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Development of a Hierarchical, Model-Based Design Decision-Support Tool for Assessing Uncertainty of Cost Estimates

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DEVELOPMENT OF A HIERARCHICAL, MODEL-BASED DESIGN DECISION-SUPPORT TOOL FOR ASSESSING UNCERTAINTY OF COST ESTIMATES

By

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DEVELOPMENT OF A HIERARCHICAL, MODEL-BASED DESIGN DECISION-

SUPPORT TOOL FOR ASSESSING UNCERTAINTY

OF COST ESTIMATES

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In order to identify ways to improve cost estimation, especially early in design, cost estimation needs to be viewed and represented as a process. An important activity within the cost estimation process is assessing the cost risk of a system. A decision-support tool that assesses cost risk should represent the impact of subsystem or system-level uncertainty and provide mechanisms to help select among competing designs.

In order to address these problems, a generic cost estimation process was developed. It is based on an extensive review of the cost estimation literature. Also, a hierarchicial product structure, model-based approach and tool to estimate system-level cost risk was developed. This tool provides a link between cost models and cost elements for each component, mechanisms for determining the impact of risk on the cost of the design, and outputs used for selecting among alternative competing designs.

DEDICATION

I would like to dedicate this research to my loving and supportive family.

ACKNOWLEDGMENTS

I would like to thank God for giving me the knowledge and strength for obtaining my graduate degree. I would also like to thank my family for supporting me throughout my education. Finally, I would like to thank Dr. Greenwood and the Department of Industrial Engineering for providing me with an excellent education.

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INTRODUCTION

Critical design decisions are currently being addressed earlier in the system development life cycle. Design alternatives are evaluated by conducting rigorous trade studies that involve the consideration of different operating scenarios, disparate criteria, and a variety of uncertain design parameters. Today's business environment is constantly growing more cost competitive due to increasing globalization. In this environment, performance and cost are both being emphasized as criteria for selecting among design alternatives.

Although cost estimation has been an enduring discipline, there have been no known attempts to develop a comprehensive generic cost estimation process. Organizations that lack a standard cost estimation process could potentially leave out crucial steps for making reliable estimates. Also, without a documented process, the task of constructing the estimate would require more time for new engineers.

Although industry has utilized cost estimation to lower design costs, the government has used cost estimation for centuries. Cost estimation has played a major role in military design since the first major United States weapon system procurement in 1794 for six frigates [4]. In today's political environment, Department of Defense budgets have been cut dramatically. The armed forces are charged with the daunting task of designing state-of-the art systems at minimum costs. To meet these requirements, each branch of the military has developed specific procedures for conducting a cost analysis. Although these cost estimation procedures have been well documented, there have been few attempts to generate a generic cost estimation process. This process could be used as a starting point for organizations and cost engineers to develop their own cost estimating processes.

Since trade studies are conducted early in design, the cost analyst typically lacks key portions of project- or component-level information that creates uncertainty in the cost estimates. Examples of key component-level information are material, component configuration, and failure rate. The degree of uncertainty could change the choice among alternatives (i.e. a more "robust" design in terms of cost may be preferred over a design with a lower expected cost but more uncertainty). This problem has prompted research in the areas of uncertainty and risk assessment of cost estimates.

1.1 Definition of Cost Estimation

Cost estimation has been classified as both a science and an art. Even though there are several mathematical tools for achieving an estimate, the analyst still has to possess the creative skill of choosing which tools and methodologies to utilize. Typically, few individuals are aware of exactly what the cost estimation process is and what it is used for in the design process. The U.S. Army [5] defines the cost estimating process as:

1) The act of developing, analyzing, and documenting cost estimates using analytical approaches and techniques.

2) The process of analyzing and estimating incremental and total resources required to support past, present, and future forces, units, systems, functions, and equipment. It is an integral step in the selection between alternatives by the decision maker.
3) A management tool used to help decision-makers evaluate resource requirements at key management milestones and decision points in the acquisition process.

The American Association of Cost Engineers [2] defines cost estimation as:

"The determination of quantity and the predicting or forecasting, within a defined scope, of the costs required to construct and equip a facility, to manufacture goods, or to furnish a service. Costs are determined utilizing past experience and calculating and forecasting the future cost of resources, methods, and management within a scheduled time frame. Included in these costs are assessments and evaluation of risks and uncertainties. Cost estimation provides the basis for project management, business planning, budget preparation, and cost and schedule control."

Creese and Pabla [2] provide the following reasons for developing cost estimates:

1. Indicates to the manufacturer whether the project under consideration is economical.
2. Enables a manufacturer to choose from various alternatives of production the one that is likely to be most economical.
3. Enables the manufacturer to fix a selling price in advance of actual production.
4. Enables manufacturer to decide whether to buy or to manufacture the product, and at what price to buy.

5. Enables management to plan for procurement of tools and raw materials.
6. Enables manufacturer to set standards for production to be achieved in actual practice.
7. Helps management plan what type of equipment is needed, what labor requirements are, and what the capital requirements are.

In today's military design environment, cost estimation is used as a major indicator for choosing between competitive designs. Cost estimation can also be used to make major high-level decisions concerning programs. In the military, there are several competing programs that will address certain needs of the government. The overall cost of the program is one of the most significant factors for determining which programs are implemented.

1.2 Relationship Between Cost Estimation and Design

Currently the military has defined the design process using a systems approach. This is usually described as the systems development life cycle (SDLC). There have been several adaptations of the SDLC. Blanchard and Fabrycky [1] developed the SDLC representation used in this research. The adaptation of the SDLC is comprised of the conceptual, detailed design, production, and support phase. During the conceptual phase, candidate design configurations are developed to address the requirements of the program. Trade studies are conducted that identify one or a few designs that will be analyzed in the detailed design phase. The detailed design phase consists of the actual implementation or creation of a bill of materials, drawings, and prototypes for the design.

The design is then sent to production. After production, the product or system is maintained, possibly modified and upgraded, and is eventually phased out. Although each phase utilizes cost estimation, design changes or improvements implemented in the conceptual design phase incur less cost than changes made during the other phases [1]; Figure 1.1 illustrates this concept. The point on the graph where conceptual design takes place has both low costs for making design decisions and high impacts on the design for making decisions.

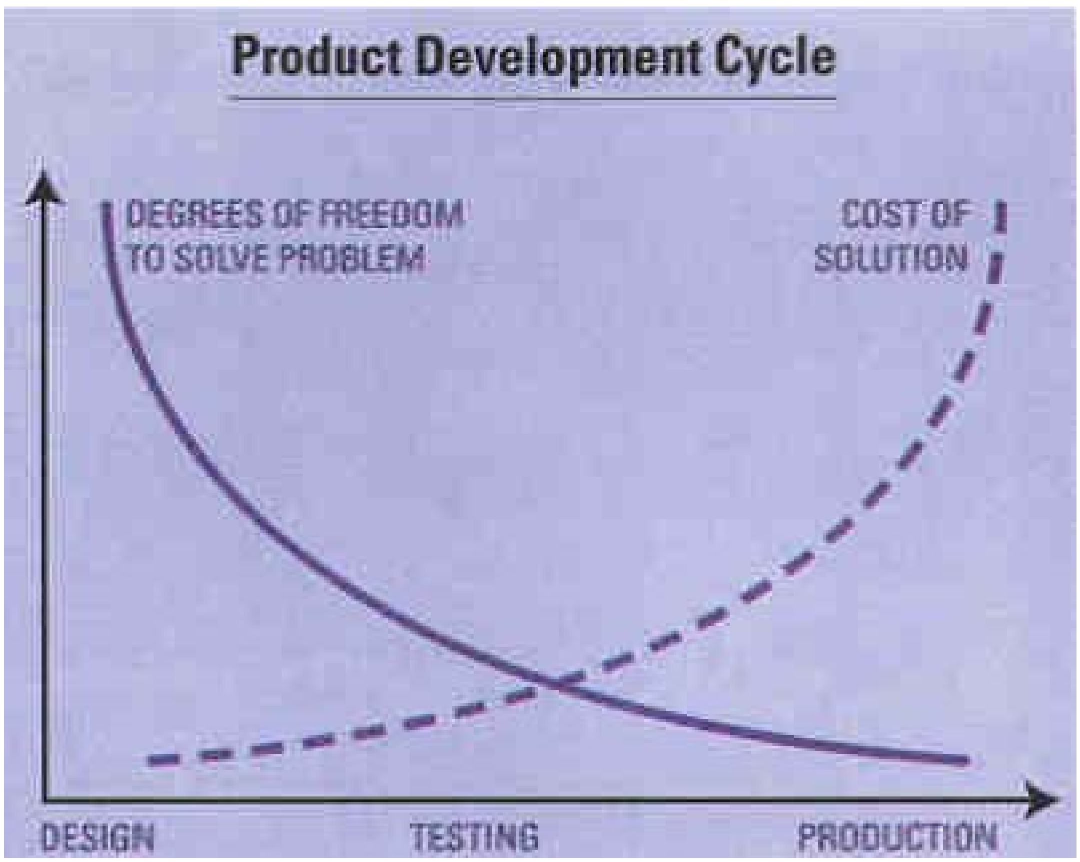

Figure 1.1 Impacts of Decision Making Within the SDLC [6]

The estimates produced during the conceptual phase can include detailed design, production, and support cost estimates. Therefore alternative selection is very important during the conceptual design phase. As discussed earlier, total ownership cost has become a major factor for choosing between alternative designs. Design trade-off studies are usually conducted to make the design selection. Below is a description of a simple process that illustrates how these studies are conducted. First, performance attributes of each design are analyzed and documented. Next, design attributes (i.e. materials, required manufacturing processes) for each component are used to predict the impact of cost on each design alternative. Although the figure indicates these studies being conducted in series, they are often performed in parallel.

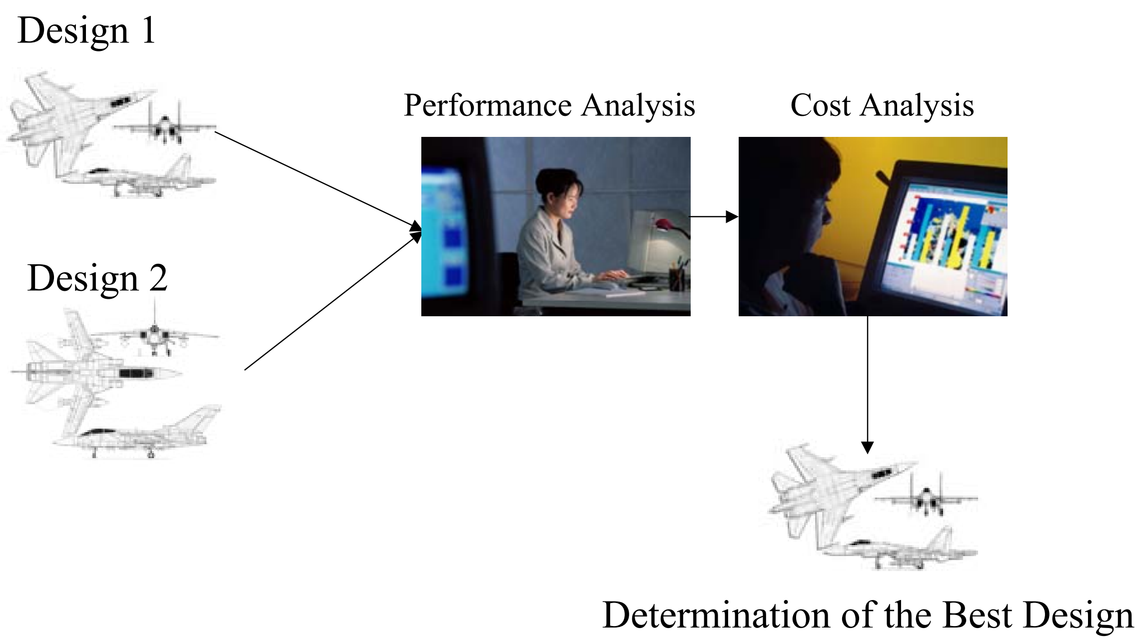

Figure 1.2 Design Trade-Study Process

Once a candidate design has been chosen, more cost estimates have to be produced in the detailed design phase. The amount of information available during the conceptual phase is typically low. Once more information is obtainable, the costs should be re-estimated and documented. These estimates help management make budget and scheduling decisions for detailed design and production. Since most design features are frozen after detailed design, cost estimation is used less during the production and support phases, except in the case of modification and upgrades.

Another important component of design is the methodologies used to represent the components of the system and the elements that will comprise the overall cost of the system. The military has developed two methodologies for both system and cost representation. The Work Break-Down Structure (WBS)[1] provides the entire design team with a hierarchicial representation of the system. An example of a simple WBS is shown in Figure 1.3.

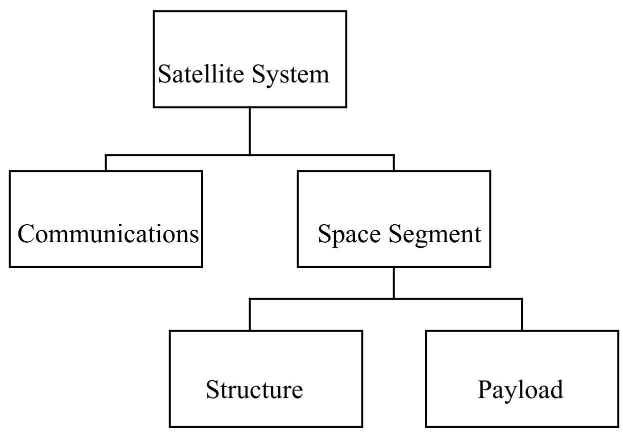

Figure 1.3 Example WBS

The Cost-Breakdown Structure (CBS)[3] gives the same type of hierarchical representation of the system's cost. The cost structure ensures that all aspects of the cost of a WBS component are addressed in the cost analysis. A simple representation of a cost structure is shown in Figure 1.4.

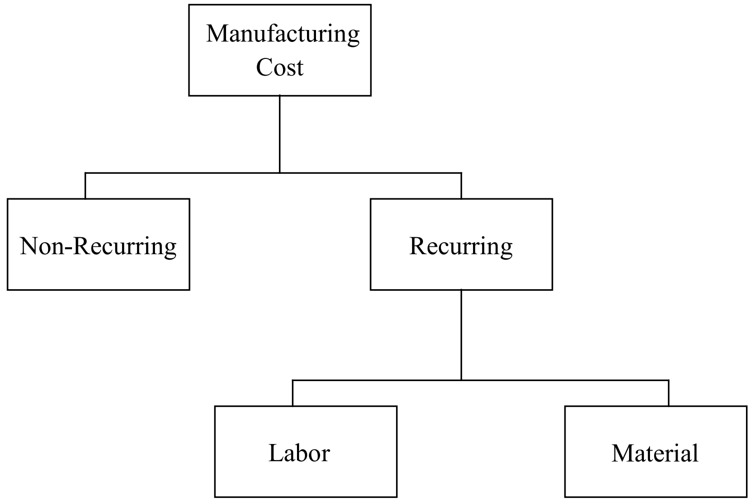

Figure 1.4 Example CBS

1.3 Problem Statement

In order to help identify ways to improve cost estimation, especially early in the product design process, and to facilitate the development of cost estimation tools, cost estimation needs to be viewed and represented as a process. Currently, there is no known documented generic cost estimation methodology that addresses the critical steps within the cost estimation process. The documented processes that do exist are industry or government organization specific. Also, the documentation does not use tools such as process modeling to effectively display the process in a coherent and efficient form. Process modeling provides a common language for defining and understanding the characteristics of a process.

Tools are developed to support and enhance the activities that are carried out in processes. Therefore, until the processes are clearly defined, tools may be developed that do not effectively and efficiently address the needs of the process, i.e., the tools may not address the critical problems, multiple tools may be developed that address the same problem and hence become redundant, and tools may not work together.

A decision-support tool for assessing uncertainty is an example of a tool that is connected to the cost estimation process. There have been several tools (i.e. *Crystal Ball*) developed for addressing the risk and uncertainty of a product's design. However, these tools are very limited for helping engineers make decisions between competing designs. Most risk tools use a spreadsheet-like format to enter the data and are not integrated with the tools that are used to estimate the cost of the system (e.g. cost models, databases). The outputs of the tools are usually confined to the basic statistics for the system (average cost and standard deviation). A design decision support tool would require a methodology to represent the impact of component or subsystem uncertainty on system-level uncertainty. The tool should also provide the engineer with mechanisms (e.g. statistical charts) to help choose between competing designs. Existing tools also do not provide the engineer with the capability of organizing data for the system in a Work Breakdown Structure[1] format. Also, the tools do not provide "cost models[2]" that the design engineer could use within each component of a "cost structure[3]" or CBS.

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[1] WBS is a product-oriented family tree that leads to the identification of the functions, activities, tasks, and subtasks within the system. [1]

[2] Categories of cost models are expert opinion, model by analogy, engineering build-up and parametric estimation. While the approach developed in this thesis is applicable to all categories of cost models, the focus is on parametric cost models. Parametric cost models are defined as a technique employing one or more cost estimation relationships and associated mathematical relationships and logic. The technique is used to measure and/or estimate the cost associated with the development, manufacture, or modification of a specified end item. The measurement is based on the technical, physical, or other end item characteristics. [3]

[3] A hierarchical structure that rolls budgeted resources into elements of costs, typically labor, materials and other direct costs. [1]

1.4 Research Objectives

- Define a generic cost estimation process.
- Develop a WBS, model-based approach and tool to estimate system-level cost risk.

Chapter 2 addresses the first research objective, i.e. it defines a generic cost estimation process. Chapter 3 addresses the second research object, the development of a WBS, model-based approach and tool to estimate system-level cost uncertainty. Chapter 4 provides the conclusions of the research and an outline of future work and research.

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[5] U.S. Army Cost and Economic Analysis Center, Department of the Army Cost Analysis Manual, Virginia, 1997.

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CHAPTER II

DEFINITION OF A GENERIC COST ESTIMATION PROCESS

As mentioned previously, the armed forces and their contractors are charged with the daunting task of developing state-of-the art systems at minimum costs. To meet these requirements, each branch of the military has developed specific procedures for conducting a cost analysis. Although these cost estimation procedures have been well documented, there have been few attempts to generate a generic cost estimation process. This process could be used as a starting point for organizations and cost engineers to develop their own cost estimating processes. This chapter defines the cost estimation processes utilized by the U.S. Army, Air Force, Navy, and NASA. These processes are assimilated into a generic cost estimation process.

2.1 Report Methodology

For each governmental organization, a description is provided that outlines their cost estimation process. Each process is represented in a common format using the IDEF0 methodology [5]. These processes are assimilated into a generic cost estimation process. The generic process is represented as an IDEF0 diagram and each activity within the process is defined. The assimilated generic cost estimation process is extended and defined based on the risk/uncertainty research presented in Chapter 3.

2.2 Brief Description of IDEF0 Diagramming [5]

IDEF0 diagrams have been used by government and industry to describe and define function of relationships. An IDEF0 diagram is a hierarchical representation offunctions and interfaces or relationships among functions. The components of the diagram are:

- activities (represented by boxes)
- arrows (represent object or collections of objects and interconnections or relationships among boxes/activities)
    - input (represent objects used and transformed or consumed by activities)
    - control (represent objects that constrain activities)
    - output (represent the objects produced by the function)
    - mechanism (represent how activities are realized.)

Figure 2.1 illustrates the concept of the IDEF0 methodology. The cost estimation process will be discussed in further detail within the later sections of this chapter.

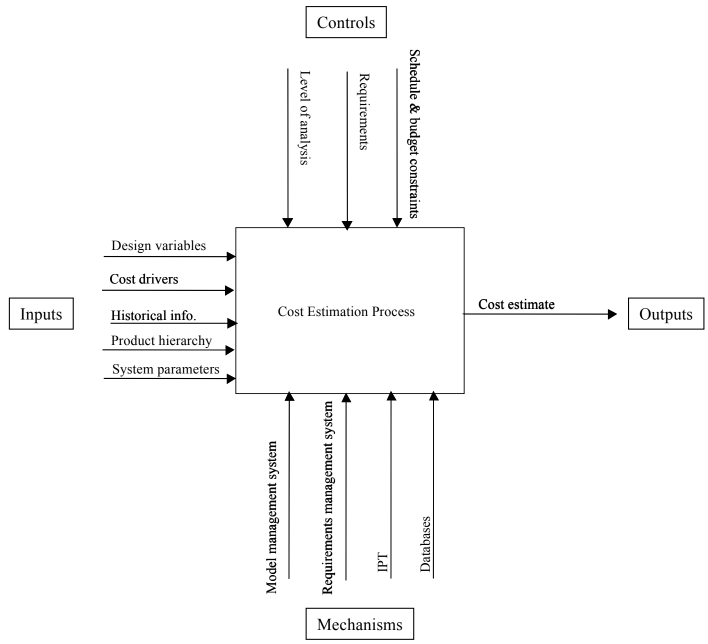


Figure 2.1 IDEF0 Example

2.3 Military Branch Cost Estimation Processes

While conducting the literature review, it was discovered that several aspects of each branch's cost estimation processes were the same. Also, some branches had more detailed literature available to the public that outlined the cost estimation process. The Department of the Army's *Cost Analysis Manual* [10] was the most detailed report that covered the entire cost estimation process. The Army report is used as a baseline and the remaining branches' processes supplement the Army approach. Portions of the cost estimation process for other military branches that are different from the Army's process are documented and shown in the IDEF0 diagrams.

2.3.1 Department of the Army

The information used to define the Army's cost estimation process was extracted from the *Cost Analysis Manual* [10].

2.3.1.1 Army Cost Estimation Process Description

The inputs for a cost analysis are:

- Indication of amount of data available and the actual data obtained
- System and Component Characteristics (e.g. weight)
- Project Description/Scope

The outputs for a cost analysis are:

- Cost estimates for components
- Cost estimate documentation.

The controls for a cost analysis are:

- Budget constraints
- Schedule constraints.

The mechanisms for a cost analysis are:

- Cost Analysis Requirements Description (CARD)[4]
- Cost analysts
- Cost structures
- Estimation methodologies

  - Data sources
  - Cost estimation software.

The CARD is basically a detailed roadmap of the cost project's objectives and activities that will be needed to meet the objectives. Typically the following information can be found in this document:

- Project description
- Cost structure
- Project ground rules and assumptions
- Project schedule
- Cost summaries for each of the cost structure elements.
- Cost methodology used for each element.

The activities of the Army's [10] cost estimation process are listed below:

1) Set up definitions, ground rules, and assumptions/constraints
2) Select the cost structure
3) Collect relevant data
4) Prepare the cost estimate
5) Test the total cost estimate
6) Prepare documentation.

Activity 1 – Set up definitions, ground rules, and assumptions/constraints

A detailed description of the component or system that will be estimated is documented. Also, an indication of the amount of historical or test data available for the component or system is given. Finally, the scope of the cost estimation project, required resources, and scheduling information should be documented. The Cost Analysis

Requirements Description (CARD) is then prepared that formally documents all previous information.

Activity 2 – Select the cost structure

Depending on the scope of the cost estimation project, different cost structures should be used to identify all cost elements (material, manufacturing, support costs…) that are relevant. This structure will ensure that the cost estimate will encompass all required cost elements. Also, a work breakdown structure (WBS) can be defined for the cost estimation process.

Activity 3 – Collect relevant data

The most important aspect of this activity is to ensure relevant and reliable data sources are identified for the cost estimation project. These sources could be obtained from local databases or on-line databases. The data can take many forms, such as historical cost reports, government contracts, cost/technical databases, data from previous estimates, and other cost studies [6]. After obtaining the data, all anomalies within the data should be addressed and the data should be adjusted for inflationary effects if necessary.

Activity 4 – Prepare the cost estimate

The first step within this activity is to determine which cost methodology to use for the project. A list of methodologies and descriptions can be found in Table 2.1.

Table 2.1 Cost Methodology Matrix [10]

Methodology	Description
Engineering approach	Using the item structure for the system, each individual component is estimated individually. These individual estimates are then combined to obtain the final cost estimate. This methodology is usually used for well-known or stable systems.
Parametric model	The analyst identifies a single attribute or group of attributes of the component or system and forms a mathematical model that relates the attribute(s) to cost. This method requires documentation of the statistical characteristics, data sources, and assumptions of the study.
Analogy	This approach uses historical cost data from an item that is similar to the system or component to estimate the cost. The data can be adjusted due to the variation in complexity and other factors. This approach requires a lot of experience and subjective opinion.
Expert opinion	The expert opinion approach uses the subjective judgement of an individual or group of experts. This can be accomplished using questionnaire techniques (Delphi) or by constructing a knowledge base. The applicability of this technique depends on the experts that are chosen for the study.

Once the methodology is chosen, the analyst produces and stores the estimate.

Activity 5 – Test the total cost estimate

The analyst should conduct a sensitivity analysis on key cost elements depending upon the type of cost estimating techniques that were applied. Also, the uncertainty of the cost estimate should be assessed. These activities require the analyst to have prior experience of conducting a mathematical or statistical analysis. A validation team should also be created to review the methodologies and techniques used to derive the estimate.

Activity 6 – Prepare documentation

The documentation for the cost estimate should be clear and concise. The documentation should include:

- All ground rules and assumptions used in developing the estimate
- The data used in the estimate and their sources
- Modifications to the data (normalization)
- Methodologies and models used for the study.

2.3.1.2 IDEF0 Diagram, Army Cost Estimation Process

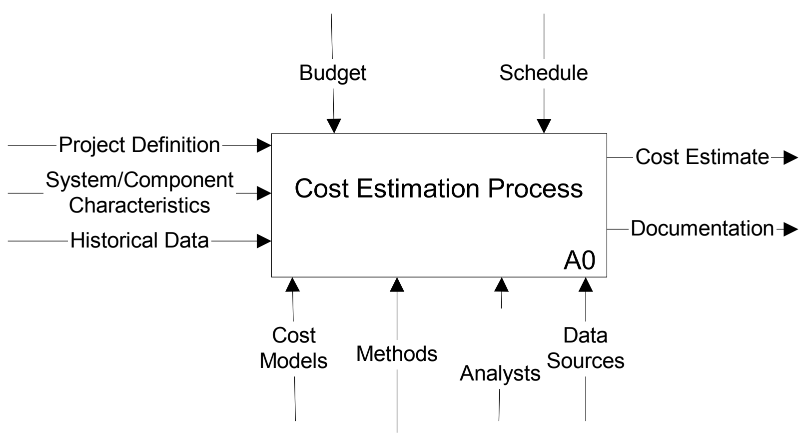


Figure 2.2 A0 Diagram, Army

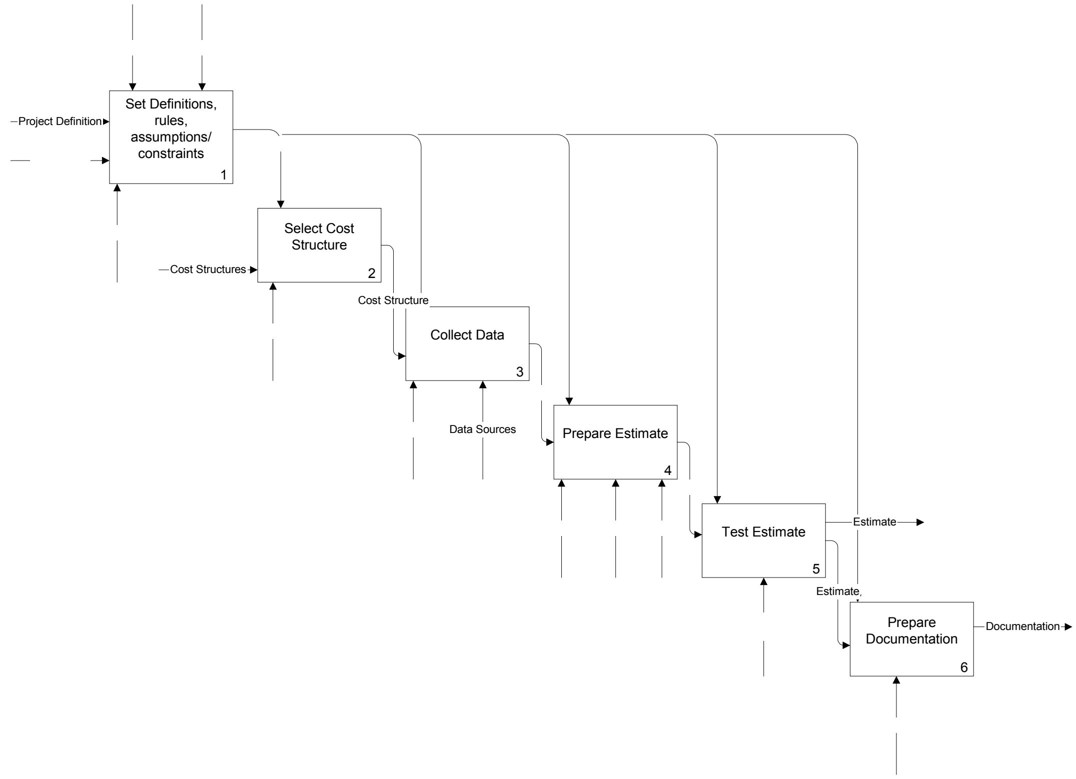


Figure 2.3 A1 Diagram, Army

2.3.2 Department of the Air Force

The information used for definition of the cost estimation process was obtained from the *Cost Analysis Guidance and Procedures* [8] document. This document focuses more on the documentation phase of the cost estimation process. Although the document did not directly provide a cost estimation process, the process was identified by referencing the detailed cost estimation activity checklist within the document [8].

2.3.2.1 Air Force Cost Estimation Process Description

The Air Force cost estimation process follows three main activities:

- The project kick-off phase
- Cost Integrated Process Team (CIPT, team that will conduct the cost estimate) development phase
- The briefing phase

During the project kick-off phase, the program office provides the team with project design descriptions, requirements, and other relevant information. The CIPT is then formalized and the following aspects of the project are defined:

- preliminary CARD (Cost Analysis Requirements Document) is defined
- project schedule
- initial identification of high cost and high risk areas
- identification of needed resources.

After, the kick-off phase, the CIPT begins the development phase. The CIPT then conducts a study of the proposed cost estimate project and prepares a report that will describe which cost structures and cost methodologies will be required for the project. After the document is approved by the Program Office, the CIPT begins work on the actual estimate. The estimate must address all appropriate levels of the SDLC. Finally, after the estimate has been calculated, a report and presentation is prepared for management. After the briefing, the report is reviewed and the estimate is either rejected or accepted. If accepted, the estimate is documented and contains the following information:

- Purpose of estimate

- Team composition
- Description of project
- Scope of estimate
- Project schedule
- Contractor information
- Cost estimate summary
- Ground rules and assumptions
- Methodologies/models used to derive the estimate
- Identification of the cost structure
- Sources used to obtain estimate
- Normalization information.

2.3.2.2 IDEF0 Diagram, Air Force Cost Estimation Process

The A0 diagram for the Air Force cost estimation process is similar to the Army diagram. However, team development and requirements gathering are discussed in more detail.

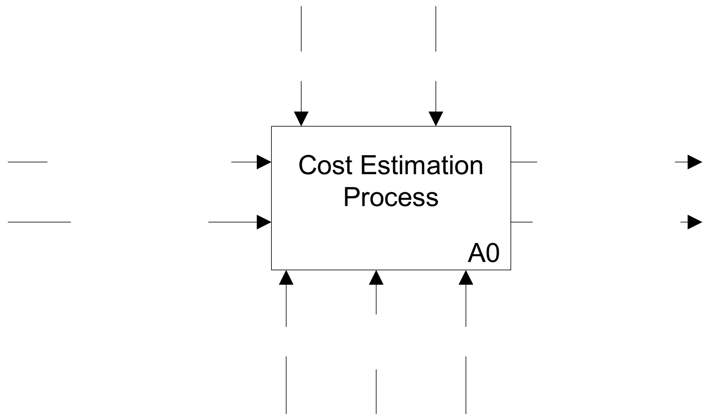


Figure 2.4 A0 Diagram, Air Force

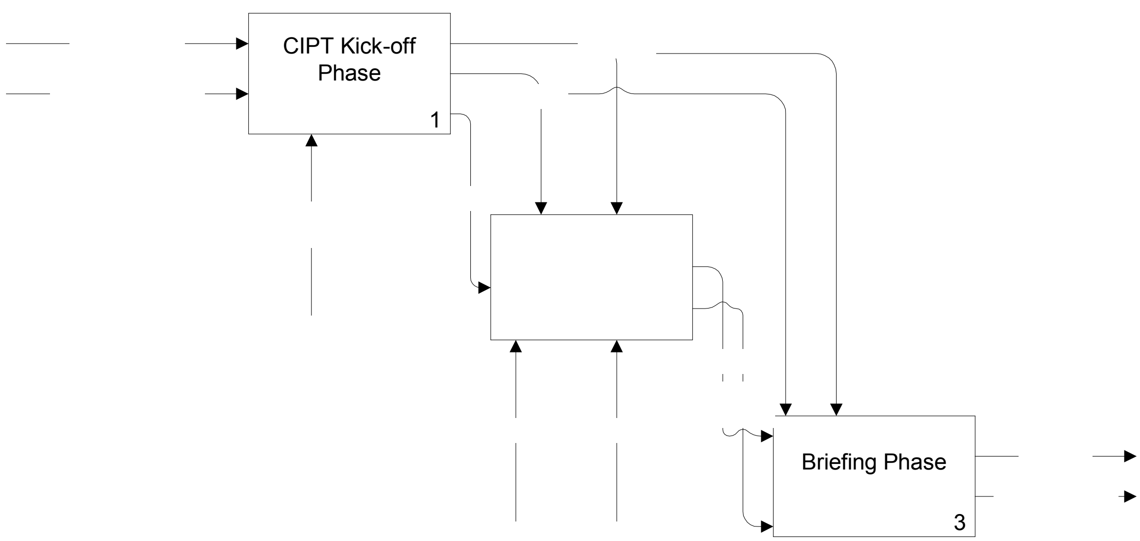


Figure 2.5 A1 Diagram, Air Force

2.3.3 Department of the Navy

Cost estimation process information pertaining to the Navy was obtained from the Parametric Estimating Handbook [2] and Navy cost estimation process report [7]. The Navy's cost estimation process was very similar to the Army's process. However, the Navy did not provide detailed definitions for each cost estimation activity. Instead, the Navy uses the cost estimation procedures from the Joint Industry/Government Parametric Estimating Handbook. The Navy also uses the Cost Analysis Requirements Document for ensuring that all cost estimates are documented and all requirements for the cost estimate are met. Although the Navy documentation does not give detailed activity information, it provides a good "check-list" of activities for developing cost estimates. After documenting all of the branch's processes, the explicit list of activities developed by the Navy is very comprehensive where the other branches were not.

2.3.3.1 Navy Cost Estimation Process Description

A list of the Navy's cost estimation process activities and the subtasks that are required for each activity are provided in Table 2.2.

Table 2.2 Navy Cost Estimation Activities and Sub-Tasks

Activities	Sub-Tasks
Establish Needs and Scope	Identify Purpose
	Define Scope/Work
	Determine Resource Requirments
	Evaluate Availability of Resources
	Identify/Resolve Issues
	Develop CARD
Develop Cost Estimate	Develop Estimating Approach
	Collect/Analyze Data
	Develop/Refine Cost Model
	Execute Model
Validate & Verify Cost Estimate	Compare Output to Previous Estimates
	Compare Output to Analogous Systems
	Perform Sensitivity Analysis
	Review with Technical Experts
Present & Defend Cost Estimate	Present & Defend Cost Estimate
Document Cost Estimate	Establish Documentation Format
	Collect Information
	Generate Document

The Navy's process gave great insight into how cost estimates can be validated. The activities of comparing the estimate to both historical and analogous systems are good benchmarks for the analyst to use to validate the cost estimate.

2.3.3.2 IDEF0 Diagram, Navy Cost Estimation Process

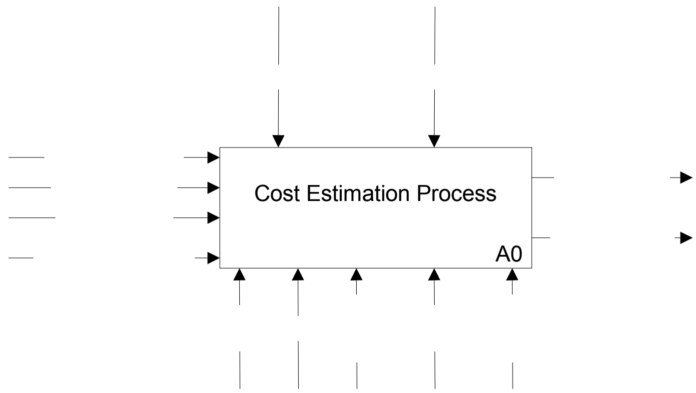


Figure 2.6 A0 Diagram, Navy

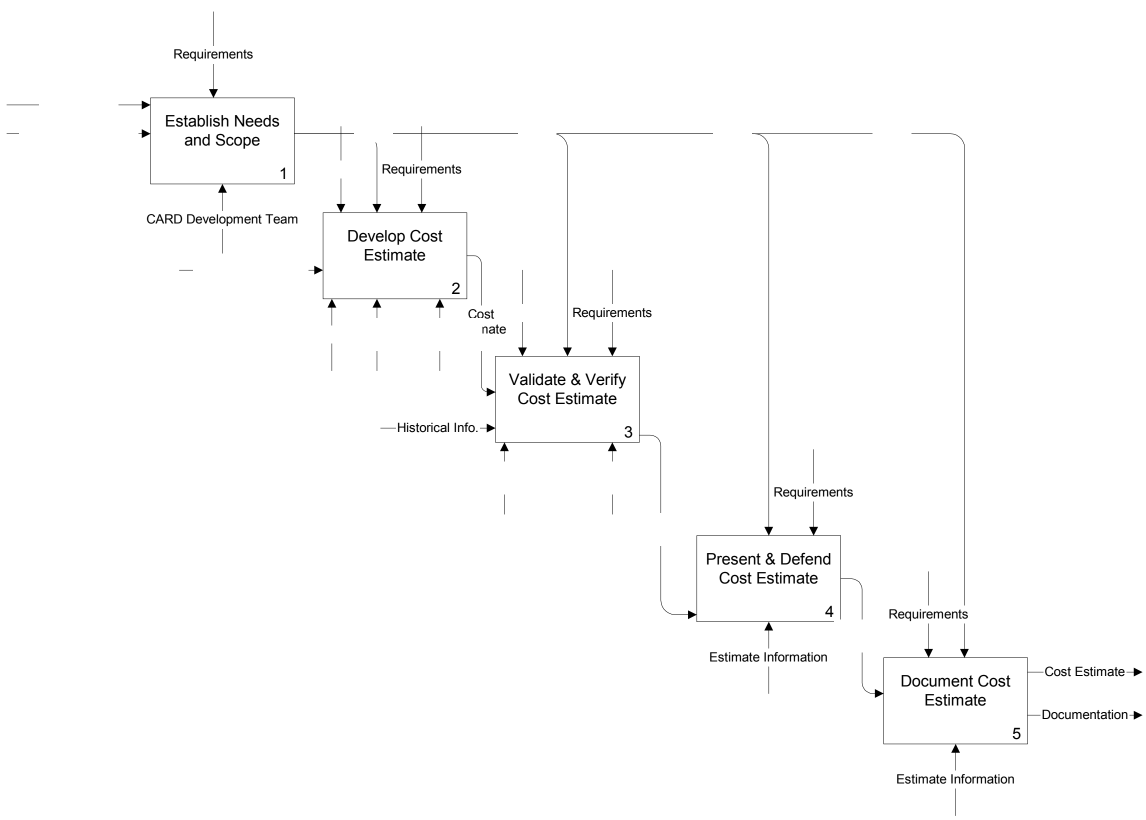


Figure 2.7 A1 Diagram, Navy

2.3.4 NASA

The information used for definition of the cost estimation process was obtained from the cost estimating section of the NASA web-site [6]. The NASA information focuses on model selection and the CARD. The model selection section describes available software models that NASA has developed and commercial products (e.g. *PRICE* and *SEER*) that are available to the engineer. Also, guidelines for using inflation and complexity factors are discussed on the web-site.

2.3.4.1 NASA Cost Estimation Process Description

The first step in NASAs' cost estimation process is to create the Cost Analysis Requirements Document (CARD). This document is updated concurrently and will eventually form the baseline for the Program Cost Commitment (PCC, formal report detailing information about the estimate).

Once the CARD is completed, the analyst chooses the appropriate model for estimating the system or component. The NASA/Air Force Cost Model (NAFCOM) [6] is used for typical spacecraft or vehicle designs. NAFCOM is composed of historical cost and technical databases from completed NASA programs. This model lends itself to the analogy methodology where the analyst identifies components that are similar to the component being estimated. The cost and technical information are then adjusted due to complexity or other normalization factors. The NASA document also recommends the use of the Advanced Missions Cost Model (AMCM) [6] for state-of-the-art systems that are being estimated during the conceptual design phase.

Once the estimate is completed, all documentation must be inserted into the CARD.

2.3.4.2 IDEF0 Diagram, NASA Cost Estimation Process

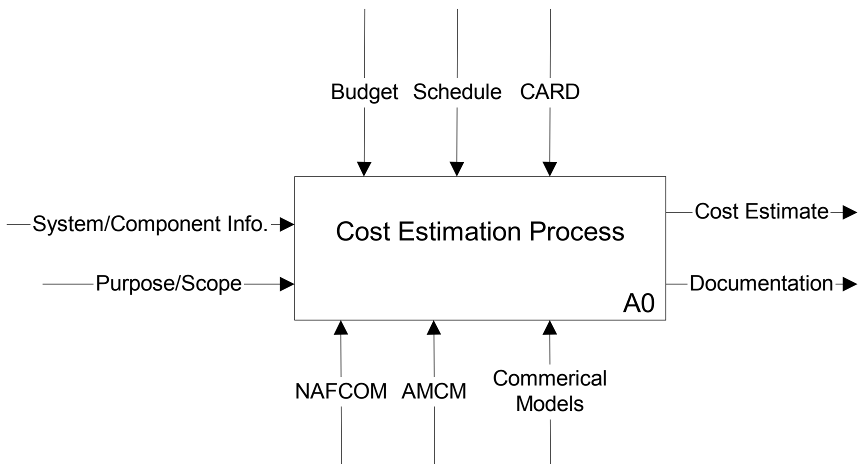


Figure 2.8 A0 Diagram, NASA

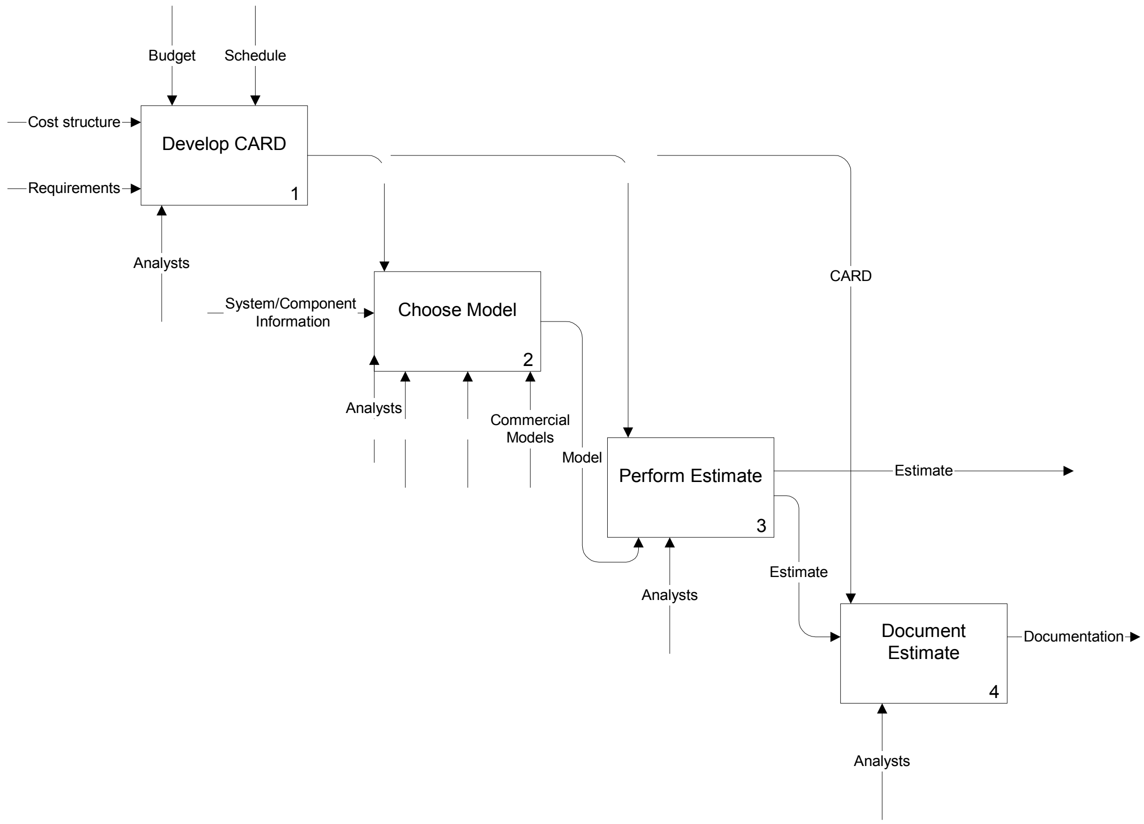


Figure 2.9 A1 Diagram, NASA

2.4 Development of Generic Cost Estimation Process

By using the processes from the Army, Air Force, Navy, and NASA, a generic process was developed. Because the Army's process was defined in more detail than the other departments, the generic process will exhibit more information from that section. Table 2.3 below lists and briefly describes all activities within the cost estimation process:

Table 2.3 Generic Cost Estimation Process Activity List

	Activity	Description
1	Develop project glossary, ground rules, and assumptions	A detailed description of the component or system that will be estimated is documented. This is typically accomplished by developing the WBS. Also, an indication of the amount of historical or test data available for the component or system is given. Finally, the scope of the cost estimation project, required resources, and scheduling information should be documented. The Cost Analysis Requirements Description (CARD) is then prepared that formally documents all previous information.
2	Define cost structure	Depending on the scope of the cost estimation project, different cost structures should be used to identify all cost elements (material, manufacturing, support costs…) that are relevant. This structure will ensure that the cost estimate will encompass all required cost elements. Also, a work breakdown structure (WBS) can be defined for the cost estimation process.
3	Choose cost methodology	Based on the level of information available for model input and the analyst's experiences and resources. Types - Engineering, Parametric, Analogy, Expert Opinion
4	Determine appropriate model/analogy	Once the methodology is chosen, a model that implements that methodology should be chosen based on the level of information available for model input and the analyst's experience and resources. For example, the analyst could choose either to perform the Delphi method or construct a knowledge base in order to implement an expert opinion methodology.
5	Perform data collection	The most important aspect of this activity is to ensure relevant and reliable data sources are identified for the cost estimation project. These sources could be obtained from local databases or on-line databases. The data can take many forms, such as historical cost reports, Government contracts, cost/technical databases, data from previous estimates, and other cost studies. (The Department of the Army, 1997)
6	Normalize data	The data that was obtained for the model might require normalization. (inflation, complexity, learning curve)
7	Calculate estimates	Utilizing the chosen model to obtain the estimate
8	Conduct sensitivity analysis	The analyst should conduct a sensitivity analysis on key cost elements based on which cost estimating techniques were used for the project
9	Assess uncertainty	Using statistical methods, the uncertainty tied with each cost estimate should be assessed and documented.
10	Validate estimates	An independent advisory team should check and validate all methodologies, models, and calculations performed to achieve the estimate. Also, the esimate should be compared to historical and analogous projects.
11	Document estimates	Document the following information for future use: - Purpose of estimate - Team composition - Description of project - Scope of estimate - Project schedule - Contractor information - Cost Estimate Summary - Ground rules and assumptions - Methodologies/Models used to derive the estimate - Identification of the cost structure - Sources used to obtain estimate - Normalization information.

2.4.1 IDEF0 Diagrams, Generic Cost Estimation Process

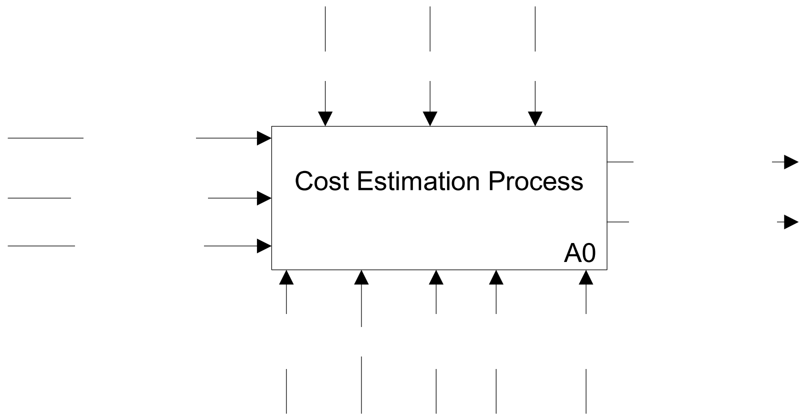


Figure 2.10 A0 Diagram, Generic Cost Estimation Process

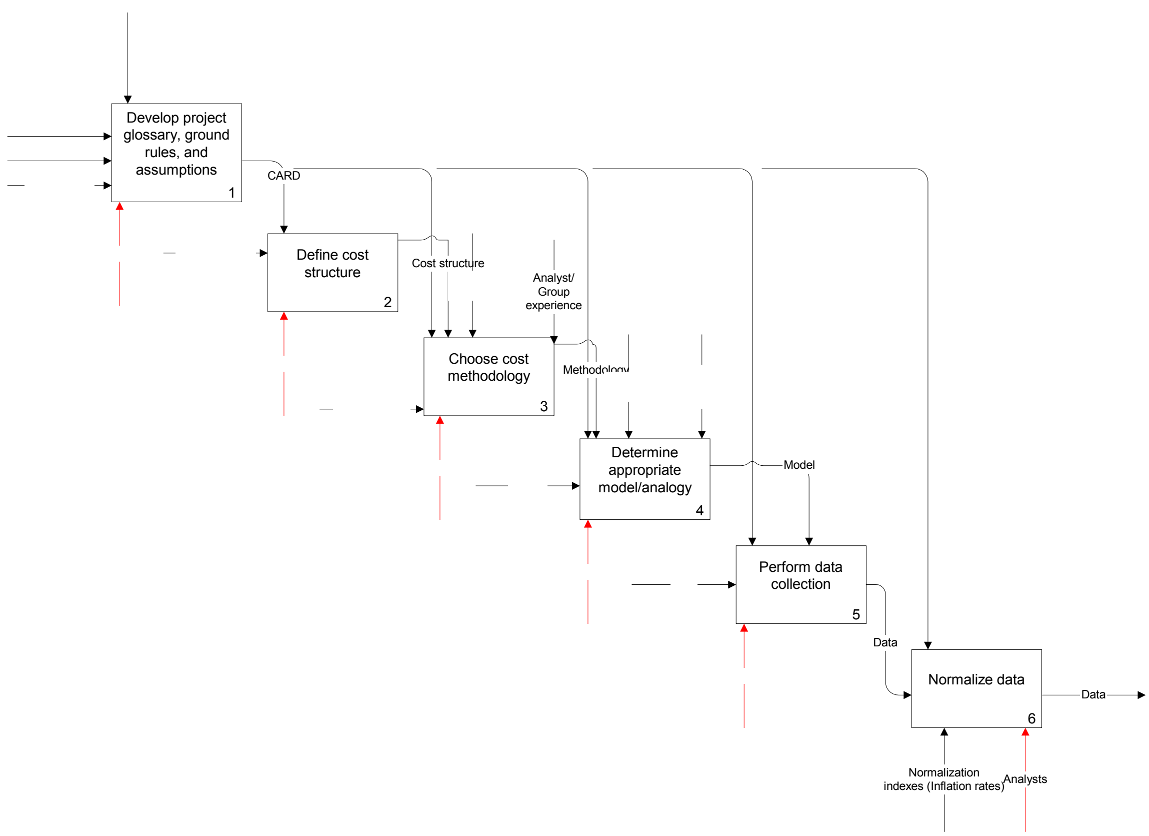
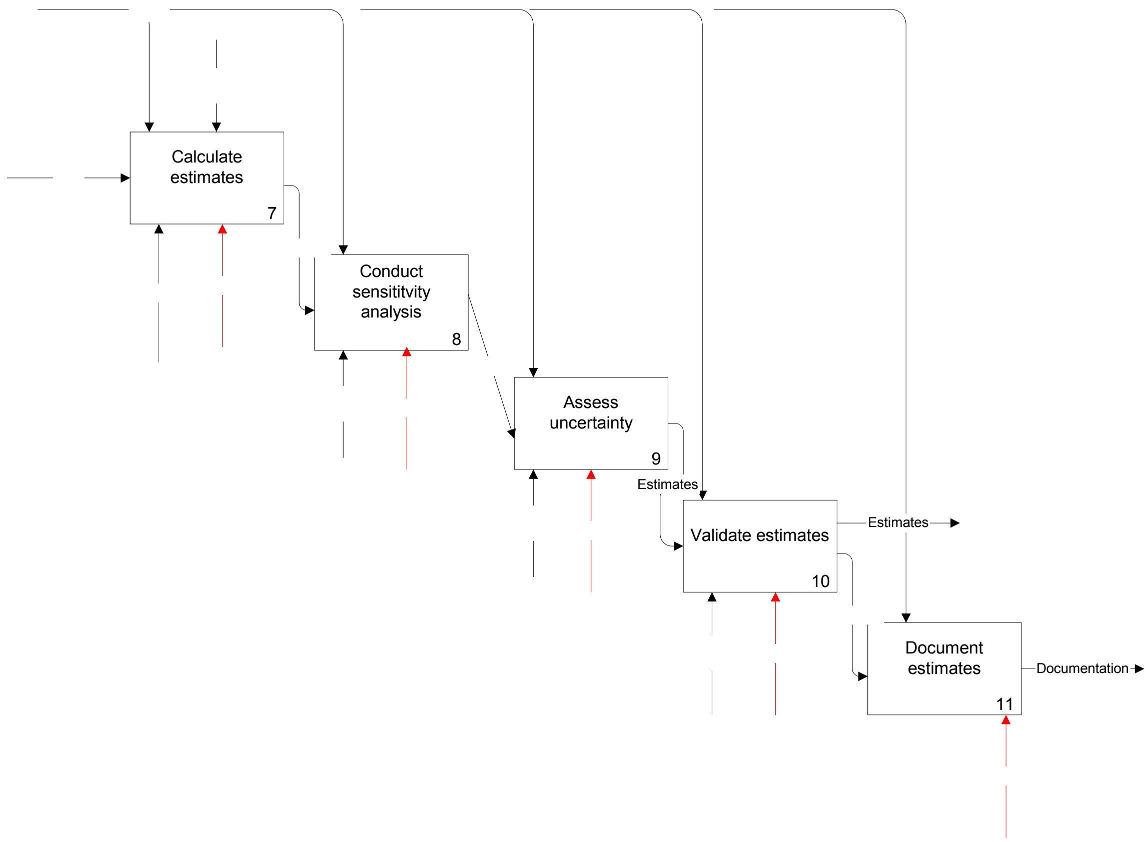


Figure 2.11 A1 Diagram, Generic Cost Estimation Process



2.5 Extension of Generic Cost Estimation Process After Risk Research

After completing the research relating to the development of a WBS, model-based approach and tool to estimate system-level cost uncertainty, as described in Chapter 3, several insights were documented that affected the generic cost estimation process developed by the government literature review. The most important insight was that the risk management process should be incorporated within all stages of the generic cost estimation process. This process is shown below in Figure 2.12 using the IDEF0 methodology.

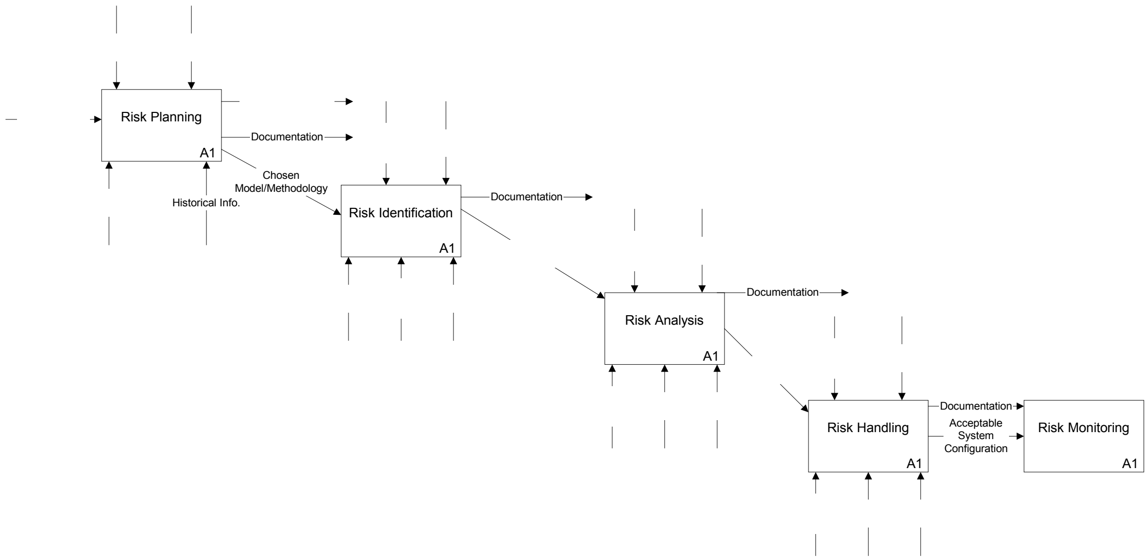


Figure 2.12 Risk Process IDEF0 Diagram

Each activity of this process is discussed in detail within chapter 3. Also, a model management system must be developed or obtained to ensure that the appropriate cost model is available for the cost analysis. All aspects of each cost estimate should be documented electronically (database management system) to facilitate future trade studies between competing design alternatives. Another important aspect of the cost estimation process is the procedure for including assembly or integrating costs between different components within the WBS. Garvey [3] suggests several different techniques for addressing this problem. The extended generic cost estimation process is shown in Figure 2.13 with the new objects indicated in bold:

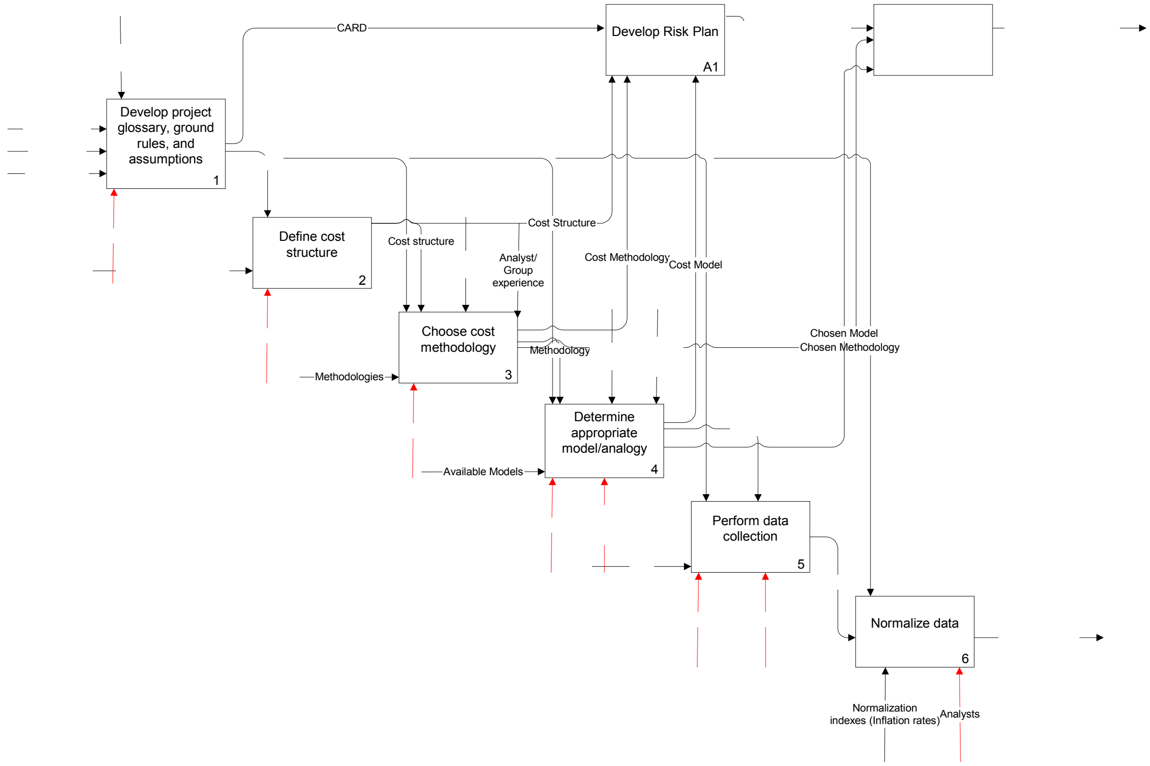
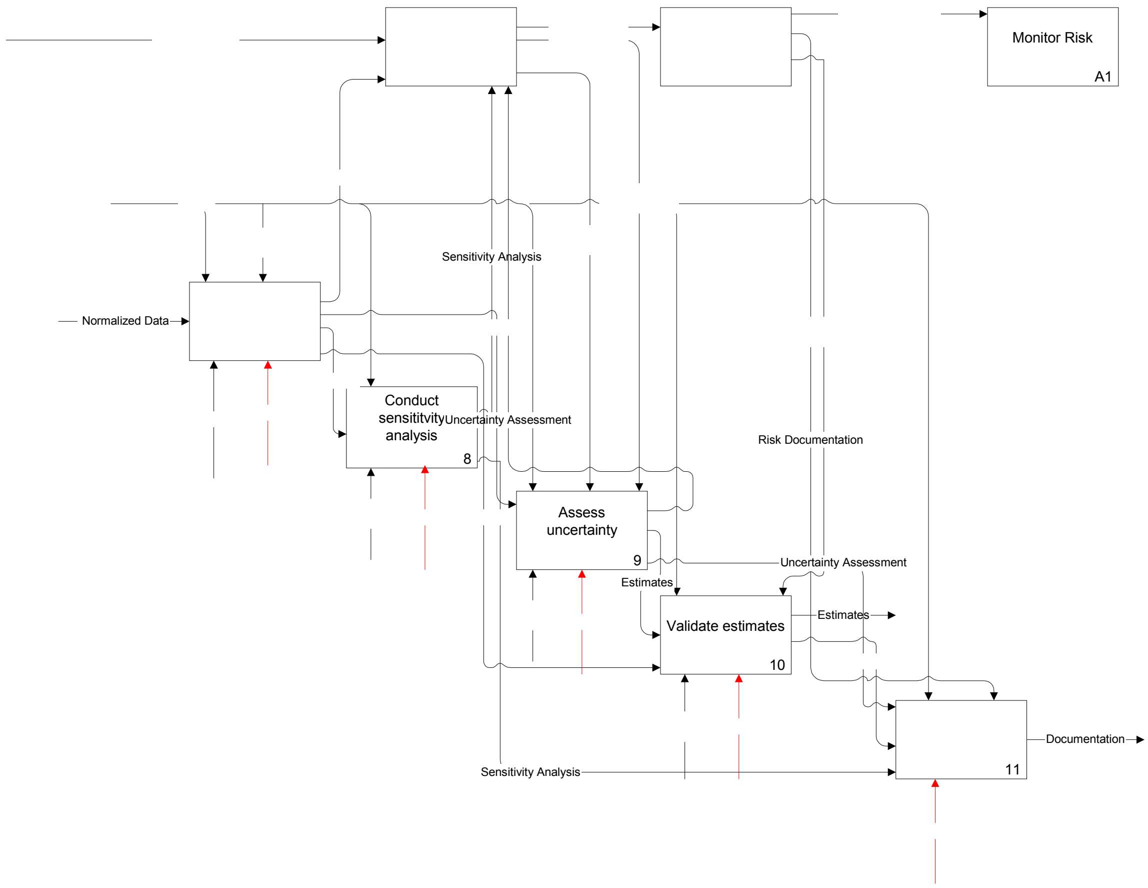


Figure 2.13 A1 Diagram, Extended Generic Cost Estimation Process.



2.6 Conclusions and Future Work

The generic model that was documented should give cost engineers and managers a baseline on conducting an estimation study. A summary of conclusions from the research are listed below:

1) NASA focused more on NASA-specific model and methodology selection.
2) The Air Force and Army's cost estimation processes focused more on the documentation requirements that are needed during the cost estimation process.

3) The process of choosing a cost methodology and model was extremely difficult. The Army Cost Analysis Manual gave the most insight into these individual processes.
4) The portion of cost estimation that was typically overlooked was the process and tools used to meet the requirements for documenting cost estimates. Without a good documentation process, the organization loses a lot of information vital to tracking cost performance. Also, the documentation provides cost engineers with a knowledge base that will reduce the time and effort to conduct future cost estimates.
5) The Navy documentation had more detailed information concerning the different methods for validating cost estimates.
6) Assessing the uncertainty of the cost estimate was one activity identified in the literature review. However, the focus has been on assessing uncertainty instead of using this information to make design decisions. This prompted further research in the assessment of uncertainty portion of the cost estimation process.

Suggested future research projects based on this work are:

1) Apply process to industry case study and obtain industry feedback.
2) Provide more detailed report on each cost estimation activity with respect to the System Development Life Cycle.
3) Develop a more descriptive process diagram that can indicate repeated activities.
4) Identify specific tools for implementing each activity of the cost estimation process.

5) Develop framework for integrating actual tools and documentation with process documentation.

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CHAPTER III

DEVELOPMENT OF A WBS, MODEL-BASED APPROACH AND TOOL TO ESTIMATE SYSTEM-LEVEL COST RISK

3.1 Introduction to Uncertainty and Risk Analysis

Garvey [6] defines cost uncertainty as "a process of quantifying the cost impacts of uncertainties associated with a system's technical definition and cost estimation methodologies". The study of risk has been defined as the analysis of uncertain characteristics of a system that could produce unfavorable results or performance [23].

By studying the effects of uncertainty within a system, the magnitude of system risk and the influence of component risk can be obtained. Sources of uncertainty within cost estimates have been shown to originate from:

- limited system design information
- project scope change (change of project requirements)
- incorrect scheduling information (e.g. expected end dates)
- uncertainty within cost models used to obtain cost estimate
- variability of resource costs and availability. [6, 23]

Limited System Design Information Available

As stated in the introduction, significant portions of system information, for example the type of material used, are not usually known with certainty at the conceptual design stage. However, the ability to estimate costs during this early stage can help choose the correct design for future stages of the SDLC. Since information is missing concerning the system's design, cost uncertainty analyses should be performed for these cost estimates.

Changes in Project Scope

The design team should have a detailed list of system requirements even during the conceptual design stage. However, these requirements usually change during subsequent phases of the SDLC. The magnitude and frequency of these requirement changes induces uncertainty within cost estimates.

Incorrect Scheduling Information

Engineers and contractors typically place "time buffers" within schedules throughout the project's life to protect against uncertainty. Unforeseen occurrences (e.g. strike, accidents) cause projects to fall behind schedule. These uncertainties dramatically affect cost estimates since scheduling information is often a parameter within cost models.

Uncertainty Within Cost Models Used to Obtain Cost Estimate

As noted in previously, different types of cost models (e.g. parametric, expert-opinion) have different levels of uncertainty. Even though a detailed estimate is used for a component, the parameters used to derive the estimate may still change after conceptual design. Also, a cost estimate developed by analogy could be a good estimate of the true cost during conceptual design but not during production.

Variability of Resource Costs and Availability

Resources such as material often exhibit uncertainties relating to their cost and availability. Due to the lack of availability of a chosen material, other materials might have to be used which will dramatically affect the cost of the system and its components.

Each time the requirements change within a project, an analysis should be conducted both on system definition uncertainty and cost estimation uncertainty. This process is repeated throughout the system development life cycle.

The importance of studying the uncertainty of cost estimates is primarily the identification of risky characteristics of the project, system, or system components. It is common for industry and governmental projects to surpass their budgets. The ability to choose which design will have the least chance of missing budget goals addresses this problem [23]. Secondly, conducting uncertainty analysis helps identify the cost/risk drivers within the system [13]. This allows analysts to focus more attention on these specific areas for improvement. Finally, the benefits of conducting uncertainty analysis are not just applicable to the conceptual design stage but the entire SDLC.

3.2 The Risk/Uncertainty Management Process

Government and industry have also researched the process of managing risk and uncertainty in projects. Risk analysis does not only focus on the quantitative techniques used to assess risk or uncertainty for a project or proposed system, it also focuses on the development of plans to address the areas of uncertainty or risk. Researchers have proposed a formal process that stresses planning and monitoring along with risk analysis

[3, 7, 9, 18]. The four main activities associated with risk management are risk planning, risk assessment, risk handling, and risk monitoring [3, 7, 9, 18]. Not only should these steps be implemented within the conceptual design phase of a project, they should also be completed for each phase of the system development life cycle.

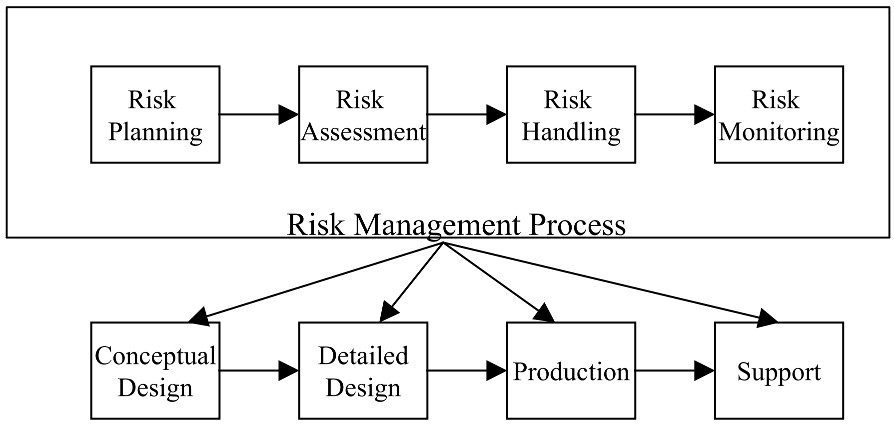

Figure 3.1 Risk Management Process applied across the System Development Life Cycle

The following definitions of each activity within the risk management process are obtained from the *Air Force Materiel Command Risk Management Report* [3] and the *Risk Management Guide for DoD Acquisition* [9].

Risk Planning is the process of developing and documenting an organized, comprehensive, and interactive strategy and methods for identifying and tracking risk areas, developing risk-handling plans, performing continuous risk assessments to determine how risks have changed, and assigning adequate resources. Also, for cost risk analysis, cost models and cost estimate methodologies should be obtained and identified during this stage of the process. Scheduling, budget, project scope, and project requirements information should also be identified and documented. Finally, the different types of tools and methodologies for assessing the uncertainty/risk for the project should be studied and the appropriate tool or methodology should be chosen depending upon the type of system under study and the available cost models. The amount of risk/uncertainty pertaining to the cost models or methodologies can then be identified.

Risk assessment is the process of identifying and analyzing program areas and critical technical process risks to increase the likelihood of meeting cost, schedule, and performance objectives. Two activities within the assessment phase are risk identification and risk analysis. Risk identification is the process of examining the program areas and each critical technical process to identify and document the associated risk. This can be accomplished by using a risk/uncertainty assessment tool. Also sensitivity analysis can be used to identify risk or cost drivers for the system. Risk analysis is the process of examining each identified risk area or process to refine the description of the risk, isolating the cause, and determining the effects. It includes risk rating and prioritization in which risk events are defined in terms of their probability of occurrence, severity of consequence (or impacts), and relationship to other risk areas or processes. The techniques and methodologies used to identify and assess risk/uncertainty will be discussed further in this chapter.

Risk handling is the process that identifies evaluates, selects, and implements options in order to set risk at acceptable levels given program constraints and objectives. This includes the specifics on what should be done, when it should be accomplished, who is responsible, and the cost associated, and schedule changes to effectively handle the risk. The most appropriate strategy is selected from these risk-handling options. Risk and uncertainty handling of cost estimates involves the cost analyst and performance analyst working together to change system or component characteristics (i.e. material used) to address the high risk. This process is very important within the conceptual design phase of the SDLC where design change costs are low.

Risk monitoring is the process that systematically tracks and evaluates the performance of risk-handling actions against established metrics throughout the acquisition process and develops further risk handling options as appropriate. This activity ensures that risk and uncertainty are evaluated throughout the SDLC. This is required due to the probable change of system requirements, schedule constraints, and budget constraints.

Risk documentation is incorporated within every activity of the risk management process. Also, these documents should be revised during each phase of the system development life cycle.

An IDEF0 diagram was developed to further describe each activity within the risk management process. It is shown in Figure 3.2.

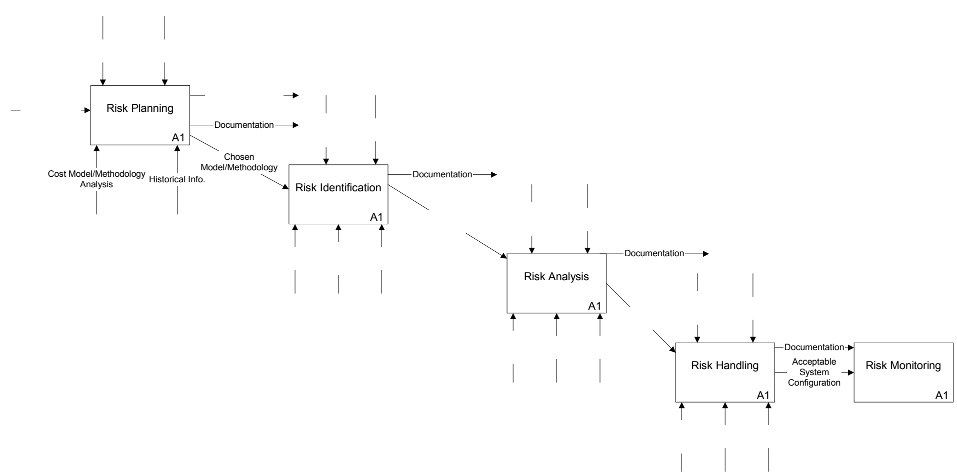

Figure 3.2 Uncertainty/Risk Management Process IDEF0 – A1 Diagram

3.3 Techniques and Tools for Assessing the Uncertainty of Cost Estimates

Although concerns about uncertainty and risk relating to engineering designs have been addressed for centuries, cost uncertainty analysis is a relatively young discipline. The first literature concerning this subject appeared between 1955 and 1962 [6]. These methodologies and tools were very mathematical and were difficult to apply to practical problems. This section will discuss the different tools and methodologies that can be used to assess the uncertainty and risk of cost estimates. The two main approaches for assessing the uncertainty and risk of cost estimates are the analytical approach and the Monte-Carlo simulation approach.

3.3.1 Analytical Approach

Garvey proposes an analytical approach for computing the expected value and variance for system cost [6]. For each component within the system, the cost analyst identifies probability distributions [10] that represent the uncertainty of the parameters used in the estimates. The analyst can also define the functional relationships by combining the components to obtain a total cost estimate for the system. An analytical cost risk analysis example is provided in Table 3.1.

Table 3.1 Example Analytical Problem Table [6]

Component	Component Cost ($M)	Distribution or Function Relationship	Expected Value	Variance
Prime Mission Product	C_1	C_1~N(12.5,6.6)	**12.5**	**6.6**
Systems Engineering	C_2	C_2=.5C_1	-----	-----
System Test & Evaluation	C_3	C_3=.25C_1+.125C_2+W, where W~U(.6,1)	-----	-----
Data and Technical Orders	C_4	C_4=.1C_1	-----	-----
Site Survey and Activation	C_5	C_5~TRNG(5.1,6.6,12.1)	**7.93**	**2.26**
Intial Spares	C_6	C_6=.1C_1	-----	-----
System Warranty	C_7	C_7~U(.9,1.3)	**1.1**	**0.01**
Early Prototype Phase	C_8	C_8~TRNG(1,1.5,2.4)	**1.63**	**0.084**
Operations Support	C_9	C_9~TRNG(.9,1.2,1.6)	**1.23**	**0.021**
System Training	C_{10}	C_{10}=.25C_1	-----	-----

Using the distributions and functional relationships, both the expected value and variance are calculated for the system of *n* components using the following equations:

As shown below, total system cost, $Cost_{Sys}$, is the sum of the cost elements, many of which could be random variables.

$$Cost_{Sys} = C_1 + C_2 + C_3 + ... + C_{10} \tag{3.1}$$

The expected value of the system cost is the sum of the expected values of the component costs.

$E(Cost_{Sys}) = \sum_{i=1}^{n} a_i E(C_i)$, where a_i is a constant that represents a functional relationship (3.2)

Using the given relationships the following equation can be derived.

$$E(Cost_{Sys}) = \frac{181}{80} E(C_1) + E(W) + E(C_5) + E(C_7) + E(C_8) + E(C_9) \tag{3.3}$$

The variance for the system cost can be calculated as:

$$Var(Cost_{Sys}) = \sum_{i=1}^{n} a_i^{\ 2} Var(C_i) \tag{3.4}$$

Using this equation and the given relationships, the following equation can be derived.

$$Var(Cost_{Sys}) = \left(\frac{181}{80}\right)^2 Var(X_1) + Var(W) + Var(X_5) + Var(X_7) + Var(X_8) + Var(X_9) \quad (3.5)$$

Substituting the data in Table 3.1 into equations 3.3 and 3.4 we obtain

$$E(Cost_{Sys}) = 40.98(\$M) \quad (3.6)$$

$$Var(CostSys) = 36.18(\$M)^2 \quad (3.7)$$

This approach assumes that the distribution function for $Cost_{Sys}$ can be approximated by a normal distribution and also assumes independence between components. Also, the correlation between cost elements must be evaluated [6].

3.3.2 Monte Carlo Simulation

Due to the complexities of most projects, most software tools that assess risk or uncertainty utilize Monte-Carlo simulation [1,12,13]. A simulation uses a computer to evaluate a model numerically and data are gathered in order to estimate the desired true characteristics of the model [12]. In the past, computer simulation was very limited due to the performance (i.e. system memory) of most personal computers that were available. Presently, the exponentially increasing performance of the personal computer allows the simulation of complex systems to be feasible. Law and Kelton define Monte Carlo simulation to be a scheme employing random numbers, that is, U(0,1) (Uniform distribution, [10]) random variates, which is used for solving certain stochastic or deterministic problems where the passage of time plays no substantive role. A random variate is a random value that has been conveniently and efficiently generated from a desired probability distribution, such as the Exponential or Triangular distribution [12].

Lorance presents a four-stage process for using Monte Carlo simulation for risk analysis [13].

1) Define the key variables that affect system cost by developing a deterministic model of the cost behavior (cost models)
2) Identify the uncertainty in the estimate by specifying possible values of the variables in the estimate with probability ranges (probability distributions)
3) Analyze the estimate using Monte Carlo simulation. The model is run repeatedly to determine the range of probabilities of all possible outcomes of the model.
4) Make decision based upon the results (i.e. average system cost) of the Monte Carlo simulation.

3.4 Outputs of Risk Assessment Tools

Researchers have identified statistical information that allow analysts to assess the uncertainty or risk for a project. Lorance and Wendling suggest that a risk assessment tool provide the following information [13]:

1) average system cost
2) system cost standard deviation and variance
3) cost histogram
4) sensitivity analysis.

The average system cost is the expected value of the system's cost. The analytical calculation was shown previously. By using Monte Carlo simulation, the average system cost is calculated as

$$AVGSysCost = \frac{\sum_{j=1}^{R} Cost_{Sys_j}}{R} = \frac{\sum_{j=1}^{R}\sum_{i=1}^{n} C_{ij}}{R} \tag{3.8}$$

where,

R = number of replications (number of simulation runs)

$Cost_{Sys}$ = system cost for replication j.

C_{ij} = cost of component i for replication j.

The average system cost provides the analyst with an indication of the magnitude of the system's cost based on the system's characteristics.

The system cost's standard deviation is a measure of the dispersion (or variation or scatter) of the outcomes about the mean of the population, and is useful in describing the "average" deviation. The variance is the square of the standard deviation and indicates the risk or uncertainty of the distribution. When the population of outcomes is close to the mean of the population distribution, the variance is small; when the variance is large the outcomes are widely scattered [13]. A high system cost could be acceptable if the cost deviation (risk or uncertainty) is low. The analytical calculation was defined in the previous section of the thesis. When using Monte Carlo simulation the system cost standard deviation ("average deviation") is calculated as

$$SysCostDev = \sqrt{\frac{\sum_{j=1}^{R}\sum_{i=1}^{n} \left(C_{ij} - AvgSysCost\right)^2}{R-1}} \tag{3.9}$$

Graphical information is very useful for conveying a lot of detailed statistical information in an efficient and effective manner. A common graphical output of risk or uncertainty analysis tools is a system cost histogram. This histogram can be generated when using Monte Carlo simulation. Hayter describes the process of creating a histogram [10]. The histogram provides a quick indication of whether the simulation of the model produced plausible results [13]. If the distribution of the population of outcomes is skewed in an unexpected direction or to an unexpected degree, or if there are multiple humps (modes), the simulation may need to be run more or the simulation may not provide a good representation of the system [13]. Also, the histogram gives a graphical representation of the system's average cost and deviation. An example of a histogram is shown in Figure 3.3:

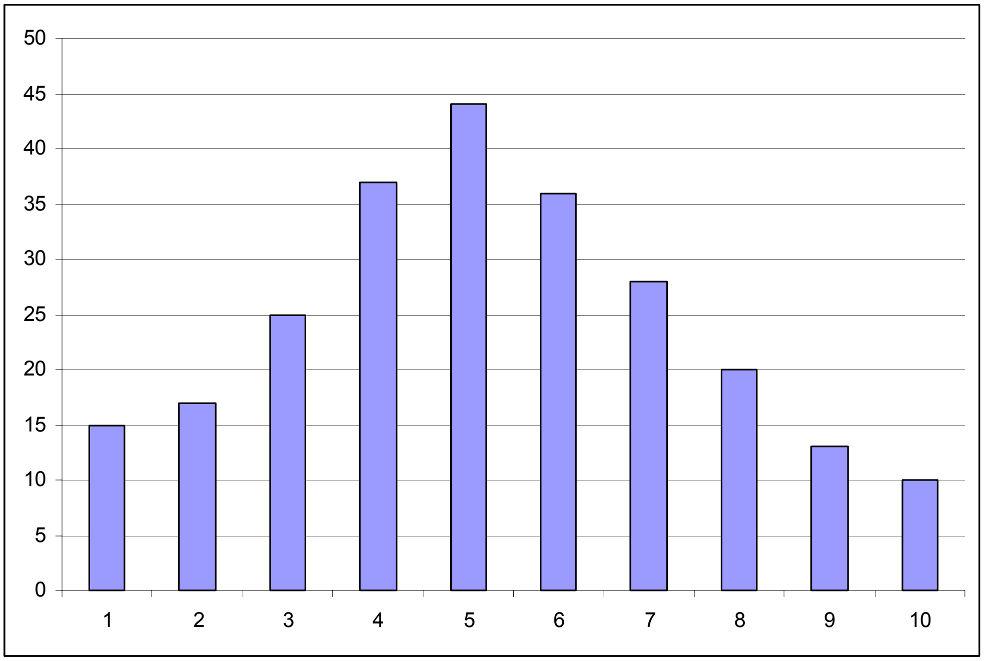

Figure 3.3 Example Histogram

Sensitivity analysis is a tool for assessing the extent to which costs and benefits are affected by changes in the value of system parameters. It repeats the cost analysis using different quantitative values to determine their effects on the results of the original cost analysis. If changing an assumed value results in a relatively large change in the outcome of the analysis, it is said to be sensitive to that assumption. Also, sensitivity analyses provide a range of possible outcomes that are likely to provide a better guide for a decision-maker than a point estimate [22]. By conducting a thorough sensitivity analysis by systematically changing a single characteristic of the system, the cost drivers for a system can be obtained. This analysis can be done for both the analytical and Monte Carlo risk assessment methods.

A tool that graphically displays the results of a sensitivity analysis is the spider-plot [14]. Three points that are plotted for each system parameter (e.g. component weight) are; the middle point (the most-likely parameter estimate) and the minimum and maximum parameter estimates. The Y-axis of the graph indicates the impact on system cost based on these different parameter values. An example of a spider-plot is shown in Figure 3.4. By inspecting the graph, the affects of changing the volume of the component do not have an impact on the component's cost. However, by increasing the weight by 100% increases the component's cost by 167%.

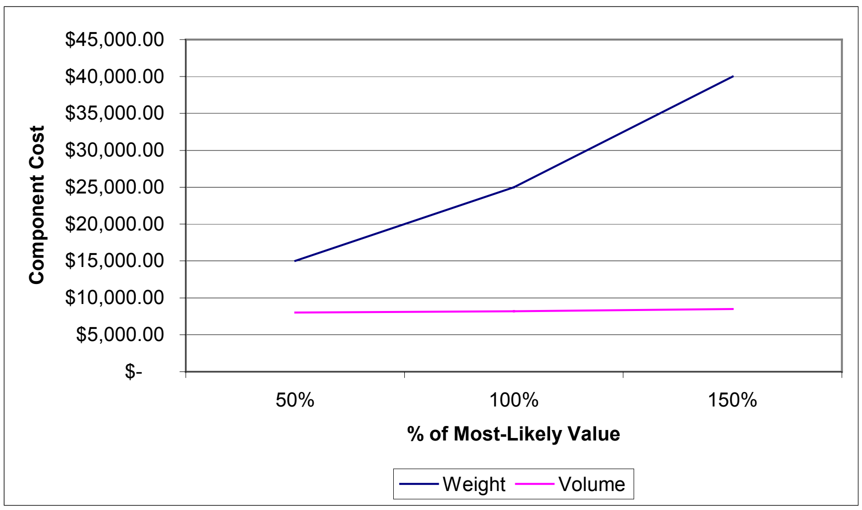

Figure 3.4 Example Spider-plot

3.5 Conceptual Model Development

As noted within the problem statement, the literature and software review indicated that there is a lack of uncertainty/risk assessment tools that are integrated with tools used for a cost analysis tools (e.g. cost models, databases). Also, no tools were discovered that used a WBS and cost structure format for representing the system and the system cost. To solve this problem, a WBS, model-based tool to estimate system-level cost risk is developed. The tool uses Monte Carlo simulation to estimate the average cost and average cost deviation for the system and all of its components. This section describes the design and assumptions of this model.

Simulation Characteristics

Several important issues must be addressed when constructing a simulation model. If the simulation is not designed using proper statistical methods, the simulation results will be useless. This section describes the following characteristics of the developed simulation:

1) Random Number Generator
2) Probability Distributions
3) Generation of Random Variates
4) Variance Reduction Techniques.

Random Number Generator

At the heart of every simulation is its random number generator. The random-number generator is a method or algorithm for obtaining a group of statistically valid random numbers. The history of the different methodologies and tools that are used to generate random numbers is described in Law and Kelton [12]; they also describe algorithms and comparisons among algorithms associated with several methods for developing random numbers. Law and Kelton also suggest using the prime modulus multiplicative linear congruential generator developed by Marse and Roberts [12]. The tool developed in this research uses this algorithm.

Probability Distributions

The probability distributions used to model the uncertainty of cost model parameters is also a very important aspect of the Monte Carlo simulation. Hayter [10] provides a complete list of the common probability distributions used in research and industry. These distributions are used based on both the attributes of the data under study and the application of the simulation (i.e. estimate durations of a scheduled activity). The tool developed in this research uses the probability distribution to estimate cost model parameter values during the conceptual design stage.

Research has been conducted on which types of distributions should be used for estimating values during the conceptual design stage when little information is known about the system. Ayyub [1], Hulett [11], Law, and Kelton [12] have suggested using the Triangular distribution for this application. However, others have indicated that the Beta distribution is more useful since it's shape can be adjusted to better "fit" the data [23]. However, the values of the parameters of the Beta distribution must be specified to arrive at the correct shape of the distribution. In order to make the tool more user-friendly, the Triangular distribution was used to estimate the uncertainty of the cost model parameters.

The Triangular distribution has three parameters; the minimum estimate, the most-likely estimate, and the maximum estimate. The user, based on prior experience or based on historical projects that have similar characteristics, determines these parameters. For example, suppose the user estimates the uncertainty of a component's weight with the minimum estimate equal to 10 lbs, the most-likely estimate equal to 30 lbs, and the maximum estimate equal to 50 lbs. The probability density function for this example is shown in Figure 3.5.

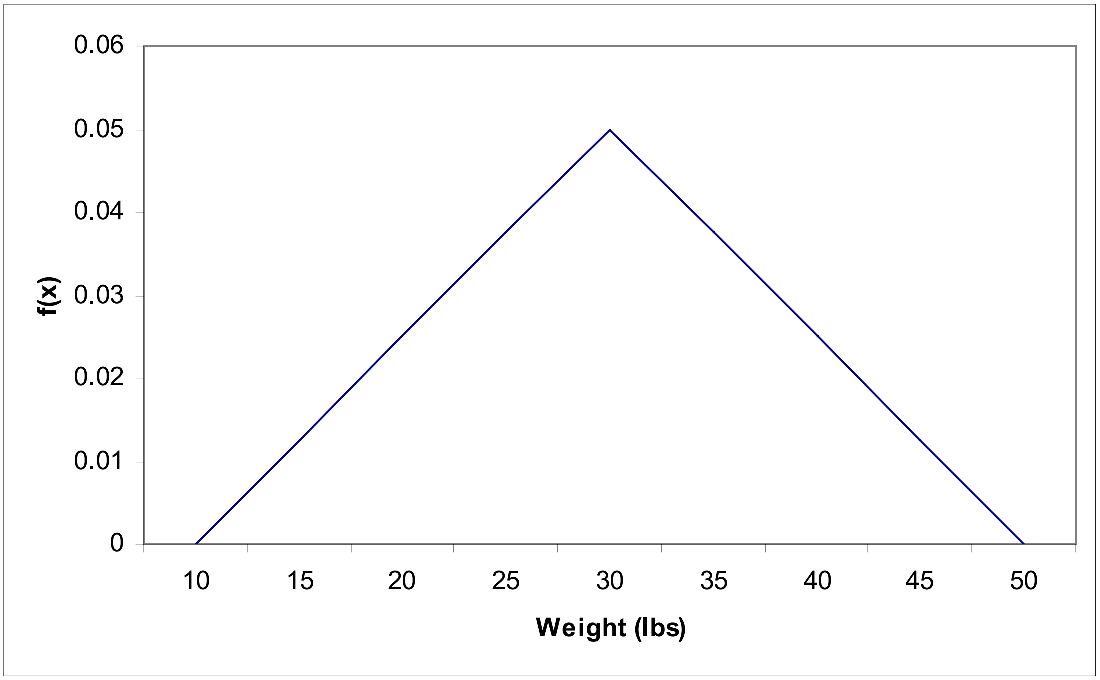

Figure 3.5 Example Triangle Probability Density Function

Generating Random Variates

Sample values from this distribution are obtained by algorithms used to generate random variates. There are several different approaches to generating random variates. The approach typically depends on which probability distribution is used for the simulation. Law and Kelton suggest using an inverse-transform algorithm for generating random variates from the Triangle distribution. According to their experience the inverse-transform algorithm is an efficient technique for generating random variates and facilitate variance-reduction techniques [12]. The inverse transformation technique involves two steps:

1) Generate a Uniformly distributed random number between 0 and 1.
2) The random variate will equal the inverse of the chosen probability's distribution function using the Uniform random number (requires the integration of the density function) [12].

For example, the inverse transformation of the Exponential distribution is:

$$F^{-1}(u) = -\beta \ln(1 - u), \text{ where } u \sim U(0,1) \qquad (3.10)$$

Variance Reduction Techniques

Variance reduction techniques are methods used to reduce the variance of the estimate without disturbing its expected value but obtaining better precision, e.g., smaller confidence intervals, for the same amount of simulating, or, alternatively, achieve a desired precision with less simulating (less simulation run time). One well-known variance-reduction technique is the use of common random numbers (CRN). The basic premise of CRN is using a set of different random numbers for each source of randomness, i.e. each random variable. For example, the simulation would use a unique set of random numbers for each source of variation. This allows the user to run the simulation less times to achieve an acceptable level of precision [12].

Conceptual View of Tool

As mentioned previously, it is beneficial to have a tool that links WBS components to the models that are used to estimate their cost. As shown below, this linkage occurs through the cost structure. The cost structure may contain several alternative cost models to estimate the cost element cost for a specific component. Each model's variables and parameters (e.g. weight, volume) either can be specified as a known value or estimated using the Triangular distribution in order to capture the uncertainty in the cost estimates. The cost estimates for each cost element within the cost structure are "rolled up" to determine the overall cost of the WBS component. Once all WBS components' cost estimates are derived, these estimates are similarly "rolled up" to derive the total estimated cost for the system. This concept is illustrated in Figure 3.6.

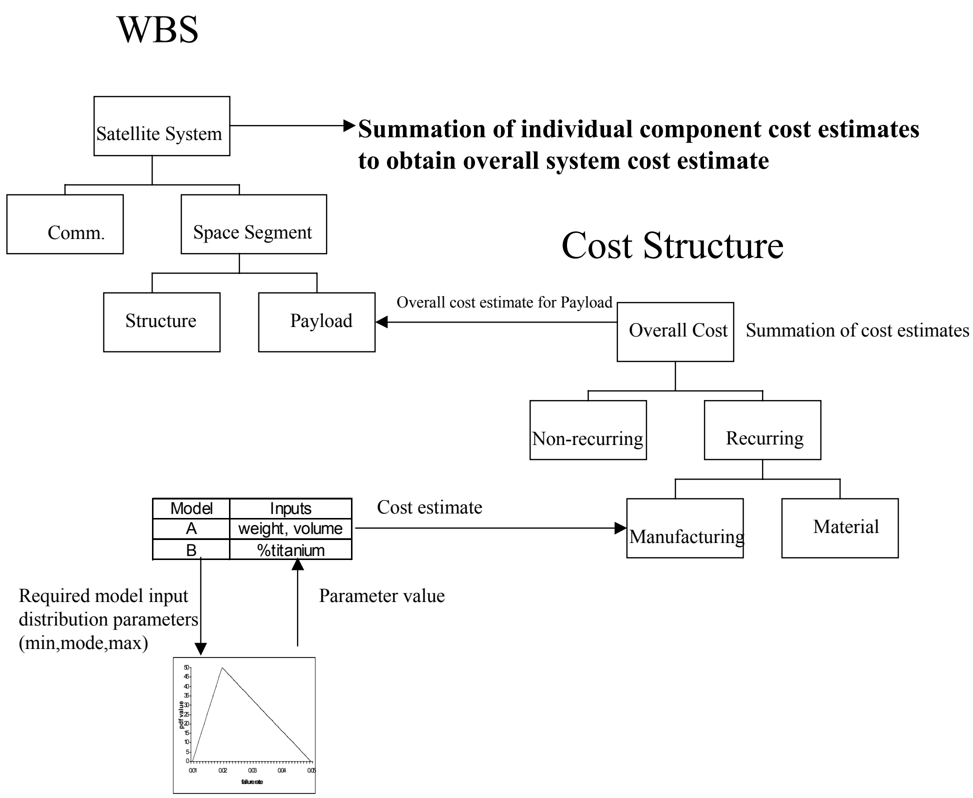

Figure 3.6 Conceptual View of Cost Risk Tool

Monte Carlo simulation is used to model the uncertainty of cost estimates. The Monte Carlo method involves the generation of values of random variables from known, or assumed, probability distributions (i.e. generating values for uncertain variables by randomly sampling from specified probability distribution). The sampled values are applied to component cost models. Repeated sampling results in a distribution of cost estimates and enables an interval estimate rather than a point estimate. The risk or uncertainty is estimated for each component and "rolled-up" to achieve a system level assessment. For this research, the cost structure has been chosen to remain static; i.e., the same cost structure is used for each component within the WBS.

As shown below, the estimated system cost $Cost_{Sys}$ is the sum of each of the component's cost, C_{ij}, where n is the total number of components in the WBS.

$$Cost_{Sys} = \sum_{j=1}^{n} C_j \tag{3.11}$$

As shown below, each component's cost is the sum of the cost for each of the s cost elements, k, defined in the cost structure, e.g. recurring manufacturing labor, engineering labor, material, overhead, operations and support.

$$C_j = \sum_{k=1}^{s} M_k{}^* \left(X_1^k, \ldots, X_k^k, \ldots, X_p^k \right) \tag{3.12}$$

where $X_j^k \sim T$ (min, mode, max) or deterministic.

Each cost element is an estimate obtained from a selected cost model, M_k^*, which is based on a set of p parameters and variables, X_j^k (where $j = 1, \ldots, p$). X_j^k is either a deterministic value or a random variable, e.g. a sampled value from a Triangular distribution with parameters (min, mode, max). The model used for each component/cost-element combination is selected from a set of applicable and available models, i.e., $M_k^* \in \{M_k^1, M_k^2 M_k^3, \ldots\}$.

Since some of the model inputs are random variables, the component costs and system cost are random variables. Therefore, the estimated total system cost is based on R simulation replications, i.e.,

$$E[Cost_{Sys}] = \frac{1}{R}\sum_{i=1}^{R}\sum_{j=1}^{n} C_{ij} \tag{3.13}$$

$$Var[Cost_{Sys}] = \frac{1}{R-1}\sum_{i=1}^{R}\left(Cost_{Sys_i} - E[Cost_{Sys}]\right)^2 \tag{3.14}$$

The user inputs the target cost and acceptable deviation from the target cost (%) for each component in the WBS. The acceptable deviation from the target cost is the acceptable cost interval for each component. If this value is 6%, then it is assumed that the interval represents +/- 3σ from the target cost. The simulation calculates both the average cost for each component of the WBS and the mean deviation from the target cost by the following equation:

$$MeanDeviation_i = \frac{\dfrac{\sum_{i=1}^{R}\left|C_i - TargetCost_i\right|}{R}}{TargetCost_i} \tag{3.15}$$

The simulation then compares the average component cost and mean deviation with the target cost and acceptable deviation from the mean to determine which components exhibit high cost or high risk.

The model also calculates the percentage of simulation runs where the component costs fit within the range of the acceptable deviation from the mean. This allows the user to see which components have high degrees of uncertainty or risk.

Tool Development

This research provides a risk/uncertainty analysis tool that integrates a WBS, cost structure, and cost models to assess risk using Monte Carlo simulation. The tool is developed using *Visual Basic* as a stand-alone application that uses *Microsoft Access*. The tool allows the analyst or design engineer to select and apply cost models to each cost structure element (manufacturing, material, labor, etc.) for each component of the WBS.

The construction of the WBS is based on a programming data structure known as a "tree structure". The terms that describe a tree structure are derived from both biology and genealogy. From botany come terms like *node* to describe where a branch might occur, *branch* to describe a link connecting two nodes, and a *leaf* to describe a node that has no branches leaving it. From genealogy comes terms that describe relationships. When one node is directly above another, the upper node is called the *parent* and the lower node is called the *child* [20].

For the purpose of this research the cost models are limited to parametric models. The tool allows variation of inputs within each cost model by obtaining random input estimates based on the Triangular distribution. Each WBS component is subsequently combined to obtain the system cost estimate. This process is then repeated and the program calculates and outputs the mean cost, standard deviation of cost, and histogram for the total system and each component. Based on user-specified values for acceptable cost and estimate deviations, high cost and high uncertainty components are identified. The system and component attributes are saved to a database for further study or comparisons. Screen shots from the software tool are provided in the following section. A high-level representation of how the program works in Figure 3.7.

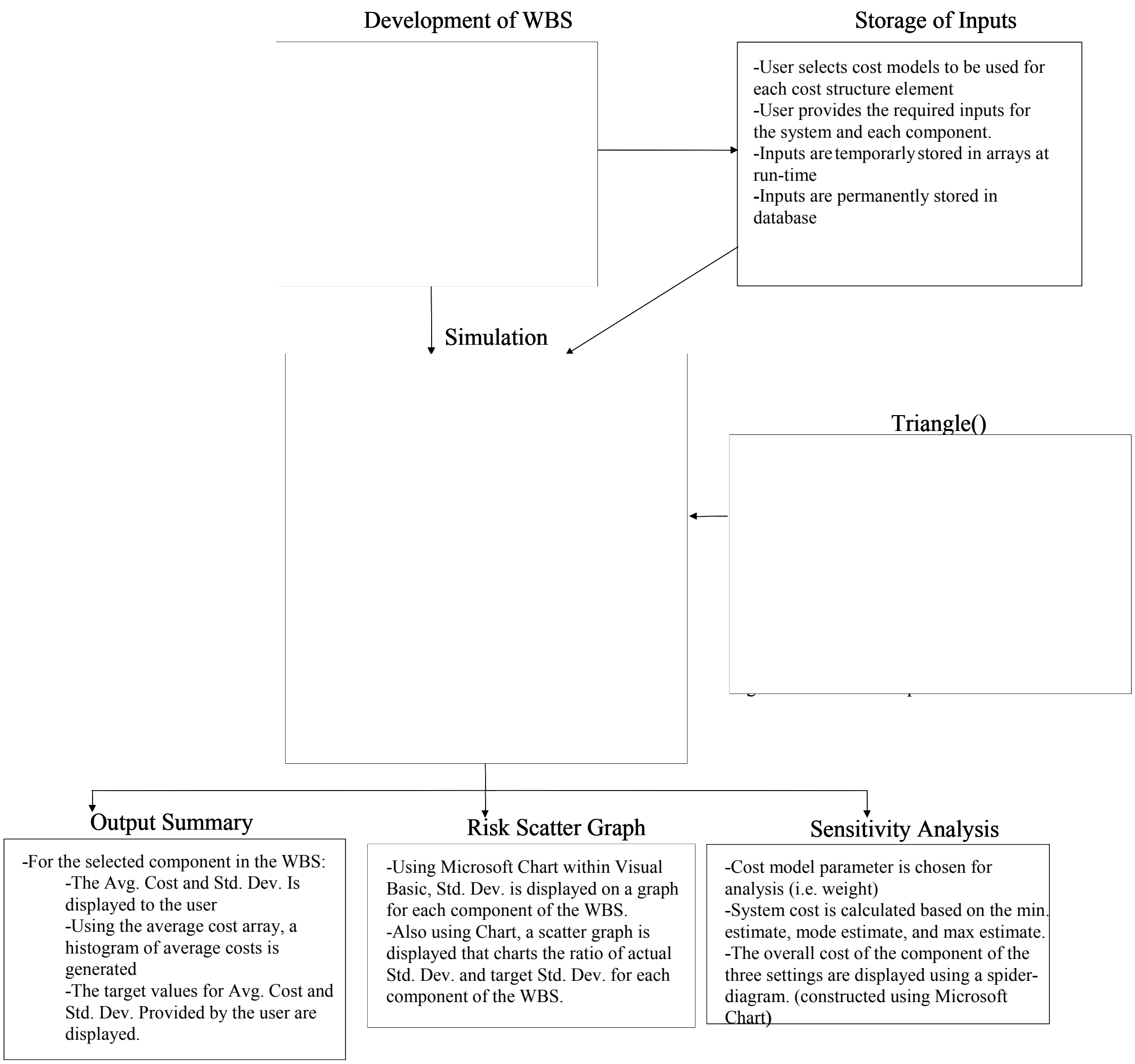

Figure 3.7 High-Level Representation of Simulation Code

Simulation Screen Shots

The first screen shot displays the environment used to construct and view the WBS. Although this tree-like representation is a good visual approach for displaying the WBS, there are size limitations due to the size of the computer screen. A *Microsoft Explorer*-like format has been suggested to display the WBS. This would compensate for the size limitation problem. The components that are highlighted in bold are components that exhibited both high cost and high risk.

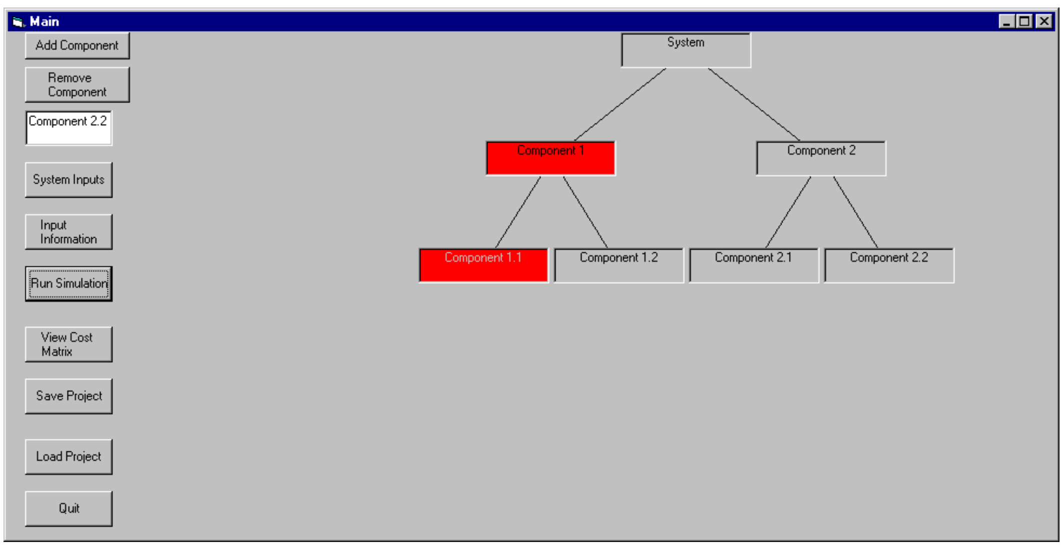

Figure 3.8 WBS Representation and High Risk/Cost Identification

The next screen shot displays the input screen for a component within the WBS. The user inputs the acceptable cost and acceptable deviation that will be used by the tool to determine if the component's cost estimate is high or the cost estimate exhibits high risk. In this case, the program allows the user to enter a percentage of the expected mean instead of the acceptable cost deviation. For each element within the cost structure, the user selects an appropriate cost model. Also, the user inputs the parameters for the chosen cost models (in this case, Weight and Complexity).

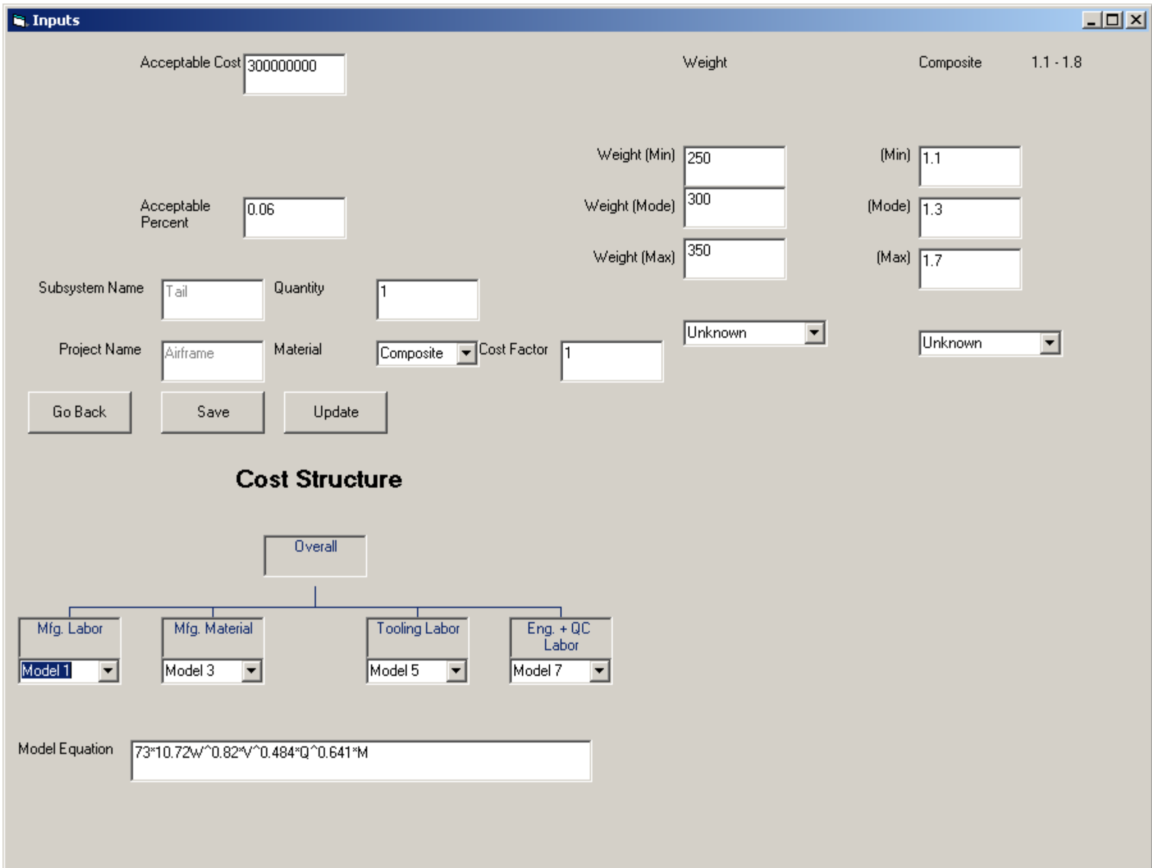

Figure 3.9 WBS Component Inputs

As shown in Figure 3.10, the user can then view the statistical outputs of each WBS component.

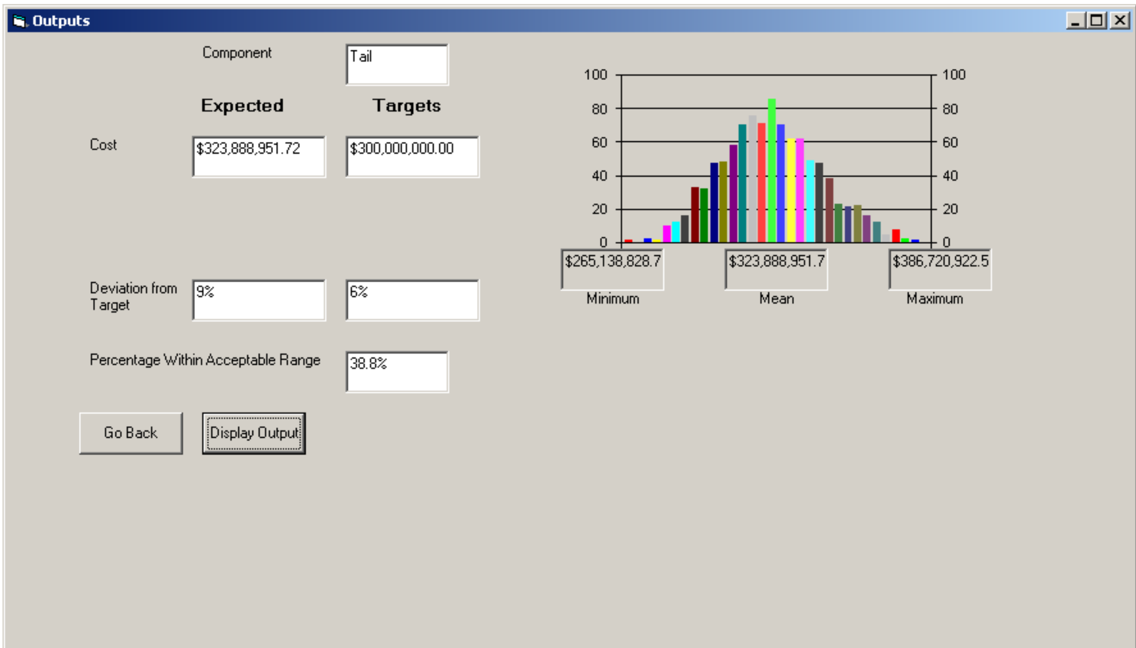

Figure 3.10 WBS Component Outputs

Components or subsystems that exhibit high cost or high uncertainty are highlighted red on the WBS. As shown in Figure 3.10, the standard outputs for each component are the average cost, average cost deviation and a cost histogram. The tool also generates an uncertainty/cost scatter graph that identifies which components exhibit high/low cost and high/low uncertainty. This allows analysts and design engineers to consider both cost and uncertainty for each component within the system. The program calculates two ratios for this chart. The risk ratio is the ratio of the estimated Mean Deviation divided by the acceptable deviation for the component. The cost ration is the ratio of the estimated C_{ij} divided by the target cost for the component. Notice how the landing gear (LG, represented by circle) is close (ratio of 1) to being on target with respect to both risk and cost. An example of the scatter graph is shown in Figure 3.11.

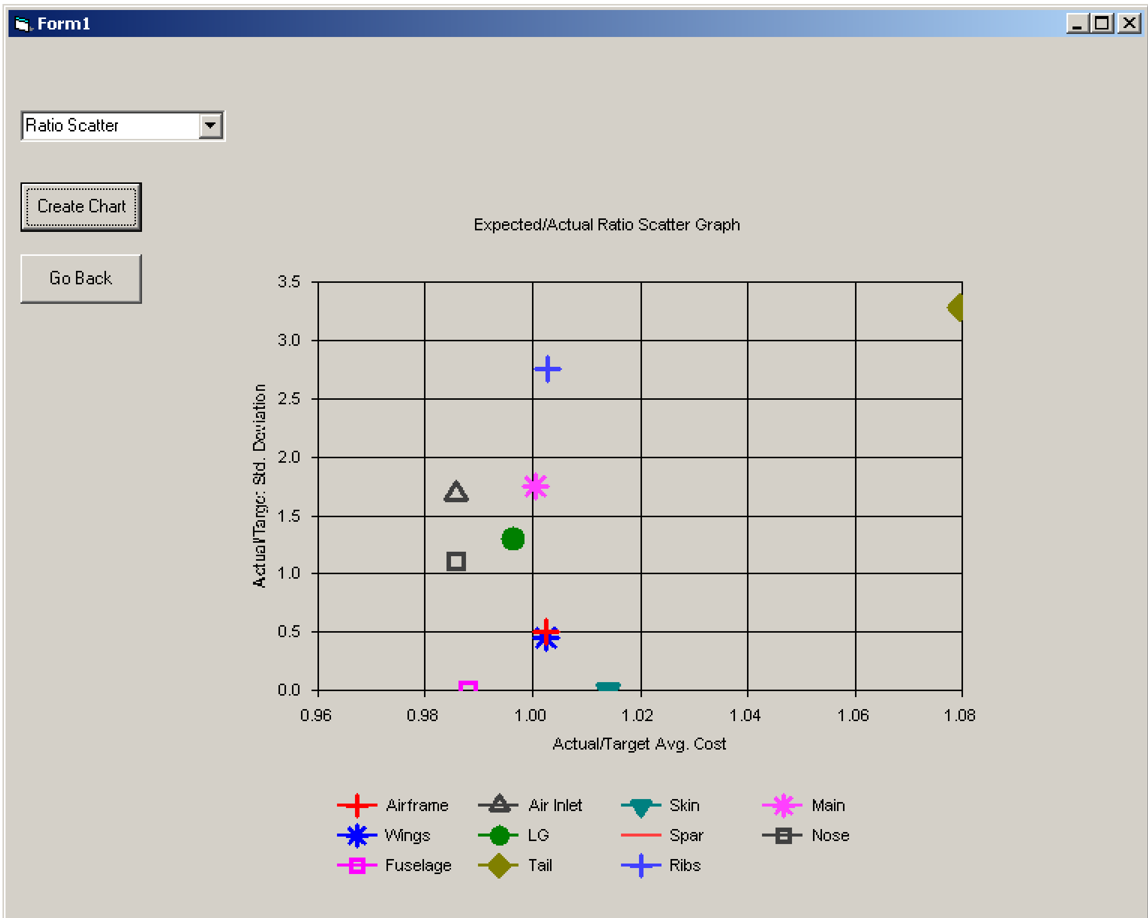

Figure 3.11 Uncertainty/Risk Ratio Scatter Graph

The user can then conduct a sensitivity analysis on the system or its components. The model uses spider-plots to graphically display the effects of changing cost model parameters for each component. This helps identify the cost drivers for the individual component and the system. An example of a system-generated spider-plot is shown in Figure 3.12.

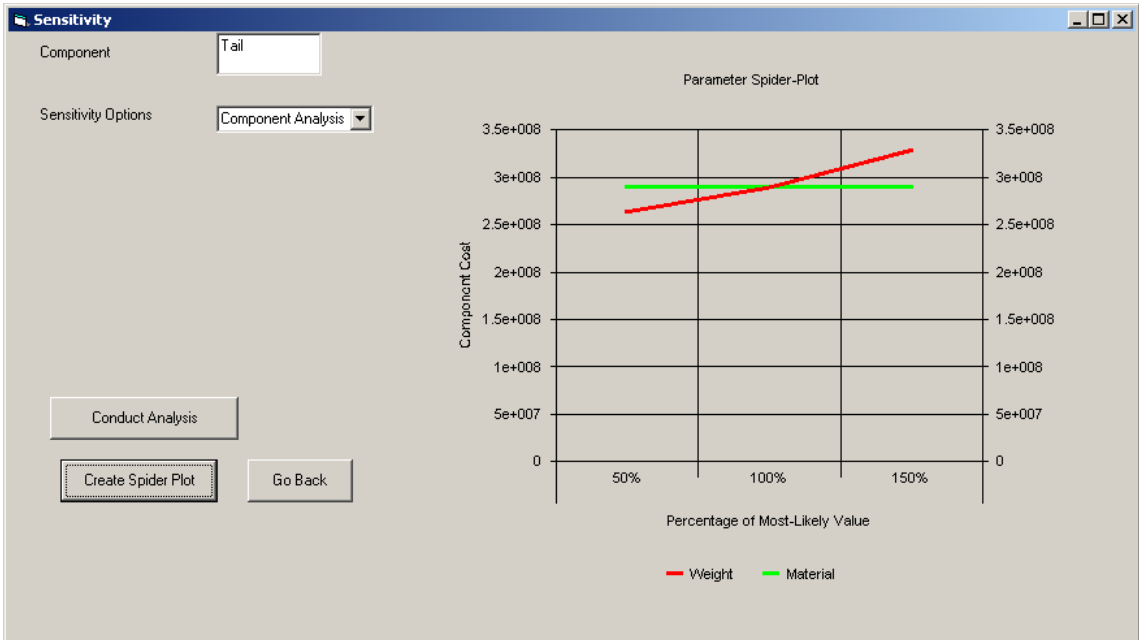

Figure 3.12 Example Spider-plot

3.6 Model Validation

In order to validate the tool, a realistic example was developed. The example is a proposed design of an airframe. The WBS for the example is shown in Figure 3.13.

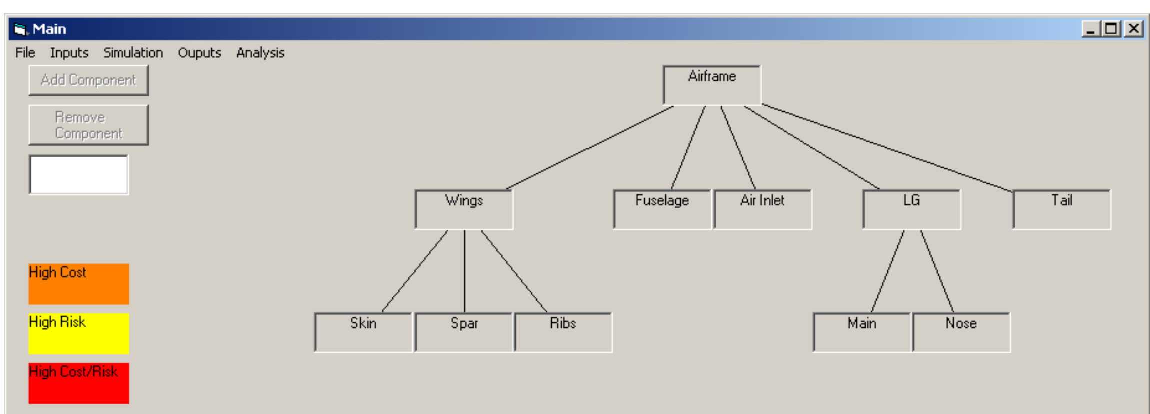

Figure 3.13 Airframe Example WBS

The cost structure used for this example is shown in Figure 3.14.

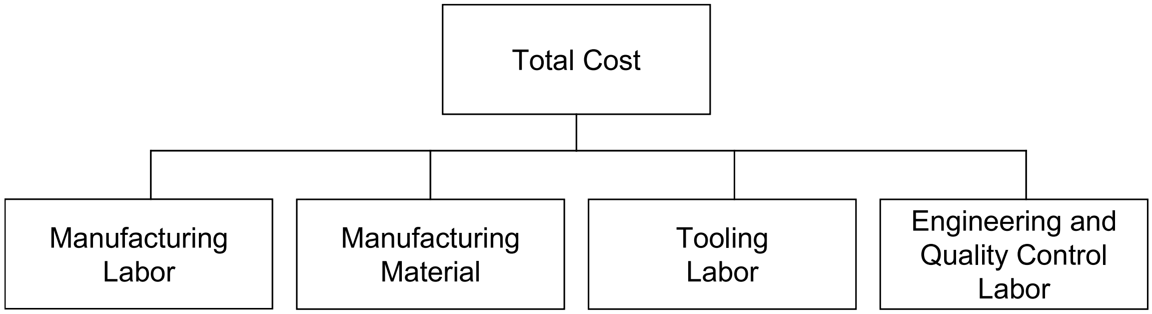

Figure 3.14 Airframe Example CBS.

Although the tool is capable of managing multiple models, the example has one available cost model for each cost element of the CBS. The parametric cost models used for the example were obtained from an aircraft design book [16] and RAND report [17]. The models are shown below.

$$Mfg.Labor = 73 \cdot 10.72 \cdot Weight^{0.82} \cdot Velocity^{0.484} \cdot Quantity^{0.641} \cdot M_L \quad (3.16)$$

$$Mfg.Material = 16 \cdot Weight^{0.921} \cdot Velocity^{0.621} \cdot Quantity^{0.799} \cdot M_M \quad (3.17)$$

$$ToolingLabor = 88 \cdot 8.71 \cdot Weight^{0.777} \cdot Velocity^{0.696} \cdot Quantity^{0.263} \cdot M_L \quad (3.18)$$

$$Eng.\&QCLabor = 86 \cdot 7.07 \cdot Weight^{0.777} \cdot Velocity^{0.894} \cdot Quantity^{0.163} \cdot M_L + 1.11 \cdot 0.133 \cdot Mfg.Labor \quad (3.19)$$

where;

M_L = *Material Labor Factor*

M_M = *Material Acquisition Factor.*

M_L is a man-hour complexity factor based on the type of material used. M_M is a material acquisition complexity factor based on the material type. This factor was obtained from a RAND report [17]. The ranges for both M_L and M_M are provided in equations 3.20 and 3.21.

$$M_L = \begin{cases} 1.0 \; for \quad Al \\ 1.1-1.8 \; for \quad Composite \\ 1.5-2.0 \; for \quad Steel \\ 1.3-2.0 \; for \quad Ti \end{cases} \tag{3.20}$$

$$M_M = \begin{cases} 1.0 \; for \quad Al \\ 5.05 \; for \quad Composite \\ .82 \; for \quad Steel \\ 3.27 \; for \quad Ti \end{cases} \tag{3.21}$$

The inputs for each WBS "leaf" component are shown in Table 3.2. As discussed previously, costs will only be estimated for WBS leaves and rolled up to obtain other costs. The Subsystem and Quantity columns are indented to illustrate the hierarchical relationships within the WBS (e.g. there are 6 ribs in each wing, 2 wings for each airframe constitutes a total of 12 ribs).

Table 3.2 Airframe Example Inputs

Subsystem	Quantity	Acceptable Deviation from Mean (%)	Target Cost (millions)	Weight (lbs)	Material
Airframe	1	6	$3,025.0	--	--
Wings	2	5	$675.0	--	--
Ribs	6	2.5	$105.0	TRNG(15,20,25)	Aluminum
Skin	2	3	$400.0	220	Aluminum
Spar	2	5	$170.0	TRNG(70,75,78)	Aluminum
Fuselage	1	3	$980.0	1575	Aluminum
Air Inlet	1	5	$340.0	TRNG(250,300,350)	Titanium
LG	1	2	$845.0	--	--
Main	2	2	$600.0	TRNG(500,600,700)	Steel
Nose	1	5	$245.0	TRNG(170,175,180)	Steel
Tail	1	6	$300.0	TRNG(250,300,350)	Composite

The results of the simulation, based on 1000 replications and a quantity of 500 aircraft, is provided in Table 3.3.

Table 3.3 Example Simulation Cost Results

Subsystem	Quantity	Acceptable Deviation from Target (%)	Mean Deviation from Target (%) - Baseline	Target Cost (millions)	Expected Cost (millions) Baseline	Percentage Within Acceptable Range (%) - Baseline
Airframe	1	6	6	$3,025.0	$3,202.2	65.7
Wings	2	5	1	$675.0	$676.6	100.0
Ribs	6	2.5	4	$105.0	$105.4	34.0
Skin	2	3	1	$400.0	$405.6	100.0
Spar	2	5	3	$170.0	$165.6	99.0
Fuselage	1	3	1	$980.0	$968.2	100.0
Air Inlet	1	5	5	$340.0	$345.3	54.1
LG	1	2	5	$845.0	$886.8	15.6
Main	2	2	8	$600.0	$645.0	8.2
Nose	1	5	2	$245.0	$241.8	95.9
Tail	1	6	6	$300.0	$325.4	52.9

This serves as the baseline design for the airframe. Two more competing airframe designs are considered. Alternative 1 modifies the design of the tail which reduces the uncertainty of its weight, the tail's weight is set at a determined value of 290lbs. Alternative 2 reduces the number of ribs need for each wing from 6 to 4. Since this design has not been tested before, the required weight of each rib is modeled using the Triangular distribution with parameters 20, 28, and 40lbs. The simulation output of these two alternatives is shown with the baseline design in Tables 3.4, 3.5, and 3.6.

Table 3.4 Alternative Design Cost Results

Subsystem	Quantity	Acceptable Deviation from Target (%)	Mean Deviation from Target (%) - Baseline	Mean Deviation from Target (%) - Alternative 1	Mean Deviation from Target (%) - Alternative 2
Airframe	1	6	6	6	6
Wings	2	5	1	1	2
Ribs	6	2.5	4	4	**10**
Skin	2	3	1	1	1
Spar	2	5	3	3	3
Fuselage	1	3	1	1	1
Air Inlet	1	5	5	5	5
LG	1	2	5	5	5
Main	2	2	8	8	8
Nose	1	5	2	2	2
Tail	1	6	6	6	6

Table 3.5 Alternative Design Cost Results (Cont.)

Subsystem	Quantity	Target Cost (millions)	Expected Cost (millions) - Baseline	Expected Cost (millions) - Alternative 1	Expected Cost (millions) - Alternative 2
Airframe	1	$3,025.0	$3,202.2	**$3,193.6**	**$3,210.9**
Wings	2	$675.0	$676.6	$676.6	**$685.4**
Ribs	6	$105.0	$105.4	$105.4	**$114.2**
Skin	2	$400.0	$405.6	$405.6	$405.6
Spar	2	$170.0	$165.6	$165.6	$165.6
Fuselage	1	$980.0	$968.2	$968.2	$968.2
Air Inlet	1	$340.0	$345.3	$345.3	$345.3
LG	1	$845.0	$886.8	$886.8	$886.8
Main	2	$600.0	$645.0	$645.0	$645.0
Nose	1	$245.0	$241.8	$241.8	$241.8
Tail	1	$300.0	$325.4	**$316.7**	$325.4

Table 3.6 Alternative Design Cost Results (Cont.)

Subsystem	Quantity	Target Cost (millions)	Percentage Within Acceptable Range (%) - Baseline	Percentage Within Acceptable Range (%) - Alternative 1	Percentage Within Acceptable Range (%) - Alternative 2
Airframe	1	$3,025.0	65.7	**66.5**	**46.0**
Wings	2	$675.0	100.0	100.0	100.0
Ribs	6	$105.0	34.0	34.0	**15.5**
Skin	2	$400.0	100.0	100.0	100.0
Spar	2	$170.0	99.0	99.0	99.0
Fuselage	1	$980.0	100.0	100.0	100.0
Air Inlet	1	$340.0	54.1	54.1	54.1
LG	1	$845.0	15.6	15.6	15.6
Main	2	$600.0	8.2	8.2	8.2
Nose	1	$245.0	95.9	95.9	95.9
Tail	1	$300.0	52.9	**54.3**	52.9

The first alternative reduces the average component cost of the tail by 2.67%. The total cost of the airframe decreased by 0.27%. The second alternative increased the cost of the ribs by 7.7%, with a significant increase in cost risk. Also, only 15.5% of the component's cost estimates out of the 1000 replications are within the acceptable target range. Based on these results, alternative one is chosen for further study.

In order to see if the differences between the baseline design and alternative design are significant, Welch's confidence interval test [12] is performed on the designs. According to the test results shown in Table 3.7, the difference in the tail's cost is significant between the baseline and Alternative 1 designs, with a level of significance of 5%. However, the difference in the airframe's cost is not significantly different at the 5% level of significance.

Table 3.7 Welch's Test Results ($\alpha = 0.05$)

Subsystem	Expected Cost (millions) Baseline - $\bar{X}_B$	Standard Deviation of Cost (Millions) - $\bar{X}_B$	Expected Cost (millions) Alternative 1 - $\bar{X}_1$	Standard Deviation of Cost (Millions) - $\bar{X}_1$	Halflength	$\bar{X}_B$-$\bar{X}_1$	Significant at α=0.05
Airframe	$3,202.2	$38.9	$3,193.6	$36.8	$10.50	$8.6	no
Wings	$676.6	$5.9	$676.6	$5.9	$1.64	$0.0	no
Ribs	$105.4	$5.6	$105.4	$5.6	$1.55	$0.0	no
Skin	$405.6	$0.0	$405.6	$0.0	----------------	--------------	----------------
Spar	$165.6	$1.8	$165.6	$1.8	$0.50	$0.0	no
Fuselage	$968.2	$0.0	$968.2	$0.0	----------------	--------------	----------------
Air Inlet	$345.3	$22.6	$345.3	$22.6	$6.26	$0.0	no
LG	$886.8	$23.8	$886.8	$23.8	$6.60	$0.0	no
Main	$645.0	$23.1	$645.0	$23.1	$6.40	$0.0	no
Nose	$241.8	$5.4	$241.8	$5.4	$1.50	$0.0	no
Tail	$325.4	$19.2	$316.7	$16.0	$4.90	$8.7	yes

An expected-versus-target cost/risk scatter graph is used to determine which component(s) are candidates for further research. The y-axis is the ratio of the expected standard deviation (based on the simulation) of component cost to the target standard deviation of component cost. The x-axis is the ratio of the expected component cost (based on the simulation) to the target component cost.

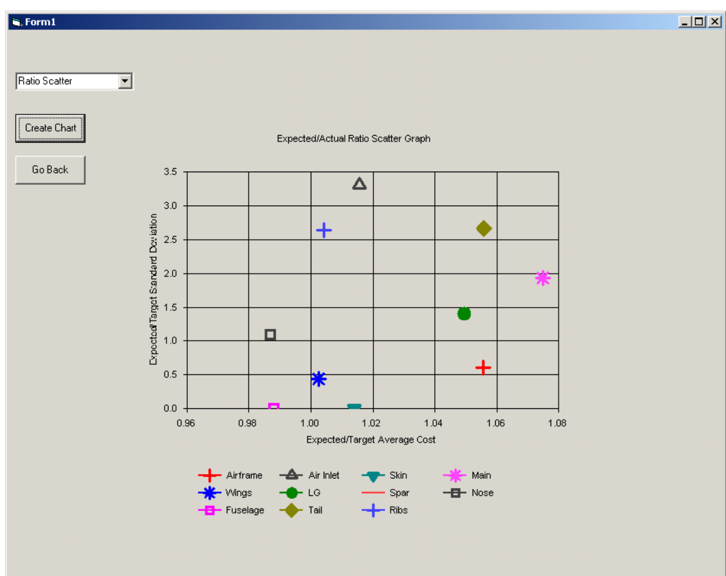

Figure 3.15 Expected versus Target Cost/Risk Scatter Graph

After inspection of the scatter graph, components can be chosen for future research. For example, the air inlet could be chosen based on its Expected-to-Target Standard Deviation Ratio, which was relatively higher than the other components. Also, the tail could be investigated based on its relatively high ratio of Expected-to-Target Cost Ratio. The main landing gear of the aircraft is chosen for further study for this example (referred to as Alternative 3) due to its relatively high Expected-to-Target Standard Deviation and Expected-to-Target Cost ratios. In order to understand the effects of modifying either the weight or material of the main landing gear, a spider-plot is produced by the tool and shown in Figure 3.16.

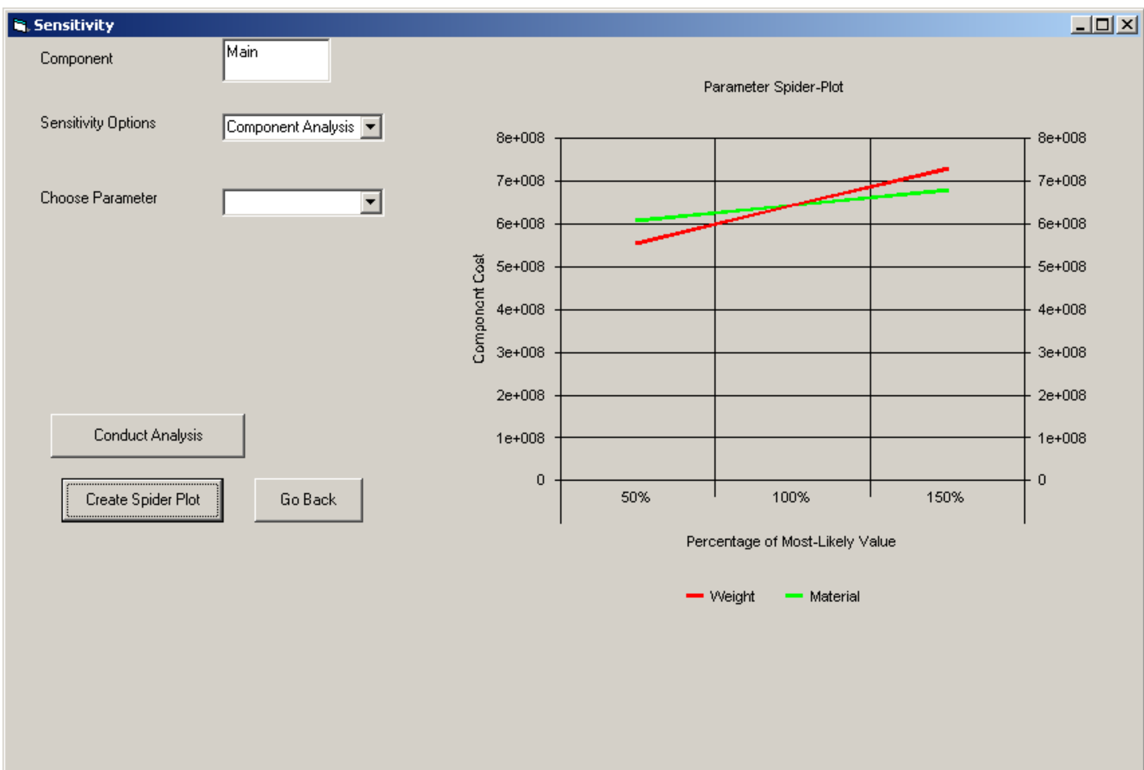

Figure 3.16 Airframe Example Spider-plot

It is concluded that varying the weight of the main landing gear has a greater impact than modifying the material. A new design for the main landing gear is developed which reduces the weight from 500, 600, and 700 pounds as the Triangular distribution parameters to 525, 550, and 575 pounds. Table 3.8 shows the results of the proposed design. The airframe's main landing gear cost decreased by 5% relative to the baseline case. Also, the cost risk decreased from 8% to 1%. The airframe's cost decreased by 1.39%.

Table 3.8 Improved Design Simulation Results

Subsystem	Acceptable Deviation from Target (%)	Mean Deviation from Target (%) - Baseline	Mean Deviation from Target (%) - Alternative 3	Target Cost (millions)	Expected Cost (millions) - Baseline	Expected Cost (millions) - Alternative 3
Airframe	6	6	**4**	$3,025.0	$3,193.6	**$3,149.3**
Wings	5	1	1	$675.0	$676.6	$676.6
Ribs	2.5	4	4	$105.0	$105.4	$105.4
Skin	3	1	1	$400.0	$405.6	$405.6
Span	5	3	3	$170.0	$165.6	$165.6
Fuselage	3	1	1	$980.0	$968.2	$968.2
Air Inlet	5	5	5	$340.0	$345.3	$345.3
LG	2	5	**1**	$845.0	$886.8	**$842.4**
Main	2	8	**1**	$600.0	$645.0	**$600.7**
Nose	5	2	2	$245.0	$241.8	$241.8
Tail	6	6	6	$300.0	$316.7	$316.7

A sensitivity analysis is conducted to study the affects of using common random numbers (CRN) in Monte-Carlo simulation. First, the simulation is executed for 1000 and 100 replications with the concept of CRN applied to each source of variation within the cost models parameters. Next, the simulation is executed for 1000 and 100 replications without applying the concept of CRN. Welch's test for significance between the baseline and Alternative 1 design are applied to each case. The results of the analysis are shown in Tables 3.9, 3.10, 3.11 and 3.12.

Table 3.9 Welch's Analysis (CRN, 1000 Replications)

Subsystem	Expected Cost (millions) Baseline - $\bar{X}_B$	Standard Deviation of Cost (Millions) - $\bar{X}_B$	Expected Cost (millions) Alternative 1 - $\bar{X}_1$	Standard Deviation of Cost (Millions) - $\bar{X}_1$	Halflength	$\bar{X}_B$-$\bar{X}_1$	Significant at α=0.05
Airframe	$3,202.2	$38.9	$3,193.6	$36.8	$10.50	$8.6	no
Wings	$676.6	$5.9	$676.6	$5.9	$1.64	$0.0	no
Ribs	$105.4	$5.6	$105.4	$5.6	$1.55	$0.0	no
Skin	$405.6	$0.0	$405.6	$0.0	----------------	--------------	----------------
Spar	$165.6	$1.8	$165.6	$1.8	$0.50	$0.0	no
Fuselage	$968.2	$0.0	$968.2	$0.0	----------------	--------------	----------------
Air Inlet	$345.3	$22.6	$345.3	$22.6	$6.26	$0.0	no
LG	$886.8	$23.8	$886.8	$23.8	$6.60	$0.0	no
Main	$645.0	$23.1	$645.0	$23.1	$6.40	$0.0	no
Nose	$241.8	$5.4	$241.8	$5.4	$1.50	$0.0	no
Tail	$325.4	$19.2	$316.7	$16.0	$4.90	$8.7	yes

Table 3.10 Welch's Analysis (CRN, 100 Replications)

Subsystem	Expected Cost (millions) Baseline - $\bar{X}_B$	Standard Deviation of Cost (Millions) - $\bar{X}_B$	Expected Cost (millions) Alternative 1 - $\bar{X}_1$	Standard Deviation of Cost (Millions) - $\bar{X}_1$	Halflength	$\bar{X}_B$-$\bar{X}_1$	Significant at α=0.05
Airframe	$3,197.8	$38.1	$3,188.4	$37.0	$10.42	$9.4	no
Wings	$676.2	$5.4	$676.2	$5.4	$1.50	$0.0	no
Ribs	$105.2	$5.4	$105.2	$5.4	$1.50	$0.0	no
Skin	$405.6	$0.0	$405.6	$0.0	----------------	--------------	----------------
Spar	$165.5	$1.9	$165.5	$1.9	$0.53	$0.0	no
Fuselage	$968.2	$0.0	$968.2	$0.0	----------------	--------------	----------------
Air Inlet	$344.4	$22.4	$344.4	$22.4	$6.21	$0.0	no
LG	$884.3	$22.4	$884.3	$22.4	$6.21	$0.0	no
Main	$642.2	$22.3	$642.2	$22.3	$6.18	$0.0	no
Nose	$242.2	$5.2	$242.2	$5.2	$1.44	$0.0	no
Tail	$324.6	$20.9	$315.2	$16.3	$5.19	$9.4	yes

Table 3.11 Welch's Analysis (Without CRN, 1000 Replications)

Not Using CRN - 1000 Replications

Subsystem	Expected Cost (millions) Baseline - $\bar{X}_B$	Standard Deviation of Cost (Millions) - $\bar{X}_B$	Expected Cost (millions) Alternative 1 - $\bar{X}_1$	Standard Deviation of Cost (Millions) - $\bar{X}_1$	Halflength	$\bar{X}_B$-$\bar{X}_1$	Significant at α=0.05
Airframe	$3,199.9	$38.8	$3,189.4	$36.7	$10.47	$10.5	yes
Wings	$676.5	$5.8	$676.9	$5.9	$1.62	-$0.4	no
Ribs	$105.2	$5.6	$105.5	$5.6	$1.54	-$0.3	no
Skin	$405.6	$0.0	$405.6	$0.0	----------------	--------------	----------------
Spar	$165.7	$1.8	$165.8	$1.8	$0.50	-$0.1	no
Fuselage	$968.2	$0.0	$968.2	$0.0	----------------	--------------	----------------
Air Inlet	$343.8	$22.6	$344.5	$23.2	$6.34	-$0.7	no
LG	$886.5	$23.8	$884.5	$23.7	$6.58	$2.0	no
Main	$644.3	$23.1	$642.6	$23.1	$6.40	$1.7	no
Nose	$242.2	$5.4	$241.9	$5.5	$1.51	$0.3	no
Tail	$325.0	$19.2	$315.4	$16.0	$4.89	$9.6	yes

Table 3.12 Welch's Analysis (Without CRN, 100 Replications)

Not Using CRN - 100 Replications

Subsystem	Expected Cost (millions) Baseline - $\bar{X}_B$	Standard Deviation of Cost (Millions) - $\bar{X}_B$	Expected Cost (millions) Alternative 1 - $\bar{X}_1$	Standard Deviation of Cost (Millions) - $\bar{X}_1$	Halflength	$\bar{X}_B$-$\bar{X}_1$	Significant at α=0.05
Airframe	$3,202.4	**$38.1**	$3,189.0	$37.0	$10.41	$13.4	yes
Wings	$676.6	$5.4	$677.8	$5.9	$1.57	-$1.2	no
Ribs	$105.3	**$5.4**	$105.2	$5.3	$1.48	$0.1	no
Skin	$405.6	$0.0	$405.6	$0.0	----------------	--------------	----------------
Spar	$165.6	$1.9	$166.0	$1.9	$0.53	-$0.4	no
Fuselage	$968.2	$0.0	$968.2	$0.0	----------------	--------------	----------------
Air Inlet	$345.6	$22.4	$342.7	$21.7	$6.11	$2.9	no
LG	$885.8	$22.4	$885.0	$25.0	$6.58	$0.8	no
Main	$644.5	$22.3	$643.7	$24.3	$6.46	$0.8	no
Nose	$241.3	$5.2	$241.3	$4.6	$1.36	$0.0	no
Tail	$326.3	$20.8	$315.3	$16.3	$5.18	$11.0	yes

The simulation results that utilized CRN indicate the only significant difference in cost is for the airframe's tail. Also, it is important to note that the components that are not affected by the alternative design do not exhibit any changes in their component cost. Without applying CRN, the components that are not affected by the alternative design did exhibit changes in component cost due to the variability caused by the random number generator. Even though these differences were shown to be not significant (α=0.05), more complicated designs that require fewer simulation replications could exhibit higher variability of the component cost that is not attributed to actual design modifications. Although the airframe cost difference was significant by not applying CRN with 100 replications, the airframe cost difference was insignificant with using 1000 replications. One potential problem of applying CRN is that the number of unique random number streams utilized by the random number generator would increase exponentially with the increase of sources of variation. Further research is needed to discover the impact of not using CRN in a Monte-Carlo simulation.

3.7 Conclusions and Further Research

The WBS representation for the proposed system facilitates a "systems engineering" approach for risk analysis. The WBS is then linked to the cost structure that contains alternative models for each cost element. This provides an environment where an entire cost analysis can be conducted (develop WBS, choose cost models, assess costs and risks, make decision). Also, the database capabilities of the tool effectively allow users to compare and contrast competing design alternatives based on the risk or uncertainty of cost estimates. The sensitivity analysis component of the tool allows the user to identify the cost drivers of the system. Although the software developed to address the lack of a decision support risk analysis tool requires further research and development, this tool is applicable for conducting risk analysis studies during the conceptual design stage.

Topics for Further Research

- The distribution parameters (min, mode, max) should be derived from user inputs that are easier for the user to specify (e.g. value within the 10^{th} percentile, 50^{th} percentile, value within the 90^{th} percentile rather than the 0^{th} percentile, mode, and 100^{th} percentile)
- The tool should support cost model management. The current tool has a fixed number of cost models that are available to the user. A system should be developed that allows the user to define new cost models or link to existing cost models for each cost element within the cost structure. The system should automatically determine the parameters that are needed and provide input means to the user.

- Cost risk optimization features should be considered for the tool. The optimum values for the model parameters would be identified that minimize system and component cost.
- The cost structure should be dynamic (i.e. the user should develop the cost structure at run time).

This prototype was developed to illustrate concepts and identify further development needs.

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CHAPTER IV

OVERALL CONCLUSIONS AND FUTURE RESEARCH

4.1 Overall Conclusions

This research has sufficiently met all research objectives. A generic cost estimation process and a tool assessing risk and uncertainty of cost estimates were developed. The risk/uncertainty tool gives engineers a valuable means for making design decisions within the conceptual design stage. The developed generic cost estimation process gives engineers a comprehensive road map for conducting a cost analysis. Also, this research serves as a foundation for further research. The specific conclusions for each research objective are discussed below:

4.1.1 Chapter 2 Conclusions

The generic model that was documented should give cost engineers and managers a baseline on conducting an estimation study. A summary of conclusions from the research are listed below:

7) NASA focused more on NASA-specific model and methodology selection.
8) The Air Force and Army's cost estimation processes focused more on the documentation requirements that are needed during the cost estimation process.

9) The process of choosing a cost methodology and model was extremely difficult. The Army Cost Analysis Manual gave the most insight into these individual processes.

10) The portion of cost estimation that was typically overlooked was the process and tools used to meet the requirements for documenting cost estimates. Without a good documentation process, the organization loses a lot of information vital to

11) tracking cost performance. Also, the documentation provides cost engineers with a knowledge base that will reduce the time and effort to conduct future cost estimates.

12) The Navy documentation had more detailed information concerning the different methods for validating cost estimates.

13) Assessing the uncertainty of the cost estimate was one activity identified in the literature review. However, the focus has been on assessing uncertainty instead of using this information to make design decisions. This prompted further research in the assessment of uncertainty portion of the cost estimation process.

4.1.2 Chapter 3 Conclusions

The WBS representation for the proposed system facilitates a "systems engineering" approach for risk analysis. The WBS is then linked to the cost structure that contains alternative models for each cost element. This provides an environment where an entire cost analysis can be conducted (develop WBS, choose cost models, assess costs and risks, make decision). Also, the database capabilities of the tool effectively allow users to compare and contrast competing design alternatives based on the risk or uncertainty of cost estimates. The sensitivity analysis component of the tool allows the user to identify the cost drivers of the system. Although the software developed to address the lack of a decision support risk analysis tool requires further research and development, this tool is applicable for conducting risk analysis studies during the conceptual design stage.

4.2 Overall Future Research

This research has benefited the risk/uncertainty assessment activity within the cost estimation process. All other activities of the developed generic cost estimation process should also be researched and documented in detail. Tools that are need for each activity should be identified and obtained or developed. Also, a framework should be developed that visually displays both the cost estimation process and the tools/documents needed for each activity within the process. The detailed list of future research for each chapter is listed below.

4.2.1 Chapter 2 Future Research

1) Apply process to industry case study and obtain industry feedback.
2) Provide more detailed report on each cost estimation activity with respect to the System Development Life Cycle.
3) Develop a more descriptive process diagram that can indicate repeated activities.

4) Identify specific tools for implementing each activity of the cost estimation process.

5) Develop framework for integrating actual tools and documentation with process documentation.

4.2.2 Chapter 3 Future Research

1) The distribution parameters (min, mode, max) should be derived from user inputs that are easier for the user to grasp (e.g. value within the 10th percentile, median, value within the 90th percentile)

2) The tool should support cost model management. The current tool has a fixed number of cost models that are available to the user. A system should be developed that would allow the user to define new cost models or link to existing cost models for each cost element within the cost structure. The system would then determine which parameters would be needed and display the required inputs to the user.

3) Cost risk optimization features could be added to the tool. The optimum values for the parameters with the cost models could be derived that would minimize system and component cost.

4) The cost structure could be dynamic (i.e. the user could develop the cost structure at run time).