CHAPTER

3a

CHAPMAN HALL/CRC

Risk Analysis in Engineering and Economics

SYSTEM DEFINITION AND STRUCTURE

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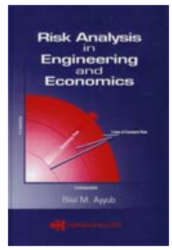

Risk Analysis for Engineering

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Introduction

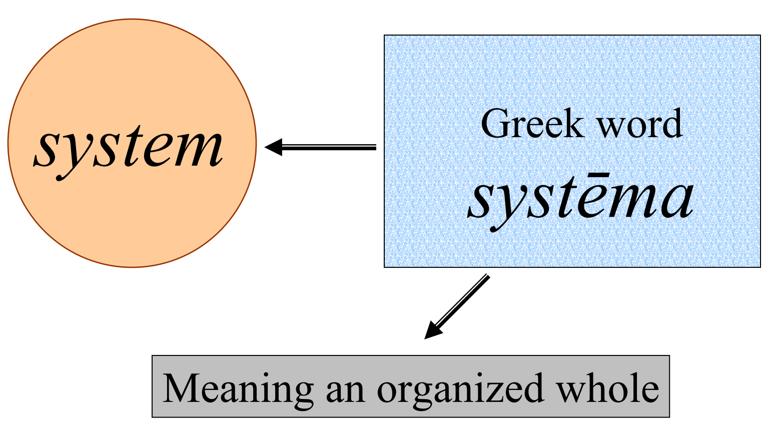
- Definition of the problem at hand is necessary for risk analysis.
- The definition and structuring of the problem requires skill.
- Risk must be assessed, analyzed, and managed within the system framework with the objective optimum utilization of available resources and for the purpose of maximizing the benefits.

Introduction

- Some Requirements for risk Analysis and Management:
  - The structure must be within a systems framework.
  - The approach must be systematic and must capture all critical aspects of the problem.
  - Uncertainties must be assessed and considered.
  - An optimization scheme of the utilization of available resources should be constructed.

System Definition Models

- Perspectives for System Definition



System Definition Models

- Perspectives for System Definition (cont'd)
  - According to the Webster's dictionary, a system is defined as "a regularly interacting or interdependent group of items forming a unified whole."
  - Also, it is defined as "a set or arrangement of things so related or connected as to form a unity or organic whole,".
  - Examples:
    - solar system
    - school system
    - system of highways

System Definition Models

- Perspectives for System Definition (cont'd)
  - ***System Science:*** is usually associated with observations, identification, description, experimental investigation, and theoretical modeling and explanations that are associated with natural phenomena in fields, such as biology, chemistry and physics.
  - ***System analysis:*** includes ongoing analytical processes of evaluating various alternatives in design and model construction by employing mathematical methods.

System Definition Models

- Perspectives for System Definition (cont'd)
  - Example of Mathematical Methods
    - Optimization
    - reliability assessment
    - Statistics
    - risk analysis
    - operations research
  - For ***scientists and engineers***, the definition of a system can be stated as "a regularly interacting or interdependent group of items forming a unified whole that has some attributes of interest."

System Definition Models

- Perspectives for System Definition (cont'd)
  - The discipline of systems engineering establishes the configuration and size of system
    - Hardware
    - Software
    - Facilities
    - Personnel

    through an interactive process of analysis and design in order to satisfy an operational mission for the system to perform in a cost-effective manner.

System Definition Models

- Perspectives for System Definition (cont'd)
  - Identification of needs by systems engineers

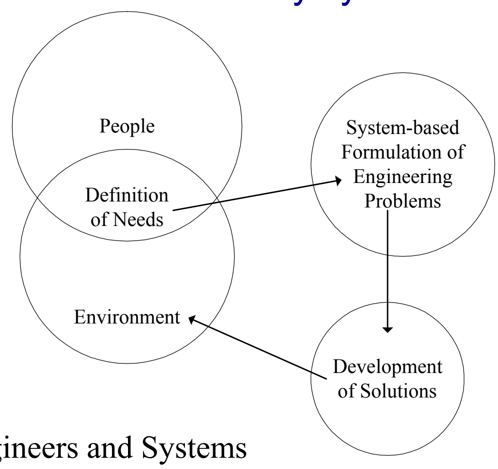


Figure 1. Engineers and Systems

System Definition Models

- Perspectives for System Definition (cont'd)
  - Systems can be grouped in various categories such as
    1. natural systems, such as river systems, and energy systems;
    2. human-made systems that can be imbedded in the natural systems, such as hydroelectric power systems and navigation systems;
    3. physical systems that are made of real components occupying space, such as, automobiles and computers;

System Definition Models

4. conceptual systems that could lead to physical systems;
5. static systems that are without any activity, such as, bridges subjected to dead loads;
6. dynamic systems, such as, transportation systems; and
7. closed or open-loop systems, such as, a chemical equilibrium process and logistic systems, respectively.

System Definition Models

- <u>Example 1:</u> Safety of Flood-Control Dams

Figure 2. Flooded Dam, Lacamas Lake Dam, Camas, WA, 1996

System Definition Models

- Example 1: Safety of Flood-Control Dams (cont'd)
  - The primary purposes of most flood-control dams are flood control and grade stabilization.
  - A secondary function is trapping sediment.
  - Flood-control dams are designed and constructed for a sufficient capacity to store runoffs from a ten- to hundred-year storm.

System Definition Models

- Example 1: Safety of Flood-Control Dams (cont'd)

Figure 3. Dam Failure, Centralia, WA, 1996

System Definition Models

- Example 1: Safety of Flood-Control Dams (cont'd)
  - The safety assessment of a dam requires defining a dam system to include
    1. The dam facility of structures, foundations, spillways, equipment, warning systems, and personnel,
    2. The upstream environment that can produce storms and floods, and
    3. The downstream environment that includes the potential sources of flood consequences.

System Definition Models

- Requirements Analysis and Work Breakdown Structure
  - Requirements Analysis
    - Requirements analysis can be defined as the detailed study of the system's performance requirements to ensure that the completed system achieves its intend utility to the customer and meets the goal stated.
    - According to this method, the customer's needs should be determined, evaluated for their completeness, and translated into quantifiable, verifiable, and documented performance requirements.

System Definition Models

- Requirements Analysis and Work Breakdown Structure (cont'd)
  - Requirements Analysis (cont'd)
    - Requirements analysis feeds directly into functional analysis, and allocation, design and synthesis.
    - A system model can be developed through requirement and functional modeling.
    - For example, dams can be modeled as systems with functional and performance requirements in an environment that has natural and human-made hazards.

System Definition Models

- Requirements Analysis and Work Breakdown Structure (cont'd)
  - Requirements Analysis (cont'd)
    - Limiting the model to only the physical system of a dam is shown in Fig. 4.
    - The functional requirements of a dam are used to develop a system breakdown.
    - The system breakdown structure is the top-down hierarchical division of the dam into its subsystems and components, including *people*, *structure*, *foundation*, *floodplain*, the *river* and its tributaries, *procedures*, and *equipment*.

System Definition Models

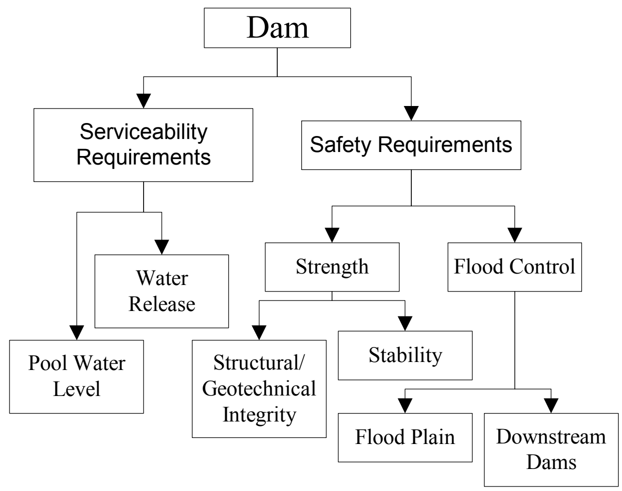


Figure 4. Functional Requirements for a Dam

System Definition Models

- Requirements Analysis and Work Breakdown Structure (cont'd)
  - Requirements Analysis (cont'd)
    - Functional analysis examines the characteristic actions of hardware, software, facilities, or personnel that are needed for the system in order to satisfy performance requirements of the system.
    - Functional analysis might establish additional requirements on all supporting elements of the system by examining their detailed operations and interactions.

System Definition Models

- Requirements Analysis and Work Breakdown Structure (cont'd)
  - Requirements Analysis (cont'd)
    - Physical requirements define the system's physical nature, such as mass, volume, power, throughput, memory, and momentum.
    - They may also include details down to type and color of paint, location of the ground segment equipment, and specific environmental protection.

System Definition Models

- Requirements Analysis and Work Breakdown Structure (cont'd)
  - Requirements Analysis (cont'd)
    - Functional requirements can be loosely assembled into hierarchy of functional, sequential, communicational, procedural, temporal, and logical attributes as follows:
      - Functional requirements with subfunctions that contribute directly to performing a single function.
      - Sequential breakdowns that show data flow processed sequentially from input to output.
      - Communicational breakdown based on information and data needs.

System Definition Models

- Procedural breakdowns based on logic flow paths.
- Temporal breakdowns for differing functions at different times.
- Logical breakdowns based on developing logical flows for functions.

• Many programs develop multiple functional hierarchies using more than one of these criteria to sort and decompose the functions.

• Each criterion provides a different way of looking at the information.

• The most common functional hierarchy is a decomposition based on functional grouping.

System Definition Models

■ Requirements Analysis and Work Breakdown Structure (cont'd)

– Work Breakdown Structure

• The work breakdown structure is a physical-oriented family tree composed of
  - Hardware
  - Software
  - Services
  - Processes
  - Data that result from engineering efforts during the design and development of a system.

System Definition Models

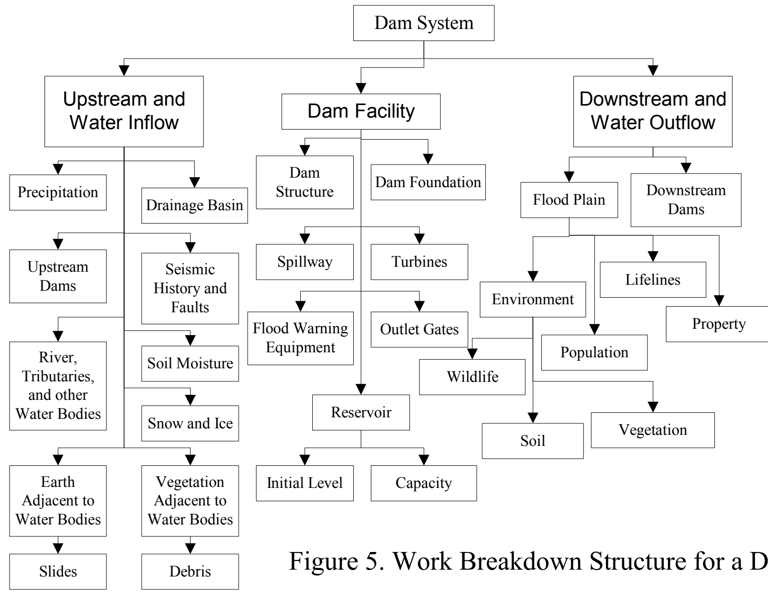


Figure 5. Work Breakdown Structure for a Dam

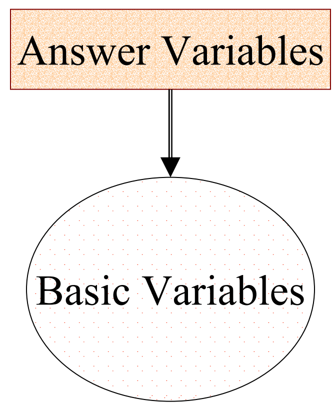
System Definition Models

- Contributing Factor Diagrams
  - The contributing factor diagrams are used to identify variables and their dependencies that can be used to analytically evaluate quantities, called ***answer variables***, selected by a risk analyst to define a risk problem.
  - A contributing factor diagram consists of variables graphically enclosed in
    - Ovals
    - Circles
    - Rectangles

    connected by directed arrows.

System Definition Models

- Contributing Factor Diagrams (cont'd)
  – Construction of a Contributing Factor Diagram



System Definition Models

- Contributing Factor Diagrams (cont'd)

Construction of a Contributing Factor Diagram:

1. Identify and select answer variables in consultation with stakeholders and specialists in various areas. Commonly, economic answer variables are selected such as the net present value (NPV) or internal rate of return defined in a subsequent section. This step can be difficult resulting in to several answer variables. These variables should be placed at the center of the diagram in oval shapes.

System Definition Models

Construction of a Contributing Factor Diagram (cont'd):

2. Select the units of measurement for the answer variables, such as dollars per year, or tons per year.
3. Identify and select primary contributing variables to the answers variables. For example income and cost variables can be used with directed arrows feeding from them to the answer variable(s). For each variable, the units of measurement should be identified. Quantitative models are needed to express the dependencies among the variables.

System Definition Models

Construction of a Contributing Factor Diagram (cont'd):

4. Define lower level variables that feed into previously defined variables and their units.
5. Repeat step 4 until sufficient refinement is established as needed for data collection or as defined by data availability.

These steps are presented in general terms to permit their use to solve various problems

System Definition Models

- Example 2: Replacement of a Highway Bridge
  - This bridge replacement need might result from structural (i.e., strength) or functional deficiencies.
  - This decision situation requires the development of an economic model to assess the annual benefit to replace an existing bridge with a new one.

System Definition Models

- Example 2: Replacement of a Highway Bridge (cont'd)
  - Figure 6 provides a contributing factor diagram for such a decision situation.
  - The answer variable in this case was identified as the average annual benefit of replacing the bridge in dollars per year.
  - This variable was placed in the middle of the figure, and was used as the starting point to develop this figure.

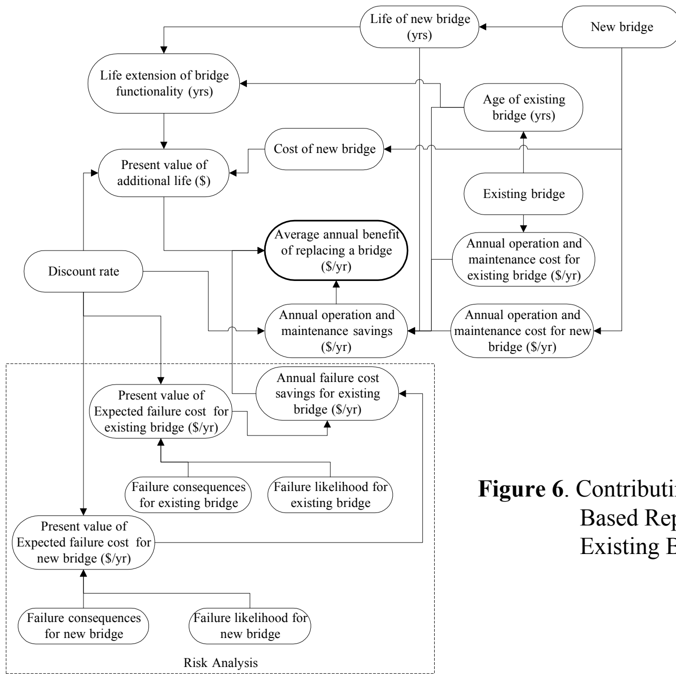


Figure 6. Contributing Factors for Risk-Based Replacement of an Existing Bridge

System Definition Models

- <u>Example 2:</u> Replacement of a Highway Bridge (cont'd)

  Three primary computational tracks are required:

  1. the annual benefit generated by an extended bridge functionality beyond the age of an existing bridge with an added life provided by a new bridge;
  2. annual benefit of reduced operation and maintenance cost; and
  3. annual benefit of reduced expected failure cost.

System Definition Models

- Decision Trees and Influence Diagrams
  - **Decision Trees**
    - One graphical tool for performing an organized decision analysis is a decision tree.
    - A decision tree is constructed by showing the alternatives for decision-making and associated uncertainties.
    - The result of choosing one of the alternative paths in the decision tree is the consequences of the decision.

System Definition Models

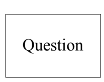
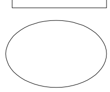
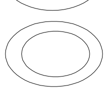
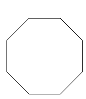
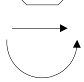
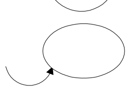
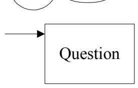
- Decision Trees and Influence Diagrams
  - The construction of a decision model requires the definition of
    - objectives of decision analysis,
    - decision variables,
    - decision outcomes, and
    - associated probabilities and consequences.
  - The boundaries for the problem can be determined from first understanding the objectives of the decision-making process and using them to define the system.

System Definition Models

- Decision Trees and Influence Diagrams
  - Decision Variables
    - The decision variables for the decision model need to be defined.
    - Ranges of values that can be taken by the decision variables should be defined.
    - Example: Mechanical or Structural Components
      - what and when to inspect components or equipment.
      - which inspection methods to use, assessing the significance of detected damage.
      - repair/replace decisions.

System Definition Models

Figure 7. Symbols for Influence Diagrams and Decision Trees

Symbol	Definition
	Decision Node: indicates where a decision must be made.
	Chance Node: represents a probabilistic or random variable.
	Deterministic Node: determined from the inputs from other nodes.
	Value Node: defines consequences over the attributes measuring performance.
	Arrow/Arc: denotes influence among nodes.
	Indicates probabilistic dependence upon the decision or uncertainty of the previous node.
	Indicates time sequencing (information that must be known prior to a decision).

System Definition Models

- Decision Trees and Influence Diagrams
  - **Decision Outcomes**
    - The decision outcomes are the events that can happen as a result of a decision.
    - They are random in nature, and their occurrence cannot be fully controlled by the decision maker.
    - Decision outcomes can include:
      - the outcomes of an inspection (detection or non-detection of a damage), and
      - the outcomes of a repair (satisfactory or non-satisfactory repair).

System Definition Models

- Decision Trees and Influence Diagrams
  - Decision Outcomes (cont'd)
    - Therefore, the decision outcomes with the associated occurrence probabilities need to be defined.
    - The decision outcomes can occur after making a decision at points within the decision-making process called chance nodes.
    - The chance nodes are identified in the model using a circle as shown in Figure 7.

System Definition Models

- Decision Trees and Influence Diagrams
  - **Associated Probabilities and Consequences**
    - The decision outcomes take values that can have associated probabilities and consequences.
    - The probabilities are needed due to the random (chance) nature of these outcomes.
    - The consequences can include, for example, the cost of failure due to damage that was not detected by an inspection method.

System Definition Models

- Decision Trees and Influence Diagrams
  - **Tree Construction**
    - The decision tree includes the decision and chance nodes.
    - The decision nodes, that are represented by squares in a decision tree, are followed by possible actions (or alternatives, A_i) that can be selected by a decision maker.
    - The chance nodes, that are represented by circles in a decision tree, are followed by outcomes that can occur without the complete control of the decision maker.

System Definition Models

- Decision Trees and Influence Diagrams
  - Tree Construction (cont'd)
    - Outcomes have both *probabilities* (*P*) and *consequences* (*C*).
    - Here the consequence can be cost.
    - Each tree segment followed from the beginning (left end) of the tree to the end (right end) of the tree is called a branch.
    - Each branch represents a possible scenario of decisions and possible outcomes.
    - The total expected consequence (cost) for each branch could be computed.

System Definition Models

- Then the most suitable decisions can be selected to obtain the minimum cost.
- In general, utility values can be used and maximized instead of cost values. Also, decisions can be based on risk profiles by considering both the total expected utility value and the standard deviation of the utility value for each alternative.
- The standard deviation can be critical for decision-making as it provides a measure of uncertainty in utility values of alternatives.
- Influence diagrams can be constructed to model dependencies among decision variables, outcomes, and system states using the same symbols of Figure 7.

System Definition Models

- Example 3: Decision Analysis for Selecting an Inspection Strategy

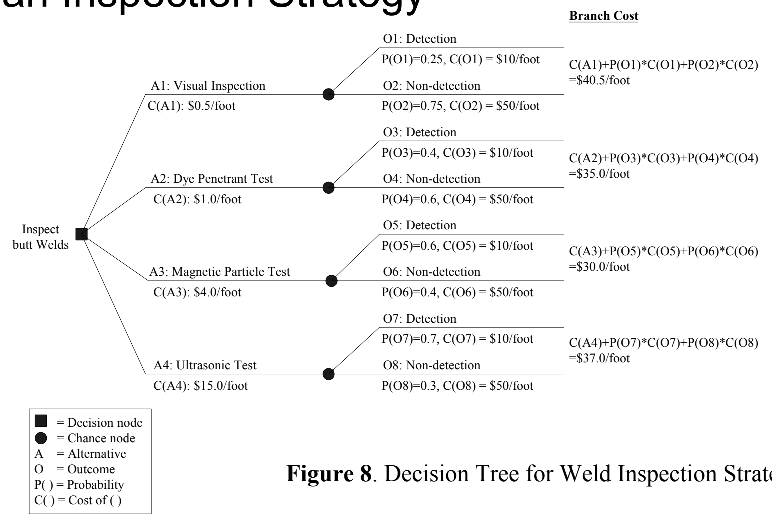


Figure 8. Decision Tree for Weld Inspection Strategy

System Definition Models

- Example 4: Decision Analysis for Selection of a Personal Flotation Devise Type

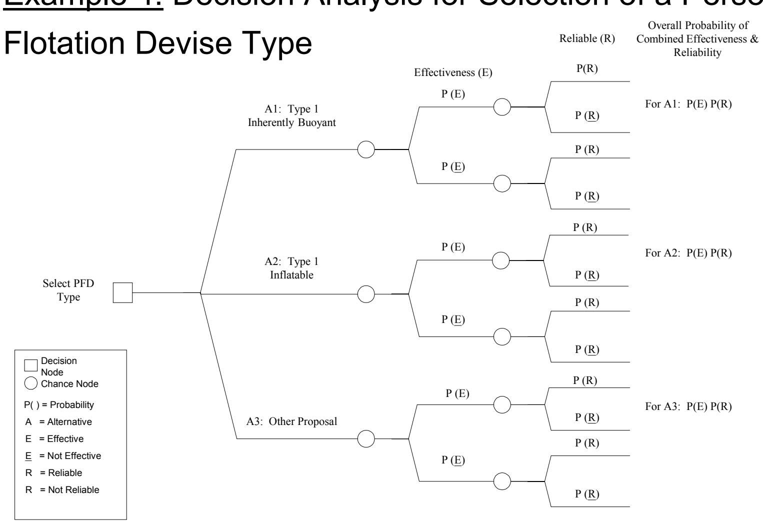


Figure 9. Selecting a Personal Flotation Devise (PFD)
Based on Effectiveness and Reliability

System Definition Models

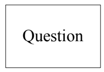
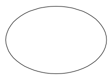
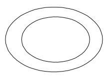
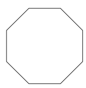
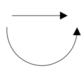
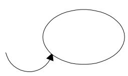
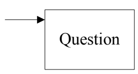
- Decision Trees and Influence Diagrams
  - **Influence Diagrams**
    - An influence diagram is a graphical tool that shows the dependence relationships among the decision elements of a system.
    - Influence diagrams are of similar objectives to contributing factor diagrams, but with more details.
    - Influence diagrams provide compact representations of large decision problems by focusing on dependencies among various decision variables.

System Definition Models

- Decision Trees and Influence Diagrams
  - Influence Diagrams
    - Influence diagrams consist of
      - decision nodes,
      - chance nodes,
      - outcomes, and
      - directed arrows indicating dependencies.
    - Symbols used for creating influence diagrams are shown in Figure 7
    - The fist ***rectangular*** shape in the figure is used to identify a decision node that indicates where a decision must be made.

System Definition Models

Figure 7. Symbols for Influence Diagrams and Decision Trees

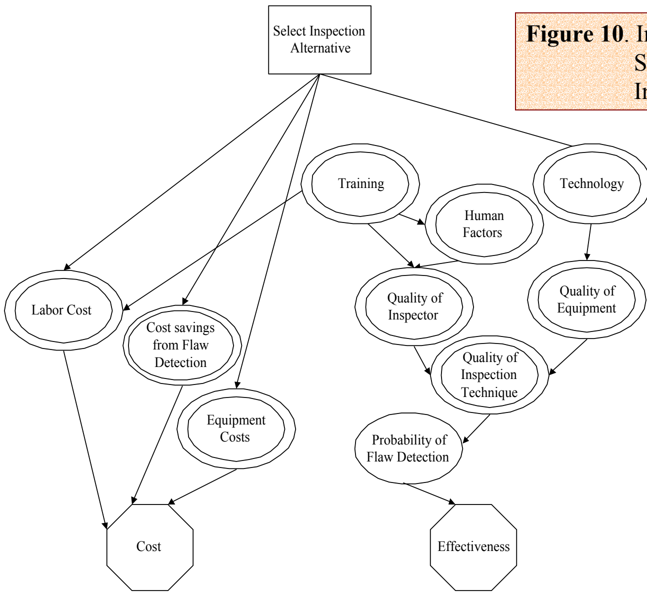
Symbol	Definition
	Decision Node: indicates where a decision must be made.
	Chance Node: represents a probabilistic or random variable.
	Deterministic Node: determined from the inputs from other nodes.
	Value Node: defines consequences over the attributes measuring performance.
	Arrow/Arc: denotes influence among nodes.
	Indicates probabilistic dependence upon the decision or uncertainty of the previous node.
	Indicates time sequencing (information that must be known prior to a decision).

System Definition Models

- A ***circular*** or elliptical shape is used to identify a chance node representing a probabilistic random variable with uncertain outcomes.
- The ***double circles*** or ellipses are used to identify a deterministic node with a quantity in it that is determined from the inputs from other nodes.
- The ***pentagon*** shape is called a value node and is used to defines consequences over the attributes measuring performance.
- The next two symbols showing ***arrows*** or ***arcs*** that are used to represent influence or dependency among nodes.
- The last ***rectangular*** shape is used top indicate time sequencing, i.e., information that must be known prior to a decision

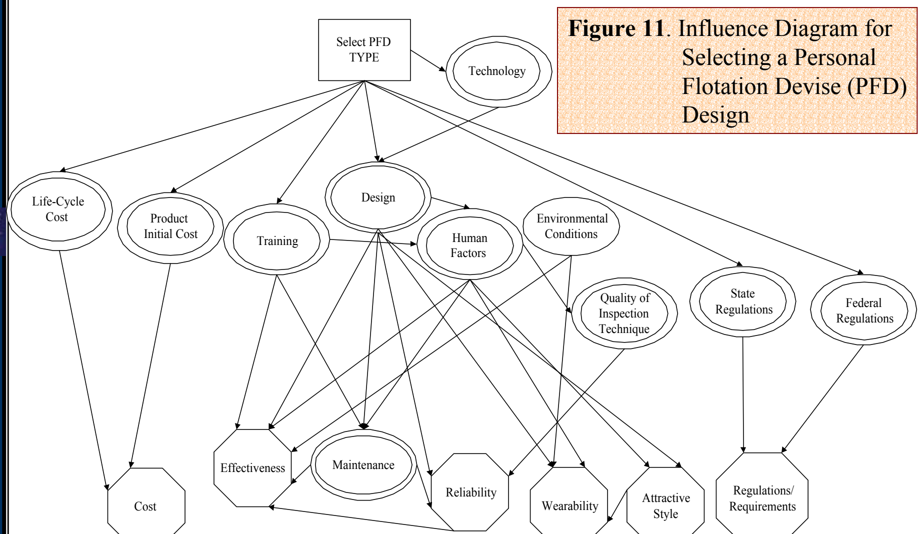
System Definition Models

Figure 10. Influence Diagram for Selection of Weld Inspection Strategy



System Definition Models

Figure 11. Influence Diagram for Selecting a Personal Flotation Devise (PFD) Design



System Definition Models

- Bayesian Networks
  - Bayesian networks constitute a class of probabilistic models for modeling logic and dependency among variables representing a system.
  - A Bayesian network consists of the following:
    1. a set of variables,
    2. a graphical structure connecting the variables, and
    3. a set of conditional distributions

System Definition Models

- Bayesian Networks (cont'd)
  - A Bayesian network is commonly represented as a graph, which is a set of nodes and arcs.
  - The nodes represent the variables, and the arcs represent the conditional dependencies in the model.
  - The absence of an arc between two variables indicates conditional independence; that is, there are no situations in which the probabilities of one of the variables depends directly upon the state of the other.

System Definition Models

- Bayesian Networks (cont'd)
  - Variables
    - A variable can be viewed as a mapping from the space of possible outcomes to discrete numerical values or continuous ranges of real values.
    - Probability models can be used to assign likelihood values to these outcomes.
    - **Example:** in medical experiment, relevant variables for men and women would be the sex, age, and experimental results. Sex can be male or female, while age can take on many values.

System Definition Models

- Bayesian Networks (cont'd)
  - Relationship in a Bayesian Model
    - The use of commonsense and real-world knowledge is permitted in Bayesian models.
    - **Example:** A model builder would likely to know that the time of day would not normally directly influence an oil leak in a car. Other direct factors such as temperature, and driving conditions would influence the leak.
    - Meaningless relationships are not explicitly declared in a Bayesian model and are exluded.

System Definition Models

- Bayesian Networks (cont'd)
  - Relationship in a Bayesian Model (cont'd)
    - After establishing all the variables in a model, variables that cause changes in the system should deliberately be associated with those variables that they influence.
    - Only these specified influences are considered and are represented by conditioning arcs between nodes.
    - Each arc should represent a causal relationship between a temporal antecedent (known as the *parent*) and its later outcome (known as the *child*).

System Definition Models

- Bayesian Networks (cont'd)
  - Inference
    - **Inference**, also called *model evaluation*, is the process of updating probabilities of outcomes based upon the relationships in the model and the evidence known about the situation at hand.
    - The model is exercised by clamping a variable to a state that is consistent with an observation, and the mathematical mechanics are performed to update the probabilities of all the other variables that are connected with variables representing the new evidence.

System Definition Models

- Bayesian Networks (cont'd)
  - Inference (cont'd)
    - After an inference evaluation, the updated probabilities reflect the new levels of belief in (or probabilities of) all possible outcomes coded in the model.
    - These beliefs are mediated by the original assessment of belief performed by the analyst.
      - ***Prior probabilities*** are the beliefs encoded in the model. They are entered before any evidence is known about the situation.
      - ***Posterior probabilities*** are the beliefs computed after evidence is entered. The reflect the levels of belief computed in light of the new evidence.