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RISK-BASED OPTIMIZATION OF PIPELINE INTEGRITY MAINTENANCE

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ABSTRACT

Integrity maintenance of the aging hydrocarbon pipeline network is a prime concern for transmission companies. With the variety of existing pipeline inspection and protection approaches and the constant improvements in inspection technologies, pipeline operators have many tools at their disposal to ensure the continued safe operation of their systems. Because pipeline systems are usually large, and maintenance budgets are limited by constraints of economic viability, operators must decide on how maintenance resources are best allocated.

A risk-based methodology to address the question of optimal allocation of maintenance resources is presented. The methodology is based on two major steps: a) to rank different segments of the pipeline with respect to priority for increased maintenance; and b) to select an optimal set of maintenance actions for high priority segments. Decisions regarding segment prioritization and maintenance optimization for a given segment are based on the level of risk associated with a given segment and the risk reduction achieved by different maintenance actions.

Risk is estimated as a function of the probability of an incident and its anticipated consequences in terms of losses in life, injuries, long term environmental effects and financial costs. The approach focuses on the development of methods to combine the effects of these consequences into a unified measure of loss and analytical estimation of the impact of different maintenance activities on the probability of failure. There is an on-going joint industry program that is developing technical and software tools to implement the approach and make it readily usable by pipeline operators to make optimal decisions on maintenance strategies.

KEY WORDS

Integrity Maintenance, Pipelines, Decision Analysis, Risk Analysis, Influence Diagrams.

1.0 INTRODUCTION

Maintaining the integrity of a vast and aging pipeline network is a subject of prime interest to pipeline companies all over the world. In Canada alone there is in excess of 250,000 km of natural gas, crude oil and petroleum product pipelines. In all of North America, over one-half of the large diameter pipeline system is older than 25 years. With limited maintenance resources, it is essential that the available funds be spent where they are most effective in reducing the risks posed by pipeline failures to life, the environment and financial assets.

The uncertainties associated with the design and operation of pipelines have led to an increasing recognition of risk analysis as a basis for making decisions on integrity maintenance. In this context, *Risk* is defined as the probability of line failure multiplied by a measure of the adverse consequences associated with failure. A quantitative estimate of operating risk is an ideal measure of the adequacy of its current maintenance strategies. For a pipeline that requires improvements in maintenance, the estimated effect of a particular maintenance strategy on the risk is an excellent measure of its effectiveness. The essence of risk-based optimization of integrity maintenance activities is to use these measures as a basis for making decisions regarding how a pipelines system should be maintained.

This paper describes a comprehensive methodology for risk-based integrity maintenance optimization applicable to onshore and offshore natural gas, crude oil and petroleum product pipelines. The methodology has been developed and is being implemented under a joint industry program sponsored by a number of transmission companies and government agencies (see acknowledgment section). The types of decisions addressed by the methodology include the choice of inspection methods (*e.g.*, right-of-way patrols, coating damage surveys and in-line inspection) and inspection intervals, as well as the choice of maintenance actions (*e.g.*, coating damage repair, sleeve repair and cut-out replacement).

2.0 STATE-OF-THE-ART IN PIPELINE RISK ANALYSIS

Risk analysis has been used extensively in the pipeline industry as a tool for decision making. Pipeline operators that have developed their own risk-based approaches include NOVA Corporation of Alberta (Urednicek *et al.* 1992, Ronsky and Trefanenko 1992, and Morrison and Worthingham 1992), British Gas (Fearnehough 1985, and Fearnehough and

Corder 1992) and Dow Chemical (Muhlbauer 1992). There are also many publications by consulting companies that have developed and applied risk analysis on behalf of pipeline companies (*e.g.*, Hill 1992, Weber and Mudan 1992, Concord 1993, Kiefner *et al.* 1990, Woodward-Clyde 1988, Kulkarni and Conroy 1991, and Kulkarni *et al.* 1993). The approaches used can be classified into two major categories, namely, qualitative index systems and quantitative risk analysis. These are discussed separately in the following sub-sections.

2.1 Qualitative Index Systems

Qualitative risk index approaches (*e.g.*, Muhlbauer 1992, and Kiefner *et al.* 1990) assign subjective scores to the different factors that are thought to influence the probability and consequences of failure. These scores are then combined using simple formulas to give an index representing the level of risk.

Index approaches provide only relative rankings of different pipeline segments, so that given two segments, one can determine (subject to limitations discussed later) which segment has a higher risk. They do not give any indication of whether the risk associated with either of the sections is unacceptable, and consequently no guidance is provided regarding whether any risk reduction action is necessary. In addition, the risk rankings produced by index systems may be inaccurate because the relative contributions of different factors that contribute to the total risk index are defined subjectively. For example, the index system scoring format suggested by Muhlbauer accounts for the use of in-line inspection tools to locate metal loss corrosion by awarding up to 8 points out of a potential 400 representing resistance to failure (*i.e.*, 2%). This underestimates the benefits of high resolution pigging, which is known to result in significant reductions to the large percentage of failures that are attributable to corrosion (20% to 40% of all failures). Therefore, index systems provide at best an approximate risk-based ranking of pipeline segments, which has serious limitations as a basis for integrity maintenance decision-making.

2.2 Quantitative Risk Analysis

This approach estimates the level of risk based on direct estimates of the probability and consequences of failure. Current quantitative pipeline risk assessment approaches focus on a single aspect of the consequences associated with failure. Most existing work deals with either life safety risk (*e.g.*, Concord 1993, and Hill 1992) or economic risk (Urednicek *et al.* 1992). Environmental damage risks associated with the failure of liquid pipelines have not been addressed quantitatively. Furthermore, the integration of life safety, environmental damage and economic risks has not been addressed adequately.

Another limitation of quantitative risk assessment approaches currently in use is that they typically base the required failure probability estimates on historical failure rates. Publicly available databases do not usually allow subdivision of the failure data according to the attributes of a specific pipeline, and where adequate subdivision is possible, the amount of data associated with a particular attribute set is very limited because of the rarity of pipeline failures. Failure probabilities estimated from public data are, therefore, not sufficiently specific to represent a given pipeline.

2.3 A General Comment on Existing Approaches

Another key element that has not been addressed in currently existing approaches is a method to quantify the effect of a proposed integrity maintenance strategy on the probability of failure. This aspect is essential if risk analysis is to be used as a basis for integrity maintenance decision-making. A limited amount of proprietary work has been conducted on this topic by British Gas (Shannon and Argent 1988) and Novacorp (Ronsky and Trefanenko 1992). For the most part, however, methods that have been suggested for risk-based analysis of pipeline systems account for the effects of inspection and maintenance actions on the risk level in a subjective manner (*e.g.*, Muhlbauer 1994). There is an on-going development (Kulkarni and Conroy 1991, and Kulkarni *et al.* 1993) that aims at quantifying the effects of integrity maintenance action, based on a combination of historical data and, if available, inspection results.

3.0 EMPHASIS AND SCOPE OF THE PRESENT PROGRAM

As discussed in Section 2.0, existing risk analysis approaches have been designed to answer the following questions: 1) how do different pipeline segments compare with respect to overall risk? and 2) is the risk to life or economic risk caused by a given pipeline segment acceptable? The answers obtained are subject to the limitations discussed in section 2.0. The operator who is attempting to optimize integrity maintenance activities needs answers to different questions, namely: 1) which line segments within a pipeline system require risk reduction through enhanced integrity maintenance? and 2) what is the optimal set of integrity maintenance actions for these segments?

The steps involved in answering these questions based on risk analysis are shown in Figure 1. The figure indicates the current status of technology in each subject area, showing subject areas where additional research and development are required. These are as follows:

1. modeling the effect of maintenance actions on the probability of failure;
2. development of a risk-based decision-oriented framework; and
3. methodologies to combine life safety, environmental damage and economic risks into one measure of failure consequences.

The present program aims to fill the gaps in present technology by focusing on these topics. The first requirement must be addressed on a case-by-case basis for different integrity actions and failure causes. The second and third requirements define the optimization method used, and are discussed further in Section 4.0. This is followed by an outline of the overall methodology being developed to utilize risk analysis as a tool for optimizing pipeline integrity maintenance activities.

4.0 TECHNICAL APPROACH FOR RISK-BASED DECISION-MAKING

4.1 Optimization Approach

Selecting an optimal integrity maintenance action is a problem of optimization under uncertainty. The most comprehensive approach for solving such problems is decision theory (*e.g.*, Keeney and Raiffa 1976), which provides a systematic and consistent method to evaluate alternatives and make optimal choices. The specific decision analysis implementation used in this work is based on influence diagrams.

Figure 2 shows a simplified decision influence diagram for the integrity maintenance optimization problem. The diagram consists of a network of nodes and directed arcs. The nodes represent the parameters affecting the decision problem and the arcs represent the relationships between these parameters. A decision parameter is represented by a square node and an uncertain parameter is represented by a circular node. In Figure 2, the decision node represents the integrity maintenance action. Pipe performance represents whether or not the pipeline will fail, and this is an uncertain parameter. The arc emanating from the decision node into the pipe performance node indicates that the latter is probabilistically dependent on the former. Similarly, the final consequences (expressed in terms of cost for example) are uncertain and dependent on both the choice made and the pipe performance.

The last node in a decision influence diagram is called the value node and is represented by the rounded square. This node defines the objective or value function that is used as a basis for optimization. If the value function is defined such that it gives a higher expected value for preferable choices, the optimal choice can be identified as the one that maximizes the expected value. The expected value associated with each choice can be calculated using an efficient algorithm developed by Shachter (1986).

4.2 Criteria for Evaluating Choices

The consequences of pipeline failure are represented by three parameters: the total cost c as a measure of the economic loss; the number of fatalities n as a measure of risk to life; and the residual spill volume v (*i.e.*, volume remaining after clean-up) as a measure of the long term environmental impact. The value node in Figure 2 is a function of these three parameters, defined in such a way as to ensure that preferred combinations of the three parameters are associated with higher values. Two distinct approaches for defining value are described below, one based on utility theory and the other based on cost optimization with life safety and/or environmental damage constraints.

Utility Function

Utility theory is a formalized approach that can be used to develop a value function that results in the selection of an optimal compromise between the different types of consequences (*i.e.*, life safety, environmental and economic). The theory can be used to define a utility function $u = u(c, n, v)$ which ranks different combinations of c, n, and v according to their perceived total impact. The optimal decision is the one that maximizes the expected utility (see Figure 3).

A value function based on utility theory has several advantages. To begin with, it allows for formal consideration of *tradeoffs* between different types of consequences. For example, it can be used to rank two options, one involving a low cost and a high expected degree of environmental damage and the other involving a higher cost and a lower expected degree of environmental damage. Secondly, utility theory can be used to quantify attitudes such as *risk aversion*. For example, the negative impact of one incident causing 100 fatalities is much more severe than the impact of 100 separate incidents, each causing one fatality. In addition, soft parameters such as public outrage can be incorporated (on a subjective basis). Overall it can be shown that utility theory is a powerful tool that can assist decision makers in identifying choices that are most consistent with their own preferences.

On the other hand, the process of defining a utility function involves explicit quantification of tradeoff values between cost and losses in life or environmental damage (*e.g.*, the cost equivalent to the loss of a human life). Decision makers may be reluctant to address these issues directly and companies may find them difficult to present to regulators and the public.

Constrained Cost Optimization

Constrained cost optimization assumes that life safety and environmental damage criteria are to be treated as constraints that are set by regulators or defined on the basis of precedent. Within these constraints, the solution that produces the least expected total cost is considered optimal. It is also possible to introduce a maintenance budget limitation as a constraint on the optimization process.

This approach is illustrated in Figure 4, which shows a typical risk vs. cost curve being optimized subject to a maximum allowable risk to life and a maximum maintenance budget. In Figure 4a, the optimal solution meets the life risk criterion and can be achieved within budget. In Figure 4b, the lowest cost solution does not meet the life risk criterion and therefore, the most economical option leading to adequate life safety should be selected. To account for environmental aspects, the same approach can be used with an environmental constraint defined as the total allowable spill volume per km of the pipeline.

The advantage of this approach is that tradeoffs between cost on the one hand and life safety and environmental protection on the other are not necessary. The operator demonstrates prudent risk management with respect to life and the environment by meeting recognized acceptable risk levels. For example, acceptable life safety risks have been proposed by various European government agencies such as the Health and Safety Executive in the United Kingdom (HSE 1989). The disadvantage of the constrained cost optimization approach is that the decisions reached may not be optimal from the operator's point of view. In particular, this may be the case for existing pipelines that require unrealistic expenditures to meet recognized life safety and/or environmental protection criteria.

Recommended Approach to Evaluating Choices

It should be recognized that for pipelines in unpopulated areas that are not environmentally sensitive, cost is the major consideration. In these cases, both the utility and constrained cost optimization approaches reduce to a simple cost minimization criterion. For pipeline segments where life safety and/or environmental damage issues are significant, it is believed that the concept of utility optimization provides the most suitable method of reaching consistent decisions. It is recognized however, that the constrained cost optimization approach may be more attractive to managers and regulators.

It is suggested that for a specific application, the constrained cost optimization approach should be attempted first and used if it provides an adequate solution. If this approach proves to be impractical, the utility approach should be adopted. It is expected that applying the utility approach will provide useful insights into the problem of consequence evaluation and that as its benefits are demonstrated, it will become more acceptable to decision-makers.

5.0 METHODOLOGY FOR RISK-BASED DECISION-MAKING

5.1 Overview of Methodology

The overall framework for risk-based optimization of pipeline integrity maintenance is illustrated in Figure 5. It begins by dividing the pipeline system into segments that have common attributes. Once this is done, the main components of the framework can be executed, namely: 1) *system prioritization* which means ranking different pipeline segments with respect to the need for integrity maintenance; and 2) *decision analysis* to assess available maintenance alternatives and determine the optimal choice for each targeted segment.

As indicated in Figure 5, the framework allows for using the information produced at the decision analysis stage to modify the system prioritization results. Initially, prioritization can be based on the risk level (*i.e.*, higher priority for segments with a higher risk level), or on the cost of risk reduction (*i.e.*, higher priority for segments that have a lower cost per unit risk reduction). At the prioritization stage, however, the cost of risk reduction can only be estimated on a subjective basis because the specific action that will be implemented to reduce risk is not known. After decision analysis of targeted segments, the optimal risk reduction choice for a given segment will be known and its cost defined, so that an accurate estimate of the cost of unit risk reduction can be obtained for each segment. This can then be used as a basis for revising the priority ranking of these segments for the purpose of risk reduction implementation.

Most of the analysis effort associated with the proposed methodology is directed at decision analysis and, to a somewhat lesser extent, system prioritization. More discussion of the work involved in these two areas is provided in Sub-Sections 5.2, 5.3 and 5.4.

5.2 System Prioritization

The prioritization process is described by the flow chart shown in Figure 6. The process consists of the following steps:

- **Estimate failure rates** by leak and rupture for each significant potential failure cause (*i.e.*, third party damage, ground movement, external and internal metal loss corrosion, stress corrosion cracking, weld cracking and other). For the prioritization process to be meaningful, the failure rate estimates must reflect the specific attributes of the line segment under investigation as much as possible. Publicly available data (*e.g.*, the data compiled by the NEB and the ERCB in Canada, and the DOT in the United States), company specific information and subjective judgment can be used for this purpose.
- **Assess failure consequences** for potential hazards (*i.e.*, jet fire, flash fire, pool fire, explosion, toxic cloud and liquid spill) by estimating their effect on the three consequence components (*i.e.*, life safety, environmental damage and financial cost) and combining the individual consequence components into a single measure of loss.
- **Estimate the risk** by summing the individual combined risk components associated with leak and rupture for each hazard type and each failure cause.

- **Define the cost of risk reduction** and the anticipated corresponding reduction in failure rate for each segment, and use this information to calculate the cost associated with a unit reduction. For example, this may require an estimate of the amount by which the failure rate due to corrosion can be reduced if a certain amount of money is spent on high-resolution in-line inspection.
- **Rank the segments** in order of decreasing risk level or increasing cost of unit risk reduction.

5.3 Decision Analysis

For the purpose of decision analysis, distinction must be made between: 1) inspection and maintenance strategies directed at preventing potential damage (*i.e.*, future mechanical damage); and 2) inspection and maintenance strategies directed at finding and repairing existing damage (*e.g.*, corrosion pits, crack-like defects and excessive longitudinal strain due to ground movement). Generic influence diagrams for the two cases are shown in Figures 7 and 8.

To simplify the presentation, the diagrams in Figures 7 and 8 use the concept of a generic compound node, which represents a group of parameters. For example, the node representing remaining damage extent in Figure 8 may contain a number of parameters representing the number, depth and length of corrosion features. For the influence diagram to be solvable, all compound nodes must be expanded to a set of individual nodes, each of which represent a single uncertain quantity. A full expansion of these nodes results in a very complex diagram. This does not present a serious problem since efficient algorithms are available to solve such diagrams.

Actions that reduce damage potential (case 1 and Figure 7) are assumed to be represented by a single decision (*e.g.*, to increase patrol frequency or implement a first call system). For actions that manage existing damage (case 2 and Figure 8), a series of decisions are considered: 1) the choice of inspection method; 2) the choice of a defect repair criterion; and 3) the time to next inspection. In this case the diagram shows the sequence in which the choices are made and the parameters that have an influence on the down-stream choices. It is noted that an arc into a decision node indicates that the outcome of the node from which the arc emanates will be known before the decision is made.

The diagrams in Figures 7 and 8 show that the value associated with a particular inspection and maintenance action is dependent upon the associated consequences, which are directly dependent on the choice of action (*i.e.*, the inspection and maintenance costs), as well as on the segment performance (*i.e.*, failure rate as it effects the hazard-related consequences). The segment performance is dependent on the damage extent (or damage potential) remaining after inspection and maintenance actions are taken, which in turn depends on the initial extent of damage (or damage potential), as well as on the choice of inspection and maintenance action.

Figures 7 and 8 are also influenced by the approach used for calculating segment performance (*i.e.*, the probability of failure). Figure 7 assumes that the segment failure probability is calculated directly from the remaining damage potential - an assumption that requires statistical data linking these two parameters, or the use of subjective probability assignments. Figure 8 reflects an analytical approach for calculating the probability of pipeline failure. This approach utilizes a deterministic failure prediction model and a probabilistic analysis that accounts for the effect on failure probability of uncertain quantities, such as pipeline damage extent (as determined from direct inspection or inferred from previous inspections), pipeline operating conditions and line pipe mechanical properties.

At the decision analysis stage, the influence diagram would be solved as discussed in Section 4.1, producing a set of choices that maximize the expected value.

5.4 Consequence Evaluation

Consequence evaluation is a necessary step for both system prioritization and decision analysis. This involves: modeling the release of product from the pipeline; determination of the likely hazard types (*e.g.*, jet/pool fires, vapour cloud fires, or explosions); estimation of the hazard intensity at different locations taking into account weather conditions; and finally calculation of the number of casualties, the extent of environmental damage and the overall cost. Because of the uncertainties associated with some of the parameters just mentioned, the consequences must be described by probability distributions. Evaluation of these distributions requires further expansion of the consequence node in Figures 8. The expanded diagram is shown in Figure 9, which provides a description of the process involved in evaluating failure consequences.

6.0 FRAMEWORK IMPLEMENTATION PLAN

Implementation of the proposed methodology for risk-based pipeline prioritization and integrity maintenance decision analysis requires the development of a number of probabilistic and deterministic models that make use of significant amounts of historical and pipeline-specific data:

1. The major probabilistic model components required include an influence diagram builder/solver and a model to calculate the probability distributions of random variables that are defined as functions of other random variables (*e.g.*, calculation of the probability distribution of the number of fatalities from the probability distributions of release rate, wind speed and failure location). The data required for the probabilistic modeling includes: a historical failure database; statistical descriptions of relevant pipeline attributes such as operating pressure, material properties and dimensions; as well as performance data for different inspection and failure prevention methods.
2. The deterministic components required include release hazard and consequence evaluation models, as well as models that predict failure based on pipeline attributes and inspection results. In addition, models are required to rank the environmental seriousness of product releases, to estimate the total cost associated with failure, and to combine life safety, environmental damage and economic aspects into a unified measure of consequences.

The required models and data have been assessed for availability and suitability for incorporation in the risk-based framework. The major conclusion of this assessment is that sufficient information is available, or likely to become available in the near future, to develop a risk-based decision analysis model.

This model is currently under development in a joint industry program sponsored by a number of transmission companies and government agencies (see acknowledgments). The development plan is shown in Figure 10, indicating completed, on-going and future developments. The program has already produced software products to build and solve an influence diagram, and to estimate and assess failure consequences for an onshore pipeline. Consequence modeling was addressed first because it is needed for all aspects of risk-based decision making. The consequence assessment program can be used to carry out a comprehensive quantitative risk assessment of any pipeline or pipeline segment, and can be used to optimize integrity maintenance activities if the user defines the impact of each choice on the failure probability.

Current program activities include the development of an offshore pipeline failure consequence model, a system prioritization module and a module for the optimization of corrosion maintenance activities. The program is being carefully planned to take full advantage of existing information to produce useful immediate outputs. New developments will be incorporated as they become available to expand the system into a complete integrity maintenance prioritization and decision analysis tool.

7.0 SUMMARY

A methodology has been developed for systematic, comprehensive and quantitative risk-based analysis, which forms the basis for system prioritization and integrity maintenance decision making. The methodology covers onshore and offshore pipelines transmitting natural gas or hydrocarbon liquids, including both High and Low Vapour Pressure products. It is applicable to individual pipeline segments with uniform attributes, or to a complete pipeline consisting of many segments with varying attributes.

The overall framework addresses all failure causes that have been identified as being potentially significant including: outside force (third party damage and ground movement); environmentally induced defects (mainly metal loss corrosion and stress corrosion cracking); and fabrication induced defects (specifically crack-like defects in welds). Failure hazards considered include: fires (*i.e.*, jet fire, pool fire and flash fire); explosions; toxic or asphyxiating clouds; and liquid spills (for LVP liquid lines only). The framework is also structured to provide for a comprehensive assessment of failure consequences by addressing: life safety, in terms of the number of fatalities; environmental impact, in terms of the residual spill volume; and economic aspects, in terms of the total cost of failure.

At the system prioritization stage, user-defined input of segment-specific attributes is processed to provide an estimate of the failure rate for individual segments as a function of failure cause, and an estimate of the potential consequences of line failure and the associated hazards in terms of the three consequence components (*i.e.*, number of casualties, environmental damage extent and financial cost). The cause-specific failure rates are then combined with a global measure of the loss potential associated with the different consequence components into a single measure of risk and used to rank segments according to the level of risk. An option is provided to rank segments according to the cost of risk reduction, if estimates of the possible reduction in risk and associated cost are available.

The decision analysis stage implements formal decision analysis theory using influence diagrams and an automated solution algorithm to determine the optimal set of decisions for a given set of integrity maintenance alternatives. The decision will be based on optimizing the expected value of a utility function, in which case the resulting set of decisions will be an optimal compromise between the three different types of consequences, or based on minimizing the expected cost subject to constraints on life safety risk and/or environmental damage risk.

In addition, the decision analysis program will refine the risk estimate made at the prioritization stage by calculating the incremental cost of risk reduction associated with the optimal integrity maintenance strategy for each segment. This refined ranking can form the basis for prioritizing the implementation of integrity maintenance activities.

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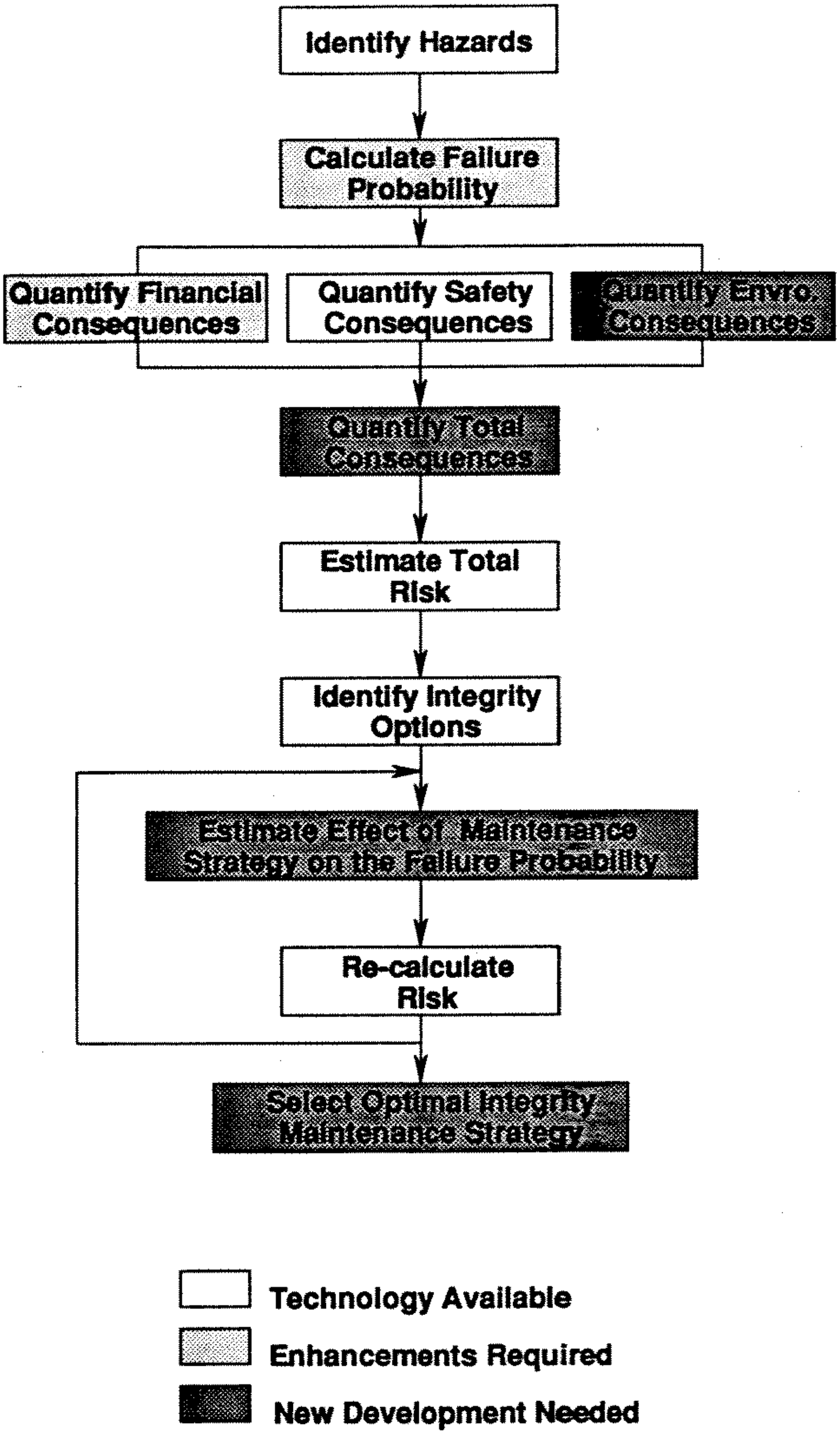
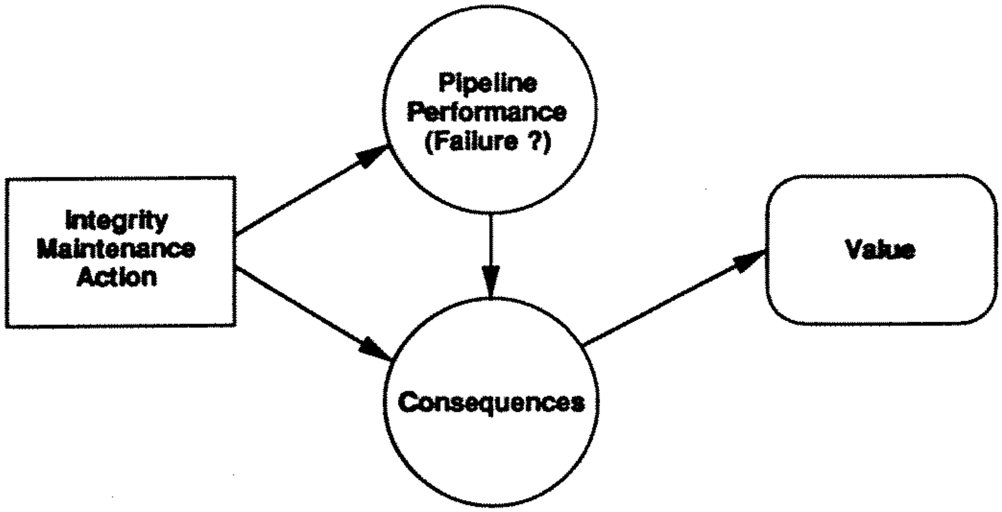


Figure 1 State-of -the-Art Assessment of the Technical Components of Risk-based Integrity Maintenance Optimization



☐ Decision node: Indicates a choice to be made
Example: Run a high or low resolution pig

○ Random variable node: Indicates uncertain parameter or event
Example: How will the pipeline perform in the next year ?
(safe, leak or rupture)

▢ Value node: Indicates the criterion used to evaluate consequences

→ Arrow: Indicates probabilistic dependence
Example: The final consequences depend on the costs associated with the maintenance action taken and the performance of the pipeline

The *Optimal Decision* is the one giving the highest expected value

Figure 2 Basic Framework for Integrity Maintenance Decision Making Using Influence Diagrams

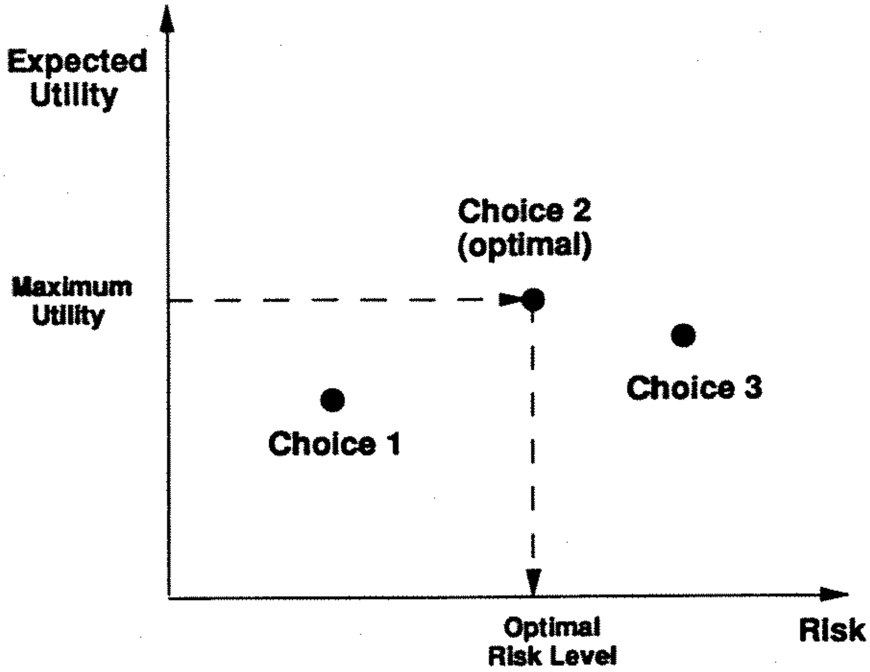
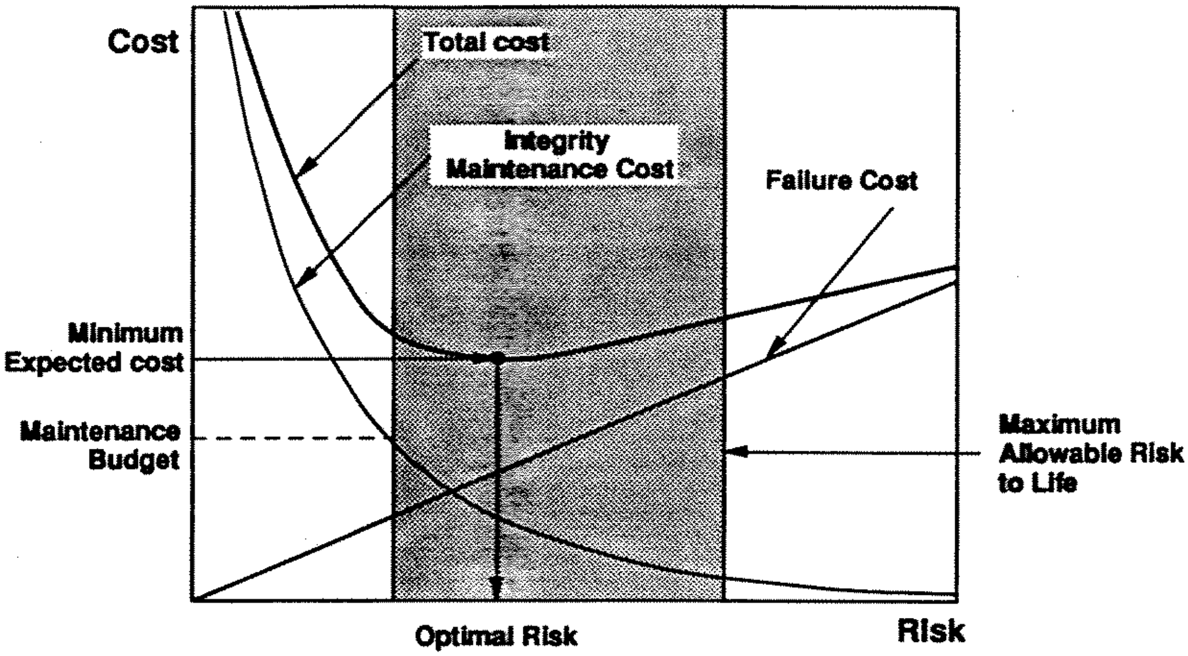
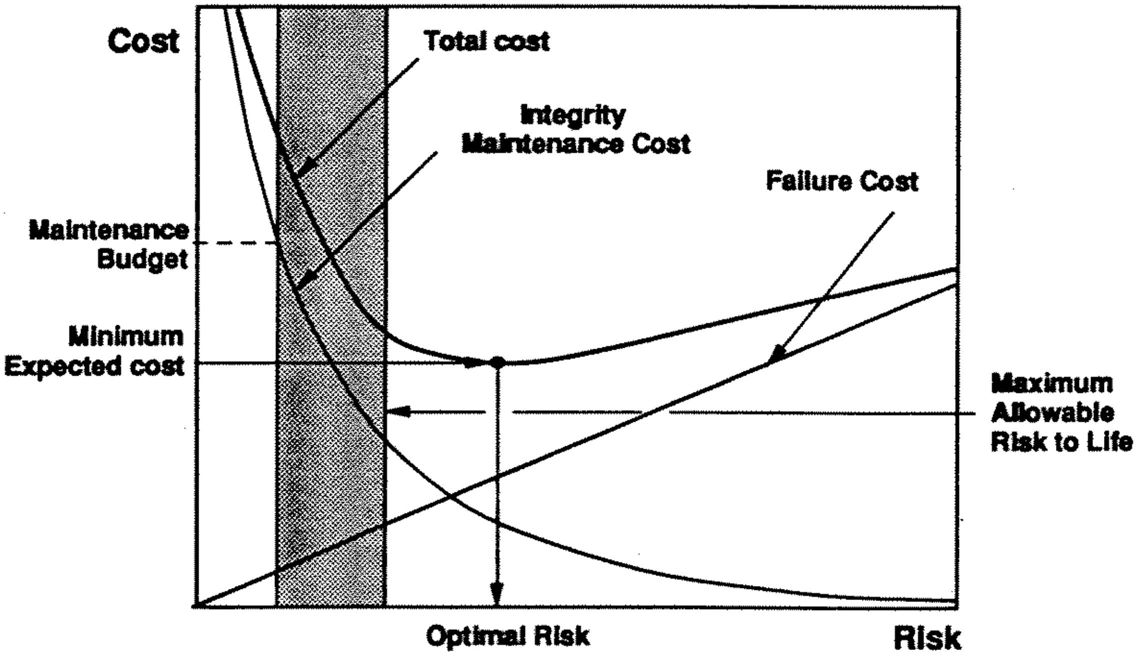


Figure 3 Illustration of the Utility Optimization Approach.



a) Optimal Solution Meets Cost and Life Risk Constraints
(Choose Optimal Solution)



b) Optimal Solution Does not Meet Life Risk Constraint
(Choose Maximum Allowable Risk to Life)

Figure 4 Illustration of the Constrained Cost Optimization Approach

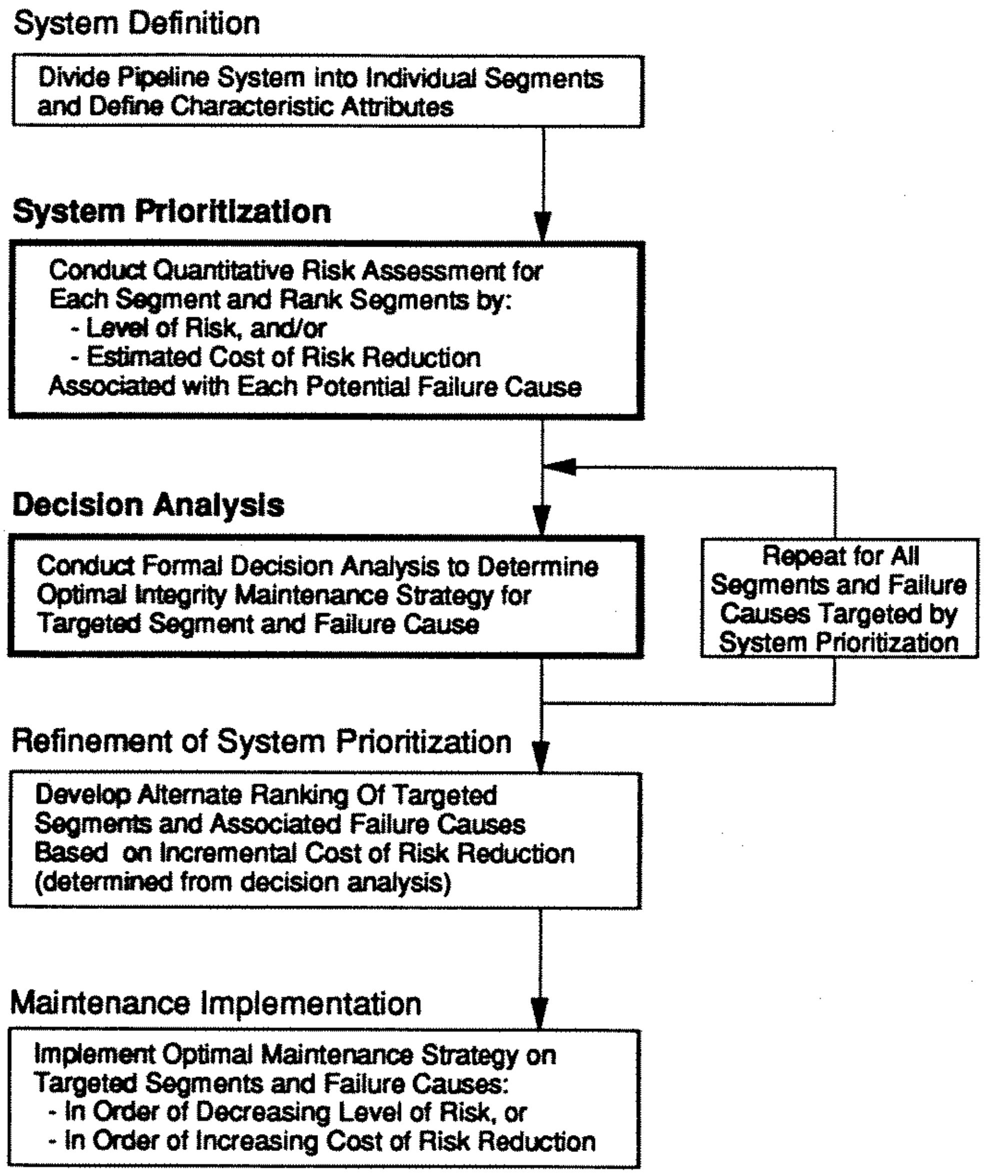


Figure 5 Framework for Risk-based Optimization of Pipeline Integrity Maintenance Activities

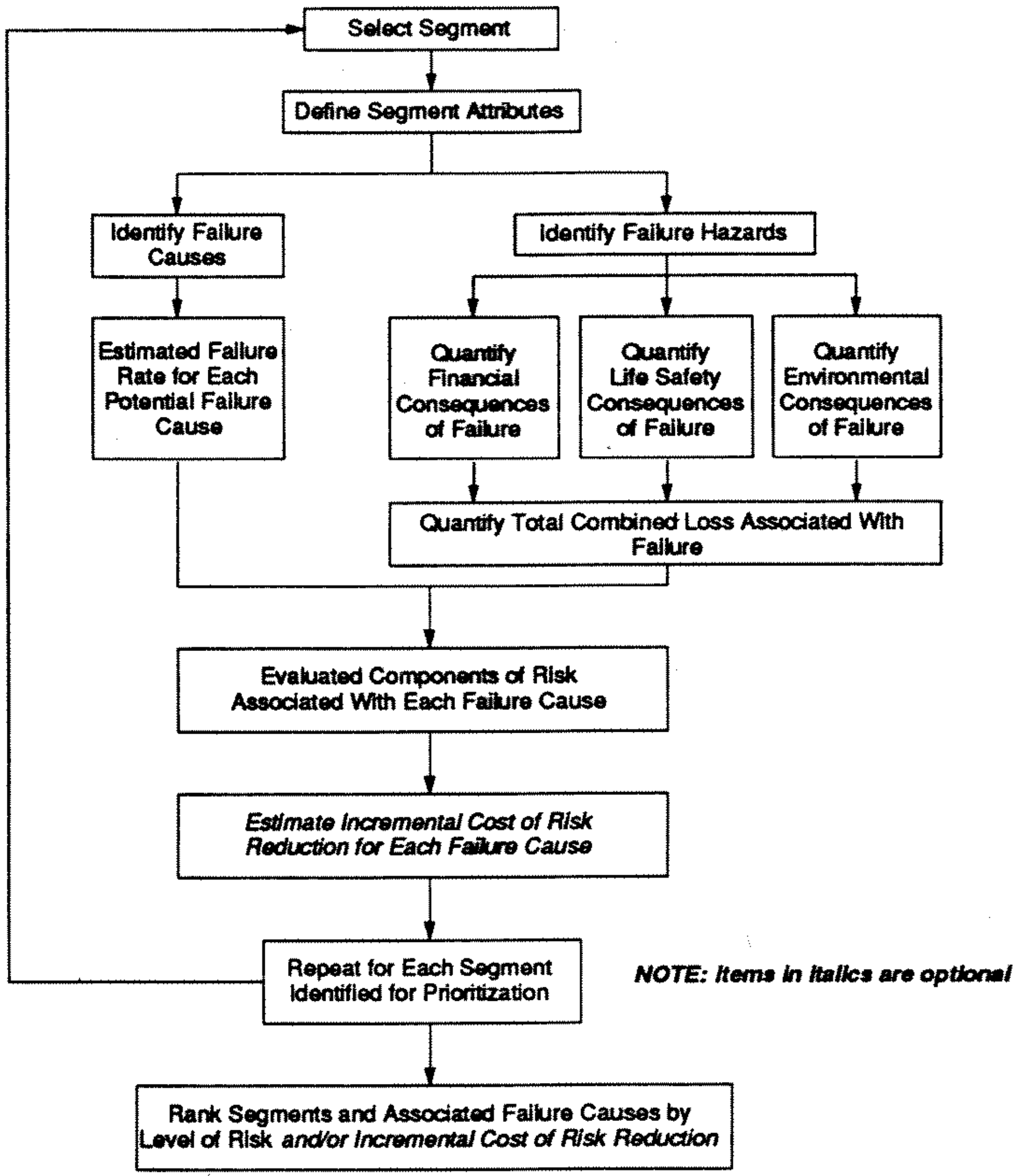


Figure 6 Flow Chart for Pipeline System Prioritization

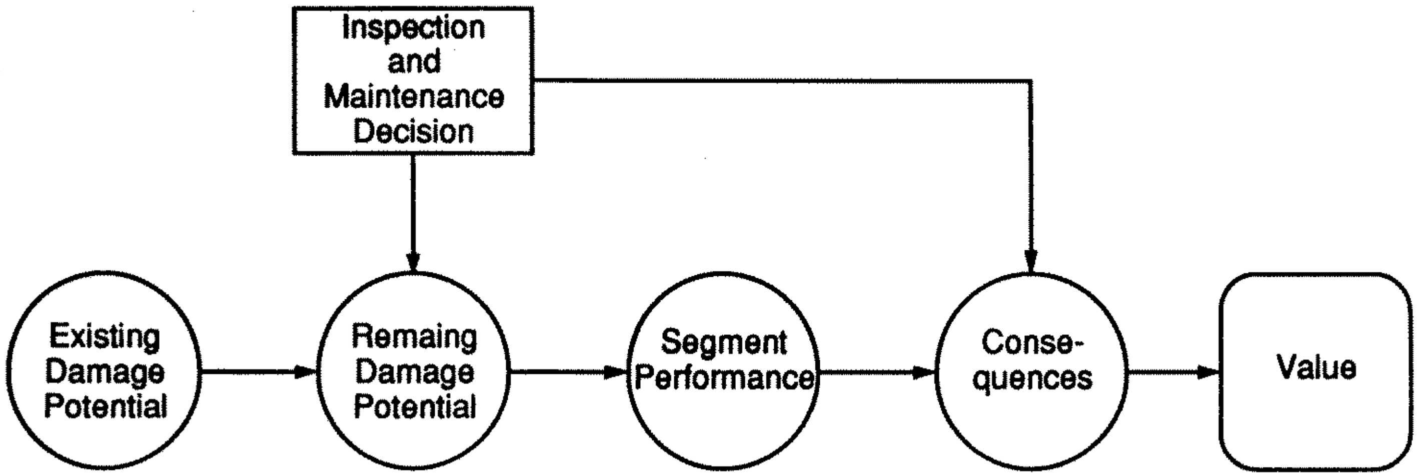


Figure 7 Conceptual Influence Diagram for Decision Analysis of Integrity Maintenance Strategies Directed Towards Reduction of Damage Potential

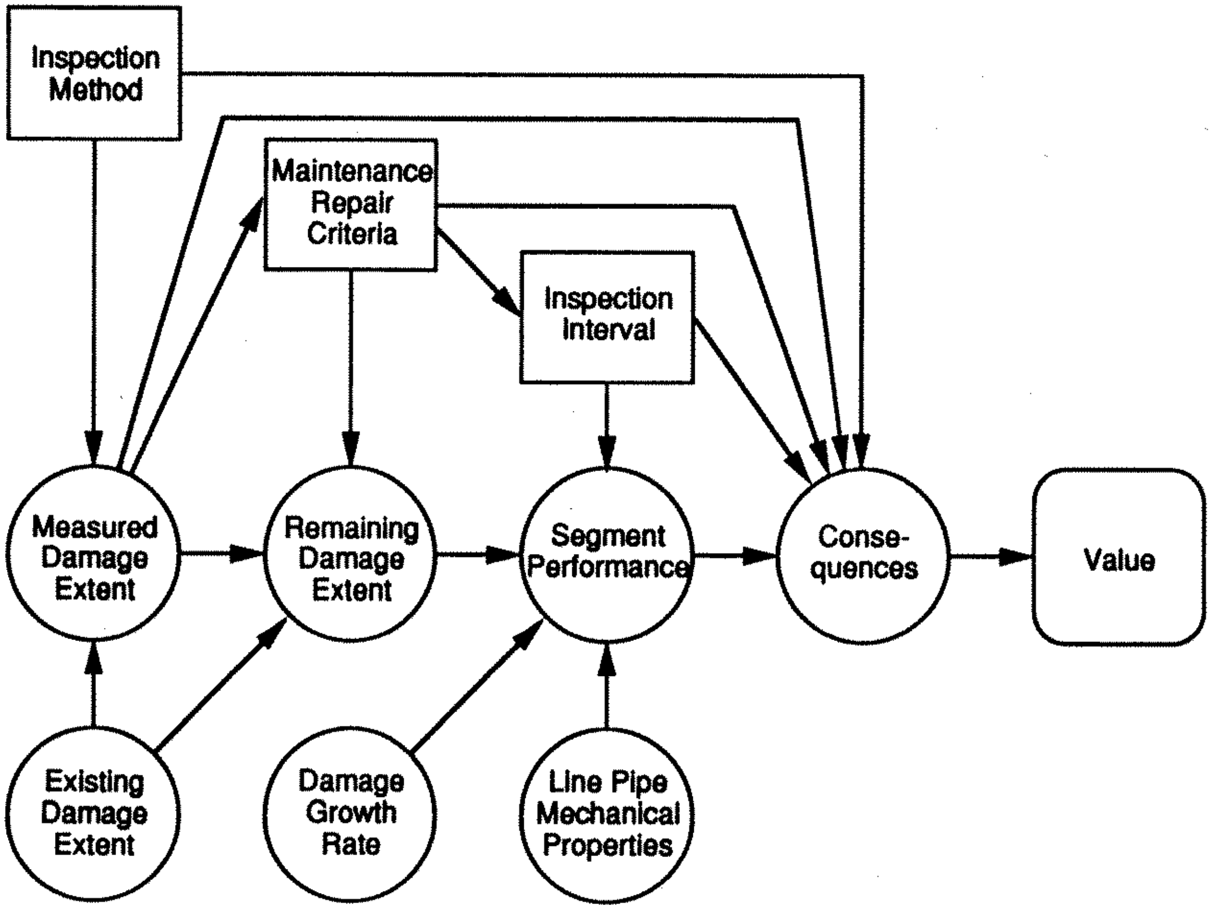


Figure 8 Conceptual Influence Diagram for Decision Analysis of Integrity Maintenance Strategies Directed Towards Reduction of Damage Extent

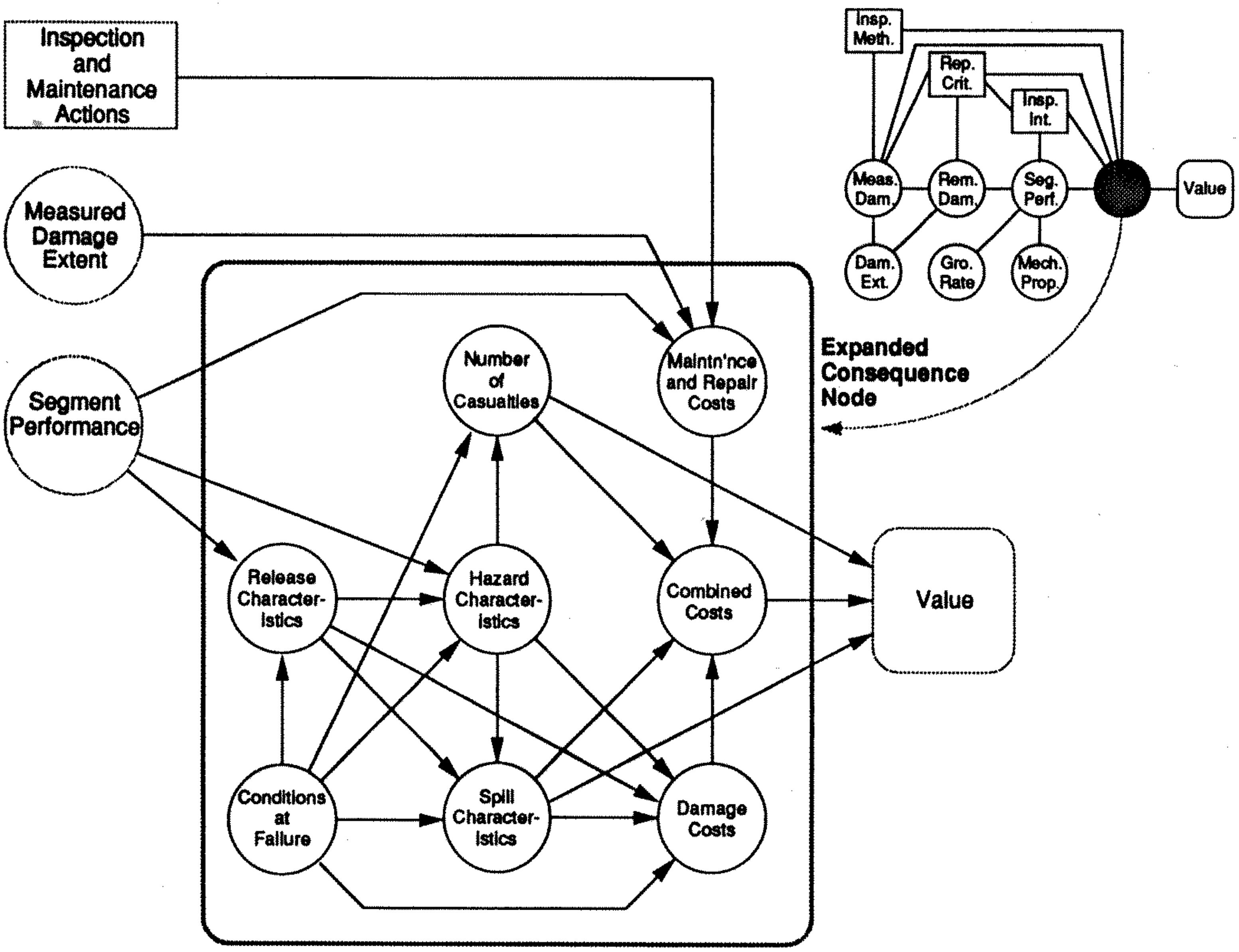


Figure 9 Expanded Influence Diagram for Consequence Assessment

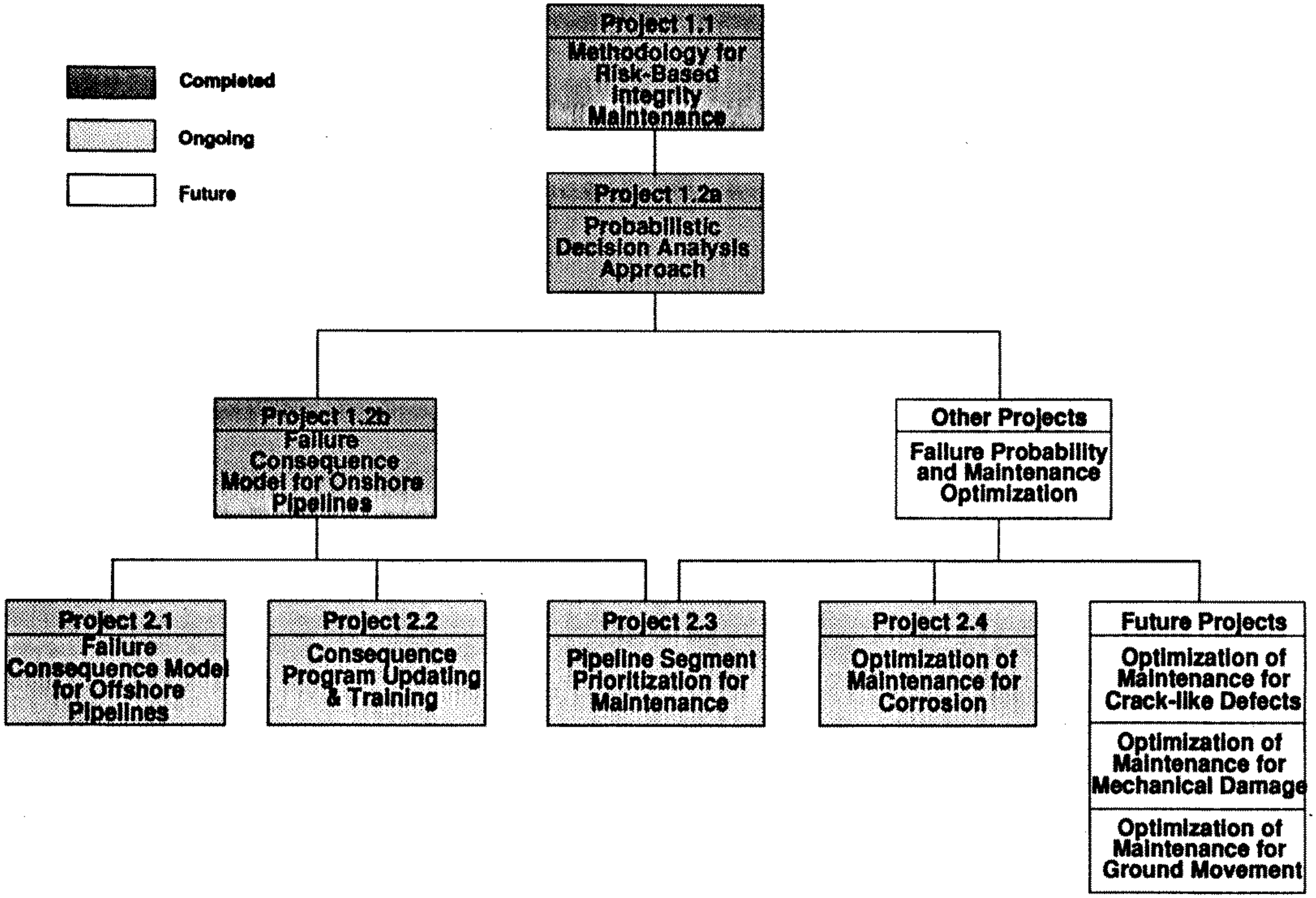


Figure 10 Summary of Risk-based Integrity Maintenance Approach Implementation Plan