Table 4.3 Basis for reference activity levels by land use type

| One-Call System Type | Dig Notification Requirement | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Not Required (voluntary) | | | Required (not enforced) | | | Required and Enforced | | |
| None | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Multiple Systems | 0.8 | 0.7 | 0.6 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.2 |
| Unified System | 0.8 | 0.7 | 0.6 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.2 |
| Unified System (min. standards) | 0.8 | 0.7 | 0.6 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.2 |
| | Below | Average | Above | Below | Average | Above | Below | Average | Above |
| | Level of Public Awareness | | | | | | | | |

Table 4.4 Event probability matrix for basic event B2 (failure to call before moving onto right-of-way)

| Right-of-Way Indication | Level of Public Awareness | | |
|---|---|---|---|
| | Below Average | Average | Above Average |
| None | 1.0 I 1.0 | 1.0 I 1.0 | 1.0 I 1.0 |
| Limited Indication | 0.8 I 0.7 | 0.7 I 0.6 | 0.6 I 0.5 |
| Intermittent (or variable) Indication | 0.5 I 0.4 | 0.4 I 0.3 | 0.3 I 0.2 |
| Continuous and Distinctive | 0.0 I 0.0 | 0.0 I 0.0 | 0.0 I 0.0 |

Note: numbers separated by I are seasonal values (winter I summer)

Table 4.5 Event probability matrix for basic event B3
(right-of-way indicators not recognized)

| One-Call System Type | Level of Public Awareness | | |
|---|---|---|---|
| | Below Average | Average | Above Average |
| **None** | 1.0 | 1.0 | 1.0 |
| **Multiple Systems** | 0.4 | 0.3 | 0.2 |
| **Unified System** | 0.4 | 0.3 | 0.2 |
| **Unified System (min. requirements)** | 0.4 | 0.3 | 0.2 |

Table 4.6 Event probability matrix for basic event B4
(parties ignore right-of-way indicators)

| One-Call System Type | Event Probability |
|---:|:---:|
| **None** | 1.0 |
| **Multiple Systems** | 0.2 |
| **Unified System** | 0.1 |
| **Unified System (minimum requirements)** | 0.05 |

Table 4.7 Event probability array for basic event B5 (failure of one call system to notify relevant operator)

| Explicit Pipeline Signage | Event Probability |
|---|---|
| **None** | 1.0 I 1.0 |
| **At selected strategic locations** | 0.6 I 0.4 |
| **Closely spaced and highly visible** | 0.0 I 0.0 |

Note: numbers separated by I are seasonal values (winter I summer)

Table 4.8 Event probability array for basic event B6 (explicit signage not seen)

| Level of Public Awareness | Event Probability |
|---|---|
| Below Average | 0.15 |
| Average | 0.10 |
| Above Average | 0.05 |

Table 4.9 Event probability array for basic event B7
(parties ignore explicit signage)

| Right-of-Way Surveillance Interval | Event Probability |
|---|---|
| Daily | 0.35 |
| Every other day | 0.55 |
| Every third day | 0.67 |
| Weekly | 0.83 |
| Bi-weekly | 0.92 |
| Monthly | 0.96 |
| Bi-monthly or longer | 0.99 |

Table 4.10 Event probability array for basic event B8
(no patrol during period of activity)

| Right-of-Way Surveillance Method | Event Probability |
|---|---|
| Aerial patrol | 0.01 |
| Ground-based patrol | 0.05 |

Table 4.11 Event probability array for basic event B9
(patrol personnel fail to detect activity)

| Dig Notification Response | Event Probability |
|---|---|
| Provide location information only | 0.50 |
| Locate and mark (no site supervision) | 0.10 |
| Locate and mark (with site supervision) | 0.05 |
| Excavation by operator | 0.01 |

Table 4.12 Event probability array for basic event B10 (operator fails to ensure correct location of alignment)

| Permanent Alignment Markers | Event Probability |
|---:|:---:|
| No | 1.0 I 1.0 |
| Yes | 0.1 I 0.0 |

Note: numbers separated by I are seasonal values (winter I summer)

Table 4.13 Event probability array for basic event B11 (permanent markers fail to convey alignment location)

| Buried Alignment Markers | Event Probability |
|---|---|
| No | 1.0 |
| Yes | 0.5 |

Table 4.14 Event probability array for basic event B12 (buried markers fail to convey alignment location)

| Dig Notification Response | Event Probability |
|---|---|
| Provide location information only | 0.05 |
| Locate and mark (no site supervision) | 0.05 |
| Locate and mark (with site supervision) | 0.05 |
| Excavation by operator | 0.01 |

Table 4.15 Event probability array for basic event B13
(accidental activity on located alignment)

| Depth of Cover | Event Probability |
|---:|:---:|
| **0.0 to 0.6 m** | 1.00 |
| **0.6 to 0. 8 m** | 0.60 |
| **0.8 to 1. 0 m** | 0.15 |
| **1.0 to 1.2 m** | 0.135 |
| **1.2+ m** | 0.12 |

Table 4.16 Event probability array for basic event B14
(excavation depth exceeds cover depth)

| Mechanical Protection | Event Probability |
|---|---|
| No | 1.0 |
| Yes | 0.0 |

Table 4.17 Event probability array for basic event B15
(failure of mechanical protection)

# 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 characteristics of the outside force associated with a mechanical interference event. The relevant characteristics are the magnitude of the applied load and the size of the loaded area, both of which have an influence on the probability of pipe body failure (*i.e.*, puncture). 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 Force

#### 5.2.1.1 Node Parameter

The Impact Force node (basic node 13.1) and its direct predecessor node are highlighted in the version of the basic node corrosion influence diagram in Figure 5.2. The parameter of this node represents the maximum force generated during a randomly selected mechanical interference event. It is defined by a continuous probability distribution that can take any value within a defined range. The influence diagram indicates that the Impact Force node is conditionally dependent on the Damage Section node, which means that a separate Impact Force 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 force distribution.

Randomness in the force associated with mechanical interference results primarily from variations in the size and type of equipment involved in excavation or digging activity and the specific type of the activity being undertaken. It is assumed that both the size range and type of equipment used, and the type of activity undertaken are to some extent dependent on the land usage in the immediate vicinity of the pipeline and whether or not the alignment is intersected by crossings or passes through special terrain conditions. The existing damage section attributes Adjacent Land Use and Crossings / Special Terrain can therefore be used to define a matrix of attribute combinations, each of which is potentially associated with a different impact force distribution. The impact force matrix is shown in Table 5.1. Note that the adopted matrix format implies that the impact force distribution is controlled by the type of adjacent land use only where crossings and special terrain conditions do not exist (*i.e.*, under typical cross country conditions). Where crossings or special terrain conditions are involved the impact force is assumed to be controlled by the type of crossing or special terrain, regardless of the adjacent land use type.

#### 5.2.1.2 Parameter Characterization

The development of a probabilistic characterization of impact force as a function land use, crossing, and special terrain type was beyond the scope of this project. However, a baseline impact force distribution was developed as follows.

Taking a bucket-type excavator as a representative class of digging equipment and assuming that the maximum quasi-static force that can be applied to the pipe by the bucket is a function of the weight of the machine, it is reasonable to assume that the impact force distribution is directly related to the probability distribution of excavator weights. (Note, this assumes that the size of equipment used for a project is not influenced by the presence of a pipeline in the vicinity of the excavation site). Figure 5.3 Shows information that was obtained from industry concerning the approximate weight distribution of the entire excavator population operating in North America. Given that the maximum force that can be applied to a pipeline is somewhat greater than 50% of the gross excavator weight (Hopkins *et al.* 1992, and Spiekhout 1995), if the value estimated by Spiekhout for a typical mid-sized machine of 57% is adopted for the full range of excavator sizes, the outside force probability distribution for a random impact event can be derived from the excavator weight distribution by linear scaling. The resulting load histogram and its best-fit probability distribution are plotted in Figure 5.4. The selected distribution is a shifted Gamma with a mean of 164 kN and a standard deviation of 74 kN.

The impact force characterization described above is a composite distribution that applies to a combination of excavator populations operating in different land use types, at different crossing locations and under various special terrain conditions. In the absence of the data necessary to develop force distributions for each case it is proposed that this baseline distribution be used for all cases as a representative impact force characterization.

### 5.2.2 Indentor Size

#### 5.2.2.1 Node Parameter

The Indentor Size 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 effective length of the indentor in contact with pipe body, measured parallel to the axis of the pipe body, for a randomly selected interference event. It is defined by a continuous probability distribution that can take any value within a defined range. The influence diagram indicates that the Indentor Size node is conditionally dependent on the Damage Section node, which means that a separate Indentor Size 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 size distribution.

The indentor involved in an interference event is assumed to have a contact footprint that is much longer than it is wide with a width dimension that is relatively constant at around 5 mm (this being considered representative of the shape of a tooth on the bucket of a typical excavator). With the indentor width assumed to be essentially constant, the contact area is fully defined by specifying its effective contact length. Randomness in the effective length of the indentor associated with mechanical interference events results primarily from variations in the size and condition of the indentor and the orientation of the indentor relative to the pipe body at the time of impact. It is assumed that the effective indentor length is a function of both the size range and type of equipment used which is further assumed to dependent on the land usage in the immediate vicinity of the pipeline and whether or not the alignment is intersected by crossings or passes through special terrain conditions. The existing damage section attributes Adjacent Land Use and Crossings / Special Terrain can therefore be used to define a matrix of attribute combinations, each of which is potentially associated with a different indentor size distribution. The indentor size matrix is shown in Table 5.2. Note that the adopted matrix format implies that the size distribution is controlled by the type of adjacent land use only where crossings and special terrain conditions do not exist (*i.e.*, under typical cross country conditions). Where crossings or special terrain conditions are involved the indentor size is assumed to be controlled by the type of crossing or special terrain, regardless of the adjacent land use type.

#### 5.2.2.2 Parameter Characterization

The development of a probabilistic characterization of effective indentor length as a function of land use, crossing, and special terrain type was beyond the scope of this project. However, assuming that a typical interference event involves pipe body contact with the tooth from the bucket of a typical mid-sized excavator, which is assumed to have a length dimension in the range of 60 to 80 mm, a representative indentor length can be characterized by a uniform probability distribution with a mean of 70 mm and a standard deviation of 5.74 mm.

# Figures and Tables

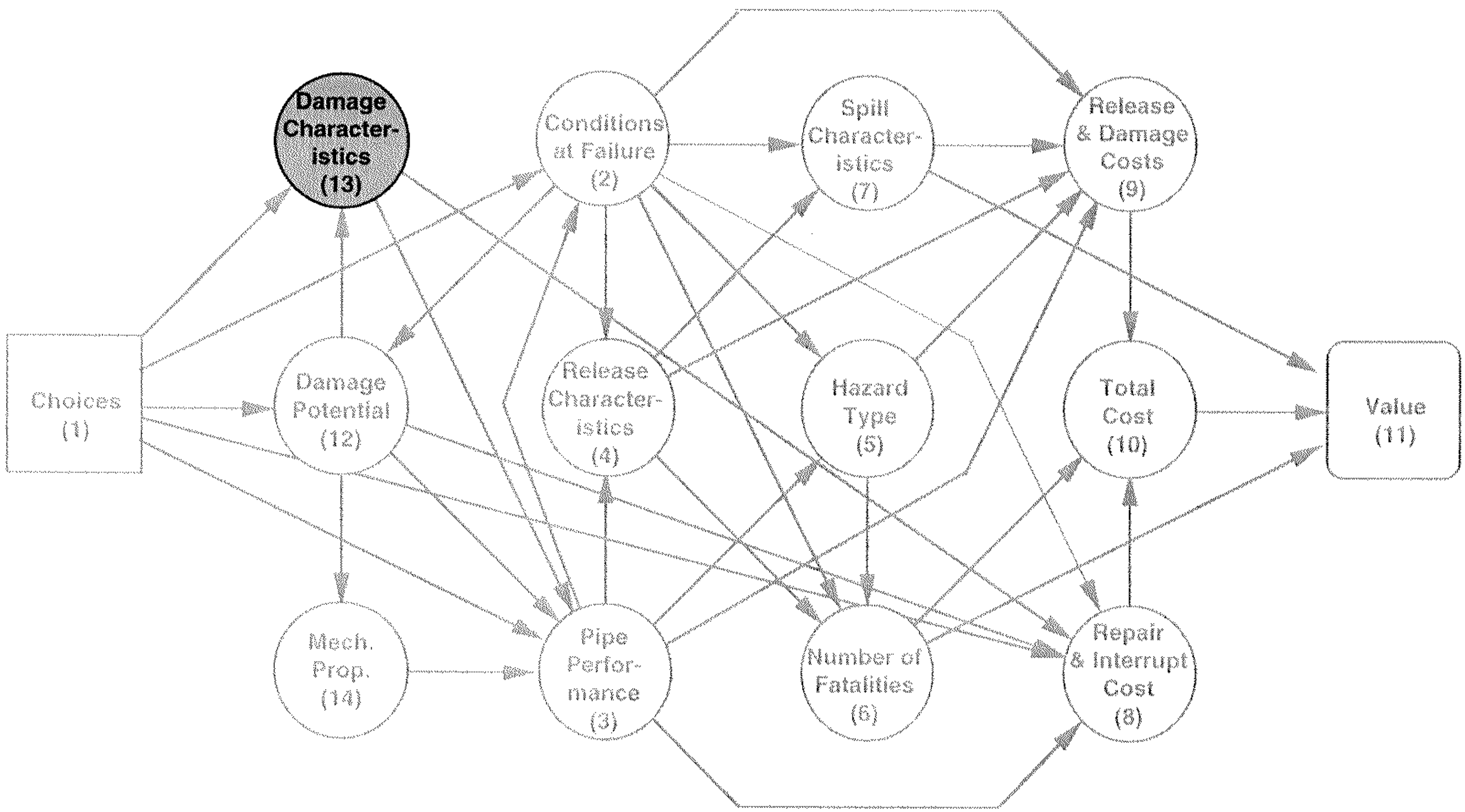



Figure 5.1 Compound node influence diagram highlighting Damage Characteristics node group

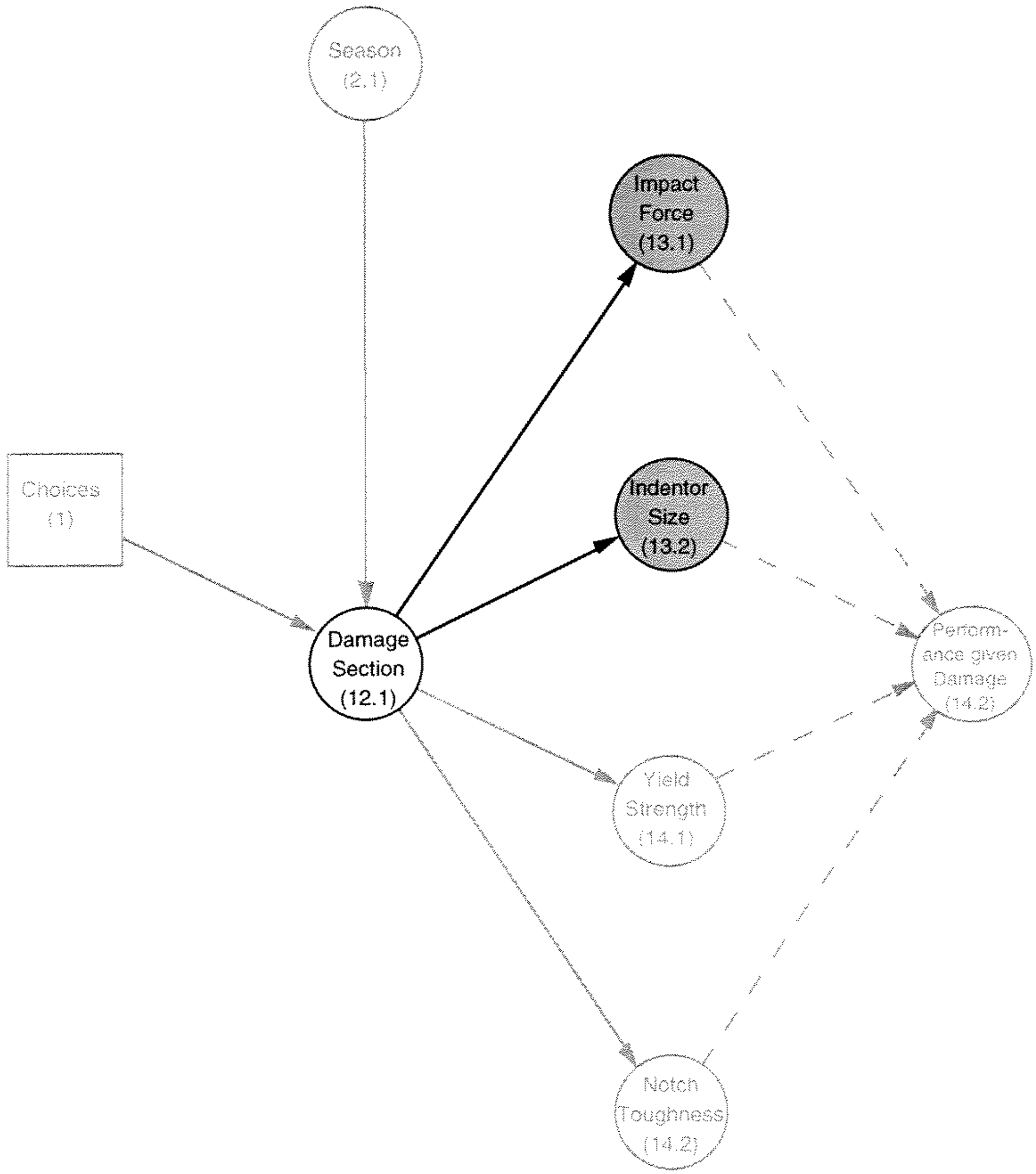



Figure 5.2 Basic node mechanical damage influence diagram highlighting Damage Characteristics nodes and associated immediate predecessor node

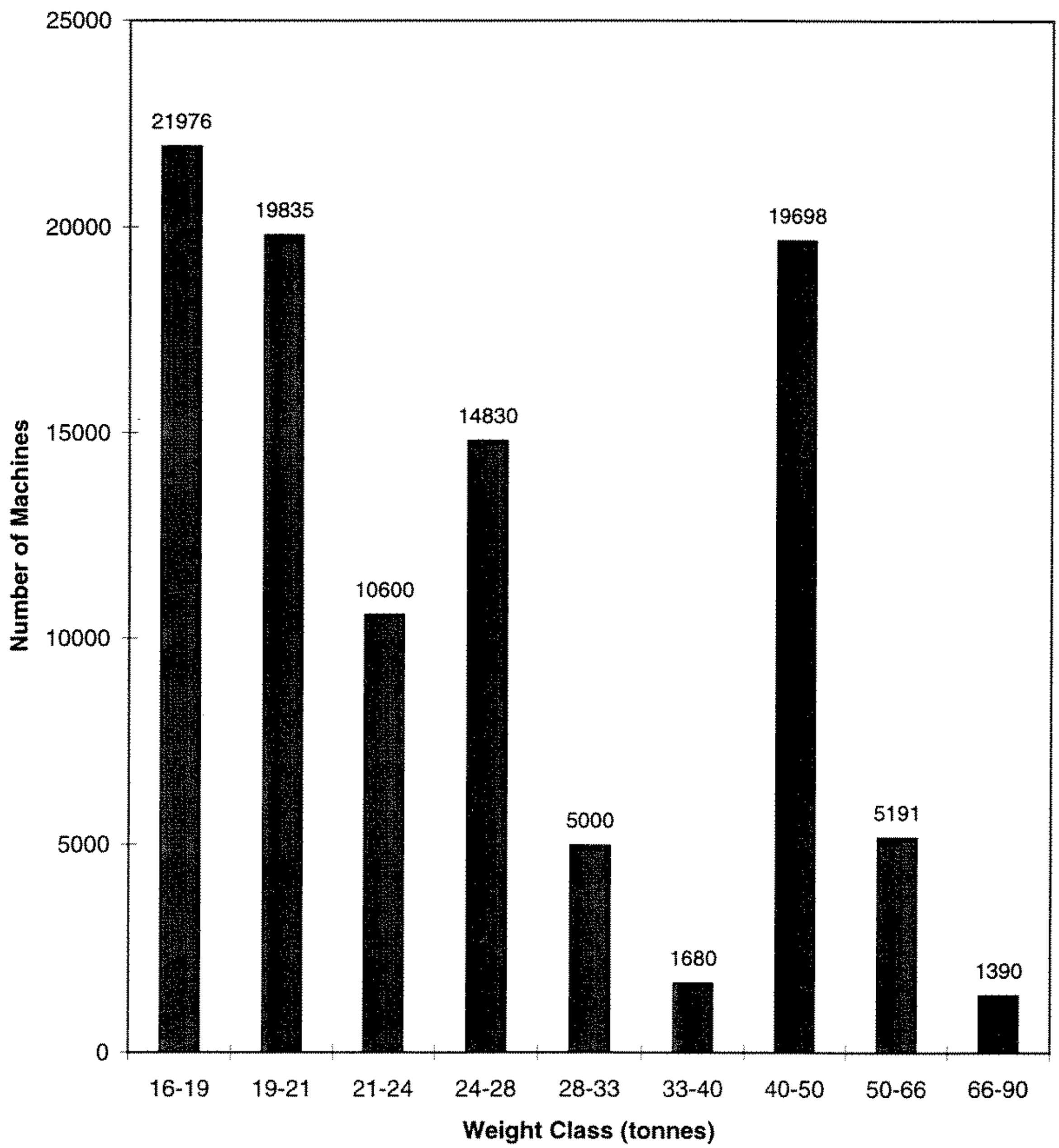



Figure 5.3 North American Excavator Population

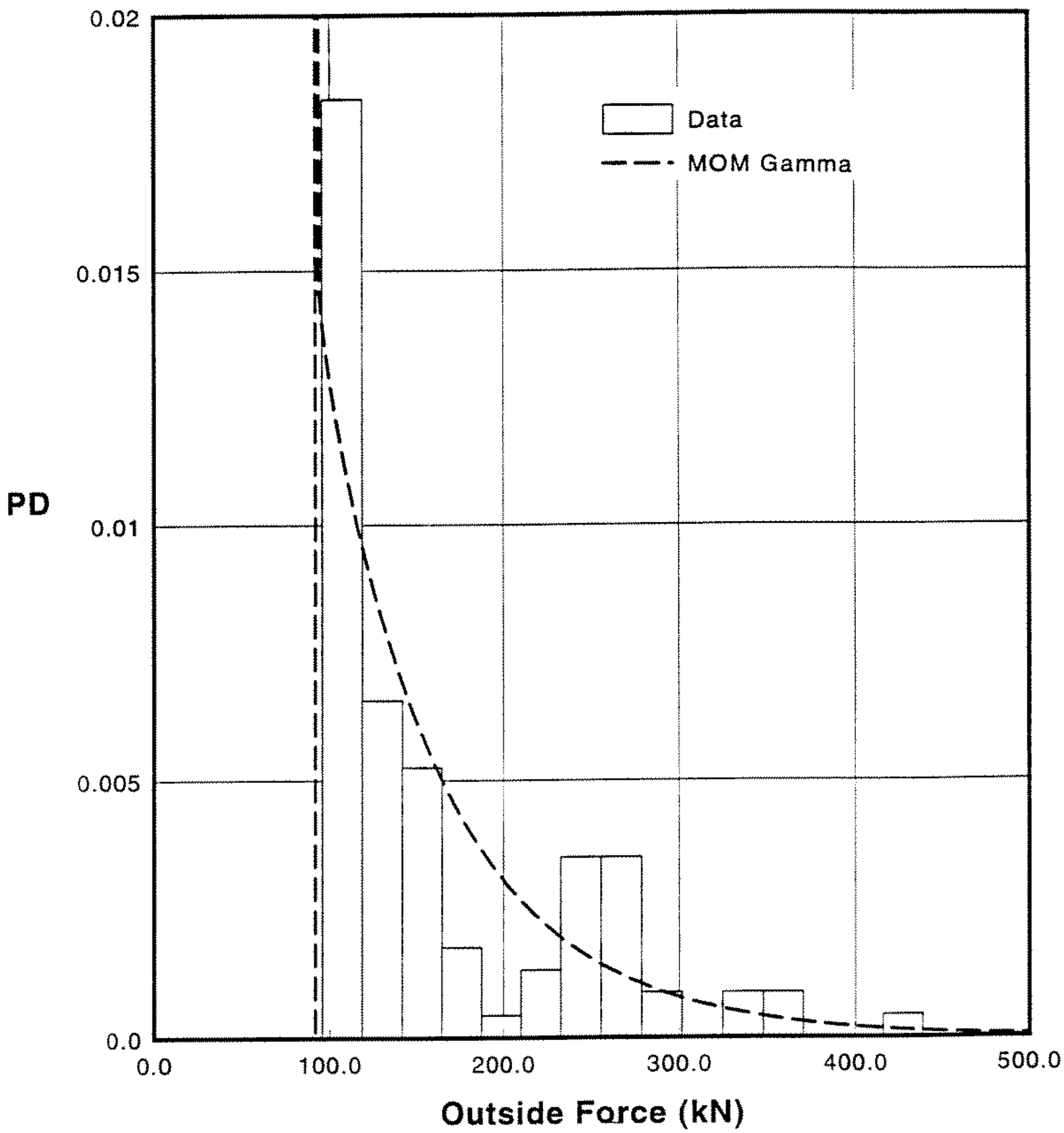



Figure 5.4 Histogram and fitted distribution for outside force due to excavator impact (PD = probability density)

| Crossings or Special Terrain | Adjacent Land Use | | | | | |
|---|---|---|---|---|---|---|
| | Urban - Residential | Commercial or Industrial | Rural - Residential | Agricultural | Parkland | Remote |
| Typical Cross-country | Gamma ($\mu = 164, \sigma = 74$) | Gamma ($\mu = 164, \sigma = 74$) | Gamma ($\mu = 164, \sigma = 74$) | Gamma ($\mu = 164, \sigma = 74$) | Gamma ($\mu = 164, \sigma = 74$) | Gamma ($\mu = 164, \sigma = 74$) |
| Bog or Muskeg | Gamma ($\mu = 164, \sigma = 74$) | | | | | |
| Marsh or Swamp | Gamma ($\mu = 164, \sigma = 74$) | | | | | |
| Lake | Gamma distribution type (mean = 164 kN, standard deviation = 74 kN) | | | | | |
| Road or Rail* | Gamma ($\mu = 164, \sigma = 74$) | | | | | |
| River or Stream* | Gamma ($\mu = 164, \sigma = 74$) | | | | | |
| Aerial Crossing* | Gamma ($\mu = 164, \sigma = 74$) | | | | | |

Table 5.1 Impact force attribute matrix

| Crossings or Special Terrain | Adjacent Land Use | | | | | |
|---|---|---|---|---|---|---|
| | Urban - Residential | Commercial or Industrial | Rural - Residential | Agricultural | Parkland | Remote |
| Typical Cross-country | Uniform ($\mu = 70, \sigma = 5.74$) | Uniform ($\mu = 70, \sigma = 5.74$) | Uniform ($\mu = 70, \sigma = 5.74$) | Uniform ($\mu = 70, \sigma = 5.74$) | Uniform ($\mu = 70, \sigma = 5.74$) | Uniform ($\mu = 70, \sigma = 5.74$) |
| Bog or Muskeg | Uniform ($\mu = 70, \sigma = 5.74$) | | | | | |
| Marsh or Swamp | Uniform ($\mu = 70, \sigma = 5.74$) | | | | | |
| Lake | Uniform distribution type (mean = 70 mm, standard deviation = 5.74 mm) | | | | | |
| Road or Rail* | Uniform ($\mu = 70, \sigma = 5.74$) | | | | | |
| River or Stream* | Uniform ($\mu = 70, \sigma = 5.74$) | | | | | |
| Aerial Crossing* | Uniform ($\mu = 70, \sigma = 5.74$) | | | | | |

Table 5.2 Indentor size 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 failure (*i.e.*, puncture) and the mode of failure (*i.e.*, leak vs. rupture). The relevant characteristics are the yield strength and the notch toughness of the pipe body material. The individual parameters associated with the Mechanical Properties node group are highlighted in the version of the basic node mechanical damage influence diagram shown in Figure 6.2. These node parameters are discussed in the following sections.

## 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 defined by the user 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 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 different Canadian pipe manufacturers or found in the literature. The table reports the mean-to-specified strength ratio, $\gamma$, 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 $\gamma$ 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 $\gamma$ 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, $\mu_s$, and standard deviation, $\sigma_s$, 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.

### 6.2.2 Notch Toughness

#### 6.2.2.1 Node Parameter

The Notch Toughness node (node 14.2) 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 is the fully ductile notch toughness of the pipe body steel (as represented by the full-size Charpy V-notch upper plateau energy) 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 defined by the user for each possible value of its predecessor node. Since the predecessor node represents the section of pipeline at which the interference event occurs, the

Mechanical Properties

Charpy V-notch impact energy distribution must be defined for each pipeline section defined at the Damage Section node.

As with yield strength, randomness in the notch toughness results from variability in the manufacturing process. The actual pipe body notch toughness 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 Charpy energy can be defined by a probability distribution calculated from the mill test data provided by the pipe manufacturer. The appropriate toughness distribution for each pipeline section defined at the Damage Section node can then be obtained by matching it with the toughness distribution obtained from the corresponding pipe order. Where mill data is unavailable or insufficient to fully characterize the Charpy energy, historical data can be helpful in developing a representative probability distribution.

#### 6.2.2.2 Parameter Characterization

In the absence of line specific data it is difficult to obtain an accurate characterization of the pipe body notch toughness. Historical data suggests that the variability in Charpy V-notch impact energy can be reasonably characterized by either a normal or lognormal distribution. Analysis of representative notch toughness data summarized in Figure 6.3 (AGA 1977 and Eiber 1977) further suggests that the standard deviation ($\sigma$, in Joules) can be estimated directly from the mean value ($\mu$, in Joules) using

$$\sigma = 0.0223\mu^{1.46} \qquad [6.2]$$

However, the problem lies in estimating the mean value of the pipe body Charpy energy. For line pipe manufactured to a minimum toughness requirement there is considerable variation in the mean-to-specified Charpy energy ratio and many lines have been built from line pipe that was not required to have proven notch toughness properties. Given this uncertainty and the fact that the specified toughness, where applicable, is generally interpreted to be a minimum all-heat average value, it is suggested that where line specific data is insufficient to characterize the mean, it is prudent to assume that the mean Charpy plateau energy is equal to the specified value.

Based on Equation [6.2] and the stated assumptions, in the absence of line specific toughness data, it can assumed that a representative Charpy V-notch impact energy characterization is given by a normal distribution type with a mean, $\mu_{CV}$, and standard deviation, $\sigma_{CV}$, calculated from the specified full-size Charpy V-notch impact energy, $C_{V_n}$, using the following relationships:

$$\mu_{CV} = C_{V_n} \qquad [6.3a]$$

$$\sigma_{CV} = 0.0223\mu_{CV}^{1.46} \qquad [6.3b]$$

For line pipe not manufactured to a specific toughness requirement it is suggested that the effective specified Charpy energy be set equal to 40 J for line pipe having a diameter of 457 mm or more and 27 J for smaller diameter pipe. The suggested mean values are consistent with the minimum requirements currently prescribed for line pipe manufactured in Canada to a proven notch toughness (CSA Standard Z245.1-95) and historical data for line pipe manufactured in North American mills (Leewis 1997) indicates that in most cases these suggested values conservatively underestimate the actual mean value.

Figures and Tables

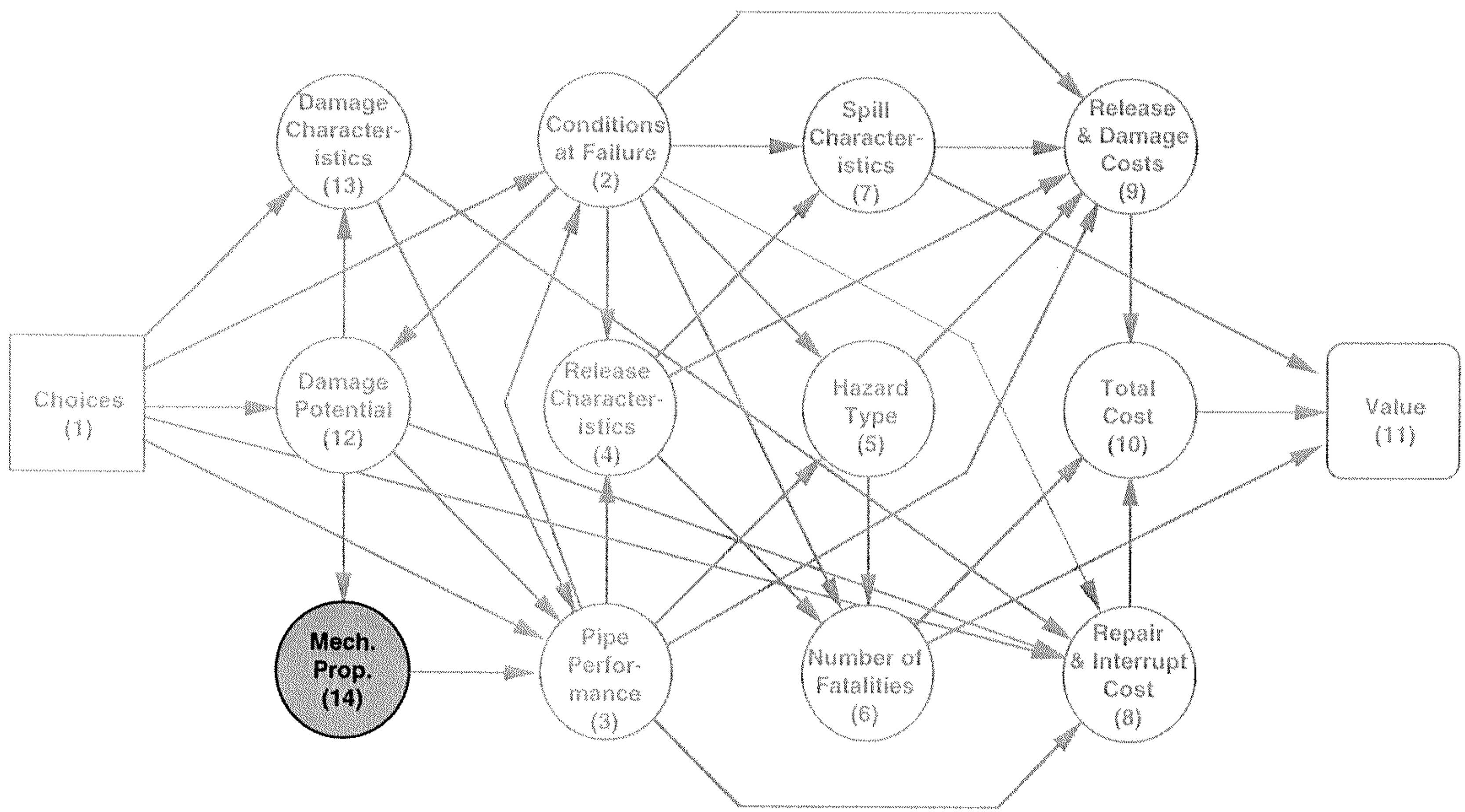



Figure 6.1 Compound node influence diagram highlighting Mechanical Properties node group

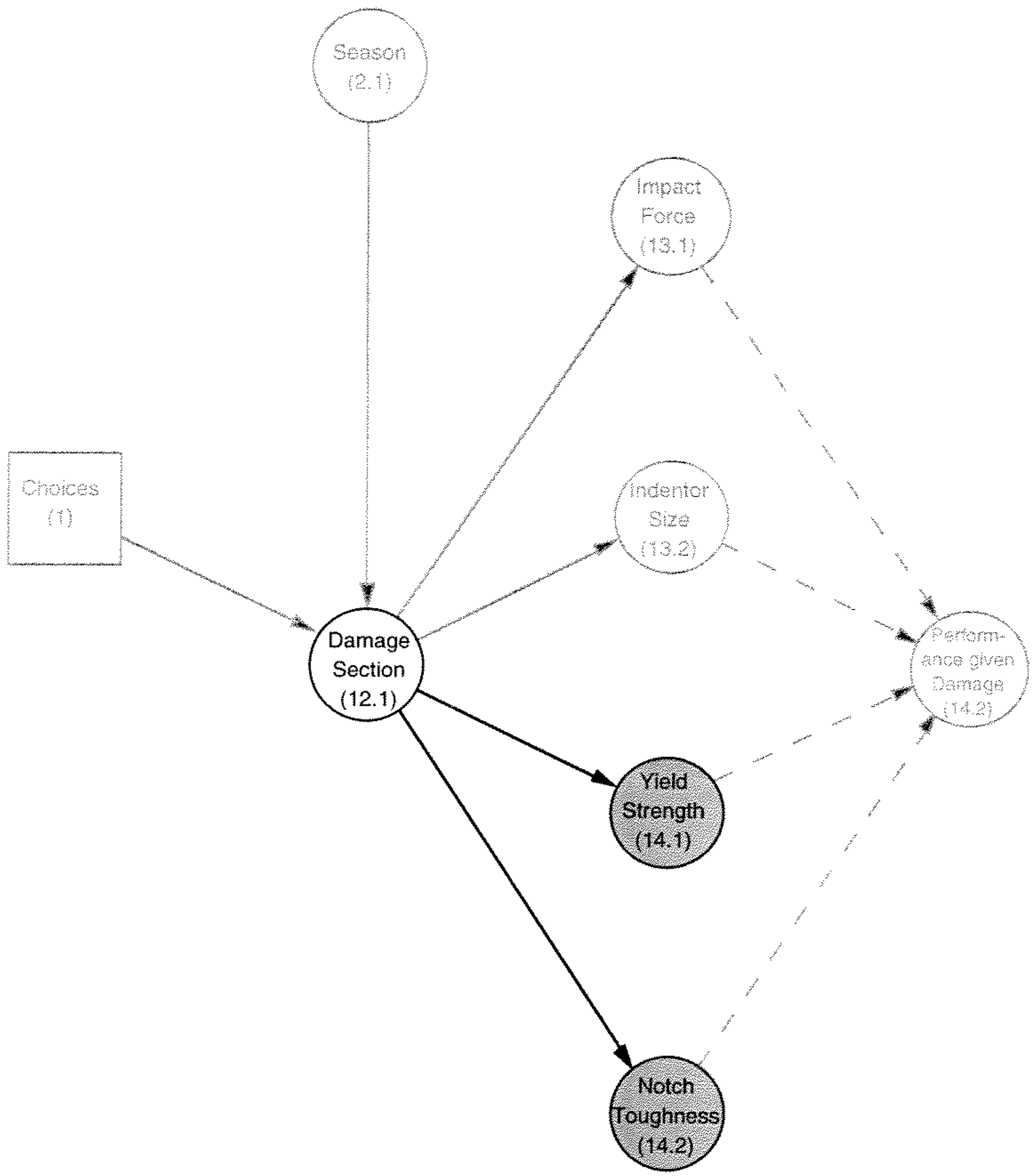



Figure 6.2 Basic node mechanical damage influence diagram highlighting Mechanical Properties nodes and associated immediate predecessor node

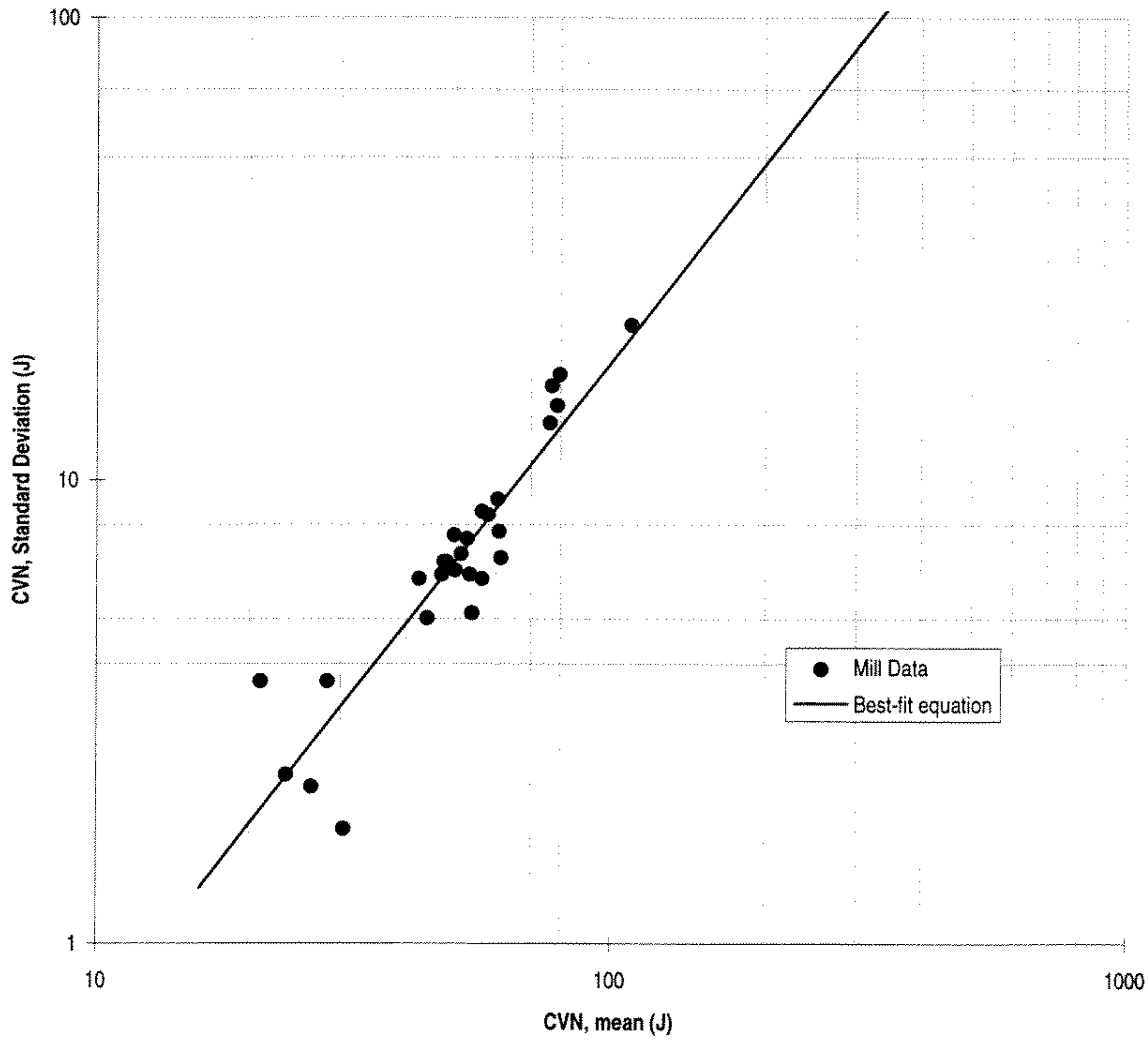



Figure 6.3 Standard deviation versus mean value of Charpy Energy

| 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 two individual nodes. The first node (Performance Given Damage - node 3.1) represents the pipe performance in the event of a mechanical interference event. Its probability distribution is evaluated from the mechanical damage portion of the influence diagram (Figure 7.2). The second node (Segment Performance - node 3.2) represents the performance of the whole segment of pipeline. It's probability distribution is evaluated from the distribution of the Performance Given Damage node (3.1) 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. 3.2 (Stephens *et al.* 1996).

## 7.2 Performance Given Impact

### 7.2.1 Node Parameter

The Performance Given Damage 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. As indicated in Figure 7.2, Performance Given Damage 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 force, indentor size, and pipe body mechanical properties (yield strength and notch toughness).

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

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

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

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

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

where $p_{P|I}$ is the probability of line puncture given impact, and $p_{i|P}$ is the probability of failure in the $i^{th}$ mode given puncture.

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 force, indentor size, pipe body yield strength, and material notch toughness) 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 puncture given impact is described in Section 7.2.2. The model used to estimate the probability of failure by leak or rupture given line puncture is described in Section 7.2.3.

### 7.2.2 Probability of Puncture Given Impact

The model used to estimate the probability of line puncture given impact assumes that, in general, mechanical interference events can be characterized by considering the pipe body response to a quasi-static load generated by an indentor having a shape corresponding to that of an excavator bucket tooth. Given an interference event, the probability of failure, $p_{P|I}$, is equal to the probability that the indentor impact force, $F$, will exceed the pipe body resistance, $R$, at the impact location. This can be written as

$$p_{P|I} = p(F > R) = p(R - F < 0) \qquad [7.2]$$

The pipe body resistance is estimated using a semi-empirical model developed by Spiekhout *et al.* (1987) to predict the collapse load of a pipe under a radially directed point load based on a plastic hinge model that includes the effects of second order membrane action and internal pressure. Ignoring second order terms in the original derivation, a simplified form of the expression is given by

Pipe Performance

$$R_P = 2.3\sigma_S t^2 \left[0.4D\sqrt{\frac{D}{2t}} + L\right]\frac{1}{(D-0.7w)} \qquad [7.3]$$

where $D$ = pipe diameter;
$t$ = pipe wall thickness;
$L$ = indentor length;
$w$ = indentor width; and
$\sigma_S$ = pipe body yield strength.

Uncertainty in estimating puncture resistance using Equation [7.3], is taken into accounted by incorporating two model uncertainty factors in the final expression for the pipe body resistance, $R$, which is given by

$$R = C_1 R_P + C_2 \qquad [7.4]$$

where $C_1$ and $C_2$ are the multiplicative and additive components of the model error, respectively. The random variables ($C_i$) were estimated through regression analysis of the test-to-predicted ratios reported by Spiekhout (see Table 7.1). Based on the static puncture test data summarized in Table 7.1, $C_1$ was found to be a constant with a value of 0.665, whereas $C_2$ was found to be best approximated by a normally distributed variable with mean value of 146.8 kN and a standard deviation of 37.6 kN.

Note that the resistance model adopted herein assumes that the indentor width variable, $w$, in Equation [7.3] can be approximated by a fixed value of 5 mm. This simplifying assumption was found to have a negligible effect on the overall accuracy of the puncture resistance model.

### 7.2.3 Probabilities of Different Failure Modes

Determination of the relative probability of small leak, large leak, or rupture given puncture is based on an estimate of the probability that the axial length of the tear that is assumed to result from line puncture will exceed the critical length associated with fracture initiation. The assumption is that if the tear is idealized as a through-wall crack-like defect, and if the initial defect length exceeds the critical defect length, then the tear will grow (*i.e.*, the crack will be unstable and propagate axially) and the effective hole size will increase significantly thereby changing the final mode of failure from a leak to a rupture.

It has been found that the critical axial defect length varies with the level of hoop stress in the pipe wall, which is proportional to the pipeline operating pressure, and for any given defect length there is a critical hoop stress level above which the axial defect will propagate. Therefore, it follows that the probability of rupture given puncture, $p_{R|P}$, is equal to the probability that the operating hoop stress, $S_h$, will exceed the critical hoop stress, $S_{cr}$, associated with the tear introduced at the impact location. This can be written as

Pipe Performance

$$p_{R|P} = p(S_h > S_{cr}) = p(S_{cr} - S_h < 0) \quad [7.5]$$

The operating hoop stress as a function of internal pressure, $P$, is given by Barlow's equation

$$S_h = \frac{PD}{2t} \quad [7.6]$$

The hoop stress associated with initiation of a through-wall crack-like defect is estimated using a semi-empirical relationship developed by Kiefner *et al.* (1973) which takes the form

$$S = \frac{2(\sigma_y + 68.95)}{\pi M_T} \cos^{-1}\left[\exp - \left\{\frac{125\pi E C_v}{c(\sigma_y + 68.95)^2 A_c}\right\}\right] \quad [7.7a]$$

where

$$M_T = \left[1 + 1.255\frac{c^2}{Rt} - 0.0135\frac{c^4}{R^2t^2}\right]^{1/2} \quad [7.7b]$$

and
$R$ = pipe radius = D/2 (mm);
$c$ = ½ defect length (mm);
$E$ = elastic modulus (MPa);
$C_v$ = full-size Charpy V-notch plateau energy (J);
$A_c$ = full-size Charpy shear area (mm$^2$);
$E$ = elastic modulus (MPa); and
$\sigma_y$ = pipe body yield strength (MPa).

Uncertainty in estimating the critical hoop stress using Equations [7.7], is taken into accounted by incorporating a model uncertainty factor in the final expression for the critical hoop stress, $S_{cr}$, which is given by

$$S_{cr} = C_3 S \quad [7.8]$$

where $C_3$ is the multiplicative error associated with the model as estimated through regression analysis of the test-to-predicted ratios reported by Kiefner *et al.* (1973). The parameter $C_3$ was found to be best approximated by a normally distributed variable with a mean value of 0.985 and a standard deviation of 0.06.

Note that in applying Equations [7.7], the defect length, $2c$, is assumed to be equal to the indentor length, $L$, based on the assumption that when puncture occurs the maximum possible axial length of the tear will be equal to the maximum dimension of the indentor.

Pipe Performance

Using the model described above to estimate the probability of rupture given puncture, $p_{R|P}$, an estimate of the probabilities of large leak given puncture, $p_{LL|P}$, and small leak given rupture, $p_{SL|P}$, can be obtained from $p_{R|P}$ as follows

$$P_{LL|P} = \beta P_{L|P} \qquad [7.9a]$$

$$P_{SL|P} = (1-\beta) P_{L|P} \qquad [7.9b]$$

where $P_{L|P}$ is the probability of leak given puncture, given by

$$P_{L|P} = 1 - P_{R|P} \qquad [7.9c]$$

and β is a constant that defines the relative likelihood that a non-propagating tear resulting from line puncture will create an opening in the pipe wall with an effective diameter (in terms of its product release rate potential) similar to that assumed for a large leak, as opposed to that for a small leak. The value chosen for β is 0.67 which is consistent with data pertaining to mechanical damage incidents on gas transmission lines as reported by Fearnehough (1985) and the European Gas Pipeline Incident Data Group (EGIG 1993), which indicates that on average large leaks are twice as likely to occur as small leaks.

## 7.3 Segment Performance

### 7.3.1 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 two nodes in the mechanical damage influence diagram, namely the probability of failure for a randomly selected interference event from node 3.1 and the rate of occurrence of interference events from node 12.1.

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 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.

### 7.3.2 Calculation of Node Probability Distribution

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 the segment will consist of different damage sections, $i$, each potentially having a different mechanical interference frequency , $r_i$, the annual segment failure probability due to mechanical damage, $pms_j$ (where the subscript $j$ represents the failure mode) can be calculated from

$$pms_j = \sum_i pmd_{ij} r_i l_i \qquad [7.10]$$

where $pmd_{ij}$ is the probability of failure in the $j^{th}$ failure mode for a single interference event in the $i^{th}$ damage section, 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, $\lambda_k$, 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 satisfied, the pipeline can be analyzed in smaller segments.

### 7.3.3 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. 4.1 - Stephens 1996). This review produced baseline failure rates representing natural gas and hydrocarbon liquids pipelines that are considered to be average with respect to construction, operation and maintenance practices. These rates are given in Table 7.2 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 7.2, since only the total failure rate per failure mode is used in the calculation. The input format in Table 7.2 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 7.2, with zero inputs in all other rows.

Figures and Tables

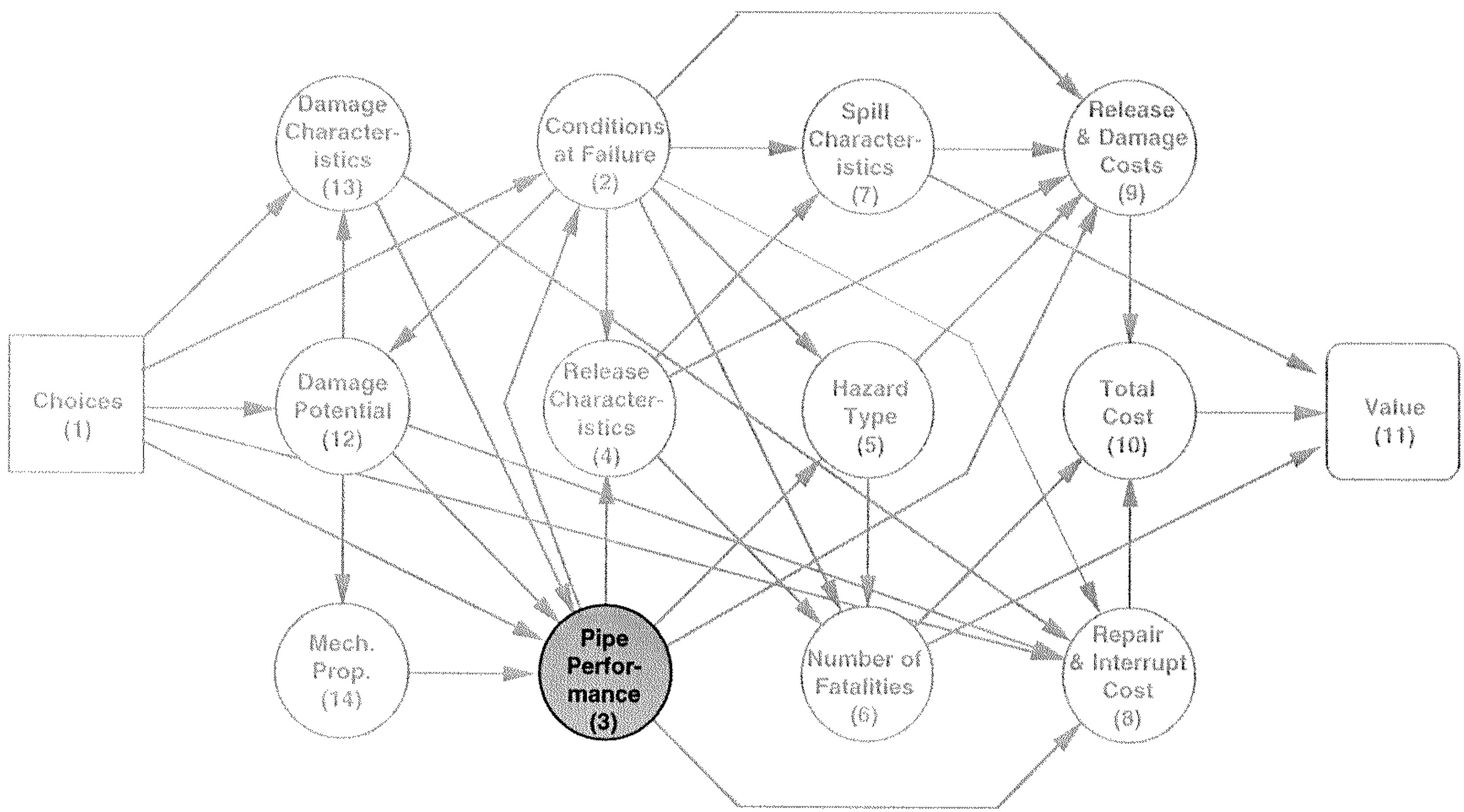



Figure 7.1 Compound node influence diagram highlighting Pipe Performance node group

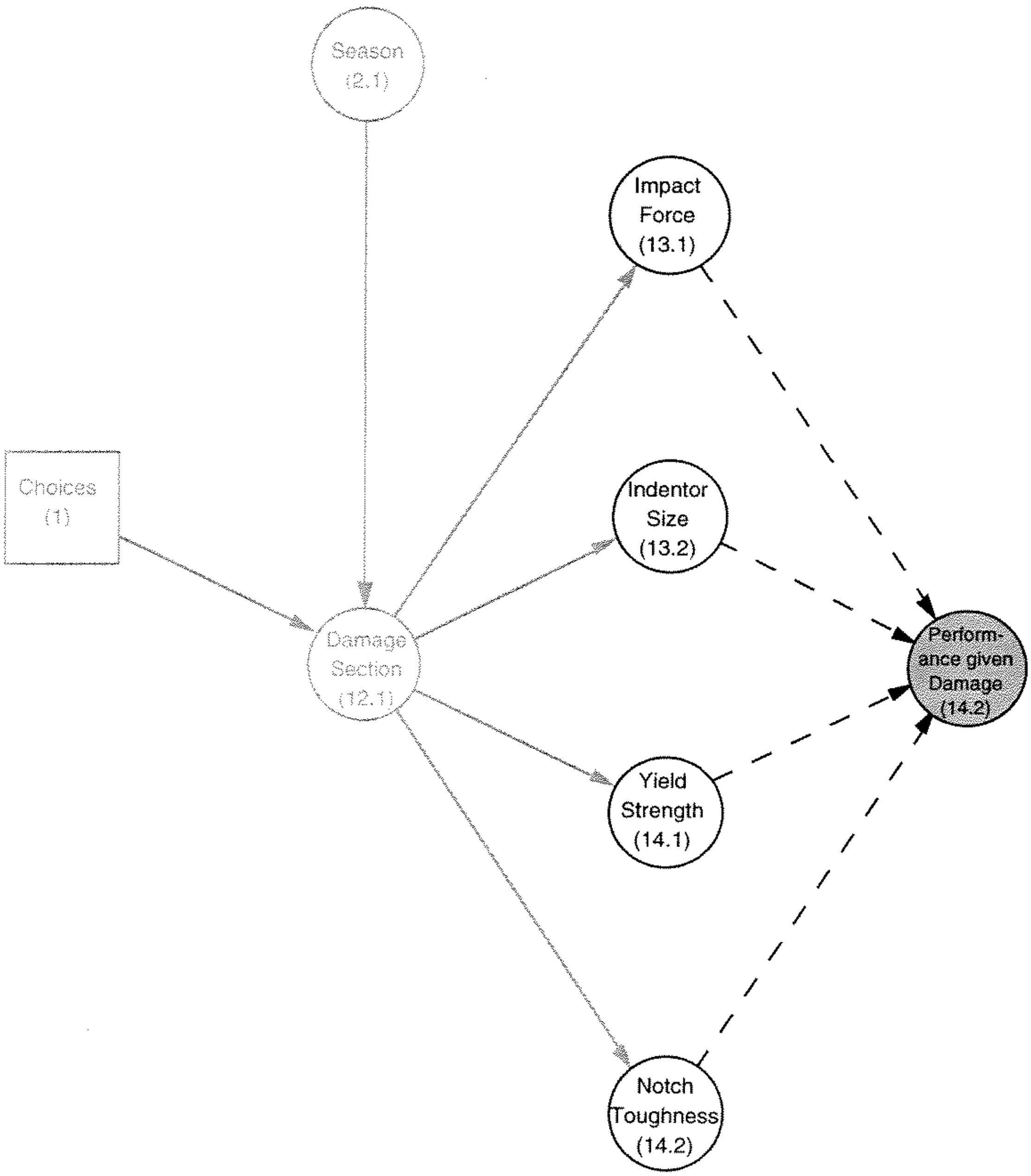



Figure 7.2 Basic node mechanical damage influence diagram highlighting Performance Given Damage node and associated immediate predecessor nodes

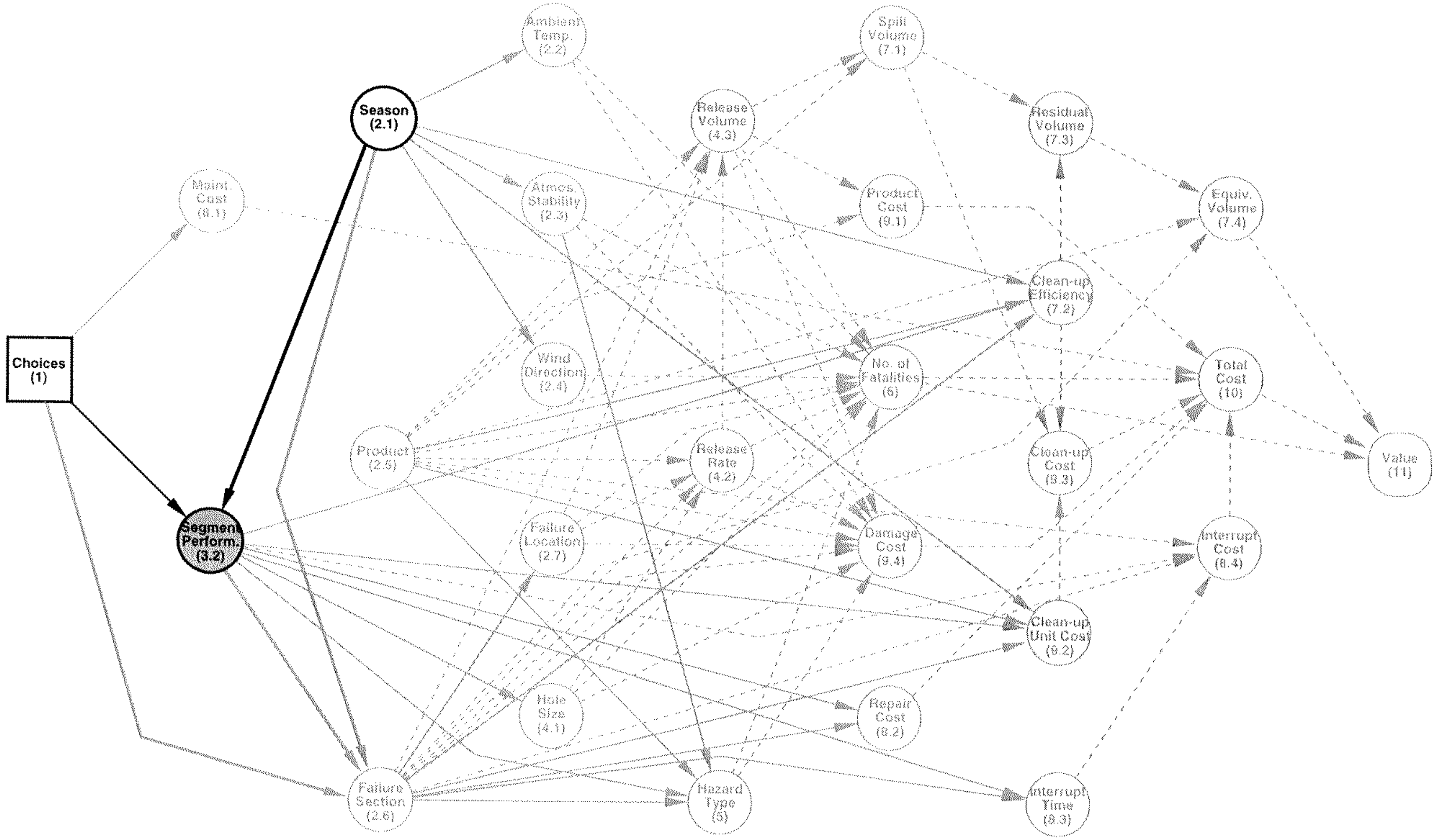



Figure 7.3 Basic node consequence influence diagram highlighting Segment Performance node and associated immediate predecessor nodes

| Test No. | Diameter (mm) | SMYS (MPa) | Wall Thickness (mm) | Puncture Force (kN) | Test to Predicted Ratio (Spikehout *et al.* 1987) |
|---|---|---|---|---|---|
| **Static Tests** | | | | | |
| 1 | 914 | 386 | 9.5 | 244 | 1.06 |
| 2 | | | | 287 | 1.25 |
| 3 | | | | 283 | 1.23 |
| 4 | | 375 | 12.5 | 405 | 1.20 |
| 5 | | | | 411 | 1.21 |
| 6 | | | | 406 | 1.20 |
| 7 | | | 12.5 | 373 | 1.10 |
| 8 | | | | 393 | 1.16 |
| 9 | | | | 419 | 1.24 |
| 10 | | 487 | 12.5 | 366 | 0.83 |
| 11 | | | | 423 | 0.96 |
| 12 | | | | 437 | 0.99 |
| **Dynamic Tests** | | | | | |
| 13 | | 386 | 9.5 | 198 | 0.86 |
| 14 | | | | 183 | 0.80 |
| 15 | | 375 | 12.5 | 363 | 1.07 |
| 16 | | | | 325 | 0.96 |
| 17 | | | | 380 | 1.12 |
| 18 | | 487 | 12.5 | 280 | 0.64 |
| 19 | | | | 450 | 1.02 |
| 20 | | | | 340 | 0.77 |

Table 7.1 Experimental results regarding the resistance of 36" diameter pipe specimens to outside force

| Failure Cause | | Failure Rate (per km yr) | Failure Mode | | |
|---|---|---|---|---|---|
| | | | Small Leak | Large Leak | Rupture |
| Metal Loss Corrosion | external | $3.0 \times 10^{-4}$ | 85 % | 10 % | 5 % |
| | internal | $0.5 \times 10^{-4}$ | 85 % | 10 % | 5 % |
| Ground Movement | | $0.3 \times 10^{-4}$ | 20 % | 40 % | 40 % |
| Crack-like Defects | environmentally induced | $0.2 \times 10^{-4}$ | 60 % | 30 % | 10 % |
| | mechanically induced | $1.0 \times 10^{-4}$ | 60 % | 30 % | 10 % |
| Other Causes | | $2.0 \times 10^{-4}$ | 80 % | 10 % | 10 % |

Table 7.2 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, ambient temperature, 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 to the consequence analysis portion of the influence diagram and were therefore discussed in detail in PIRAMID Technical Reference Manual No. 3.2 (Stephens *et al.* 1996). The node group is included in the present document because the Season node (node 2.1) is also required by the mechanical damage portion of the influence diagram, and one other node, namely node 2.6 representing the Failure Section, was modified as a consequence of incorporating the mechanical damage analysis portion of the influence diagram. These nodes are discussed in detail in the following sections.

## 8.2 Season

The Season node (node 2.1) is common to both mechanical damage and consequence analysis and is therefore shown in a highlighted version of the basic node mechanical damage influence diagram shown in Figure 8.2 and a highlighted version of the basic node consequence analysis influence diagram shown in Figure 8.3. The specific Season node parameter is the season at a randomly selected point in time. In the context of this project, the parameter is defined by a discrete probability distribution that can take one of two possible values: ‘summer’ or ‘winter’.

Definition of the node parameter requires specification of the percentage of time during the year when summer and winter conditions apply. The discrete probability distribution for Season is calculated directly from this information by assuming that the probability of occurrence of a given season is equal to the percentage of time that the time the season is specified to apply.

In the context of this project, winter is defined as the period during which the ground and/or water surface are assumed to be frozen and where applicable, snow covered. With regard to mechanical damage probability estimation, this climate distinction serves to acknowledge the potential for seasonal variations in both the level of excavation and digging activity, and the potential desire to vary preventative maintenance actions (such as right-of-way patrol frequency) with season. It is noted that the relative season split also affects the consequence analysis through dependent node parameters relating to liquid spill clean-up efficiency and clean-up cost, both of which are assumed to be dependent on whether or not the ground surface is frozen.

Conditions at Failure

For a discussion of the data required to defined the Season node parameter refer to Section 4.2 in PIRAMID Technical Reference Manual No. 3.2 (Stephens *et al.* 1996).

### 8.3 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. 3.2 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, operating pressure, adjacent land use and crossings / special terrain. Attributes that affect probability but not consequences include pipe body yield strength and notch toughness 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 3 Damage Sections (*i.e.*, sections with uniform probability-related attributes) and 4 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 3 Damage Sections and the consequence analysis to be carried out for the 4 Failure Sections. If the pipeline were divided into uniform sections with respect to all attributes combined, it would have 6 different sections, requiring both probability and consequence analyses to be carried out 6 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.

Conditions at Failure

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

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

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 1. 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

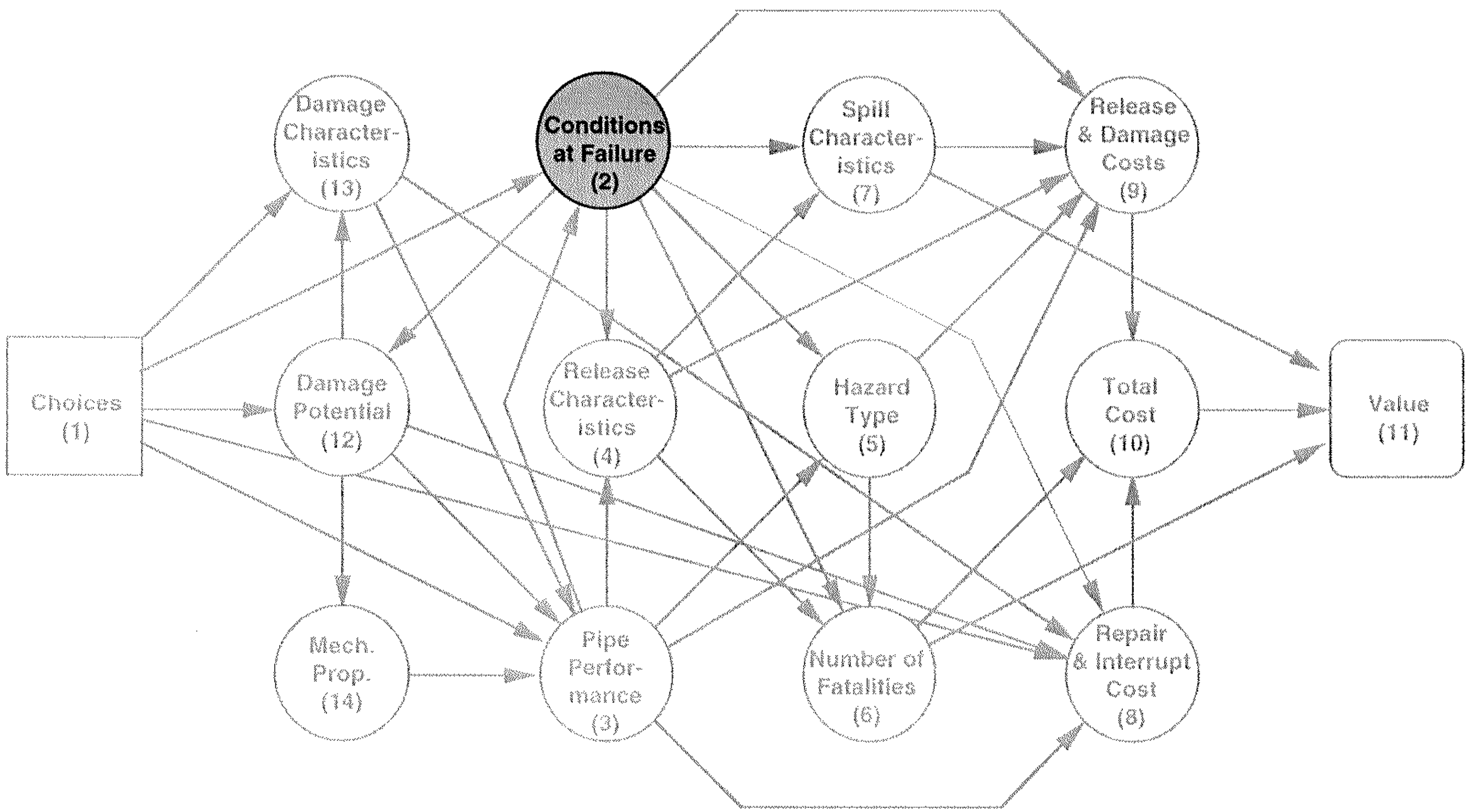



Figure 8.1 Compound node influence diagram highlighting Conditions at Failure node group

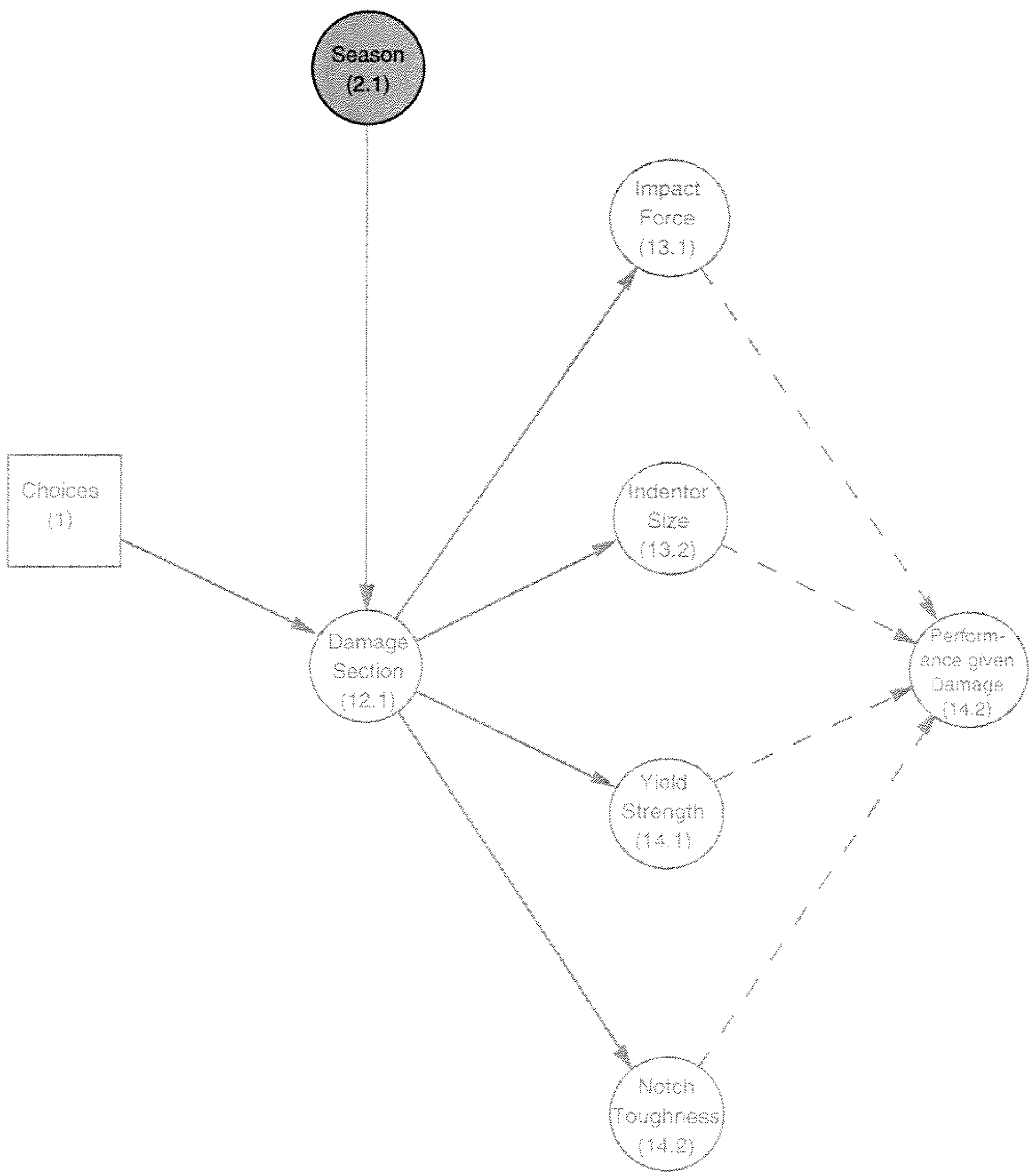



Figure 8.2 Basic node mechanical damage influence diagram highlighting Season node

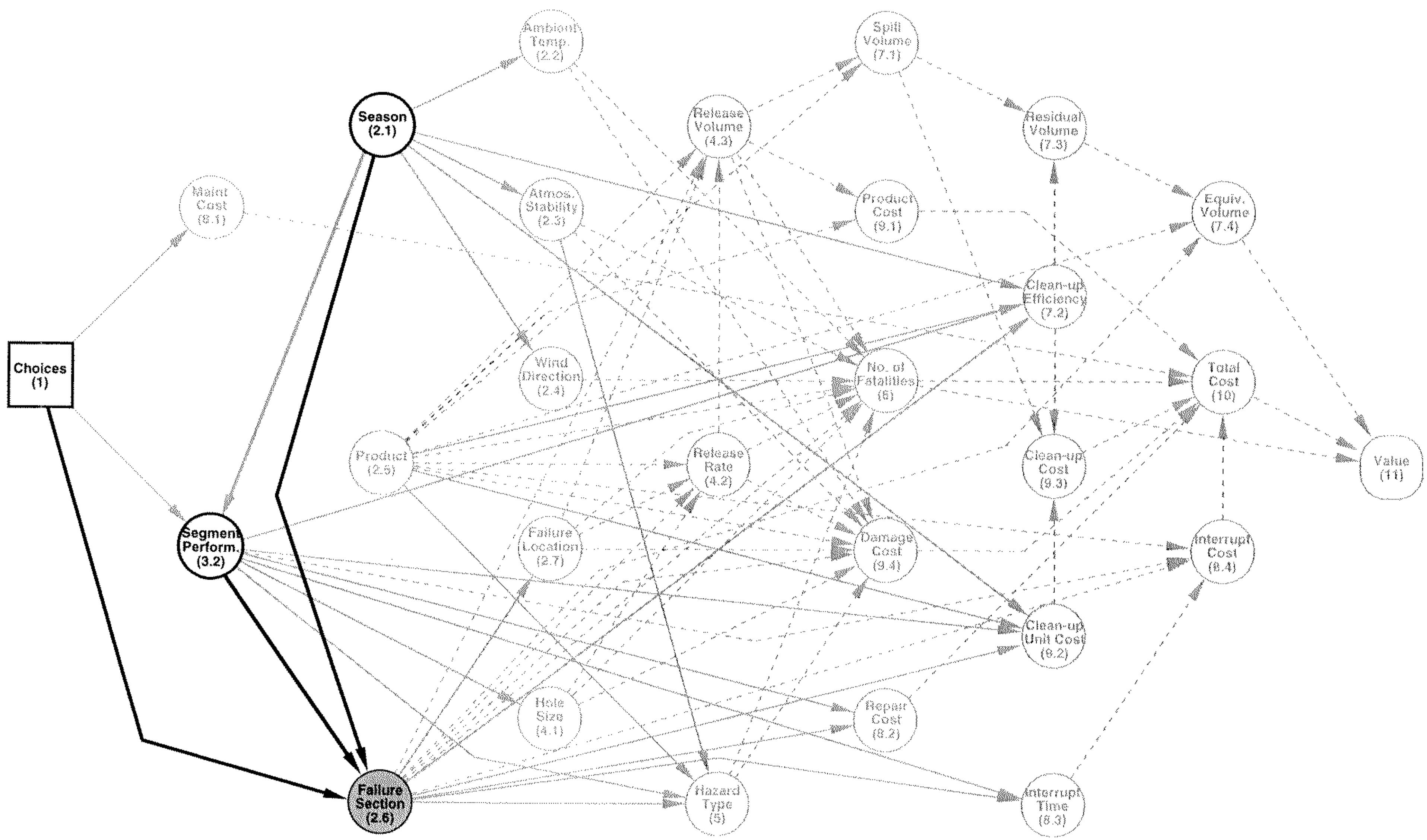



Figure 8.3 Basic node consequence influence diagram highlighting Failure Section node and its associated immediate predecessor nodes

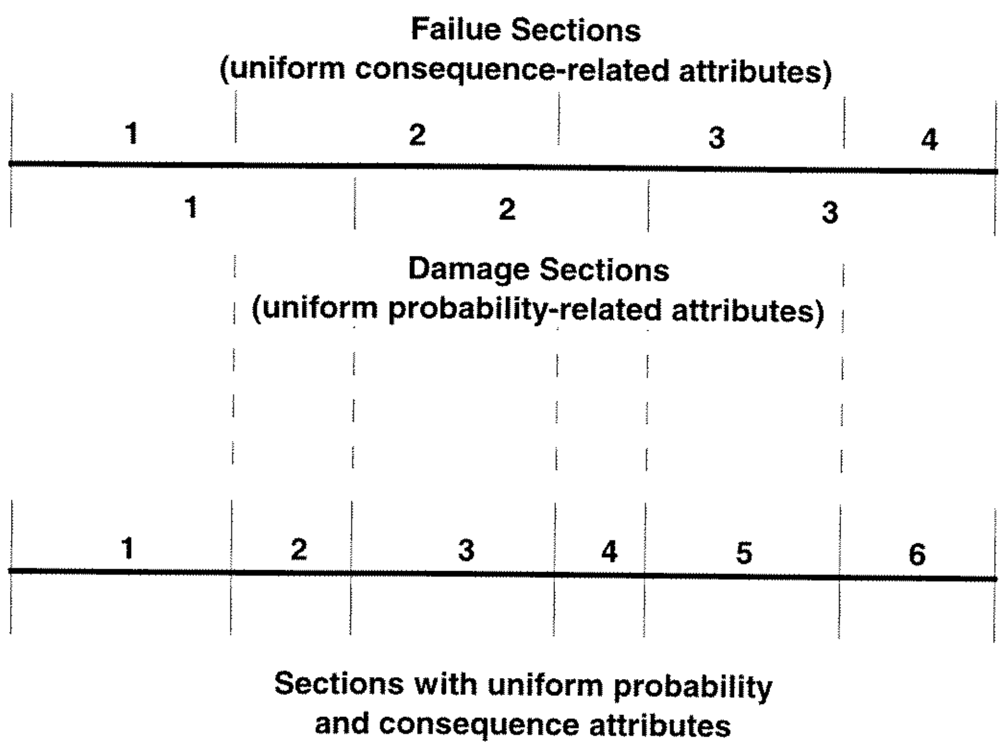



Figure 8.4 Illustration of pipeline segmentation with respect to probability-related and consequence-related attributes

# 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. 3.2 (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, $\tau$, 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 3 to 5 percent range and the total annual cost estimate is not highly sensitive to variations in the assumed interest rate within this range.

Figures

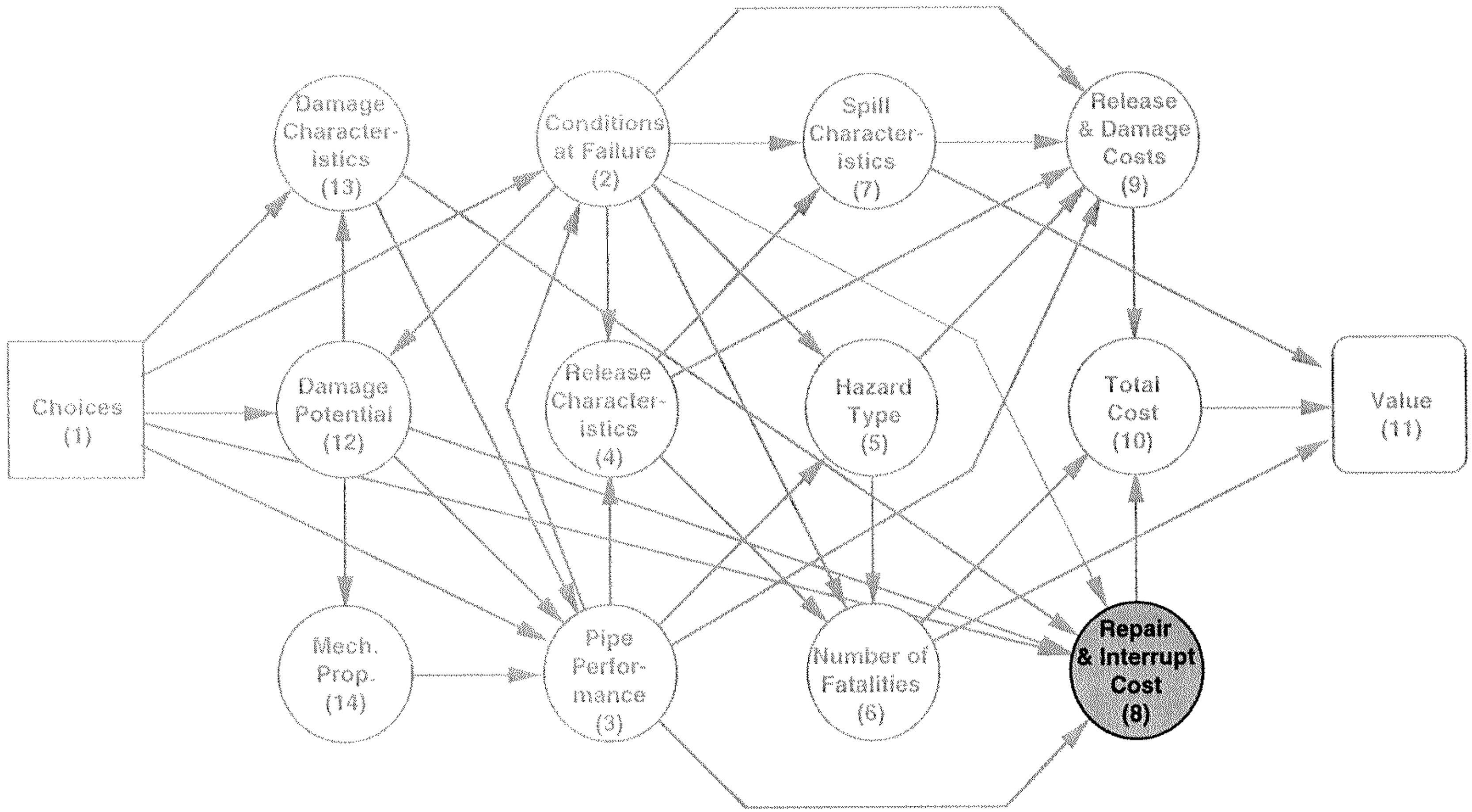



Figure 9.1 Compound node influence diagram highlighting Repair & Interrupt Cost node group

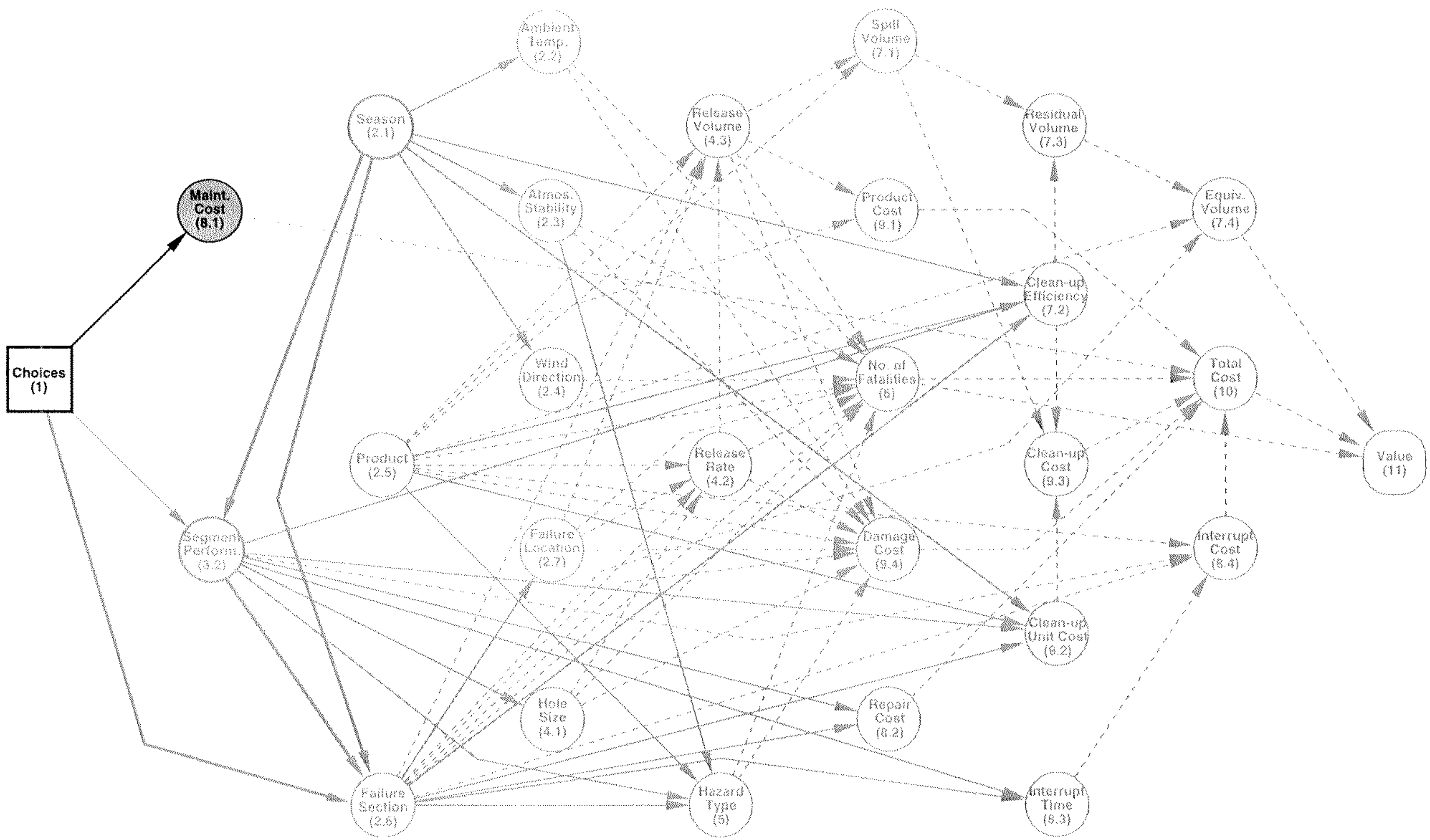



Figure 9.2 Basic node consequence influence diagram hightlighting Maintenance Cost node and its associated immediate predecessor node

## 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 levels of safety and environmental risks.

Details of the inputs and calculations associated with the value node are given in PIRAMID Technical Reference Manual No. 3.2 (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

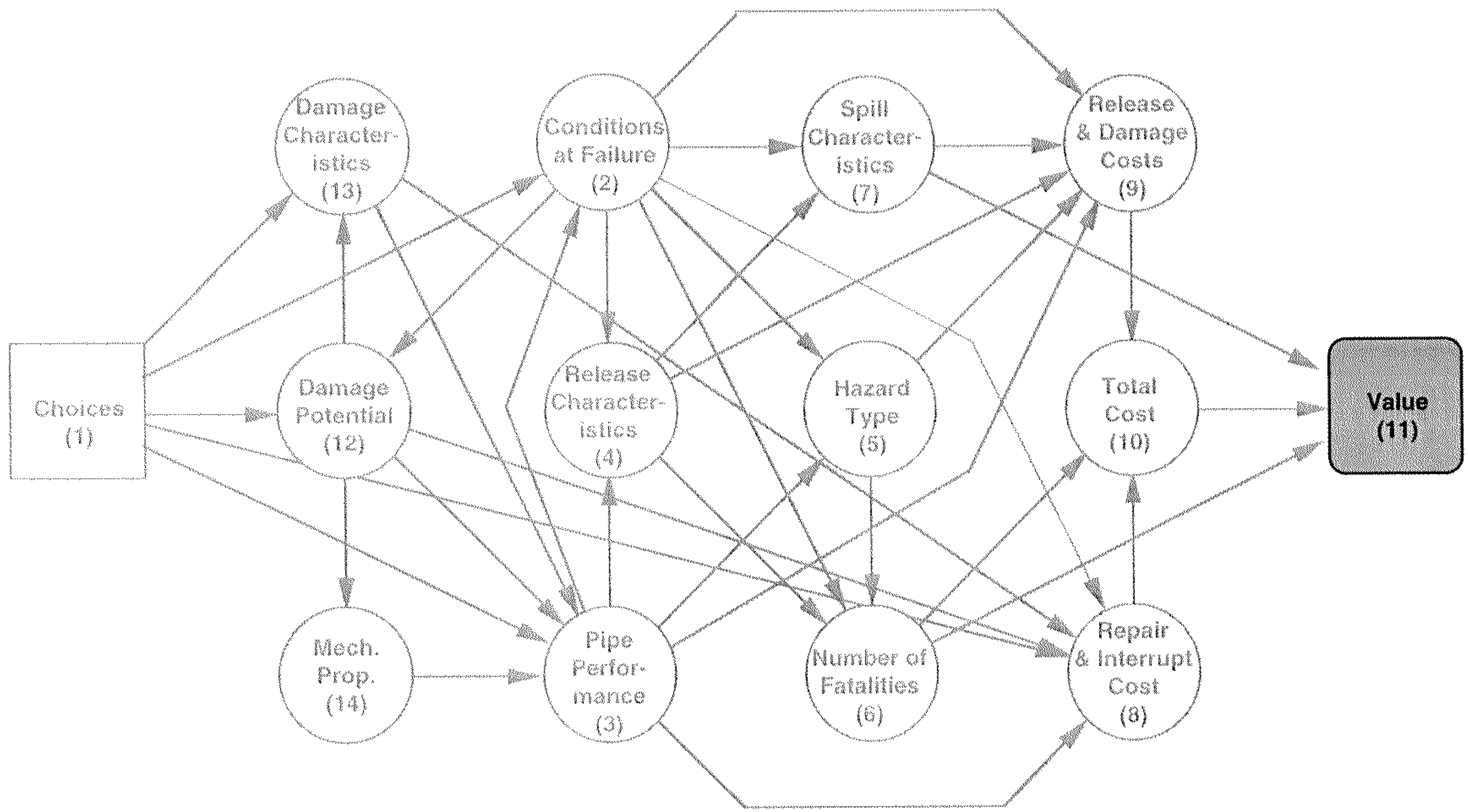



Figure 10.1 Compound node influence diagram highlighting Value node group

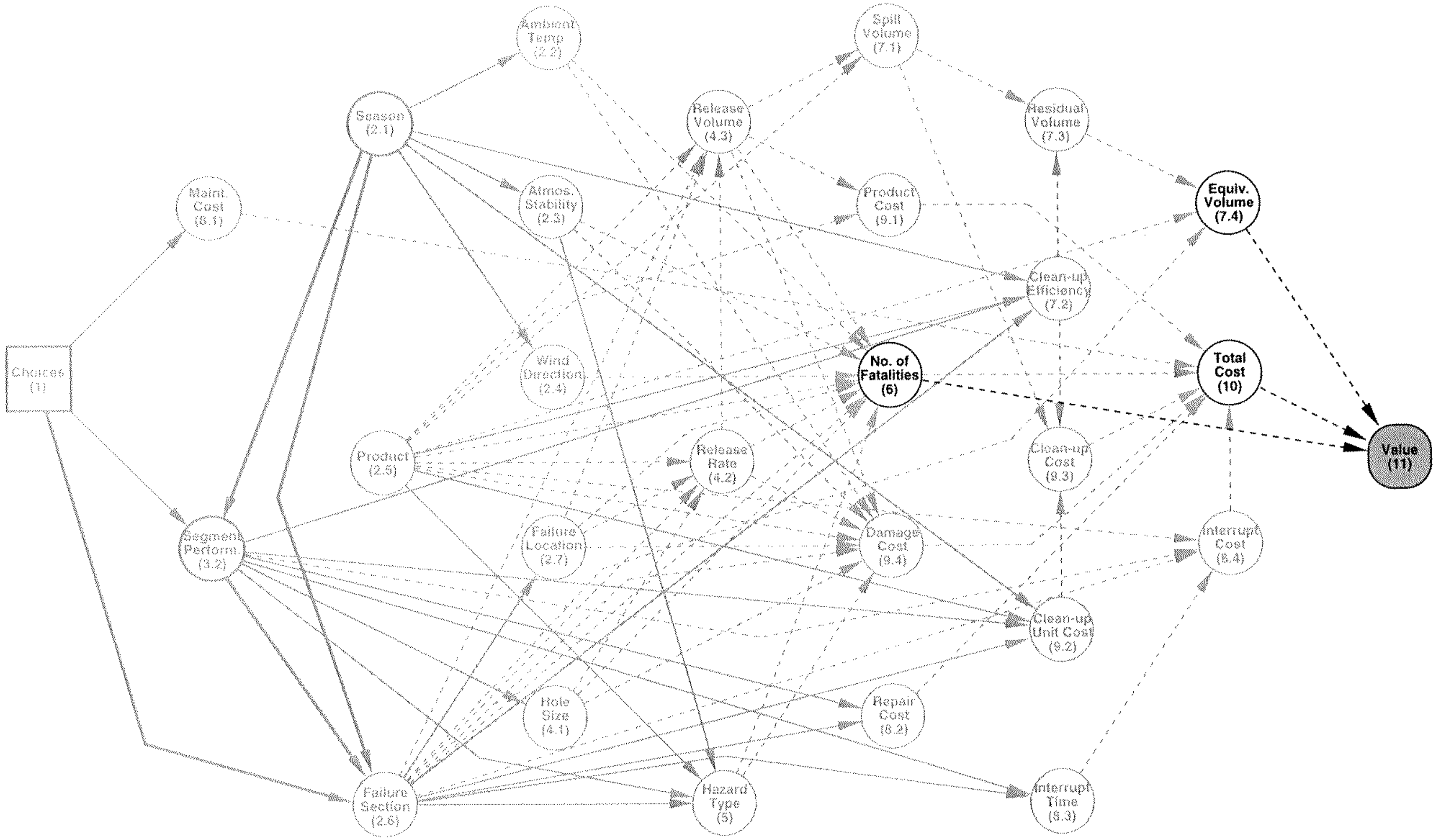



Figure 10.2 Basic node consequence influence diagram hightlighting Value node and associated immediate predecessor nodes

## 11. REFERENCES

American Gas Association (AGA) 1977. Statistical Properties of the Arrest Criterion as Related to the Pipe Mill Data - Appendix B. AGA Sixth Symposium on Line Pipe Research.

Barlow, R.E. and Lambert, H.E. 1975. Introduction to Faulty Tree Analysis, In Reliability and Fault Tree Analysis. Society for Industry and Applied Mathematics, Philadelphia, Pennsylvania. Barlow, R.E. and Fussel, J.B. (eds.)

Courtney, W.J., Kalkbrenner, D. and Yie, G. 1977. Effectiveness of Programs for Prevention of Damage to Pipelines By Outside Forces. Final Report prepared for U.S. Department of Transportation DOT/MTS/OPSO-77/12, November.

CSA-Z245.1-M90. 1990. Steel Line Pipe. Canadian Standards Association, Ontario, May.

EGIG 1993. Gas Pipeline Incidents Report 1970-1992, European Gas Pipeline Incident Data Group.

Eiber, R. J. 1977. Investigation of Charpy Plateau Energy Variation in Production Pipe Orders. Proceedings of the Nineteenth Mechanical Working and Steel Processing Conference, pp. 55-73.

Fearnehough, G.D. 1985. The Control of Risk in Gas Transmission Pipeline. Institute of Chemical Engineers, Symposium Series No. 93, pp. 25 - 44.

Hopkins, P., Pistone, V. and Clyne, A. J. 1992a. A Study of the Behaviour of Defects in Pipeline Girth Welds: The Work of the European Pipeline Research Group. Proceedings of the CANMET International Conference on Pipeline Reliability, Calgary, pp. VI-3-1 to VI-3-16.

Hopkins, P., Corder, I and Corbin, P. 1992b. The Resistance of Gas Transmission Pipelines to Mechanical Damage. Proceedings of the CANMET International Conference on Pipeline Reliability, Calgary, pp. VIII-3-1 to VIII-3-18.

Kiefner, J. F., Maxey, W. A., Eiber, R. J. and Duffy, A. R. 1973. Failure Stress Levels of Flaws in Pressurized Cylinders. Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, American Society for Testing and Materials, pp. 461 - 481.

Leewis, D. 1997. Gas Research Institute (GRI), personal communication.

McCormick, M.J. 1981. Reliability and risk Analysis. Academic Press Inc., New York.

Meadows, R.C. and Sage, J.W. 1985. One Call Systems Can Limit Third Party Damage Exposure. Pipe Line Industry, October.

References

Melchers, R.E. and Harrington, M.V. 1982. Human Error in Simple Design Tasks. Civil Engineering, Monash University, Australia, Research Report No. 3/1982.

Nessim, M. A. and Hong, H. P. 1995. Probabilistic Decision Analysis Using Influence Diagrams - PIRAMID Technical Reference Manual No. 2.1. Confidential to C-FER's Pipeline Program Participants, C-FER Report 94022, October.

Spiekhout, J. 1995. A New Design Philosophy for Gas Transmission Pipelines - Designing for Gouge-Resistance and Puncture-Resistance.

Spiekhout, J., Gresnigt, A. M. and Kusters, G. M. A. 1987. The Behaviour of a Steel Cylinder Under the Influence of a Local Load in the Elastic and Elasto-Plastic Area. Proceedings of the International Symposium on Shell and Spatial Structures: Computational Aspects (July, 1986), Leuven, Belgium. Springer-Verlag, Berlin, Germany, pp. 329-336.

Stephens, M. J. 1996. Prioritization of On Shore Pipeline Systems for Integrity Maintenance: PIRAMID Technical Reference Manual No. 4.1. Confidential to C-FER's Pipeline Program Participants, C-FER Report 95007, November.

Stephens, M. J., Nessim, M. A. and Chen, Q. 1995. A Methodology for Risk-Based Optimization of Pipeline Integrity Maintenance Activities - PIRAMID Technical Reference Manual No. 1.2. Confidential to C-FER's Pipeline Program Participants, C-FER Report 94006, October.

Stephens, M. J., Nessim, M. A. and Chen. Q. 1996. Probabilistic Assessment of Onshore Pipeline Failure Consequences: PIRAMID Technical Reference Manual No. 3.2. Confidential to C-FER's Pipeline Program Participants, C-FER Report 94035, November.

Transportation Research Board (TRB) 1988. Pipelines and Public Safety - Damage Prevention, Land Use, and Emergency Preparedness. National Research Council, Special Report 219, Washington, D.C.

## APPENDIX A - MECHANICAL DAMAGE FAULT TREE

### Tree Description

The fault tree in Figure A.1 models the top event of a pipeline hit by an excavator. The first level of branching states that a line hit occurs if: there is excavation activity on the alignment (basic event B1), the preventative measures fail to stop uncontrolled activity (intermediate event E2), and the protective measures fail to prevent uncontrolled activity leading to line impact (intermediate event E3). These events must all be true for the hit to occur and therefore they are connected with an AND gate (gate 1).

At the second branch level, Gate 2 states that preventative measures will fail if either the alignment is not correctly located (intermediate event E4) OR if the contractor accidentally hits the correctly located line (basic event 13). Gate 3 indicates that protective measures will fail if both the excavation depth exceeds the depth of cover (basic event B14) AND the mechanical protection, if present, fails to prevent a line hit (basic event B15).

At the third level, Gate 4 states that the alignment will not be correctly located if: permanent above-ground markers fail to convey alignment location (basic event B11) AND buried markers fail to convey location (basic event 12) AND temporary measures fail to correctly locate the alignment (intermediate event E5). Note that it is assumed that if permanent above-ground or buried markers are not present that the corresponding basic event probability is equal to 1.

At the fourth branch level, Gate 5 indicates that temporary measures will fail to correctly locate the alignment if: the pipeline operator is not notified of pending activity (intermediate event E6) OR the operator fails to correctly locate the alignment when notified of pending or on-going activity (basic event B10). At the next level, Gate 6 states that the operator will not be notified of pending activity if: the one-call system fails to notify the operator (intermediate event E7) OR the contractor fail to notify the operator directly regarding pending activity (intermediate event E8) OR the operators right-of-way patrol fails to detect activity (intermediate event E9).

At the sixth branch level, Gate 7 indicates that the one-call system will fail to notify the operator if parties fail to use the one-call system (intermediate event E10) OR the one-call system, if used, fails to notify the relevant operator (basic event B5). Gate 8 states that parties will fail to notify the operator directly if explicit pipeline signage is not seen by the contractor (basic event B6) OR the explicit signage is ignored (basic event B7). Gate 9 indicates that the right-of-way patrol will fail to detect activity is there is no patrol during the on-site mobilization and activity period prior to impact (basic event B8) OR patrol personnel fail to detect on-going activity during a patrol (basic event B9).

At the seventh level, Gate 10 states that parties will fail to use a one-call system if they do not call before moving onto the right-of-way (basic event B2) AND do not call when on the right-of-way (intermediate event E11). Finally, at the last level, Gate 11 indicates that parties fail to call when on the right-of-way because right-of-way indicators are not recognized (basic event B3) OR the parties ignore right-of-way indicators (basic event B4).

### Estimation of Top Event Frequency

***Top Event***

E1 Pipeline hit by mechanical equipment
E1 = B1 E2 E3

***Intermediate Events***

E2 Failure of preventative measures
E2 = E4 + B13 - (E4 B13)

E3 Failure of protective measures
E3 = B14 B15

E4 Alignment not correctly located
E4 = B11 B12 E5

E5 Temporary measures fail to correctly locate alignment
E5 = B10 + E6 - (B10 E6)

E6 Pipeline operator not notified of pending activity
E6 = E7 E8 E9

E7 One call system fails to notify pipeline company
E7 = B5 + E10 - (B5 E10)

E8 Parties fail to notify operator directly
E8 = B6 + B7 - (B6 B7)

E9 Right-of-way patrols fail to detect activity
E9 = B8 + B9 - (B8 B9)

E10 Parties fail to use one call system
E10 = B2 E11

E11 Parties fail to use one-call system when on right-of-way
E11 = B3 + B4 - (B3 B4)

Appendix A

***Basic Events***

B1 Activity on alignment
note, event B1 is a 'rate' in units of incidents per km yr
R(B1) = f(land use type, crossings)

B2 Parties fail to call before moving onto right-of-way
P(B2) = f(level of awareness, prior notification requirement, one call system type)

B3 Right-of-way indicators not recognized
P(B3) = f(level of awareness, right-of-way indication)

B4 Parties ignore right-of-way indicators
P(B4) = f(level of awareness, one call system type)

B5 One-call system fails to notify relevant operator
P(B5) = f(one call system type)

B6 Explicit signage not seen
P(B6) = f(level of awareness, explicit pipeline signage)

B7 Parties ignore explicit signage
P(B7) = f(level of awareness)

B8 No patrol during period of activity
P(B8) = f(right-of-way surveillance interval)

B9 Patrol personnel fail to detect activity
P(B9) = f(right-of-way patrol method)

B10 Operator fails to ensure correct location of alignment
P(B10) = f(notification response)

B11 Permanent above-ground alignment markers fail to convey alignment location
P(B11) = f(permanent alignment markers)

B12 Buried alignment markers fail to convey alignment location
P(B12) = f(buried alignment markers)

B13 Accidental activity on located alignment
P(B13) = f(notification response)

B14 Excavation depth exceeds cover depth
P(B14) = f(depth of cover)

B14 Mechanical protection fails to protect pipe
P(B15) = f(mechanical protection)

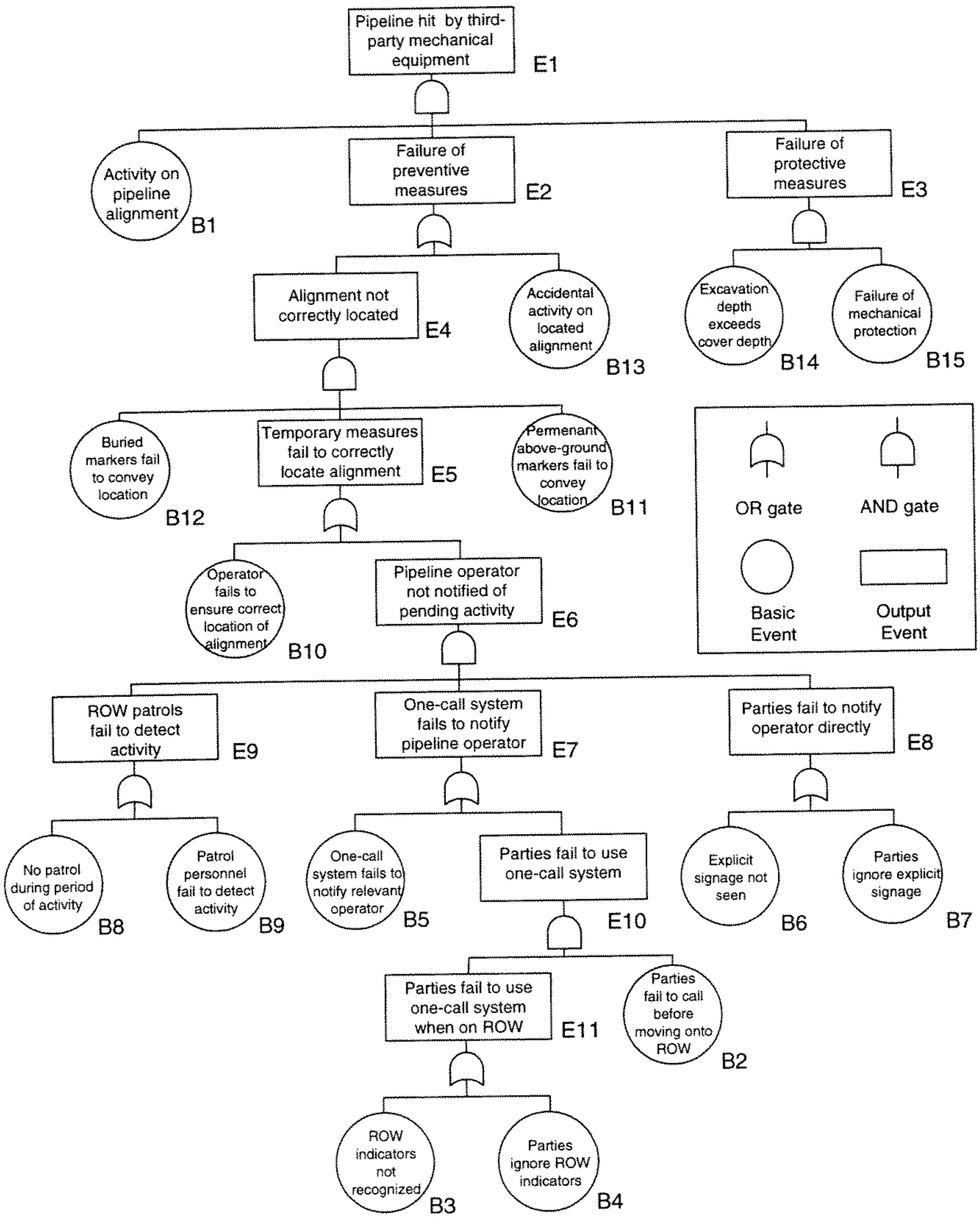



Figure A.1 Fault tree for mechanical interference

# APPENDIX B - RIGHT-OF-WAY PATROL DETECTION MODEL

## Activity Detection Model

This Appendix describes an analytical model developed for estimating the probability of detecting excavation activity on or near the right-of-way.

Basic Assumptions:

- Inspection is performed periodically (*i.e.*, no randomness) such that the inspection interval, $t$, is a constant.
- An outside force incident can occur randomly, with a probability $P_x = 1/t$. within the inspection interval.

The probability of detecting an incident before it damages the pipeline, $P_D$, is given by

$$P_D = p[\text{time to next inspection} < \text{time to impact}] \qquad [1]$$

If we let $f_H$ denote the probability density function of the time to impact, given that an activity is taking place on the pipeline right-of-way, and if it is assumed that $f_H$ follows a triangular distribution (see Figure B1), the probability of detecting an incident is given by

$$P_D = [b^3 - (b-t)^3]/(3tb^2) \quad \text{for } b \geq t \qquad [2a]$$

$$P_D = b/(3\,t) \quad \text{for } b < t \qquad [2b]$$

where $b$ is the duration of the excavation activity.

A parameteric study showing the variation of $P_D$ with respect to $b$ and $t$ is summarized in Figure B.2.

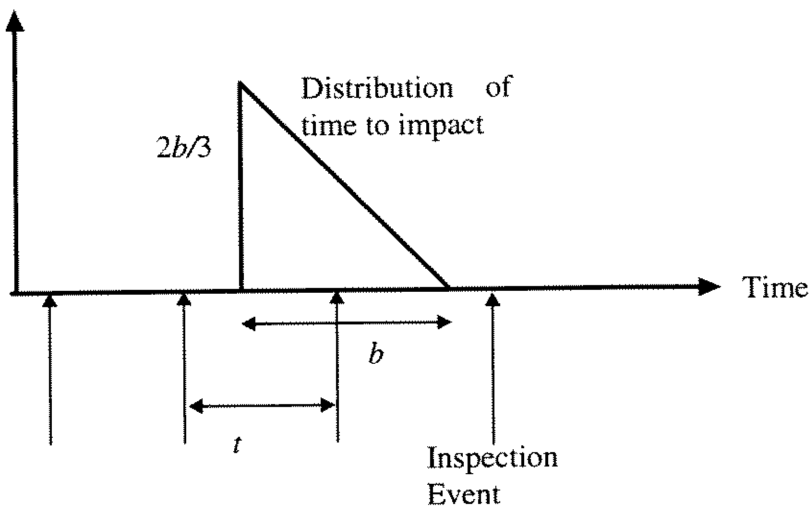



Figure B1 Inspection model

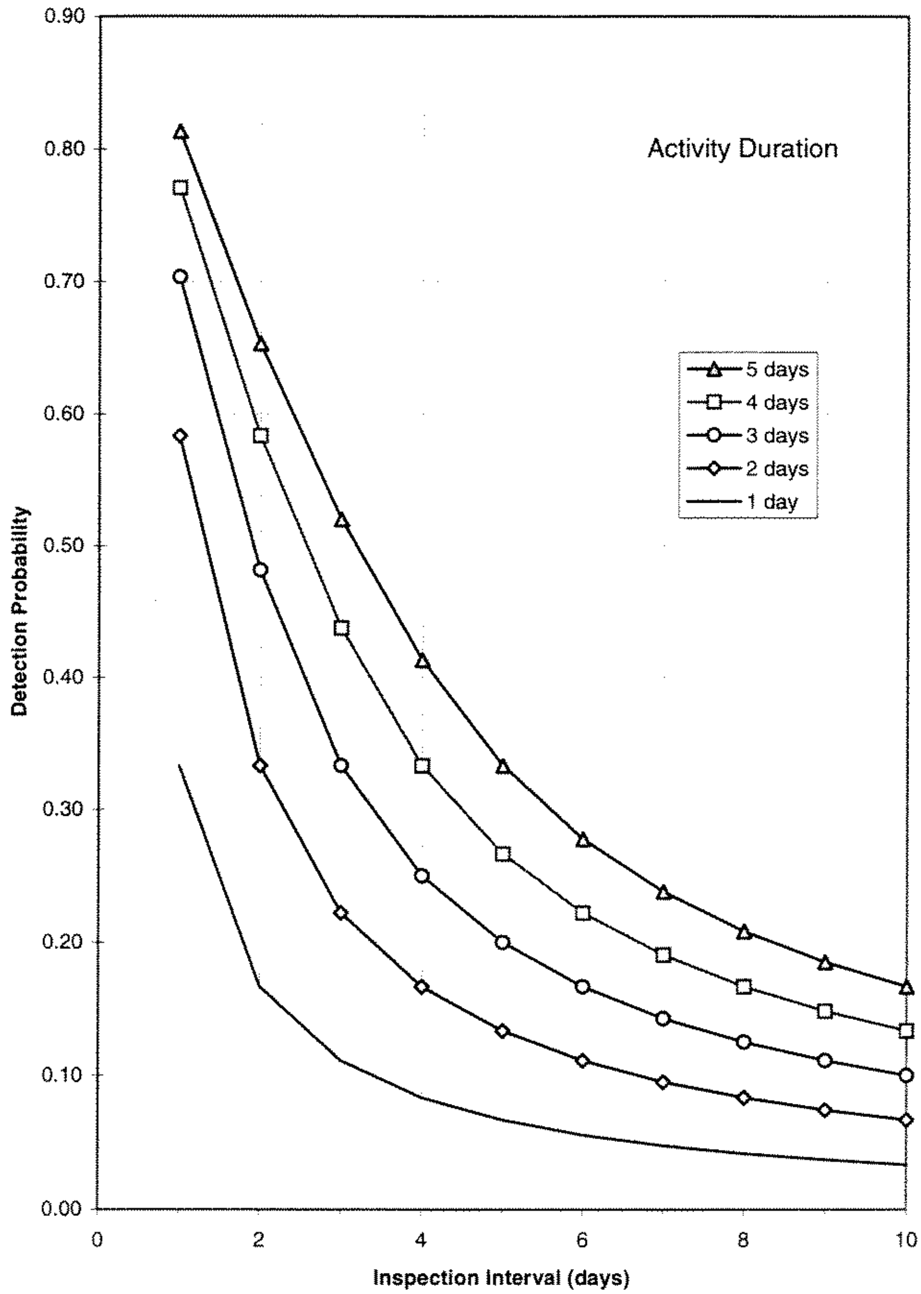



Figure B2 Variation in detection probability with activity duration and inspection interval