DESIGNING A COST ESTIMATION METHOD FOR THE DESIGN OF PROTOTYPE SYSTEMS

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LIST OF SYMBOLS AND ABBREVIATIONS

σ	Standard Deviation
ABC	Activity-Based Costing
ABM	Activity-Based Management
ASME	American Society of Mechanical Engineers
BOE	Basis of Estimate
CAD	Computer Aided Design
CAIV	Cost as an Independent Variable
CeBOK	Cost Estimation Body of Knowledge
CER	Cost Estimate Relationship
CCA	Circuit Card Assembly
COCOMO	Constructive Cost Model
CNC	Computer Numerically Controlled
DOT	Department of Transportation
EVM	Earned Value Management
EVMS	Earned Value Management System
FAR	Federal Acquisition Regulation
GDOT	Georgia Department of Transportation
GTRI	Georgia Tech Research Institute
IP	Intellectual Property
ISO	International Standards Organization
LED	Light Emitting Diode
MWH	Maximum Work Hours
NASA	National Aeronautics and Space Administration
R&D	Research and Development
ROI	Return on Investment
RPM	Raised Pavement Marker
SCEA	Society of Cost Estimation and Analysis
SEER	Software Evaluation and Estimation of Resources
SLA	Stereo-Lithography Apparatus
STL	Standard Tessellation Language
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
WBS	Work Breakdown Structure

SUMMARY

Research and development environments present unique challenges to designers in that each new project can vary greatly from the last. Often, a major portion of these developments is related to the design and production of a prototype. The need for a prototype is driven by the need to demonstrate critical operations of a system or subsystem such that it will serve as a basis for how a design will move forward. Due to the fact there is typically some aspect of a prototype that is not well understood there can be considerable uncertainty associated with the amount of resources needed to support the design and fabrication of such a prototype and the resources which will allow the continuation of the organization creating prototypes. The frequent need for prototype creation in R&D environments means that cost estimation exercises must be flexible and able to account for high levels of uncertainty.

First the problem, definitions and assumptions are delineated. Of particular importance is a clear definition for what a prototype is as well as what will make the method robust. A prototype is a primitive or original development item. It is often a physical representation of a theory that has yet to be proven. In terms of robustness, one must set goals that will define when the result of the estimation process is satisfactory. Leveraging these definitions, the primary challenge of this work becomes addressing a key question: "*When is enough information gathered to generate a robust estimate for the design of prototype systems?*"

The argument is made that prototype systems inherently have a high amount of uncertainty and that the level of robustness is a matter of risk the estimator is willing to take related to the acceptance of uncertainty. In this case, the risk is related to undesirable consequences the estimator is willing to accept related to the chance of

failure in producing an appropriate prototype. All of these points are made while considering cost, schedule, and performance concurrently.

A detailed literature survey was performed to ensure the most appropriate cost estimation tools and methods for incorporating uncertainty in the process were considered during the design of the proposed cost estimation method. While considering these arguments, the proposed cost estimation method was designed using proven design methods as a logical framework. The estimation method leveraged the design process of Pahl and Beitz while monitoring the structural soundness of the development using the Validation Square. Lastly, some unique tools were proposed to incorporate information on organizational resources and the assignment of those resources as well as a mathematical representation of for evaluations including cost, schedule, and performance.

Although the focus of this thesis is the cost estimation method and not the specific applications, in order to demonstrate the proposed method and its effectiveness, the method was applied to two projects developed at the Georgia Tech Research Institute. A theoretical model based upon an actual development, and a sponsored research project completed at the Georgia Tech Research Institute. The theoretical example was based on the development of SIMON, a robotic head for experimental use by a faculty member at the Georgia Tech College of Computing. The other project was sponsored by the Georgia Department of Transportation and related to research for the automatic filing of cracks on road surfaces.

The thesis concludes with a critical evaluation of the method’s performance in the example problems leading up to statements made on the expected utility and limitations of the proposed method. The value of incorporating methodical cost estimation techniques is made evident in the thesis with an emphasis placed upon the value of implementation of the method to the Georgia Tech Research Institute. In general, the

introduction of design methodology to cost estimation techniques is also demonstrated to be effective.

Several future research opportunities resulted from the work presented in the thesis. These opportunities were made evident through a critical review of the method. Despite improvements identified in the example applications, a more detailed analysis of the efficiency of the proposed method in comparison to other accepted methods needs to be made. Also, applying the method to projects with larger teams could serve as a means to broaden the applicability of the method while also improving the implementation of various work planning tools. Lastly, only the basics of the relationship between the estimator, design engineers, and the organization were explored. A detailed consideration of this relationship could offer great benefits by building on past research performed in enterprise design.

CHAPTER 1

Proposed Cost Method Introduction

1.1 Motivation for New Estimation Method

Cost estimation is a difficult task to accomplish effectively, and to define what “effectively” means in this context is equally challenging. In order to address the definition of effectively in this context, one needs to consider uncertainty, consequence, and the general desires of the estimator when approaching this problem. Further complications are encountered when considering estimation as it applies to prototype systems. The design of prototype systems increases the complexity of uncertainty calculations because prototypes inherently include at least one major task that contains a sizeable number of unknowns.

To address this complex issue, it is proposed that a unique approach to estimation be taken. The unique nature of the method proposed is based upon design theory in coordination with proven cost estimation techniques. It is postulated that the estimation process be approached as a high level design problem and that a prescriptive design methodology be applied to enhance the structure of the estimation process. By taking this approach, the proposed estimation method can improve estimation processes by including techniques found in both cost estimation and established mechanical design processes.

In tackling this issue, the role of effectiveness must be scrutinized such that a clear definition is given to define when an estimate is satisfactory. The term robust has been chosen to reflect the need for the cost estimation method to be effective. It is postulated that the level of robustness is tied to the characterization of uncertainty as it relates to the estimation process particularly in goals provided by an estimator. Additionally, an argument is made specific to systems involving the construction of prototypes. Prototypes are oftentimes on the critical design path, and by their nature include high levels of uncertainty. This is because there is typically some aspect of a prototype that is not well understood meaning a considerable amount of uncertainty can be associated with what is needed to complete the design such a prototype. The proposed method will address how to systematically reduce this uncertainty for the purpose of creating a robust estimation for design resources. The clear problem remaining is that of defining what a robust estimate is, which results in addressing the key question driving this research:

"When is enough information gathered to generate a robust estimate for the design of prototype systems?"

It is important to note the selection of tense in this key question. The gathering of information is ongoing during the estimation process meaning the cost estimation method must not only generate a suitable estimate based upon the goals of the estimator, but it must work in an environment where the information is continuously evolving.

1.1.1 General Need for Better Estimation Tools in the Design of Prototypes

Anyone that has worked early in the design phase of a project has been faced with generating an estimate with little information. The estimator, as referred to throughout this document, is the individual (or committee) that must make a decision about when information is sufficient to balance the interactions between the level of risk the estimator is willing to accept, and the resources available to generate the estimate. As a matter of clarification, it must be understood that the level of consequence is directly related to the accumulation of uncertainty that is part of any estimate. A good example to illustrate this notion of uncertainty as it relates to consequence is to think of how one may generate the most accurate estimate. The only way to generate an exact estimate with no uncertainty is to complete the work before the estimate is completed. This notion seems ludicrous as it should, but highlights the necessity of characterizing uncertainty and approximation in any estimate and is even captured in the definition of the word:

> *An estimate is "to judge tentatively or approximately the value, worth, or significance of [1]"*

When dealing with the design of a prototype system, the crux of the problem lies in how to characterize the risk and thus consequence associated with the cost, schedule, and performance. Regardless of how systems may be broken down, uncertainty exists at each division. Another difficulty in the estimation process, which can affect the confidence in the estimate, is how the estimation is actually generated. Three types of estimates are discussed that range from high level initial estimates to a more in depth estimate generation. The terms used for these types of estimates are: 1) Basic Estimate, 2) Intermediate Estimate, and 3) Detailed Estimate. The different types of estimates are discussed at length in Section 3.2. Varying levels of estimates are needed throughout the proposal stage as one must first decide whether to pursue the opportunity, which may eventually lead to a detailed proposal effort that must bring to light the potential for cost overruns prior to committing an organization's resources.

The proposed method will be applied to real prototype estimates and tracked throughout the prototype design period as a demonstration of the method's effectiveness. The examples will be one theoretical model, and one project completed at the Georgia Tech Research Institute (GTRI). The theoretical example will be based on the robotic development of SIMON, which will include design information from that implementation. In this example, several concepts will be demonstrated such as the ability to apply the method at varying levels of detail, and the ability to characterize uncertainty. The other example includes the development of a project sponsored by the Georgia Department of Transportation (GDOT) related to research for the automatic filling of cracks on road surfaces. In this example, the results of applying the proposed method beyond application within a theoretical construct are demonstrated. Additional details are also explored such as using various staff assignment tools, progressive tracking of estimation results, and the overall effectiveness of the method in practice. These particular examples present a case for better estimation tools in research and development environments.

1.1.2 Intellectual Questions and Validation of Methods

Prior to engaging a large endeavor such as generating a new estimation method, one must have a clear path to follow as well as a means to evaluate the resulting solution. To set the initial guidance for this research, a set of intellectual questions was compiled with a focus on addressing the question of "when is enough information gathered for an estimate?" In order to answer this question a number of intellectual questions have been proposed:

1) ***When is enough information gathered to generate a robust estimate for the design of prototype systems?***

2) ***How do you characterize uncertainty in the estimation process?***

3) ***Why do estimates need to consider interactions between performance, schedule, and cost?***

4) ***Why is the assignment of staff critical to an accurate estimate?***

The first question introduces the term of robust, which means the method should be capable of performing without failure under a wide range of conditions [2]. This key question also narrows down the development to focusing on prototype systems. The second question builds on the question of "when is enough information gathered?" In order to know when enough information is gathered, there must be a formal representation of uncertainty so that the estimator can understand the consequences of various activities diverging from the original plan, which is inevitable. The third question suggests that the construct of the method be based upon interactions between performance, schedule and cost. This is an important distinction because these three items are the tenets of project management and estimation. Considering one of these variables without considering the others can quickly generate a plan that is not feasible. The fourth and last question addresses the assignment of staff. This question is raised as a way to include individuals into the estimation process. By considering individual staff members the estimation process can become better integrated into an organization.

The second piece of research mentioned previously was that of evaluation. Answers to these intellectual questions can be formed with little or no utility if there is no consideration placed upon the effectiveness of the result. Several things can be done to verify a proposed methodology has utility such as applying the method and evaluating those results as compared to the current method of approach. For this thesis, the Validation Square [3] was chosen. This approach, which was generated specifically for evaluating the effectiveness of newly proposed methodologies, serves as a framework to organize this thesis. Validation is broken into four sections within this evaluation technique:

- Theoretical Structural Validity
- Empirical Structural Validity
- Empirical Performance Validity
- Theoretical Performance Validity

This approach can be further broken down into a qualitative process of steps:

1. Accepting the construct's validation
2. Accepting method consistency
3. Accepting the example problems
4. Accepting usefulness of method for some example problems

5. Accepting the usefulness is linked to applying the method
6. Accepting usefulness of method beyond example problems

This approach is covered in more detail in Section 1.5.2 but it is important to note that a qualitative process has been followed to characterize the usefulness of the proposed cost estimating methodology by using the Validation Square.

1.2 General Framework of Estimations

Generating an estimate for a prototype system development is an attempt to leverage the history of developments in order to provide the expected time and cost to complete a particular development. Whether using personal design experience or past performance captured in a database, the goal is to be as accurate as possible when obtaining these estimates. One must understand that the estimation process is essentially an abbreviated design process as some knowledge about the design must be created in order to generate a reasonable estimate. Due to this link, we will discuss existing design methods prior to cost estimation methods. The goal of this exercise is to show the similarities between the two areas while leveraging core concepts to improve the estimation process.

1.2.1 Design Methodology Basis

1.2.1.1 Overview of Design Methods

Several design methods have been used in various manufacturing sectors. Some methods of importance are those discussed by Pahl and Beitz as well as Cross [4] [5]. These authors cover design methods ranging from prescriptive to descriptive, and touch on the various models such as VDI 2221 and March's Model. The method by Pahl and Beitz has been leveraged primarily for this work. The general prescriptive form of the method proposed by Pahl and Beitz is shown in Figure 1.

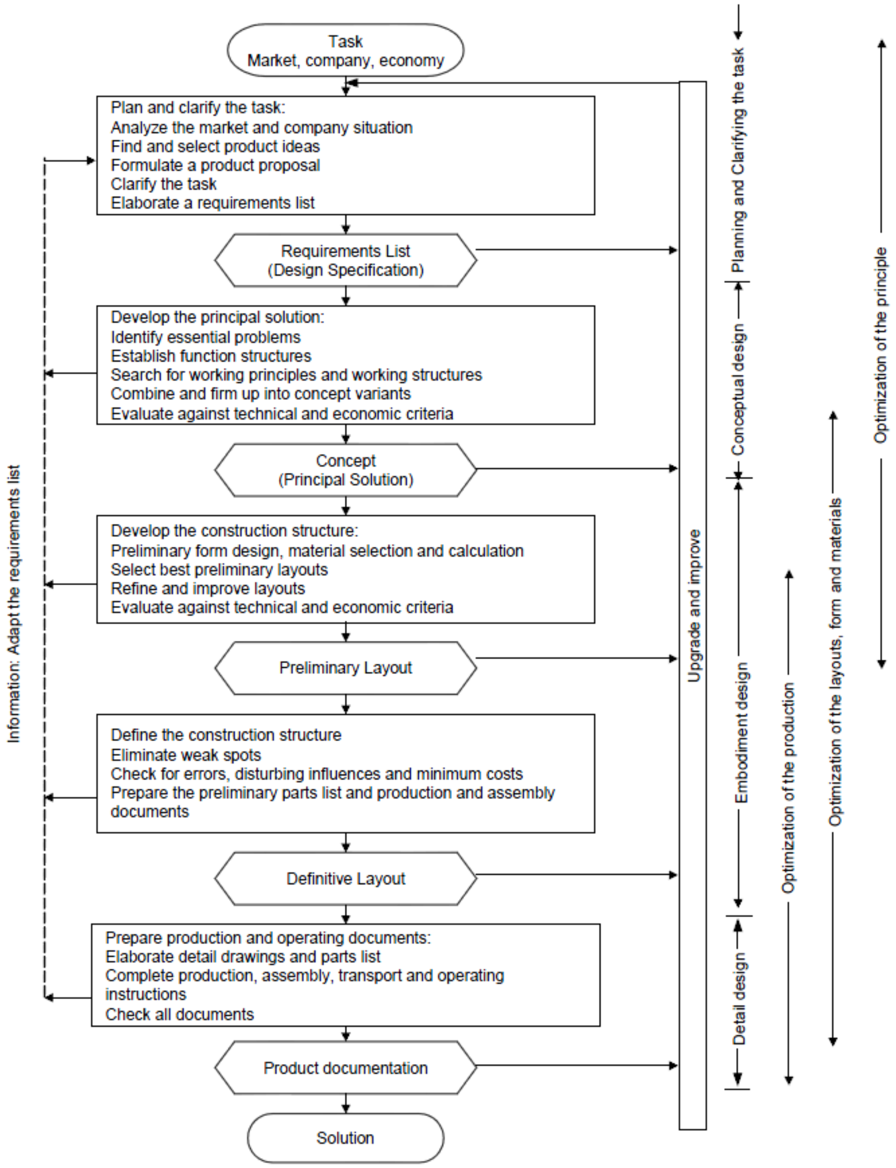


Figure 1: Steps of the Planning and Design Process from Pahl and Beitz [4]

Pahl and Beitz describe a novel approach to engineering design in that a solution is not discussed until the general function of the system is addressed in detail. This is captured in the section referred to as “Specification” in Figure 1. In order to evaluate the effectiveness of these various solution principles, a detailed clarification of the task must be generated which is captured in a detailed list of requirements. From this point, a preliminary and detailed layout can be generated to complete the design.

Additional benefits are that the Pahl and Beitz method is structured to be modular [6]. Individual pieces of the method can be used on their own because each module of the method has a clear input and output. This allows the method to be flexible enough for multiple design types such as those the authors refer to as original, adaptive, and variant designs. Subtle pieces of this method also set it apart from most. These important pieces of the method, which could be referred to as core transformations, are: 1) clarification of the task and generating a requirements list, 2) recognizing the essential problems through multiple levels of abstraction, and 3) selection of preliminary designs. The second point is the most important core transformation. What is occurring here is that the design is broken apart in order to expose the most important or core issues. The pieces of the design are then abstracted to a high level by understanding the energy, mass, and information flow between various parts of this design. From this point of abstraction the problem can then be formalized into working principles and furthermore into concept variants. The beauty of this approach is enabling the designer to look beyond his or her personal bias and create a solution that is focused on solving the core issues of the design.

Considering that the method of Pahl and Beitz was grounded in the manufacture of mechanical systems, there are several limitations that apply to its use today. These limitations are: 1) not being effective for teams, 2) not multidisciplinary – only for the design of mechanical components/assemblies, 3) considered a “throw it over the wall” approach to manufacturing, and 4) does not address increasing use of computers well. These issues must be addressed if this method is to be used effectively in cost estimation exercises.

1.2.1.2 Design Methods for Estimation

The need for design methodology in the design of complex systems is clear, but the use of design theory in estimation is also reasonable. The key goal of a design method is to progress from a loose set of requirements to an object or deliverable item when followed through its entirety. Ultimately a “good” product is desired at the end of the design process whereas “good” is measured by the initial design goals and requirements. This can be extended into manufacturing when considering all systems, but the focus on prototype systems shall remain for this discussion. As stated previously, the only way to accurately predict the cost of a design effort is to perform that effort. Only at that point can a post hoc review be completed to provide the actual cost of the design effort. The goal of cost estimation is to predict as accurately as possible what that actual cost will be. In this case a “good” estimate will be measured upon the amount of uncertainty as captured in the initial estimate and how well it matches the initial cost and time constraints that were generated. In both cases the exercise involves validation at the completion of the estimation or design task to truly understand how “good” the original model was. This level of success becomes increasingly better through iterations because as more knowledge is available to an estimator related to similar estimations, future estimates will be improved.

Although it is clear that cost estimation and design theory overlap from this discussion, it can also be argued that the differences between the two are a matter of terminology. Both approaches must consider interactions between cost, schedule, and performance despite the output of the two fields of study being slightly different. Essentially the proposed cost estimation method is the result of a design process. Based upon this observation a case has been made to leverage the tools from both design theory and cost estimation to enhance the estimation effort early in the design process of prototype systems.

1.2.2 Literature Review of Cost Estimation Methods

Prior to generating or modifying a new estimation method, a detailed literature survey was completed. This survey included estimation tools relevant to the estimation of prototype systems. Several estimation resources were reviewed for consideration when creating the proposed estimation method including but not limited to the Cost Estimating Body of Knowledge (CeBOK) offered by the Society of Cost Estimating and Analysis (SCEA) [7]; the United States Government Accountability Office (GAO); Galorath (introduced Software Evaluation and Estimation of Resources also known as the SEER model); NASA's Parametric Cost Estimating Handbook; The Journal of the Association for Computing Machinery; and many others. This source as well as several others was used to generate a comprehensive list of current cost estimation techniques used today.

1.2.3 Types of Estimation Methods

Several established methods are used for cost estimation across a range of industries. Estimation tools range from software estimation to the estimation of building construction. These methods have different needs and goals based upon the desires of the estimator. The primary goal of any estimate is to generate a good prediction of the cost and time to complete a project using as few resources as possible. Because of the large range of estimation tools available, they can typically be characterized as falling into one of the following categories [8], [9]:

- Top-down
- Bottom-up
- Estimation by Analogy, Past History
- Expert Judgment, Guesstimates
- Design to Cost
- Parametric Models

1.2.3.1 "Top-Down" and "Bottom-Up"

These two general categories approach estimation differently as implied by the name of this type of estimate. The "top-down" approach is a more of an analogous model whereas the "bottom-up" approach is more in line with the ideals of industrial engineering. The first approach is generally used when there is not as much information on a product and the second approach is used as more historical information becomes available as the product matures [10].

A Top-Down estimation method consists of high level breakdown that is then refined into smaller tasks. This often involves generating a work breakdown structure (WBS) that is then assigned amount of resources to each stage of the program often referred to as phase distribution [11]. Several software estimation processes take this approach to estimation such as COCOMO and SEER-H. Top-Down estimation is also associated with the Delphi method as it begins with a group of experts generating the high level organization of the project [12].

Bottom-Up approaches start from the most detailed breakdown of the project and then estimate in detail the cost of each activity. Activity-Based Costing falls into this category as the division of each activity is broken down and then estimated to support the overall estimation. This approach can be time consuming, but also can yield better results if done properly. Similarly to Top-Down estimation, Bottom-Up estimations require a detailed WBS in order base the estimate upon. This makes the importance of providing sufficient detail to the WBS important as forgotten tasks can lead to the resulting estimate being too low.

Jorgensen provided a review of differences between Top-Down and Bottom-Up estimates among experts in software engineering estimation exercises [13]. This led to the suggestion of using Bottom-Up estimations in lieu of having little experience or data on execution of previous software tasks. Several interesting points of discussion were also noted and are summarized below. Keep in mind these points are all based upon software developments.

- Non-technical estimators (75%) prefer top-down estimation strategies whereas technical estimators (90%) prefer bottom-up estimation strategies.

- Generating an accurate WBS for bottom-up estimation is crucial as several test cases were under-estimated using bottom-up estimation strategies due to unexpected activities.
- Top-down estimation does not require much technical expertise or prior experience.
- Bottom-up estimation requires the estimators to spend more time understanding requirements.
- Top-down estimation introduces more history-based thinking to the estimation exercise.
- Decomposition, as it applies to bottom-up estimation strategies, is not needed when there is low uncertainty for a given task.
- Top-down estimation requires metrics to be captured and cataloged well in order to have better history-based results.

These points of discussion highlight the fact that top-down and bottom-up estimation techniques are not a perfect solution and that the need for a combination of various techniques from the two approaches is needed. This is especially important as complexity of estimation increases sharply in a multi-disciplinary endeavor.

1.2.3.2 Estimation by Analogy

Estimation by analogy requires the estimator to have some form of knowledge about a similar system or systems in order to provide that prior knowledge for the purpose of estimation improvements [14]. Similar to some of the strengths of top-down estimation provided in the previous section, estimation by analogy can provide a good estimate based on past performance with little experience from the estimator. An extension of analogy based estimation is the estimation of particular types of systems or article based estimation.

Several texts have been dedicated to the estimation of particular types of systems. For example, several cost estimation texts have been dedicated to both the construction of avionics platforms [15] as well as large ship building endeavors [16]. These methods oftentimes consider a Cost Estimate Relationship (CER) or a formula relating to the cost of an item's physical or functional characteristics that are tied to a Work Breakdown Structure (WBS). The CERs can be manual, calculated, predictive, empirical, or a mixture. Due to the large history of designing these types of systems, the ability to leverage cost data associated with previous developments is the common basis to these estimates. This type of structure, especially when considering CERs, leads towards another cost estimation approach – parametric model estimation.

The primary drawback to this approach is the need for a detailed database of projects in order to create these "similar-to" estimates. First, this method requires an organization to keep careful time keeping records to the task level for each project knowing that later there may be a similar project that can be better understood by the use of past data. This proves to be good information in practice to collect and supports such tools as the earned value management system (EVMS), which has proven useful for the management of projects. Although the tracking and storage of such metrics is not free and increases the overhead expenditures related to programs within an organization.

Another potential drawback is the fact that similar projects are needed for the analogous approach to be effective. An organization that has a standard product line and frequently produces similar products can easily leverage the technique of estimation by analogy. A developer or consulting firm that encounters a wide variety of engineering problems will face more difficulty in the creation of a useful database for estimation. However, there still may be sub tasks of the project that are similar such as general project management tasks or basic integration tasks such as wiring of digital electronics or analyzing a particular type of test data for example.

Ultimately, estimation by analogy can offer considerable benefits. Those benefits come at the expense of tracking of relative metrics requiring project managers to track information carefully that is tied directly to a well-planned work breakdown structure. A major limit is acquiring data on multiple similar projects, which is not often the case when performing research activities and constructing prototypes due to the inherent nature of prototype design often involving new developments.

1.2.3.3 Expert Judgment

Expert judgment, as it implies, is founded primarily upon the expert judgment of key staff on an estimation team. The experts in this case are relying upon their personal past experience, which may go beyond experience accessible from their current employer. One has to take care in how expert judgment is evaluated though because if evaluated against a standard, the result will find that no expert can exceed the result set forth by the standard. Therefore, it is required that an individual's intuition is compared to that same individual's analysis [17]. This means that validation of a method involving expert judgment benefits from also involving the tracking of performance by estimator's throughout the duration of the effort.

The benefits of expert judgment range from the speed at which good estimates can be generated to the estimation of complex efforts that involve integration of multiple disciplines and/or subsystems. The negative components of expert judgment are related to repeatability of results and the subjective nature of human decision making. These topics are discussed in further detail in Section 1.2.6.2 as expert judgment is also a useful tool in the area of risk assessment.

1.2.3.4 Design to Cost

The premise of design to cost (DTC) is that cost should be included in the entire design cycle based upon the assertion that design should converge on cost as opposed to cost converging upon a design [18]. Although described by Michaels, et. al. as a method for cost estimation, this approach can be considered more of a concept that should be followed as opposed to a method. This is in part because DTC, which goes back to the department of defense funding in the mid-1970s, has morphed into different techniques such as Cost as an Independent Variable (CAIV) [19].

1.2.3.5 Parametric Models

A prime example of using parametric models for estimation would be the SEER model developed by the Galorath consulting firm in the 1980s [20]. In the context of cost estimation, parametric models are mathematical equations that have been developed to describe a system and these models allow the estimator to predict the cost of a particular development. The model becomes a series of cost estimation relationships or CERs containing all of the parameters to characterize a particular system. These black box models are based upon analogous cost data and formalized into models that allow estimators to make quick decisions without going through the exercise of generating a detailed bottom-up estimate [21]. Similar to the drawbacks from estimations based upon historical data, these types of estimates require the capture of metrics from similar systems as well as the availability of a comprehensive database of information.

1.2.3.6 Summary of Estimation Approaches

The description of approaches previously described provides a representative list of estimation tools available for cost estimation purposes. An important distinction is to consider these approaches in the context of estimation for prototype systems. The term prototype implies there is a novel characteristic to the development. In the context of this work this means the prototype development would include an original design or a novel combination of components suggestive of an adaptive design. Due to these characteristics, analogous approaches become difficult to apply due to the need for history on similar developments. When designing prototype systems, there is a strong likelihood that similar systems may not be available. This does not preclude the use of historical data, but implies there is at least one major task that will require a different approach. This limits the core of the estimate, original and or adaptive tasks, to using approaches such as a bottom-up approach or expert judgment. The concept of design to cost may also be applied as a limiting factor required for making the development economical.

1.2.4 Existing Methods of Estimation

1.2.4.1 Activity-Based Costing

This approach introduces a key technique to cost estimation leveraging concepts from cost management techniques. The core of this approach is based upon the fact that resources are consumed by activities, which are then consumed by objects whereas cost accounting has previously relied on making the transition straight from resources to objects [22].

1.2.4.2 Delphi Process

The Delphi Process is a process developed by the RAND Corporation in the 1940s. This has been adapted to become the “Wideband Delphi Model” for the estimation of software tasks. The general form of this technique is to follow a general flow of events in the form of: 1) choose a team, 2) hold a kickoff meeting, 3) prepare individual inputs, 4) hold an estimation session, 5) assemble inputs from team, 6) review results [12]. This approach addresses the implementation within the dynamics of a team environment and relies on the team members to address individual cost estimation tasks within the preparation of individual inputs.

1.2.4.3 SEER-H

The SEER-H model was developed by Galorath [23]. It is an extension of the SEER method with a focus on hardware developments. The focus is on a “system of systems” approach thus generating system level cost (SLC). A point of uncertainty in this approach is related to the differing definitions for what a system or sub-system is. This can vary significantly among individuals. One important piece of SEER-H is the inclusion of a System Engineering and Integration (SEI) element. This particular approach is geared towards capturing the cost and complexity associated with integration of hardware elements and can be useful in this regard.

1.2.5 Limitation of Current Methods

The positive aspects and drawbacks of each cost estimation technique can be considerable when attempting to use these techniques for the estimation of costs related to prototype systems. The following table summarizes the key pros and cons related to the various approaches discussed. The goal is to highlight the positive aspects of each of these techniques and to leverage those positive aspects for inclusion into a prototype system estimation tool set. This is only a small set of estimation methods considered in order to allow the reader to become familiar with cost estimation techniques. Some important methods such as Marschak's "Cost of Information" or a "mission-oriented" approach are not presented [24]. These approaches may be valuable as a means to estimate the value of information in the context of prototype system development; however, the notion of the cost of information was not considered in this work.

Table 1: Comparison of Cost Estimation Techniques

Technique	Limitation	Utility for Prototype System Estimations
Activity-Based Costing	Founded in economics, this approach is confined to the relationship of resources, activities, and objects.	Serves as a framework for basic estimation tasks when relating engineering time to a physical object or engineering service related task.
Delphi Process	Does not specify what tools to use for various methods and only addresses the general layout of the estimation process. Also does not address organization for small estimation teams well.	Can be leveraged to form a general flow of information for the estimation process.
SEER-H	Costly and time consuming to implement. Requires use of Galorath tools to implement properly. Creates uncertainty in the definition of what a system is.	Provides a framework for capturing integration costs, which can be important in the design and building of prototype systems.

1.2.6 Literature Review of Risk Assignment Methods

Risk assessment is a key component of the proposed estimation method due to the importance of characterizing uncertainty in cost estimation. Several risk assessment methods are listed in the following sections based upon a cost risk analysis for Air Force systems [25]. The approaches considered important to the estimation of prototype systems are discussed in detail. It should also be mentioned the several types of risk that are evident in projects as stated in the Cost Estimator's Reference Manual [26]:

- Risk assessment of whether to do the work or not
- Risks among selection of concept alternatives
- Risks related to cost, schedule, and performance
- Alternatives for risk reduction activities
- Assessing performance based upon initial estimate
- Risk assessment revisions

Although some alternatives will be discussed for risk reduction activities (Section 3.5.1), the primary focus of risk assessment will be placed upon the risks related to the relationships between cost, schedule and performance.

1.2.6.1 Benefit-Cost Analysis

Benefit-cost analysis is often discussed when considering social impacts of risks involved with developments for political purposes [27]. It is also considered as a purely economic evaluation technique for high level decisions related to business opportunities such as whether or not to undertake a project. The benefit-cost can be considered from several viewpoints as well. For instance, to whom the benefit or cost is designated upon is a key decision that must be made. The analysis can be addressing the benefit-cost to the owner, shareholders, or a region within a state or country. In summary, it is a high level tool to assign values to the benefits and investment required in order to quantify the range of outcomes to the estimator [28].

1.2.6.2 Expert Judgment

Expert judgment is a technique born from the field of psychology. The technique resulted from the task of defining what an expert is. In defining an expert, the cognition required to reduce a multifaceted, multi-dimensional problem to a small number of key criterion in a repeatable manner is the basis for an expert judgment [29]. In many areas of cost estimation, accounting for 62-86% of the estimation process in various industries. Although it is often necessary to use as an estimation tool, expert judgment has the major limitation of generating results that are not recoverable in regards to the reasoning process [30].

1.2.6.3 Fault Tree Analysis

A fault tree analysis consists of understanding the failure space of a particular development in a graphical model. The consideration is made for the entire spectrum of expected outcomes ranging from a total success to a complete failure [31]. This technique is oftentimes more closely aligned with the format of a decision tree tracking the logical flow of potential outcomes given various decision points within a process. This technique has value in order to generate a better understanding of potential failures and ultimately risk within a system, and can provide a statistical output when probabilities are assigned to these decision points [32].

1.2.6.4 Root Cause Analysis

A root cause analysis is often used as a means of understand what went wrong during a development after it has happened [33]. Essentially, it is the post hoc form of a fault tree analysis. The goal of a root cause analysis is to provide a more objective measure of causal factors during an event to prevent an evaluator from providing the majority of focus on substantial factors while ignoring others. In respect to cost estimation, this technique can be useful for understanding what has gone wrong with previous developments when considering a database of cost history values. In dissecting previous cost history in this way, an objective evaluation can be applied to past projects in order to understand why various endeavors cost more than others while looking forward to how that information can be applied to improve future estimations.

1.2.6.5 Cost Estimation Predictive Modeling

A vast array of cost estimation modeling techniques has been employed across several industries. Fuzzy logic, artificial neural networks, and least squares regression models have been employed to name a few. Neural networks in polynomial form have been shown to perform better than regression models when there is little prior information about a system such as prototype system developments [34]. Fuzzy logic approaches as applied to cost estimation often suffer similar drawbacks to expert based analysis. Also, the required need of probability distributions for fuzzy sets as opposed to the use of intervals generates additional uncertainty when detailed information is not available [35]. Due to the nature of developments related to prototype systems, a simpler interval based method will be considered as part of the estimation tool set. Costs cannot be considered simply as single values and should be considered as a range of values with uncertainty. A method of approaching this based upon the “method of moments” will be considered as part of the tool set for the proposed estimation method [36].

1.2.7 Summary of Risk Assessment Survey

Several methods of risk assessment were discussed with the goal of providing an estimator with the appropriate tool set to understand and characterize risk during cost estimation for prototype systems. The tools range from high level approaches such as the benefit-cost analysis to more detailed predictive modeling techniques. Typically, the limitations with the approaches are related to the amount of information required to execute that given technique. The additional information required for more advanced techniques can also be a negative component as the collection of that information requires additional resources. Ultimately, the balance of information required with resources available must be considered in order to achieve a suitable cost estimate. Weighting factors applied to cost, performance, and schedule help to guide these decisions in order to better utilize resources.

1.2.8 Consolidating Design, Estimation and Risk Assessment Tools

The proposed cost estimation method leverages many aspects of the Pahl and Beitz design method. The primary points that were leveraged are related to the inclusion of clarification of the task as well as implementing a conceptual design that includes the abstraction of design. These benefits are used in the major example problems within the thesis and are at the core of the proposed cost estimation method.

The implementation of estimation and risk assessment tools is not as clear in the thesis example problems. There is some discussion in the example problems such as the inclusion of risk assessment tools discussed in Section 3.5.1, but these discussions are not exhaustive. The previous discussions on estimation and risk assessment tools is meant to serve as a basic primer to the estimator to understand what types of tools are available for estimations. The type of work performed by the estimator or prior experience in various estimation tools may affect what tools are used. The real point is to recognize there are established methods for cost estimation while illustrating how they can be incorporated into the design process itself.

1.3 Contextual Terminology

Several key terms are used in this document ranging from terminology typically used in design and estimation theory to specific terms related to the example problems. The following two sections provide definitions to key terms in order to set the context for future sections.

1.3.1 Definitions of Related Terminology

This section serves as a glossary for related terminology.

- **Accounting:** A statement of debits and credits [1].
- **Activity-Based Costing (ABC):** a methodology that measures the cost and performance of activities, resources and cost objectives. Resources are assigned to activities, then activities are assigned to cost objects based on their use. Activity-Based Costing recognizes the causal relationships between cost drivers to activities [37]. Furthermore, ABC adopts an attention to focusing on long-term, resource consumption [38].
- **Activity-Based Management (ABM):** A discipline that focuses on the management of activities as the route to improving the value received by the customer and the profile achieved by providing this value. This discipline includes cost driver analysis, activity analysis and performance measurement. ABM draws on Activity-Based Costing as its major source of information [39].

- **Adaptive Design:** A design containing previously demonstrated features that have been adapted for a new environment or function.
- **Baseline:** Refers to an initial schedule generated to compare potential changes to schedules in the future.
- **Cost to Complete:** This is a term used to describe the total amount of resources needed to finish a contract. Oftentimes, this is the term used by the contracting office as an estimate of the contractor's ability to finish the contract, which may be higher than the contractor's estimate in order to include an amount of management reserve funds.
- **Critical Requirements**: Critical requirements are the result of requirements that support activities that are on the critical path. This means critical requirements exist that have been defined to satisfy successful demonstration of the prototype. The requirements must be in place that will allow designers to evaluate the prototype and draw conclusions as to whether that prototype is successful – if not; the project has not been properly clarified.
- **Estimator:** The individual generating an estimate for a system development for the purposes of cost proposals, planning activities, etc.
- **Gantt Chart:** A chart used for tracking and displaying the dependencies between tasks and schedule based upon the work of Henry Gantt in "Organizing for Work." [40]
- **Human Effort:** The effort related to the completion of tasks, which can also be described as the productivity of staff members. Human effort is considered different from resources and is only represented in hours.
- **Interval:** An interval is a closed set of bounded real numbers [41].
- **Milestone:** A specific task that becomes a key deliverable during a progression of planned activities.
- **Original Design:** A design that contains new or features never demonstrated previously.

- **Prototype:** Comes from the Greek word protos (first) and typos (impression). When combined the meaning becomes “original” or “primitive.” [42]

- **Research:** Research is when information is gathered to solve a particular question or problem. The new knowledge you gather is a result of questions asked while performing research [43].

- **Resource:** An economic, energy related, or waste/mass related element that is consumed by the performance of activities. Resources, like activities, can be aggregated into hierarchies. In special cases, such as waste, resources may be generated by activities instead of consumed. Human effort is considered separate from resources.

- **Risk:** Applies to situations for which the outcomes are not known with certainty but about which we have good probability information [44]. It must also be understood that risk does imply that failure is a possibility. Risk can also be considered among individuals as being more or less risk averse such that a more risk averse decision-maker will invest more into a riskless asset [45].

- **Robust:** The term robust, as it applies to estimation, is best defined as the maintaining stability in the result of an estimate. For instance, as uncertainty begins to enter the estimation process, the end result must characterize this uncertainty within the expectations of the estimator.

- **System:** a set of interacting or independent entities, real or abstract, forming an integrated whole. Systems exhibit abstractions (of reality), structure, behavior, and interconnectivity (assumes there is a boundary) [1].

- **Uncertainty:** Applies to situations about which we do not even have good probability information (see also 'Risk') [44]. In general, uncertainty is the umbrella term for things that are unknown.

- **Validation:** As a philosophical term, *validation* refers to internal consistency (i.e., a logical problem), whereas *verification* deals with justification of knowledge claims [3].

- **Variant Design:** A design that does not include any adaptive or original components. This type of design describes a system using previously demonstrated parts in a similar fashion that have only been recombined for a new operation or environment.

1.3.2 Characteristics of Prototypes in Research

In order to develop the characteristics of prototypes in research, there must be a clear understanding of the meaning of both "prototype" and "research." Building upon the previous definitions provided in the previous section, let us expand to include the meaning that will be applied in the context of this paper:

- **Prototype:** A prototype is a primitive or original development item. It is often a physical representation of a theory that has yet to be proven. At the least, it can be generalized to state that a prototype is a product that is used to demonstrate the feasibility to achieve a number of goals.
- **Research:** Research is based upon the notion that something new is achieved – often referred to as creating new knowledge. The focus of this means that it is not a mere development where things are well understood, but that there is at least one major portion of the activity where a particular task or a combination of tasks has never been attempted – this results in the potential for a novel application. This new knowledge is now the result of the research activity. What is implicit to this inclusion of novelty is that there is also a level of uncertainty associated with this novel activity or activities. Because there is some task that has never been attempted, it means there is some activity that has not been designed. Continuing with this thought process can be extended to uncertainty and risk. A research activity can therefore be said to be an activity that contains at least one task that includes a sizeable amount of uncertainty.

Now that a clear meaning of the terms have been stated, let us consider the combination of the terms in the challenge we are addressing – why are better estimation tools needed for the design of prototypes in a research environment? By combining the terms and stating "prototypes developed within a research environment," we have extended the term of research to include a demonstration product, or prototype, that can be analyzed in some form and thus quantify the performance of the theories expressed in this new knowledge. This understanding is critical and must be internalized in order to fully appreciate the need for better estimation tools. The implications of this statement are that: 1) the result must be measurable; it is possible to demonstrate or construct some product that will either validate or invalidate the research questions proposed, 2) even if the measurement or validation task are not performed under the contract that they will be at some later time, and 3) two instances of uncertainty and risk are often present; one related with the research and one with development of a prototype.

1.4 Goals and Focus of the Work

This work is to address ultimate goal of generating improvements to current estimation approaches with a focus on prototype systems. The distinction with prototype systems is that although adaptive, original, and variant designs may exist there is a portion of the work that is potentially original or adaptive and requires a variation that has not been attempted. These developments contain portions that hold a high level of uncertainty and require special attention to improve the accuracy of the estimate. This goal has been captured in a number of intellectual questions and has been elaborated upon to describe the scientific relevance of this work. Following these questions, a number of assumptions are made to further focus the research and determine a set of requirements for the proposed cost estimation method.

1.4.1 Intellectual Questions for Investigation

A number of intellectual questions have been explored which revolve around the notion of “when is enough information gathered?” The real question to be answered however is: “How do you design an estimation method for prototype systems?” Several questions have been formulated that stem from this question as it pertains to design. The primary goal of any estimation process is to generate an accurate estimate with a minimal amount of resources. The following questions capture the desire of this research as it applies to cost estimation:

1) ***When is enough information gathered to generate a robust estimate for the design of prototype systems?***
2) ***How do you characterize uncertainty in the estimation process?***
3) ***Why do estimates need to consider interactions between performance, schedule, and cost?***
4) ***Why is the assignment of staff critical to an accurate estimate?***

The first question is related to the balance of resources and confidence. The relationship between these two measures must be carefully understood to meet the goals of the estimator. The level of confidence can be described as a level of uncertainty, which in turn applies to risk. The individual or group of individuals responsible for making a decision of whether to proceed with the work will inject their own level of risk into the decision by either accepting the amount of uncertainty or rejecting it. The job of the estimator is simply to quantify it as well as possible to provide a tool for the decision to be made.

The first question also includes the challenge of estimation as it relates to prototypes due to the inclusion of the term "robust" in addition to specifically addressing the term of "prototype." This question aims to ensure the method is capable of handling estimation as it relates to systems with at least one portion of the development containing a high level of uncertainty. It is these uncertain tasks that make estimation particularly challenging requiring a careful evaluation of tools to characterize uncertainty.

Questions 2-4 all relate to the ultimate challenge provided in Question 1. A clear understanding of uncertainty is paramount and furthermore uncertainty related to the three primary measures of cost, performance, and schedule are of keen interest. Question 4 addresses a lesser goal related to the assignment of staff to perform work. This, however, is important for an organization to better optimize the allocation of resources within that organization. Although some of these ideas have been touched upon in the sections the general framework of estimations, these questions will become the theme of the development of an estimation tool for prototype systems.

1.4.2 Assumptions and Requirements of the Estimation Method

As we gain a better understanding of these terms it is helpful to generate a clear set of goals. In established design methodologies, this statement of goals is the result of a clarification exercise within the design process. The product of this clarification task is a list of requirements. However, in order to share a set of requirements, one must set a clear context for these requirements. A suitable list of assumptions was also compiled in order to set the context for these requirements. The following tables contain a list of assumptions as well as a list of requirements that will be used to guide the development of this estimation process. Each table is followed with a more detailed description of each item as a way to clarify the meaning of each term for the reader. Before delving into these tables, keep in mind that just as an estimate must have clear goals and requirements, an estimation method must offer the same. We will explore this notion in more detail as we discuss The Validation Square in following sections, which will elaborate on the logical tests required to satisfy a methodology just as a prototype can satisfy a particular theory or idea.

Table 2: Assumptions Made for the Development of the Estimation Method

No.	Description
1	Material estimates are not prone to high levels of uncertainty for this case
2	Consider an experience level in labor estimates
3	Assume 40 hour weeks for a given employee
4	All skill-sets needed are available and location of engineering resources are irrelevant
5	All state of the art engineering tools are available and staff know how to use tools
6	Assume constant price of everything
7	Intellectual Property issues are ignored
8	It is feasible to evaluate the performance
9	Functional and working structures can be completed
10	Designer control over all tasks to be estimated
11	Corporate management requirements and indirect costs are ignored
12	Limits for uncertainty calculations are defined through intervals
13	No more than 10% of total effort dedicated to estimation

A more detailed explanation of each assumption follows:

Assumption 1: Material estimates are not prone to high levels of uncertainty for this case

The focus of this development is not on the estimation of materials. The assumption is made that materials are known and that the uncertainty for materials is expected to be low for these developments. There are clear exceptions that could exist such as if the research topic itself were a material development, but materials in the context of this thesis will be considered to be supporting hardware for the construction of prototypes that are well understood.

Assumption 2: Will need to define experience levels to give a correct labor estimate

The level of the engineer or employee that is a part of the development will be important. For instance, a highly experienced designer of jet engines will be able to do many design tasks more efficiently than a new graduate from an aerospace engineering program. Also, the higher cost of the experience must be considered in order to offer realistic estimates.

Assumption 3: Assume 40 hour weeks

Many government agencies are subjected to oversight from Federal Acquisition Regulation (FAR). For fairness in competitive bidding, employees are required to report time judiciously and to account for any overtime, absences, and most importantly which task was been worked on at any given time. Because GTRI is a state agency, this often means that engineers are salaried and limited to 40 hour work weeks. The assumption has been made to stay in line with FAR and remain with a 40 hour work week.

Assumption 4: All skill-sets needed are available and the locations of engineering resources are irrelevant

A different topic altogether is the study of how distributed engineering resources can affect the outcome of a particular design effort. The notion of distributed resources will not be addressed so it is assumed that these impacts are negligible despite the fact that it is known that challenges arise as engineering teams are dispersed in global operations.

Assumption 5: All state of the art engineering tools are available and staff members know how to use tools

As with the previous assumption, it is known that training or lack thereof can have a negative impact on the time it takes to complete a particular task. This particular result is not part of this research and will not be addressed.

Assumption 6: Assume constant price of everything

The cost of money, inflation, and ideas such as current market value will not be addressed.

Assumption 7: IP (Intellectual Property) issues are ignored

The development of intellectual property or IP as it relates to research projects can be time consuming in some instances. Large corporations that carefully protect IP as a way to preserve their technologies must integrate patent lawyers, and various business development individuals into the design process in order to carefully decide which ideas must be protected. This activity will not be addressed.

Assumption 8: It is feasible to evaluate the performance

Some theories have never been tested and take years for technologies to advance in order to prove or disprove. For instance, various results related to Einstein's theory of relativity took years to prove. We will focus on developments that have a component that is able to be tested.

Assumption 9: Functional and working structures can be completed

As with Assumption 8, various high level theories associated with basic research are difficult to prove at times. These theories can also result in the need for devices that have components not even achieved and requiring an invention of new technologies. If various working structures are not present, such as the laser, then the development of a technology, such as that of a compact disc, could not have been achieved. We will only focus on results that although they are challenging, are feasible at the time of the estimation. In the timeline of the typical prototype development these new found working structures will be ignored. Furthermore, the definition of functional structures in this context is in slight contrast to the functional structures prescribed by Pahl and Beitz.

As they prescribe a single preferred decomposition. The intent is to support a number of decompositions at this early stage of the design process [46].

Assumption 10: Estimator control over all tasks to be estimated

The estimator has all control over the estimation process. This is not always the case as this task may be shared by many people and that only portions are controlled by a subset of estimators, but the notion of several estimators in the estimation process will not be explored.

Assumption 11: Corporate management requirements and indirect costs are ignored

In many organizations, an amount of overhead either monetarily or in the form of required management tasks is mandated. Required management may be the inclusion of earned value management (EVM) or other project management items including appraisals for employees or corporate staff meetings. These overhead tasks will be assumed to be included in a percentage of employee labor and the in the individual breakdown of this overhead will not be considered. This also extends to various database methods in that the collection of metrics (such as those collected in EVM) is included in overhead.

Assumption 12: Limits for uncertainty calculations are defined through intervals

This assumption is reinforced with a mathematical formulation of uncertainty in a future section.

Assumption 13: No more than 10% of total effort spent on estimation

Estimation tools and methods are valuable, but need to be limited in order to retain resources for project performance.

Table 3: Requirements List for the Estimation Process

J. Holmes 1/1/2011	**Requirements list for estimation process**
Problem Statement: To determine an appropriate estimation methodology for a research environment. This requires the method to be very adaptable and to stay current with new technology and methodologies. It is also important that this system will be able to handle changes in the engineering environment.	
D/W	**Requirement**
	Key Characteristics
D	1. Adaptable for all engineering principles
D	2. Incorporate tools to account for uncertainty in the estimation process
W	3. Incorporate checks and balances throughout the process
D	4. Adaptable to meet the needs of designing prototypes in a research environment
W	5. Create normalization terms to compare cost, schedule and performance
	Communication
W	6. Easily communicate within organization
	Safety
W	7. Must incorporate safety considerations throughout the process
	Usability
D	8. Must be organized and written such that a college graduate can understand the methodology
	Production
W	9. Must be articulated clearly to allow for transmission of ideas through standard documentation
	Quality Control
D	10. Accuracy of references for readers to check content
	Maintenance
D	11. Adaptable to changing design environment
W	12. Able to be revised for frequent changes
	Costs
D	13. Can incorporate a dynamic cost database
D	14. Improve the determination of the cost of labor
	Schedules
D	15. Must not create negative impacts to existing design methods

The requirements list is broken down into various sections similarly to the formulation of a requirements list by Pahl and Beitz [4]. In addition to this breakdown, demands and wishes are captured separately. A "demand" can be thought of as an item that must be addressed, it is compulsory and there is no option as to whether the estimation method must include this particular requirement. The notion of a "wish" is difficult to ascertain in the context of contract execution because they are not compulsory in the direction of the project. Wishes are often ignored because there is little benefit to completing work that is not required in the scope of a project in the rigid sense. However, wishes are important because there are frequently enhancements that can be made to a particular development with little added work to the developer. In fact that is the goal of a wish – if the effort required to achieve a wish is minimal, it is often in the best interest of the overall development team to attempt to include this in the final product. These terms can also be considered in the context of objectives and thresholds, which are commonly used in government contracting. These terms are used to describe the goal as well as the limiting acceptable value [47]. As it pertains to the estimator, this must be handled carefully because it can be considered as "scope creep" to a management team and takes away from the compulsory design tasks. The requirements listed in Table 3 are further explained in the section below.

Key Characteristics

1. Adaptable for all engineering principles – The method must work for interdisciplinary based design teams. Many research activities can include a number of engineering disciplines working together as is the case with larger research integrations. It is imperative that the method address these types of activities.

2. Incorporate tools to account for uncertainty in the estimation process – Uncertainty has been stated to be an extremely important piece of estimation as it relates to risk in the cost estimation process. It is crucial to include a robust means of tracking uncertainty in the estimation process.

3. Incorporate checks and balances throughout the process – Checks and balances provide a means for the estimator to know when a project is at risk of overextending a budget. Just as EVM addresses this through the use of cost and schedule performance indexes, a similar tracking method is desired.

4. Adaptable to meet the needs of designing prototypes in a research environment – As mentioned in the opening statements of this thesis, the design of prototypes in a research environment is the goal of this estimation method. This requirement is directly tied to the clear definition of the terms “research” and “prototype” previously provided.

5. Create normalization terms to compare cost, schedule and performance – It is perceived that the need for such normalization terms is needed in order to capture the dependencies between cost, performance and schedule. In normalizing these terms, the estimator is given the flexibility to trade the importance of one term with that of the other. For example, meeting deadlines may be more important than the overall cost of some projects meaning that a normalization term is required to capture a higher preference for schedule as it is compared to cost.

Communication Requirements

6. Easily communicate within organization – If the method cannot be easily shared with others, then the overall impact of a good method will be minimized. Communication must be fostered by an organization to facilitate better staffing decisions during project completion.

Safety Requirements

7. Must incorporate safety considerations throughout the process – Although provided as a wish, it is always good practice to consider how safety may be impacted in a given process. For the estimation process, this could be extended to make sure that proper safety is considered in the development process that will not place human contributors to the research at risk.

Usability

8. Must be organized and written such that a college graduate can understand the methodology – Similar to being easily communicated, a literal understanding of the material must be provided for the purpose of disseminating the knowledge further.

Production

9. Must be articulated clearly to allow for transmission of ideas through standard documentation – Although seemingly the same as previous requirements on communication and ergonomics, this requirement is meant to address the ability of the estimator to reproduce this estimation method. For instance, no unrealistic computation goals should be required that would entail the need for super computers in order to institute the use of this estimation method.

Quality Control Requirements

10. Accuracy of references for readers to check content – This is true of all sound academic developments and will be properly addressed in the literature review section.

Maintenance Requirements

11. Adaptable to changing design environment – Stated as a wish, this requirement is meant to preserve the usability of this estimation over time. As the design process evolves, the estimation method must evolve as well. This implies that there must be a sound basis on design methods in order to appropriately apply estimation methods for future design methodologies.

12. Able to be revised for frequent changes – An estimate is usually not static and can be updated many times throughout a given development. If the estimation tools are not flexible, the utility of the estimation process is limited to being used only at the beginning of the design effort.

Cost Requirements

13. Can incorporate a dynamic cost database – History in the form of costs associated with previous developments can enhance the confidence in future estimations that are similar to previous ones. Although there may be certain aspects that are not well understood, the average uncertainty and thus risk as well can be reduced.

14. Improve the determination of the cost of labor – The overall goal is to improve efficiency of the method, and that is captured here. This is the natural normalization standard as performance, schedule and cost are so closely related. The assumption will also be made such that money and time are independent. Expenditures such as a training purchase to increase the effectiveness of engineering staff for instance will not be considered in this activity.

Schedules

15. Must not create negative impacts to existing design methods – This requirement is borne of future adoption of an estimation method. Although the overall improvement may be great, if it requires an even greater amount of work the benefit can be minimized. Further, if the increased work is not met with even greater improvements, estimators will not be enthusiastic about its implementation.

1.4.3 Engineering and Scientific Relevance of the Work

A number of entities have investigated cost estimation as it applies large systems, high volume manufacturing, and software engineering tasks. Large systems as well as high volume estimates can often overlook the peculiarity of what is encountered during the development of a prototype system. The vast amount of research devoted to estimation as it applies to software tasks is applicable in several ways for prototype systems, but the lack of a multidisciplinary approach to complex systems engineering problems is a limitation of these estimation tools. Furthermore, little has been done to tie together the vast amount of information available in design theory to that of cost estimation tools. There are exceptions, of course, such as work done to incorporate axiomatic design theory into cost estimation [48] or using case based reasoning to incorporate cost estimation theory into the design process [49].

1.5 Organization of the Work

In previous portions of this chapter, this work has been clarified by generating a literature survey of approaches to design methods and cost estimation tools and then progressing to introducing a set of requirements (See Table 3). Based on this information, following chapters will discuss the proposed cost estimation method leading to example applications of this method. A logical framework for this flow of information will be captured in the form of a Validation Square. Following this progression will be interpretations of the results of the research and the relevant contributions to the scientific community.

1.5.1 Overview of the Implementation Strategy

Many of the previous sections serve as modules of information that can be combined to create unique cost estimations. The need for a unique cost estimation method is based upon the fact that estimators will face many unique challenges related to:

- Organizational Differences
- Personal Experience and/or preference
- Resources Available
- Tasks to be Estimated

The thought of treating these various estimation tools as modules stems from the same approach taken by Pahl and Beitz. By providing a number of modules, the designer (or estimator for this case) can tailor the method to a specific set of needs. The remainder of the thesis focuses on a small number of these combinations of modules and how these combinations can be applied to theoretical as well as actual examples. The following section related to validation addresses the impact of the suggested combination of estimation modules and what utility they have as utilized in the example problems.

1.5.2 Framework of Validation

Validation of the proposed method will be achieved by leveraging the Validation Square, which is a logical framework to assess the validity of a proposed engineering design methodology [3]. In this instance, we can apply this validation technique to the proposed cost estimation method contained in this work.

The Validation Square consists of six major steps as a method progresses from initial concept to satisfying a logical proof related to the structure and performance of the method.

1. Accepting the validation of the construct of the method
2. Accepting method consistency
3. Accepting the example problems
4. Accepting usefulness of method for some example problems
5. Accepting that usefulness is linked to applying the method
6. Accepting usefulness of method beyond example problems

The structure of the method is related to the logical framework of the method itself. This requires a proof of utility, validity, consistency, and the ability to generate reasonable example problems to demonstrate performance. During the performance validation the method must be accepted on the grounds of performance in an objective manner as it relates to examples until the final step is addressed. The final step can be paraphrased as being a “leap of faith” by satisfying enough of the logical tests to allow the reviewer to consider the method appropriate for implementation beyond the example problems.

Figure 2 is a graphical representation of these steps that can be followed by the method reviewer.

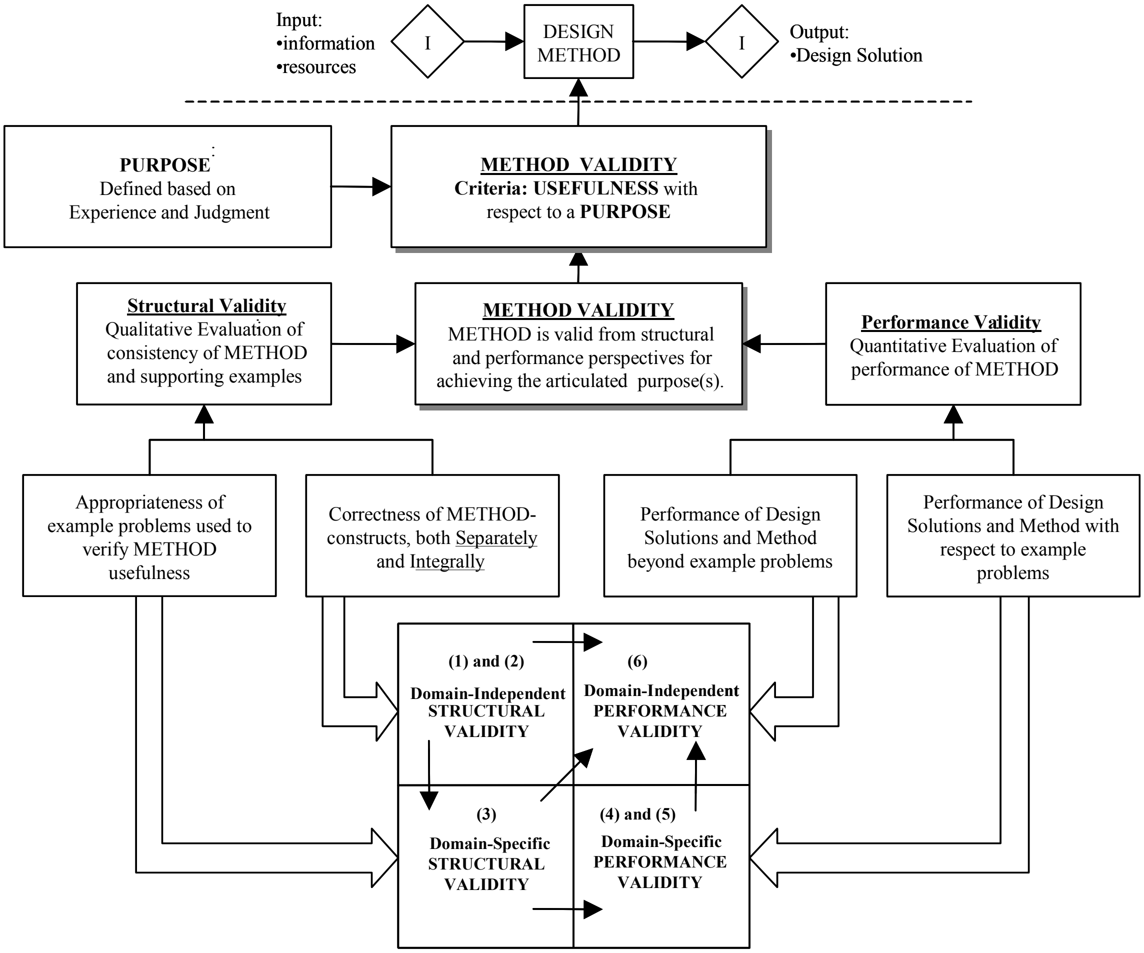


Figure 2: Diagram of the Validation Square Structure [3]

The Validation Square has been applied to the proposed cost estimation method by first identifying the gaps in a literature review, which has been accomplished in Chapter 1. The intent of Chapter 2 is to provide an overall description of the method. This detailed description provides the needed information to satisfy the empirical structural review of the method. The empirical and theoretical performance review of the method occurs primarily in Chapter 3 where the example problems are discussed. This is achieved by using one theoretical example problem followed by an example applied to a project conducted for the Georgia Department of Transportation. The final chapter, Chapter 4, discusses the ramification of the results and elaborates on the previously described "leap of faith" required to extend this cost estimation beyond example problems to any related cost estimation task for prototype systems. The final chapter includes a section on the final results of the application of the Validation Square and the resulting impact that approach has had on the research.

1.5.3 A Road Map for the Work

The following table indicates where in this thesis the intellectual questions are addressed as well as what sections of the Validation Square are addressed. This table does not reflect all discussions relative to the intellectual questions or Validation Square, but only the primary focus of a given chapter. The intent is that the primary focus of the thesis is to continually address the various intellectual questions proposed while using the Validation Square as a logical framework to exercise the proposed cost estimation method. Some validation is discussed in the thesis, but the final results related to the application of the Validation Square are saved for the final chapter in Section 5.2.

Table 4: How the Intellectual Questions will be Addressed and Validated

		Chapters				
Intellectual Questions		**1**	**2**	**3**	**4**	**5**
1) When is enough information gathered to generate a robust estimate for the design of prototype systems?		X	X	X	X	X
2) How do you characterize uncertainty in the estimation process?			X	X	X	
3) Why do estimates need to consider interactions between performance, schedule, and cost?			X	X	X	
4) Why is the assignment of staff critical to an accurate estimate?			X		X	
Validation Square	Theoretical structural review of the method	X	X			X
	Empirical structural review of the method	X	X	X		X
	Empirical performance review of the method	X		X	X	X
	Theoretical performance review of the method	X			X	X

CHAPTER 2

Designing a Cost Estimation Method

Chapter 1 described the overall goals of the proposed cost estimation method and how this proposed method would be validated. These goals include using design methodologies combined with cost estimation tools to generate a more robust approach to estimating the cost of prototype systems. The core problem, however, is related to how uncertainty can be accounted for in estimation exercises, which addresses the question of "when is enough information gathered?" Specifically this question refers to the amount of information needed to provide sufficient confidence to the estimator such that the result of an estimation exercise is acceptable. Chapter 2 describes the details of the method that give an estimator the tools required to address these aspects of estimation.

The proposed method was the result of a combination of tools from a literature review of existing techniques, which included cost estimation tools, design methodologies, and risk assessment methods. Additionally, personal experience was leveraged to determine a logical combination of various tools from these areas with the goal of generating an estimation tool suitable for the design of prototype systems. This activity was guided by the intellectual questions, which led to a number of assumptions and requirements for the method. In summary, the proposed cost estimation method was designed.

In regards to the Validation Square, this chapter shall serve to address the theoretical structural validity as well as the empirical structural validity. The majority of the discussion within Chapter 2 is related to the theoretical structural validity portion of the Validation Square. This is due to the fact that this chapter is where the method is formulated and introduced to the reader in a logical manner. The last portion of the chapter introduces some examples of basic calculations involved with implementation of the example. It is not until Chapter 3 and Chapter 4 that more detailed example problems are presented to the user thus providing a path of acceptance for the example problems as well as the usefulness of those example problems.

2.1 Designing the Cost Estimation Method

The general steps to a design process are: 1) clarification of the task, 2) conceptual design, 3) preliminary design, and 4) detailed design. This section describes how the cost estimation method was designed using a set of logical steps based upon the information gathered in literature and industry.

2.1.1 Clarification of the Task

An important starting point in any design exercise is clarifying the task at hand in order to guide the overall design process. This exercise was described in Section 1.2.1 and resulted in a detailed list of requirements (See Table 3). To further develop a methodology, it is often required to limit the design space through the generation of assumptions that accompany requirements. A number of assumptions were made during the design process to limit the scope of the work to focus on the intellectual questions posed. By taking this approach, a designer can remain focused on achieving the desired goals of the design exercise while recognizing limitations in the method's applicability. A number of assumptions were presented in Table 2 to highlight the various shortcomings of the proposed method to the estimator. These initial assumptions were improved upon and are listed in Table 5 as they were extended to address the cost estimation method limitations. It is imperative that the estimator using this method become familiar with these limitations in order to preserve any validation that has been performed on that particular method. The assumptions are listed in Table 5.

Table 5: Assumptions Required for Proposed Cost Estimation Method

No.	Assumption
1	Material estimates are not prone to high levels of uncertainty for this case
2	Will need to define experience levels to give a correct labor estimate for employee assignments a. 2-5 levels of experience are recommended b. Based upon relevant experience of individuals
3	Assume no conflicts between skill-sets required and time constraints on employee availability
4	Assume 40 hour weeks
5	All skill-sets needed are available and location of engineering resources are irrelevant a. Internal and external resources are available and cost the same b. Example: overseas resources not influential
6	All state of the art engineer tools are available and people know how to use tools a. Stay away from development of tools in this work b. Future work could look into using the method to make decisions on how people will be trained
7	Major requirements defined at the outset
8	Assume constant price of everything
9	Ignore life cycle impact
10	Intellectual property (IP) issues ignored
11	It is feasible to evaluate the performance – in other words, there is a means to validate the performance
12	Functional and working structures can be completed
13	Designer control over all tasks to be estimated
14	Corporate management requirements ignored
15	Risk taken at proposal phase is consistent (not variable)
16	Limits for variance calculations are defined through intervals

The assumptions in Table 5 are typically straightforward, but a detailed explanation has been provided for each of the items in the following descriptions.

Assumption 1: Material Estimates and Uncertainty

There is some discussion within this method related to the estimation of material costs, but that is not the focus of this effort. Several techniques to address the cost of materials have been addressed in literature but are not detailed in this exercise.

Assumption 2: Data Required for Employee Assignment

A tool is discussed in this work related to the assignment of labor resources to complete the work. In order to assign these individuals, it is recommended that some database exists to capture the relevant experience of individuals considered for staffing a particular program. This particular section of the method may be ignored if an existing and/or competing system is already in place within the organization for assignment of research staff. Additionally, expert judgment oftentimes is sufficient for the assignment of resources as long as the known limitations of using such a technique are considered.

Assumption 3: Employee Availability is Secured

Particular employees may be required for a given task. This becomes especially important for smaller organizations where a particular individual may have key knowledge that is needed on several programs and there is no alternative to using this staff member. These issues are ignored and not a focus of the proposed method.

Assumption 4: 40 Hour Work Weeks

When assigning tasks and generating schedules, the use of overtime can be leveraged to reduce task durations. However, many government organizations are subjected to the Federal Acquisition Regulations and do not offer overtime to salaried individuals. The assumption is made to use 40 hour work weeks and ignore the effects of overtime.

Assumption 5: Skill Sets are Available to the Research Team

There are two occurrences that this assumption is intended to address: first that skills needed are present, and second that the location of individuals is insignificant. In practice, these assumptions do not necessarily represent the real effect of these occurrences. When skills that are not held within an organization are needed, the need for hiring a consultant is often considered. Although the use of a consultant or consultants can add skill sets that are not present in an organization, relying upon these individuals can introduce inefficiencies related to the transfer of information in and out of the organization. A similar effect is present when physical locations differ such as time zones affecting the ability to transmit ideas readily among team members. These known effects are not addressed.

Assumption 6: All Engineering Tools are Available

The assumption is made that all state of the art engineering tools are present as well as staff being trained to use these tools. This is an important distinction to make because if this is not the case, then there will be additional cost required to train staff or buy new engineering tools to allow the organization to act in an efficient and competitive manner. Typically, overhead rates applied by organization will account for the purchase of new tools and may also cover training of individuals hence the reason this effect has been ignored.

Assumption 7: The Requirements are Fully Defined

A key concept of design methods is related to the generation of requirements as a result of clarifying the needs of a customer. This may involve frequent clarification from the customer and several iterations to generate a full list of requirements. For the use of this method, it is assumed that all key requirements are in place prior to estimating the work.

Assumption 8: Constant Prices Assumed

Economic principles related to the fluctuation of prices over time are not addressed.

Assumption 9: Manufacturing and Life Cycle Costs are Ignored

Although it is clear that for high-volume manufactured items the cost of the entire life cycle is important, this cost as it applies to prototype systems does not have a similar impact on the overall cost of the project. The resulting prototype is simply stored or recycled after the useful life has expired making the costs minimal associated with this act.

Assumption 10: IP Issues Ignored

The costs associated with intellectual property rights have been ignored. When these issues arise, the cost of patent lawyers and business development staff may influence the cost of the research and this has not been addressed.

Assumption 11: Performance Evaluation is Feasible

If the performance cannot be validated at the end of the development, then the object can never be compared to the initial requirements to see if they were actually achieved in the development or not. This in turn means the cost of the development could never be validated. There are unique prototype systems that may fall into this category such as a satellite development for capturing anti-matter of which no reliable validation means exists.

Assumption 12: Functional and Working Structure Representation Possible

Based on leveraging principles from the design method of Pahl and Beitz, the design must be able to be represented in the form of functional and working structures.

Assumption 13: Designer Control Over Tasks

The designer must have control over all design tasks in order for the estimator to generate a reasonable estimate. For example, if the customer will not allow the designers to use solid state memory for data storage it may have an impact on the overall cost of the design to package and test spinning disc storage media. As long as these tasks are captured in the project requirements, the lack of flexibility will be reflected in the resulting estimate.

Assumption 14: Corporate Management Techniques Ignored

Many organizations have a number of protocols for capturing data throughout a design process or generating reports intended to benefit the organization outside of the customer's needs. These tasks are assumed to be covered by overhead funds. This includes the collection of metrics that may be used to populate cost estimation databases in the future.

Assumption 15: Risk is Consistent

As discussed in following sections, there is a strong relationship between risk and uncertainty. If the desired risk level of decision makers changes drastically throughout the design process, then the estimate must also change in order to accurately reflect this. Risk is assumed to be consistent or unchanged through developments.

Assumption 16: Variance is Captured Through Intervals

Although a number of techniques may be employed to characterize uncertainty (fuzzy sets, probability distributions, etc.) the use of intervals has been used for this work. Intervals are often suitable to capture inputs from designers and estimators. More advanced techniques can be more complex, cumbersome, and confusing. Simply put, this limits bounds to simple interval determination and does not explore complicated methods that involve the detailed information solicitation from the estimator and/or design engineers.

This list of assumptions captures many different facets of an organization from labor resources, engineering tools, and ability to capture cost data for future cost estimation exercises. Steps 1-3 of the cost estimation method are devoted to having an understanding of these assumptions and capturing whether the assumptions made will otherwise invalidate the use of the method. Some key assumptions that are made are those related to requirements being available at the start of the estimation process. If these are not captured well from the outset, then the estimator must take on the additional risk of estimating the clarification of the task or use a different approach altogether.

2.1.2 Conceptual Design

Having clarified the task through requirements generation and a list of assumptions, the conceptual design phase of development is intended to serve as the point at which the general form or "concept" is created. In this case, the goal is a cost estimation method that satisfies these requirements with a focus on addressing the intellectual questions.

An abstract form of the proposed estimation technique is provided in Figure 3 to capture the general desired flow of information. The flow of information presented in Figure 3 was chosen due to the reliance on the design method structure of Pahl and Beitz from Figure 1. Because there is no equivalent to the flow of energy or material within this representation, the sole input/output is that of signals or for the purpose of this exercise it is information. Although this figure only addresses the high level flow of information it serves as an important guide for how various estimation tools can be combined during the preliminary design of the method described in Section 2.1.3.

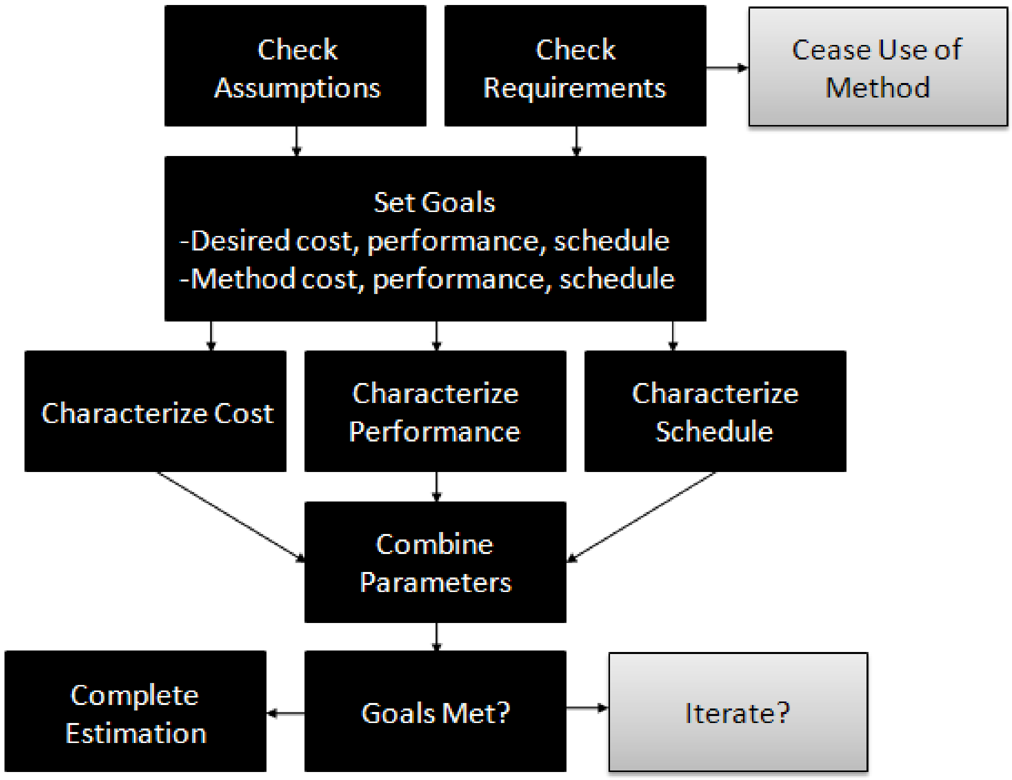


Figure 3: Abstract Sequence of Proposed Method

2.1.3 Preliminary Design

An affinity diagram was generated to start the initial concept development with key components or rather expectations of the method grouped into related sections. The results of this affinity diagram exercise are given in Table 6. The table contains the collective groups of tools or approaches considered for inclusion into the proposed method.

Table 6: Affinity Diagram Results

Checks	Databases	New Techniques	Existing Cost Methods	Risk Tools	Planning Tools
Appropriateness Evaluation Check Assumptions Cost, Schedule, Performance Goals Met?	Workforce Database Existing Cost Database Material Database	Normalization Equations Skill Set Database Staff Assignment Calculator Material Estimator	Delphi Activity-Based Cost Top-Down Bottom-Up COCOMO	Cost-Benefit Fault Tree Predictive Modeling Expert Judgment Root-Cause	Gantt Chart Capturing Metrics

Starting with the various components and tools identified in Table 6, the first step was to remove obvious components that did not meet either the requirements or the assumptions described previously. The use of a material database was removed due to an assumption that material costs would be generally ignored as the cost of material is not a major focus of the exercise. This same assumption also limited the importance of including a new material estimation technique initially considered for the method.

With the previously mentioned items removed from the set of tools, a number of alternatives were considered based upon the desired abstraction described in Figure 3. These high-level alternatives are described in Table 7.

Table 7: Alternatives Considered for the Proposed Cost Method

<table>
<tr><th>Abstract Step</th><th colspan="3">Alternative Considerations</th></tr>
<tr><td rowspan="2">Check Assumptions and Requirements</td><td>Treat as Boolean Decision</td><td>→</td><td>Allow to modify but characterize with uncertainty</td></tr>
<tr><td colspan="3">The ability to modify the method when assumptions and requirements were made to enhance utility of the method while maintaining the estimator’s awareness of risks for either meeting or not meeting various assumptions.</td></tr>
<tr><td rowspan="2">Generate Method Goals</td><td>Expert judgment</td><td>←</td><td>Prescribe a generation technique</td></tr>
<tr><td colspan="3">These goals related to the cost and schedule goals as they relate to the estimation process itself. The meaning here is that the goals will be applied from the expertise of the estimator as opposed to generating these goals numerically from inputs. There is some discussion on sensitivity analyses related to these parameters and the importance to understand this sensitivity as it relates to the estimation process.</td></tr>
<tr><td>Generate Goals of Desired Results</td><td>Expert judgment</td><td>←</td><td>Prescribe a generation technique</td></tr>
<tr><td></td><td colspan="3">These goals will be collected as weights from cost, performance, and schedule. The meaning here is that the goals will be applied from the expertise of the estimator as opposed to generating these goals numerically from inputs. There is some discussion on sensitivity analyses related to these parameters and the importance to understand this sensitivity as it relates to the estimation process.</td></tr>
<tr><td rowspan="2">Characterize Cost</td><td>Use a single tool</td><td>→</td><td>Leverage Multiple Tools</td></tr>
<tr><td colspan="3">Instead of using only one tool, the option is left open to use multiple tools. This will mean that estimation tools better suited for hardware developments can be used on hardware related activities whereas software tools such as COCOMO may be used for software alone.</td></tr>
<tr><td rowspan="2">Characterize Performance</td><td>Ignore wishes and assume performance is static</td><td>→</td><td>Treat wishes separately and combine</td></tr>
<tr><td colspan="3">Instead of ignoring wishes, it was determined to consider them separately in order to gain a better understanding of the customer desires by including those wishes.</td></tr>
<tr><td rowspan="2">Characterize Schedule</td><td>Phase Event Information Diagram</td><td>→</td><td>Gantt Chart</td></tr>
<tr><td colspan="3">Due to familiarity with Gantt charts, it was decided to use these types of charts for the method due to their common use in industry.</td></tr>
<tr><td rowspan="2">Combine Parameters</td><td>Normalized Functions</td><td>←</td><td>Treat separately</td></tr>
<tr><td colspan="3">It is important to consider all three key parameters (cost, schedule, performance) as related in order to capture the true overall cost and schedule of a program. It was decided to determine these based upon a normalized function that would compare all three terms based upon their initial weighting factors.</td></tr>
<tr><td rowspan="2">Check Goals</td><td>Allow for multiple iterations</td><td>→</td><td>Only one iteration</td></tr>
<tr><td colspan="3">It was decided that because the method cannot likely continue through several iterations and still meet the estimator’s goals, the iterations are limited to one-full iteration. Otherwise, the cost of the estimation method exercise would become too expensive.</td></tr>
</table>

The alternatives described in Table 7 were then considered in the context of the assumptions and requirements to generate the candidate cost estimation method. The alternative that was chosen is indicated by an arrow. The logical next step in the design process is to include a detailed design phase; however, this phase is addressed in Section 2.2.

2.2 The Proposed Cost Estimation Method

Figure 4 provides a graphical representation of the proposed cost estimation method. The goal of this planning and estimation method is to provide an estimator with the tools required to make decisions about technical developments that satisfy the initial requirements. The top-level flow of information describing each step within the general method is described in Figure 4. Following the figure is a table describing each numbered section from the flow chart. Viewing Figure 4 in conjunction with Table 8 provides a quick reference to the structure of the proposed cost estimation method. The following sections in Chapter 2 explain the various modules of this method in more detail such as how to apply each of the major steps referenced in the visualization. The assumptions and generation of the method were described in previous sections.

Chapter 3 addresses some use of the proposed method, with a focus on the different levels of estimation that can be performed. In Chapter 4, the steps of the method are strictly demonstrated. The GDOT example problem in that chapter follows each step and illustrates how the proposed method in Figure 4 can be implemented.

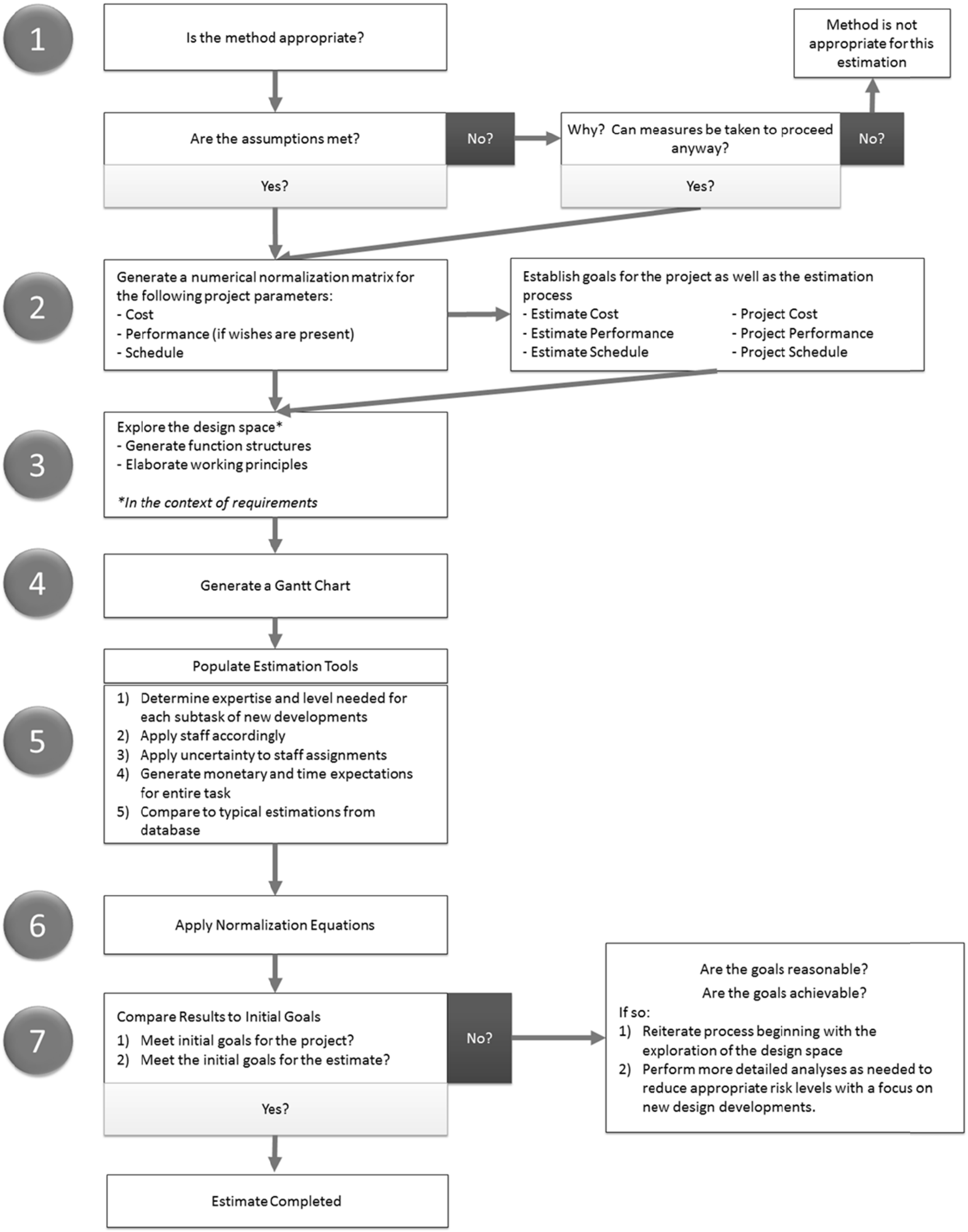


Figure 4: Flow Chart of Proposed Method

Table 8: Explanation of Sections from the Top Level Flow Chart (Figure 5)

Step		Description
1	Is the Method Appropriate	A clear definition has been provided of what technical tasks fall within the scope of this method. This definition has been defined as a set of assumptions and requirements. The project under consideration must be checked in order to verify whether or not it is suitable for application of the method.
2	Generate a Numerical Normalization Matrix	In order for the method to be represented in a mathematical formulation, it is crucial to have a clear representation of cost, performance, and schedule. These terms are associated with three different terms being money, ability to meet project requirements, and time. A normalization must be developed to place these terms in a single unit of measure for the method to be quantitative in nature.
3	Explore the Design Space	Leveraging the work done in previous methods, particularly methodologies developed by Pahl and Beitz, the design space of the problem is to be explored in this step. It is here where the distinction of design methodologies can be coupled directly with ideas of cost estimation. A continuing theme in this thesis is supported here – "In order to properly estimate a technological development, a high level design process must take place."
4	Generate a Gantt chart	A Gantt chart capturing the dependence of time and tasks is to be developed in this step. If there are multiple major designs, each variant will require its own Gantt chart. This creates a parallel path within the method.
5	Populate Estimation Tools	This step is where a large portion of the implementation of the method occurs. This step is where the staff assignment is made, and where it is applied directly to the Gantt chart generated previously. There are also steps of generating a level of expertise needed which requires a database within the organization to exist for staff capabilities. Additionally, these capabilities are joined with project technical needs through selection algorithms described later in the section devoted to explanation of the calculation spreadsheets.
6	Apply Normalization Equations	At this point in the process, the normalization equations are applied to the outputs from the previous step.
7	Compare Results to Initial Goals	Early in Step 2, the estimator established criteria to evaluate at this point. These criteria are simplified to an acceptable set of goals for cost, performance, and schedule. If the specified ranges of these values are met, then the estimation can end – if not, then the following decision must be made: Does the current collection of goals and results seem to be incompatible?

2.3 Numerical Normalization of Cost, Performance and Schedule Terms

There are three key ingredients to generating a good cost estimate: an understanding of cost, performance, and schedule. There are generally two key outputs of a cost estimate or proposal and these are simply cost and the time to complete the activity. As the time to complete the activity is often specified by the customer, the cost proposal is reduced to only one variable – cost. This reduction in variables can be made because both performance and schedule are dictated by the customer. This is not to say that performance and schedule should not be considered during the estimation process, as they are important to generating the final cost value.

Depending on the customer, various contracting terms may be specified but they generally fall into two categories. The first category is a firm fixed price contract. In this case the customer is paying for the uncertainty of the contracting organization. The organization must consider the risks associated with this uncertainty and adjust the overall cost to reflect these anticipated issues. A term commonly used to capture this uncertainty is “management reserve.” The other category of contracts is a cost-plus contract. These estimates are generated assuming some risk is evident but the customer is willing to cover additional expenses if costs increase due to variability or unexpected occurrences during a development. In either case, an understanding of the variation is desired so either the customer or the contracting organization can quantify the expected risk involved in the work.

2.3.1 Numerical Normalization Equations

Now that the argument has been made that the ultimate goal of an estimate is to capture cost and the variation associated with it then we need to describe how this impacts the high level organization of the proposed cost estimation method. The goal can be represented in a simple equation relating the three key ingredients previously discussed:

$$P + U_P = C + U_C + S + U_S \tag{1}$$

Where P refers to performance, C refers to cost, S refers to schedule, and U refers to uncertainty with the subscript specifying which variable is described by this uncertainty. Performance is related to the requirements list, cost is typically represented in dollars, and schedule is in terms of time. An important distinction about performance is the uncertainty associated with performance. In general, one desires to meet all performance goals and this would be critical to satisfying a contract. However, there can be wishes, as described earlier in the context of demands and wishes that become requirements that may or may not easily be met. These wishes become the uncertainty in performance for these calculations.

In order to normalize these terms, the preferences of the estimator must be captured in order to reflect the estimator's desires.

$$P_{Pref} + C_{Pref} + S_{Pref} = 1 \tag{2}$$

These preferences are critical to the formulation of an estimate because they capture the desires of the estimator. Furthermore, it must be understood by the estimator that slight variations in these values can have a substantial impact on the end result. The selection of these variables is best described in table form to show the interaction between the three preferences. Note that 1/3, approximated by 0.33, is neutral in regards to these preferences. In the case of performance, a number greater or less than 0.33 corresponds to the general risk level the estimator is willing to take compared to the requirements. If greater than 0.33, the estimator is conservative whereas if less than 0.33, the estimator is willing to take risk with performance. Table 9 contains a detailed description of the meaning of these preferences when varied with examples of different preferences an estimator may wish to have during a specific estimation process.

Table 9: Examples of Preferences and the Resulting Consequence on an Estimation

	Estimator is willing to accept risk associated with:		Estimator is conservative towards:
$P_{Pref} < 0.33$	Performance and the ability to meet requirements.	$P_{Pref} > 0.33$	The ability to achieve requirements.
$C_{Pref} < 0.33$	Cost overruns more than other areas	$C_{Pref} > 0.33$	Cost meaning it is critical that cost goals are achieved
$S_{Pref} < 0.33$	Missing schedule dates is not as much of an issue.	$S_{Pref} > 0.33$	Schedule is more important than other areas and meeting dates is critical.
Examples			
$P_{Pref} < 0.50$	$C_{Pref} < 0.25$	$S_{Pref} < 0.25$	Schedule and cost are equally important, but the ability to meet requirements is critical.
$P_{Pref} < 0.30$	$C_{Pref} < 0.45$	$S_{Pref} < 0.25$	Cost is very important, and performance is slightly more important than schedule.
$P_{Pref} < 0.20$	$C_{Pref} < 0.40$	$S_{Pref} < 0.40$	Schedule and cost are equally important with less concern in the ability to meet requirements.

Building on Equation 1, there is a need to normalize the terms to a single parameter. Cost was chosen as the normalization factor to describe both schedule and performance. This is done by assuming there is a set estimate that describes the relationship between performance, cost, and schedule. From that assumption, the uncertainty is normalized relative to the base cost by the following set of equations:

$$C_{SU} = (S_{Pref}/C_{Pref}) \cdot (U_S/S) \tag{3}$$

$$C_{SUW} = (S_{Pref}/C_{Pref}) \cdot (U_{SW}/S_W) \tag{4}$$

$$\begin{gathered} C_P\text{, lower bound} = C \\ C_P\text{, upper bound} = C + U_C + C_{SU} \end{gathered} \tag{5}$$

$$\begin{gathered} C_{PU}\text{, lower bound} = C_W \\ C_{PU}\text{, upper bound} = C_W + U_{CW} + C_{SU} + C_{SUW} \end{gathered} \tag{6}$$

Where:

C_W	Cost of Wishes in dollars
U_{CW}	Uncertainty of cost of Wishes in dollars
S_W	Schedule related to Wishes expressed in days
U_{SW}	Uncertainty of schedule related to Wishes expressed in days
C_{SU}	Uncertainty of schedule expressed in dollars
C_{SUW}	Uncertainty of schedule related to wishes expressed in dollars
C_P	Cost needed to achieve performance in dollars
C_{PU}	Cost of performance uncertainty in dollars, or cost to achieve Wishes

Notice that the cost to achieve performance, C_P, and the cost of performance uncertainty, C_{PU}, are represented as intervals. Due to the structure of contracts as well as the more common occurrence of over-running cost as opposed to under-running costs on a program, uncertainty is only expressed as an upper bound of the interval. The baseline cost from the estimate then becomes the lower bound of the interval.

This completes the system of equations required and also defines how information is exchanged between the estimator and the estimation process. The division of variables is captured in Table 10. This table describes how the variables are separated into whether they are an input from the estimator or a calculation from the process. This means the estimator must define the preferences and the initial plan must include the cost, schedule, and uncertainty associated with those terms. Additionally, this estimation process needs to be repeated for wishes in order to gather the difference in cost to achieve demands and wishes.

Table 10: Variable Description for Cost Estimation Method

Process	Estimator
C_{SU} C_{SUW} C_P C_{PU}	P_{Pref} C_{Pref} S_{Pref} C, U_C S,U_S C_W, U_{CW} S_W,U_{SW}

2.3.2 Uncertainty in the Method

This leaves a clear definition of how the estimator will interact with the process, yet there has not been a discussion on an important aspect of uncertainty in the context of this method. Uncertainty plays a critical role in the estimation process because the level of uncertainty can affect decisions of whether or not to pursue costly activities. This method addresses uncertainty only at the major areas as it relates to the initial cost and schedule estimate for both demands and wishes. These uncertainties are then used to determine the overall uncertainty of the estimate expressed in dollars as an upper and lower bound. However, there are several bits of uncertainty that are overlooked in this assessment:

Determining Uncertainty: The determination of uncertainty contains an inherent amount of uncertainty as well. For instance, the lower and upper bounds that result from this method could be considered similar to the standard deviation of 2σ on a Gaussian distribution or a 97.7% confidence interval. In other words, the result of the method is not definitive as it represents an unknown quantity.

Preferences: The selection of preferences is meant to be used as a tool to show the effect of the estimator's preference between performance, cost and schedule. As shown in a later example, it can be seen that modifying preferences can alter the resulting interval from 30% to as much as 50% of the overall cost simply by adjusting preferences. It is recommended for terms that have a substantial impact, such as preference, that a sensitivity analysis be performed to better characterize the impact of modifying preferences.

These are the two primary means of uncertainty in the proposed method; however uncertainty is prevalent throughout any estimation process. The estimator must understand these limitations and make adjustments according to their level of risk. Interval mathematics has been chosen to represent this uncertainty.

2.3.3 Interval Mathematical Representation of Uncertainty

Interval mathematics has been employed to characterize uncertainty for this method. In areas where there is little known about the distribution of parameters, the system is considered to have epistemic uncertainty [50]. This type of uncertainty could be determined, yet may not because of what has been ignored or there has not been enough time to investigate. Aleatoric uncertainty is another type of uncertainty where the uncertainty is always evident in the system such as characteristic thermal noise in a sensor. In the estimation of prototype systems, only sparse data is generally available to define a range of inputs. The uncertainty can be a result of either aleatoric or epistemic characteristics. This method will primarily address epistemic uncertainties and how they can be characterized to improve the estimation process. Uncertainty will be represented using interval mathematics for implementation in this method. There are recognized limitations to taking this approach to uncertainty. The key characteristics of intervals are listed below:

Linearity: The upper and lower bound of an interval do not imply any type of distribution between the two boundaries. This result is inherent to interval mathematics. The equi-probability model of intervals is used in this method [51].

Fixed Boundaries: The upper and lower bounds of intervals act as maximum and minimum barriers that are not present in many distributions such as a Gaussian distribution. In standard mathematical distributions, one or both of the bounds may extend infinitely allowing a sensitivity analysis to produce unrealistic results.

Single or Multiple Intervals: Intervals can be represented as a single interval or a collection of several intervals. These several intervals could be the result of multiple inputs from different experts. Only single intervals are considered for this method and instances of overlap (or non-overlapping) are ignored.

Inclusion: An assumption often made in regards to intervals is that there is a strong likelihood that the actual value is contained within the specified interval. In many cases the interval is defined by an expert within a given area making this assumption as good as the individual defining the bounds of the interval.

This section describes how a proven methodology, the equi-probability interval model, has been leveraged to represent uncertainty in this method. The following section begins to describe how this is implemented within the method. As stated before, this method treats the interval as the initial or base estimate becoming the lower boundary of the interval and the upper boundary being the base estimate with the addition of uncertainty.

2.3.4 Numerical Normalization Example

This section describes a theoretical exercise of estimating a general development through the various design stages. Relying only upon engineering estimates or rather expert judgments, this exercise is meant to highlight the mathematical formulation of normalization and the impacts on the overall estimated cost using equations from Section 2.3.1.

The first step of performing the estimate is to detail the work such that the cost of employee labor can be estimated. Each task has been identified and given an appropriate amount of labor in Table 11 to determine the overall cost as well as the amount of cost uncertainty. The data contained in Table 11 was generated simply by engineering judgment. Table 12 contains similar data for the schedule. The information in these tables had to be generated iteratively to meet the goals of the estimator. The calculations including the normalization are listed in Table 13. This table also includes multiple results for varying preference.

Let us turn our focus to the information provided in Table 11. The skill level of four employees is listed and the number of hours they are tasked for is applied to each major task. Following this, a percentage of uncertainty is applied to each task where some ideas such as concept generation at 25% have more uncertainty than the fabrication of parts with an uncertainty of 5%. The schedule detail, Table 12, is generated much the same but related to the time in weeks to complete the tasks. This could be in the form of a Gantt chart, but a simple spreadsheet was used since task dependency was not crucial to this example problem. Table 13 includes the information from the estimator not captured in the raw cost estimation details such as preference and goals. The final result is shown here where total cost is summarized by the expected value ($33,704) and the maximum value ($51,694). This range reflects neutral uncertainty (all preferences = 1/3), and covers the range of minimum cost of performance for demands only and maximum cost of performance for demands and wishes. The term neutral uncertainty is used because no additional preference is given to either parameter making each parameter equal in weight for the given the intervals used.

The results in Table 13 can be summarized by a number of steps describing how the numerical normalization is applied:

1. Cost is determined through a bottom-up labor estimate
2. Uncertainty of cost is determined at the task level
3. Schedule is determined through a bottom-up estimate
4. Uncertainty of schedule is determined at the task level
5. Preferences are assigned to the three key parameters (cost is given a slight preference of .40, over performance and schedule, .30 each)
6. Steps 1-4 are repeated to determine cost and schedule estimates related to wishes
7. Interval of costs associated with demands and wishes are calculated separately

An important point to make is that the interval mathematics are included in this example simply by the uncertainty bounds placed on cost and schedule items. For example, the concept generation task may have an expected cost of $5,872, but uncertainty adds $1,468 to that value. This makes the interval for the cost of concept generation to be $5,872 to $7,340. To clarify how the interval is calculated, it is the result of the basic input for the lower bound with the upper bound resulting from the basic input plus uncertainty. In regards to the overall cost of the effort, the owner of the cost of the uncertainty may be the customer or contracting organization depending on the terms of the contract.

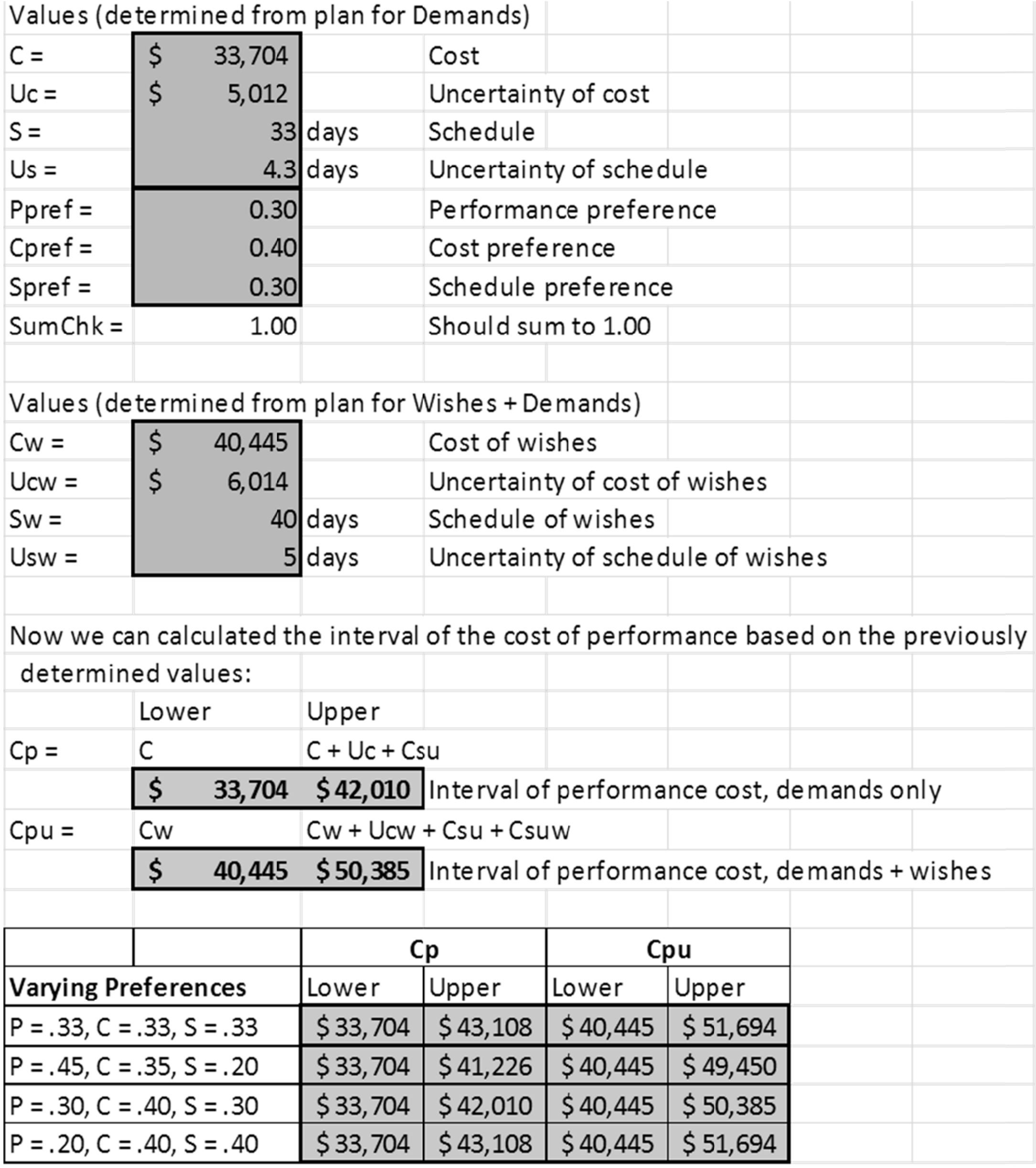
Table 11: Detailed Cost Estimate for Example Numerical Example

	Hours				Per Task	Uncertainty	
Skill Level	3	4	2	5	$	%	$
Rate ($/hr)	85	110	57	115			
Project Clarification	4	8		4	$ 1,680	5%	$ 84
Detailed Estimation		8			$ 880	5%	$ 44
Data Collection							
Recall Evaluation		4	16		$ 1,352	5%	$ 68
Plant Interviews	4	4			$ 780	5%	$ 39
Summarize Data Collection		4			$ 440	5%	$ 22
Conceptual Design							
Concept Generation	16	16	16	16	$ 5,872	25%	$ 1,468
Concept Selection	8	8	16		$ 2,472	10%	$ 247
Embodiment Design							
Elaborate Concept Details		8	16		$ 1,792	20%	$ 358
Define Prototype	4	4	4	4	$ 1,468	10%	$ 147
Detailed Design							
Proof Concept Detailed Dsgn		8	16		$ 1,792	15%	$ 269
Fabrication of Parts			40		$ 2,280	5%	$ 114
Assembly of prototype	16		16		$ 2,272	20%	$ 454
Testing and Verification		4	16		$ 1,352	20%	$ 270
Final Report	8	16	16	8	$ 4,272	10%	$ 427
	$ 5,100	$ 10,120	$ 9,804	$ 3,680			
Total Labor Cost	**$ 28,704**					**14%**	**$ 4,012**
Estimated Prototype Cost	**$ 5,000**					**20%**	**$ 1,000**

Table 12: Detailed Schedule for Example Numerical Example

	Time	Uncertainty	
	(Weeks)	(%)	(Weeks)
Project Clarification	6	10%	0.6
Detailed Estimation	2	10%	0.2
Data Collection	3	10%	0.3
Recall Evaluation	-	-	
Plant Interviews	-	-	
Summarize Data Collection	-	-	
Conceptual Design	4	25%	1
Concept Generation	-	-	
Concept Selection	-	-	
Embodiment Design	4	15%	0.6
Elaborate Concept Details	-	-	
Define Prototype	-	-	
Detailed Design	8	10%	0.8
Proof Concept Detailed Design	-	-	
Fabrication of Parts	-	-	
Assembly of prototype	-	-	
Testing and Verification	4	15%	0.6
Final Report	2	10%	0.2
Total	**33**	**13%**	**4.3**

Table 13: Equation Application for Numerical Example



Values (determined from plan for Demands)

C =	$ 33,704		Cost
Uc =	$ 5,012		Uncertainty of cost
S =	33	days	Schedule
Us =	4.3	days	Uncertainty of schedule
Ppref =	0.30		Performance preference
Cpref =	0.40		Cost preference
Spref =	0.30		Schedule preference
SumChk =	1.00		Should sum to 1.00

Values (determined from plan for Wishes + Demands)

Cw =	$ 40,445		Cost of wishes
Ucw =	$ 6,014		Uncertainty of cost of wishes
Sw =	40	days	Schedule of wishes
Usw =	5	days	Uncertainty of schedule of wishes

Now we can calculated the interval of the cost of performance based on the previously determined values:

	Lower	Upper	
Cp =	C	C + Uc + Csu	
	$ 33,704	**$ 42,010**	Interval of performance cost, demands only
Cpu =	Cw	Cw + Ucw + Csu + Csuw	
	$ 40,445	**$ 50,385**	Interval of performance cost, demands + wishes

	Cp		**Cpu**	
Varying Preferences	Lower	Upper	Lower	Upper
P = .33, C = .33, S = .33	$ 33,704	$ 43,108	$ 40,445	$ 51,694
P = .45, C = .35, S = .20	$ 33,704	$ 41,226	$ 40,445	$ 49,450
P = .30, C = .40, S = .30	$ 33,704	$ 42,010	$ 40,445	$ 50,385
P = .20, C = .40, S = .40	$ 33,704	$ 43,108	$ 40,445	$ 51,694

2.4 Cost Estimation Tools for Estimation with Uncertainty

Based upon the literature review performed in sections 1.2.2 and 1.2.6 both cost estimation and risk assessment techniques were discussed. The first area provides a framework to develop cost estimation methods. The area of risk assessment can be argued to describe uncertainty in estimation. Due to the nature of risk in design, the ability to estimate the cost of unforeseen events can be altered by the path the risk can take. A fault tree analysis can identify the different paths the risk can take, and by applying the appropriate cost technique, the cost of these unforeseen events can be forecasted. This section describes how these tools are tailored for the type of estimate being generated by an estimator.

Recall the various techniques discussed for cost estimation in section 1.2.2 including: Top-Down Estimation, Bottom-Up Estimation, Activity-Based Costing, Delphi Process, and Article Based Estimation. Now consider that there are several types of estimates that may be desired ranging from a low level of detail for an initial decision to be made to a high level of detail for an estimate that will be used to support a multi-million dollar proposal. It is important to understand that this range of estimates has value and the different techniques of estimation may or may not apply for the different types. In order to provide clarity to this matter, let us first define this range of estimates as conforming to one of three types of estimates: Basic Estimate, Intermediate Estimate, and Detailed Estimate. A definition for these terms is supplied below:

Basic Estimate: An estimate intended to make only high-level decisions. For instance, a simple estimate may be generated to determine whether a proposal effort would be worthwhile. This level of estimate may also be needed prior to determining the potential cost-benefit ratio of a new program area. These estimates rely primarily on expert judgment and contain a great deal of uncertainty. The total time to generate such an estimate may only be on the order of one to a few hours.

Intermediate Estimate: This type of estimate can be a nice balance between basic and detailed estimates. There should be a set of requirements and assumptions captured in this estimate that serve as a basis for the estimate. Uncertainty is reduced as the level of detail is increased by the estimator. Uncertainty can begin to be captured using various planning tools in order to provide a quantitative level of confidence. The time to generate a mid-level estimate may range from several hours to several weeks.

Detailed Estimate: The increased amount of information included in this estimate can be rather detailed and will require a significant effort. These estimates may take several days or even weeks to generate. The reduction in uncertainty and thus risk comes at the expense of several engineering resources. This approach may be required to reduce the uncertainty level of the deciding body for continuation in order to satisfy risk of those personnel.

Using this terminology combined with these estimation tools, a matrix can be generated to illustrate how this data can be combined with risk management tools depending on the level of complexity.

Table 14 describes how these various tools and techniques interact and can be combined to satisfy the goals of the estimator. An additional discriminator is carried over from the discussion on Gantt Charts in Section 2.1, which is whether a particular task is well understood or contains significant uncertainty. These items can be thought of as being either variant, adaptive, or original designs. The terms variant, adaptive, and original design are defined in Section 1.3.1. For instance, original designs often carry high uncertainty due to the unexplored nature of these developments whereas variant designs are well understood.

Table 14: Approaches to Cost Estimate Based on Level of Detail Desired

	Variant and Adaptive Designs		Original and Adaptive Designs	
Estimation Type	**Applicable Cost Estimation Tools**	**Applicable Risk Tools**	**Applicable Cost Estimation Tools**	**Applicable Risk Tools**

Basic Estimate	Bottom-Up	Expert Judgment	Top-Down, Activity-Based Costing	Expert Judgment, Fault Tree Analysis
Intermediate Estimate	Bottom-Up, Article Based	Expert Judgment, Fault Tree Analysis, Predictive Models	Top-Down, Bottom-Up, Activity-Based Costing, Article Based	Expert Judgment, Fault Tree Analysis, Predictive Models
Detailed Estimate	Bottom-Up, Activity-Based Costing, Article Based	Expert Judgment, Fault Tree Analysis, Predictive Models	Top-Down, Bottom-Up, Activity-Based Costing, Article Based	Expert Judgment, Fault Tree Analysis, Predictive Models

Notice in Table 14 how in a greater number of tools are suggested for original and adaptive designs. This is an important distinction because the introduction of new technologies will contain more uncertainty requiring more scrutiny by the estimator. Keep in mind that uncertainty goals will be considered by task as well as the overall project in order to satisfy the risk requirement imposed upon the estimation task. Implementation of the ideas discussed in Table 14 is discussed in the theoretical example problem from Section 3.2.

The importance of the information in Table 14 is that it can be supplied within the same framework of the general method described in Section 2.2. Each of the steps can be followed as prescribed although some amount of tailoring may be required. For instance, a Basic Estimate may not need a detailed list of tasks in a schedule lessening the burden of generating a Gantt chart, which is recommended in Step 4 of the proposed method. Furthermore, the use of estimation tools to assign various resources to tasks may not be required for a Basic Estimate which lessens the need for applying Step 5 of the proposed cost estimation method.

2.5 Abstraction of the Design

Once the normalization terms have been defined by the estimator, the next step in the estimation process is to capture the actual design. This can be as rudimentary as simple hand sketches moving up to a detailed breakdown of all the functions of a system. Depending on the uncertainty thresholds of estimator, the level of design needed may be less or more depending on the amount of uncertainty associated with individual tasks. For instance, if a Basic Estimate is desired, a simple hand sketch of the system with subsystems identified may be sufficient. If Detailed Estimate is desired, a set of function and working structures may be defined. The complexity of the design is driven by the amount of uncertainty associated with the solution and whether that uncertainty is acceptable based upon the estimator's goals. Because fewer individuals are familiar with the notion of function and working structures, the following sections will provide the overview needed to apply these techniques, which are leveraged from the design methodology of Pahl and Beitz [4].

2.5.1 Conceptual Design

Conceptual design in most design methods involves a general amount of brainstorming to generate system diagrams that includes a designer or number of designers leveraging their experience with existing working principles. This is done by abstraction from the leading designers on a project, but there is often little or no methodology behind the decisions made by these project leaders. By prescribing an approach to allow designers to follow the process of generating functional and working structures a formalized level of abstraction is placed on the decision making process. The largest benefit comes from the ability of the designer to remove engineering bias from their decision making process and think of ways to solve the true problem at hand.

2.5.2 Function Structures and Solution Principles

As described by Pahl and Beitz, function structures are a representation that describes the desired functions of a system prior to consider the solution principles that are associated with those functions. The general form of a function describes the conversion of energy, materials, and signals. For instance, if data storage is a function that is needed in a prototype system then the designer or estimator can immediately imagine several solution principles for this desired function, but the abstract level could be described as shown in Figure 5. For this given structure there are several options for the various inputs and outputs. Material could be in the form of magnetic tape, a magnetic disk, solid state memory, or paper and ink. Energy could be supplied by electrical, mechanical work, or even heat. Signals could be in the form of a bit stream, or acoustics. By describing data storage in such broad terms, the desire to immediately apply a solution principle such as the use of a spinning disc medium to store the data will be delayed. By describing functions in this manner, the immediate bias of the designer or estimator is reduced thus opening the door to more unique solutions and innovative system designs.

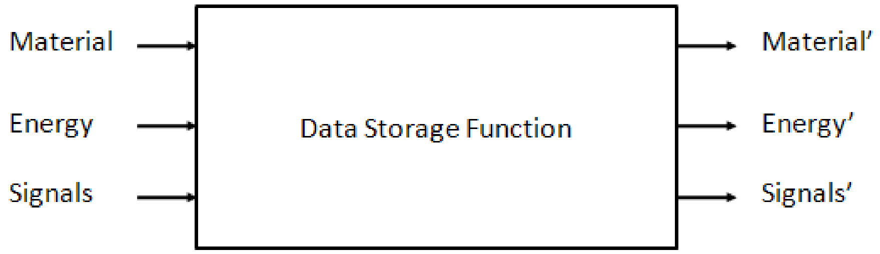


Figure 5: Function Structure for Data Storage

As functions continue to remain in the abstract form within a system, this lack of bias can progress to the system level highlighting new ways to combine functions that would otherwise be overlooked.

2.5.3 Function Structures Applied to Robotic Example

Looking forward to the cost estimation example for a robotic humanoid head, consider the interactions required between the servo controllers required to control the position of actuators in the head as it relates to the design of actuators in the neck of the device. In the following example in Figure 6, the actuators of the head are considered to be one device, the neck actuator is considered to be one device, and each actuator requires its own controller.

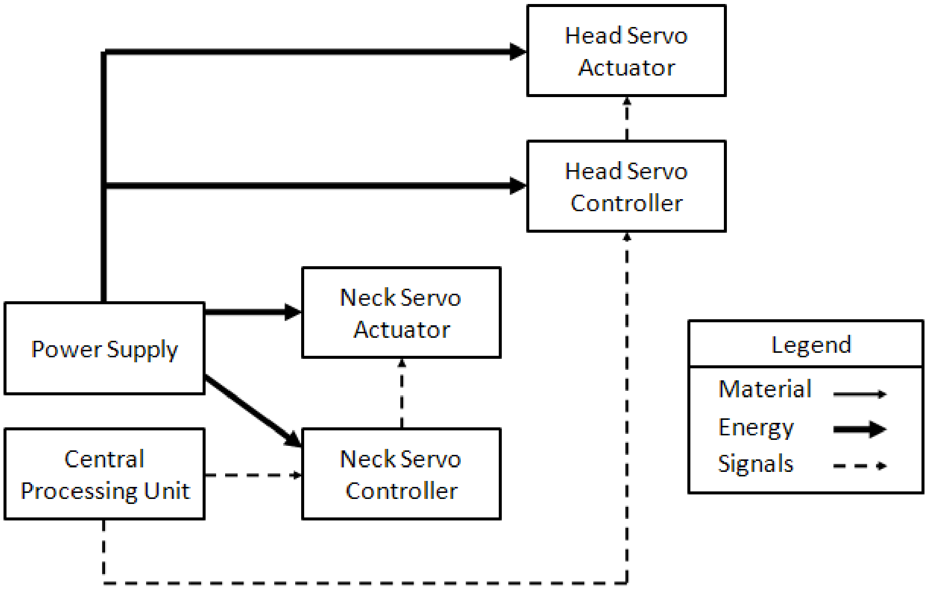


Figure 6: High Level Function Structure of Humanoid Actuator Controls

After examining Figure 6, the controls of the two sets of actuators is straightforward once the decision has been made to use electrically commutated servo motors. Once this distinction has been made there is an additional consideration of mass though. Figure 7 shows an additional decision in how the various components can be combined within the humanoid robot head assembly. If mass is considered in this example, it is clear that there will be a strong impact on the placement of the controllers within the system and the impacts on the resulting solution. If the choice is made to place all of the supporting hardware (controllers, actuators) within the head cavity (See Option 1) of the robot then the physical requirements of the head will be greatly impacted. If each device is assumed to weigh 500g each, then the one embodiment would require the neck mechanism to support 1 kg whereas using a different combination in the embodiment of these function structures reduces that to 500 g. Doubling the weight of the actuator mass on the humanoid head could have a strong influence on the neck motor selection and thus cost of those drive components. Results such as these are not always intuitive. It is possible that requirements may determine the outcome of such decisions, but this example highlights the potential positive effects of using a function structure representation in the design process.

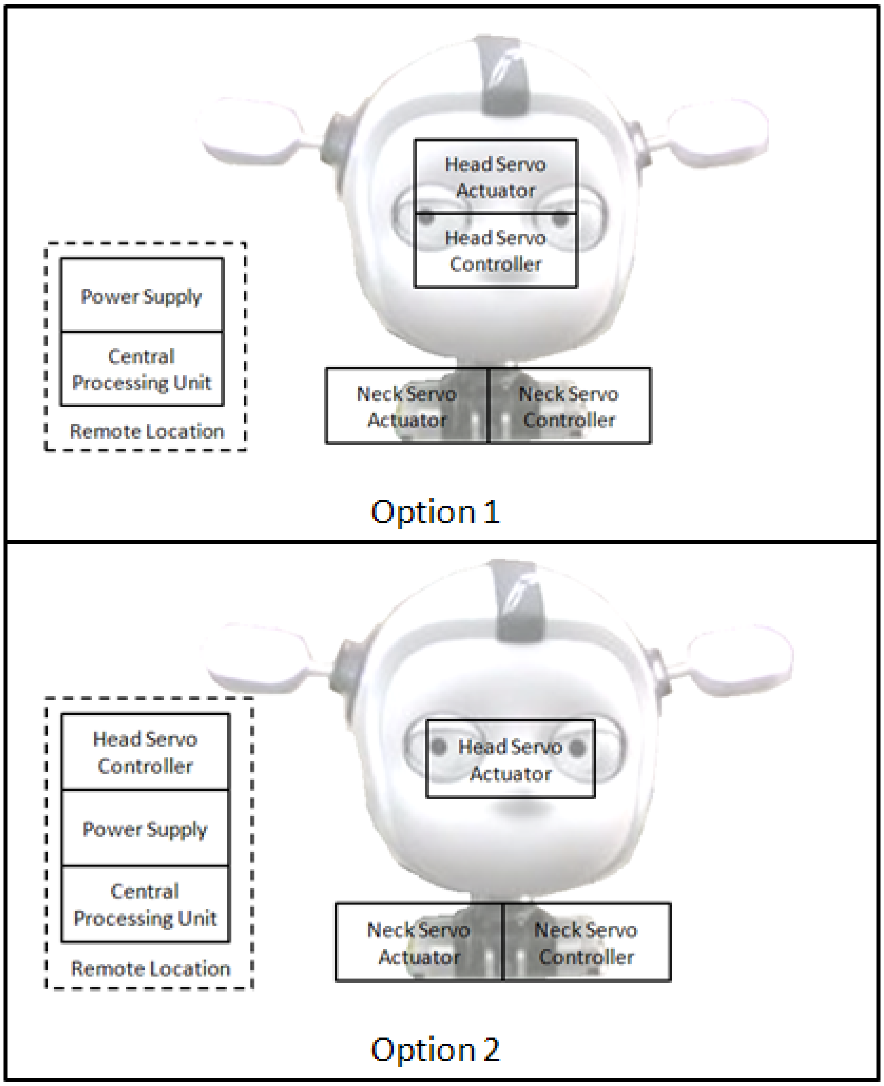


Figure 7: Controller Configuration in Humanoid Head Example

2.6 Gantt Chart for Estimation

Gantt charts are a result of the work performed by Henry Gantt almost a century ago to describe how work tasks can be organized [40]. These charts remain prevalent in the workforce today as a tool to capture the dependencies between tasks on a given endeavor. As part of this cost estimation method, this type of representation of the work is considered important to capture the level of work associated with the embodiment of desires captured within the conceptual design effort. There are multiple reasons that these charts are considered useful as listed below:

1) Assign estimated completion times to tasks in order to generate an overall schedule.
2) Capture interactions between various tasks on a project. These interactions may result in the identification of a critical path where key resources are highlighted as being crucial to the completion of the work.
3) Provide a timeline of when resources are needed that can ultimately lead to expected utility of the workforce of an organization. Furthermore, concepts such as those defined in the Theory of Constraints may be applied to better utilize the workforce when bottlenecks have been identified within the critical path [52].
4) Can be used to show the impacts of tasks with a high level of uncertainty on both overall schedule determination and the effective use of organization resources.

A detailed Gantt chart was completed for the example problem related to work for the Georgia Department of Transportation, which is contained in Section 4.3.4. This example uses a Gantt chart to organize the work thus highlighting the importance of this tool to the proposed estimation method.

2.7 Work Estimation Tools

The estimation method proposed in this thesis consists of gathering information about the cost of resources, a detailed schedule, skill sets of employees, skills required of a project and utilizing that information simultaneously through a series of calculations. This section covers a specific tool that can be used to estimate work and effort required by staff for a particular job. Particularly, the job itself is first assigned a set of needed labor resources and then compared to a database of organizational manpower resources in order to guide the assignment of labor. Figure 8 provides a graphical representation of how this concept is used. This tool, which was implemented at a high level in Microsoft Excel for this exercise, is demonstrated in a simple example.

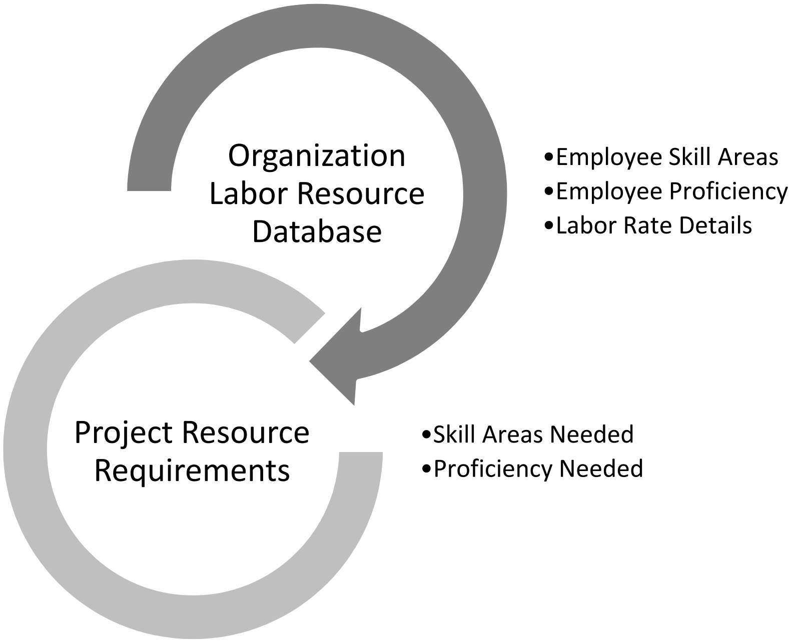


Figure 8: Graphical Representation of Skill Database

2.7.1 Skill Set Database

The skill sets of each employee must be captured in a database in order to effectively assign resources to use this tool. Ultimately, a complete system would be used to track the proficiencies of all staff within an organization. At a minimum, the applicable skills of those who may potentially work on the project of interest must be captured. Concerning cost estimation, this tool provides value related to staff assignment. By providing a numerical tool to assign individuals to various tasks on a project, the organization can do a better job of assigning staff thus limiting the amount of expertise required for a given task.

Table 15 contains the format of a skill set table, which has been organized to work well within Excel. The first column contains the number of the skill set. This is used to track various skill sets numerically and allows for a simpler implementation of the "VLOOKUP" command within Excel for future processing. The "VLOOKUP" command searches a row to find an adjacent value to associate with the original value as a result based upon a logical condition [53]. The skill description column is simply a text description that allows the estimator to quickly input proficiencies of staff. Notice that skills are organized by type, which also helps the estimator when entering new or modified data. The next column contains the project skills required. This column is important for general staffing purposes. The following column is used in conjunction with the previous column and can be used to tell when staff is initially assigned to a project whether those members are well suited for the project or not. The final columns contain the labor rate and an identifier of each potential staff member. Staff members are assigned in increasing order of labor rates because one of the goals of the estimation method is to minimize the cost to the program. To clarify what is happening during the assignment, consider skill number 2. The project has a task that requires an individual extremely experienced in testing as it relates to systems engineering. It can quickly be seen that only employee E4 is capable of satisfying this requirement. Had this been a database of employees within a larger organization, the number of matching results would likely be much higher. This technique provides the estimator or design engineer a tool that can show how many individuals are suitable for various tasks thus improving the task of employee assignment within an organization.

Table 15: Set Data Required for Estimation Method

		Project Skills Required	Criteria Met?	T1	E1	E2	E3	E4	E5
Skill #	**Skill Description**								
	SYSTEMS ENGINEERING	**3.00**							
1	OVERALL INTEGRATION	3	YES	1	1	2	1	3	0
2	TESTING	3	YES	1	2	2	2	3	0
	SOFTWARE DESIGN	**2.67**							
3	OPEN CV ARCHITECTURE	3	YES	0	3	1	0	0	2
4	GENERAL CODE MAINTENANCE	2	YES	0	2	1	0	2	3
5	C++	3	YES	0	3	0	0	0	2
	MACHINE VISION	**2.50**							
6	STEREO VISION PROCESSING	3	YES	0	2	0	0	0	1
7	CALIBRATION AND REGISTRATION	3	**NO**	0	2	1	1	2	1
8	MATLAB IMAGE PROCESSING	3	YES	0	2	0	0	0	1
9	CAMERAS	1	YES	0	2	1	1	1	1

2.7.1.1 Skill Assignment

The next table is implemented in Excel to apply the skill sets to the project. This portion starts out with a detailed list of all tasks within the project. The number of the task and the description of the task are captured in the first two columns. Also, note the "max hours per week" value – this value is used to set the maximum number of hours expended by a given staff member in any week on the project. This is one of the other goals required of the method, which is to limit the number of hours and not overuse any of the resources. The next two columns define the skills required for each task. Notice that each task may have multiple skill sets required to complete that given task. To complete this section of the estimation, the skill level and the number of hours required for that level are needed from the estimator. The level is a parameter that works for employees as well as tasks referring to either the proficiency of a given individual or proficiency needed for a given task. There are 4 levels that are used in this tool ranging from 0 to 3. The scale is defined for the employee as follows:

0 = no experience at all (default value)

1 = education on the matter with little practice

2 = intermediate level of proficiency in this area

3 = expert on the matter

The '0' ranking is self-explanatory, but rankings '1', '2' and '3' require some expanding.

1 - Some amount of education on the matter. Applicable course work and some practice in application.

2 - This requires education on the topic and at approximately two or more years of using or practicing this knowledge.

3 – Knowledge of the basic information as well as the more specialized information surrounding a topic. This usually requires several years of experience on the matter.

There is a similar ranking system used to determine the skill set required for executing a task. There are also four categories for tasks:

0 = skill not required

1 = skill needed to a small extent

2 = skill needed

3 = requirement for this skill

The task levels are the task equivalent of the employee skill rankings.

Table 16 contains an example of how these skill levels are applied to an example from a transportation system.

Table 16: Initial Values Needed for Task Assignment within the Estimation Method

GDOT Tasks 20 Max hours per week					
		Task Details			
Number	Description	#	Skill	Level	Hours
1	Wiring - small melter				
		15	SCHEMATIC GENERATION	2	10
		16	GENERAL WIRING SKILLS	2	10
2	Wiring - larger melter				
		14	POWER COMPONENT SELECTION	2	4
		15	SCHEMATIC GENERATION	1	2
		16	GENERAL WIRING SKILLS	2	8
		18	SAFETY CIRCUIT DESIGN	2	4
		25	BI-TUMINOUS ASPHALT	2	2

For this portion of the calculation actually assigning the staff, a “VLOOKUP” command is used to compare to the skill set and level required and check to see if each employee is capable of doing the task. If they are capable, a value is assigned relative to their rank within the cost structure. A value of ‘99’ is assigned if the employee is not capable of the specific task. The next two columns choose the first and second staff member capable in order of increasing labor rate. The last set of five columns is how the schedule is captured within the estimation method. The duration, in number of weeks and the weeks of the calendar year are tracked by adding a ‘1’ in the week column to indicate whether work will be done on a specific task for that given week. Based on the duration of the task, the number of hours for the task is divided by the number of weeks to assign the total number of hours per week.

Table 17: Staff Assignment and Schedule of Estimation Method

Staff Capable?							Staff Used		Duration	Weeks			
T1	E1	E2	E3	E4	E5	E6	1st	2nd	(Weeks)	33	34	35	36
									2	1	1		
1	99	99	99	5	6	99	T1	E4		5	5	0	0
1	99	3	99	5	99	99	T1	E2		5	5	0	0
									3	1	1	1	
1	99	3	99	5	99	99	T1	E2		1.3	1.33	1.3	0
1	99	3	99	5	6	99	T1	E2		0.7	0.67	0.7	0
1	99	3	99	5	99	99	T1	E2		2.7	2.67	2.7	0
99	99	3	4	5	99	99	E2	E3		1.3	1.33	1.3	0
99	99	3	99	5	99	7	E2	E4		0.7	0.67	0.7	0

2.7.1.2 Maximum Hours per Week

A major portion of the estimation and tracking spreadsheet is dedicated to the implementation of a Maximum Hours per Week (MHW) variable. The point of MHW is to limit the number of hours a given staff member can devote to the project. As the FAR was described in the Introduction section, it is useful to set this variable to 40 hours at a minimum. It is also evident that there would be utility in making this variable customizable for each employee so that MHW could be fully customizable. For the purpose of this thesis, the MHW is a global variable set for all of the staff.

MHW was implemented in the estimation and tracking spreadsheets by using a number of nested IF statements. The general form as represented in pseudocode is as follows:

```
IF SUM(EmployeeHours) <= MHW
    IF SaturationFlag = NO
        IF StaffNo = PrimaryStaffAssigned
            TaskHours -> Staff
        END
    ELSEIF SaturationFlag = YES
        IF StaffNo = SecondaryStaffAssigned
            TaskHours -> Staff
        END
    END
END
```

Given:

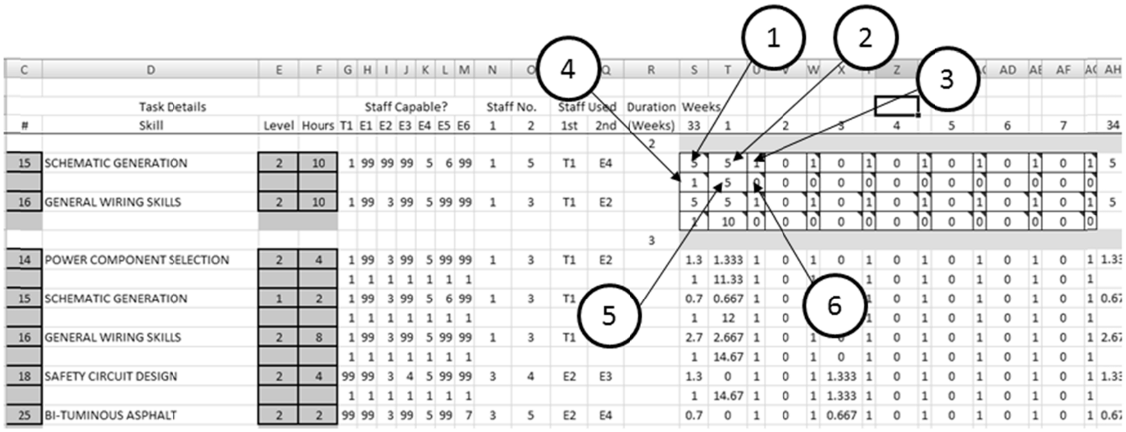
EmployeeHours – The number of hours required for the task of a given employee

SaturationFlag – A single variable to indicated whether an employee has any remaining hours for a work period

TaskHours – The number of hours required for the task

StaffNo – The number or identifier for a staff member.

The following formulation is the implementation in Microsoft Excel, which proves to be rather tedious. Figure 9 shows the various steps in the calculation spreadsheet and is followed by a table that describes each individual calculation performed on the various cells. As one would expect, these calculations are repeated for each staff member with hours increasing with each new task assignment. The saturation check is the most tedious of these steps, which was described in the previous pseudocode. The difficulty lies in that this check must implement a running total of employee hours for a given period while comparing this to the maximum work hours per week. Results are totaled at the bottom of the spreadsheet.



C	D	E	F	G	H	I	J	K	L	M	N	O		Q	R	S	T	U	V	W	X	Y	Z			AC	AD	AE	AF	AG	AH
	Task Details						Staff Capable?				Staff No.		Staff Used		Duration	Weeks															
#	Skill	Level	Hours	T1	E1	E2	E3	E4	E5	E6	1	2	1st	2nd	(Weeks)	33	1		2		3		4		5		6		7		34
															2																
15	SCHEMATIC GENERATION	2	10	1	99	99	99	5	6	99	1	5	T1	E4		5	5	1	0	1	0	1	0	1	0	1	0	1	0	1	5
																1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	
16	GENERAL WIRING SKILLS	2	10	1	99	3	99	5	99	99	1	3	T1	E2		5	5	1	0	1	0	1	0	1	0	1	0	1	0	1	5
																1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	
															3																
14	POWER COMPONENT SELECTION	2	4	1	99	3	99	5	99	99	1	3	T1	E2		1.3	1.333	1	0	1	0	1	0	1	0	1	0	1	0	1	1.33
				1	1	1	1	1	1	1						1	11.33	1	0	1	[illegible]	1	0	1	0	1	0	1	0	1	
15	SCHEMATIC GENERATION	1	2	1	99	3	99	5	6	99	1	3	T1	[illegible]		0.7	0.667	1	0	[illegible]	[illegible]	1	0	1	0	1	0	1	0	1	0.67
				1	1	1	1	1	1	1						1	12	1	0	[illegible]	[illegible]	1	0	1	0	1	0	1	0	1	
16	GENERAL WIRING SKILLS	2	8	1	99	3	99	5	99	99	1	3	T1	[illegible]		2.7	2.667	1	0	1	0	1	0	1	0	1	0	1	0	1	2.67
				1	1	1	1	1	1	1						1	14.67	1	0	1	0	1	0	1	0	1	0	1	0	1	
18	SAFETY CIRCUIT DESIGN	2	4	99	99	3	4	5	99	99	3	4	E2	E3		1.3	0	1	0	1	1.333	1	0	1	0	1	0	1	0	1	1.33
				1	1	1	1	1	1	1						1	14.67	1	0	1	1.333	1	0	1	0	1	0	1	0	1	
25	BI-TUMINOUS ASPHALT	2	2	99	99	3	99	5	99	7	3	5	E2	E4		0.7	0	1	0	1	0.667	1	0	1	0	1	0	1	0	1	0.67

Figure 9: Annotated Spreadsheet for Maximum Hours per Week Variable

Table 18: Explanation of Calculations for Maximum Hours per Week

Item	Description
1	Hours per task divided by the number of weeks for the task. This is based upon the notion of a 1 or 0 being present for the task for that given week.
2	If the previous task's saturation check passes, and if primary staff checks, assign hours, elseif saturation check fails, assign hours to secondary if matches.
3	Check to compare to maximum number of hours allowed per employee per week.
4	Multiplies all the saturation checks. If a -1 shows up, then it means this value will be negative and the secondary staff will be used. This is valid only because the current implementation only uses a primary and secondary staff member. Clearly, it can be envisioned that the secondary staff member can become saturated in this configuration.
5	Total hours of particular staff member. This is used to perform a saturation check using the maximum hours per week value.
6	Check if staff is used - if so, assign a -1 if saturated or a 1 if not saturated compared to the maximum hours.

It is worth elaborating on the point made in Item 4 of Table 18 about using only a primary and secondary staff member. Clearly, it would make more logical sense to apply a fully tiered approach to the assignment of tasks based on employee availability and those capable of performing the task in order to fully utilize the staff. Furthermore, the use of a customized MHW variable per employee would provide more utilization as well. These improvements would be considered for a full-scale commercial implementation of these planning tools, but were not considered for the initial development of this method due to the small size of the example groups.

2.8 Reviewing the Proposed Method

The proposed method has been described to show the potential benefits of using various components of the method. This chapter has described the construct's validity, and has presented the material in a means of establishing consistency of the method as it relates to validation. The detailed description of each of the individual tools illustrates the logical soundness considering current tools in place and the need for the proposed approach in the context of prototype systems. Prior to moving forward with the application of the method, several limitations are already evident as demonstrated in the following section. This intermediate critical evaluation serves as a developmental step with the final evaluation capturing the complete critical evaluation.

2.8.1 Critical Evaluation of Method Formulation

The most obvious way to critically evaluate the method is to first evaluate the methodology based upon the initial goals. The initial goals of the method are essentially the requirements that were generated in Table 3 and have been enhanced to include rational relative to the critical review as displayed in Table 19. The sixteen individual requirements listed in that table are discussed below in terms of how well the proposed method addresses the individual goals.

Table 19: Critical Evaluation of Method Requirements

No.	Requirement	Discussion
Key Characteristics		
1	Adaptable for all engineering principles	The method is disassociated with specific engineering principles to ensure utility across all principles.
2	Incorporate tools to account for uncertainty in the estimation process	The normalization equation representation discussed specifically holds uncertainty in bounds in order to represent the range of costs expected for a given estimate.
3	Incorporate checks and balances throughout the process	Initial goals are defined at the beginning of the estimation processing supplying a means for checks and balancing later in the estimation method. These checks are prescribed to be performed at the end of the estimation process as a means of whether to iterate through more estimation steps to further refine the uncertainty or to proceed with completion of the estimate.
4	Adaptable to meet the needs of designing prototypes in a research environment	Satisfaction of this goal is addressed in further sections of the document through demonstration in example problems. The fact that this method is applied to prototype developments successfully serves as a good indicator of addressing this requirement.

Table 19 (continued)

No	Requirement	Discussion
5	Create normalization terms to compare cost, schedule and performance	This is a core component of the estimation method. The section describing normalization, Section 2.3, covers this in detail.
	Communication	
6	Easily communicate within organization	Communication is not addressed well in the method. There is an assumption that the organization has sufficient means to control communication and this requirement was not addressed specifically by this research.
	Safety	
7	Must incorporate safety considerations throughout the process	Safety was not address specifically in the estimation process. It is a recommendation that safety be considered as a task especially when generating a detailed work breakdown structure for a development. Although not addressed specifically, the ability to represent safety in the estimation process is preserved.
	Usability	
8	Must be organized and written such that a college graduate can understand the methodology	This particular goal is considered to be demonstrated.
	Production	
9	Must be articulated clearly to allow for transmission of ideas through standard documentation.	No special tools other than typical software packages used in the business environment (such as Microsoft Excel, Project, etc.) are used.
	Quality Control	
10	Accuracy of references for readers to check content	All references are captured sufficiently.
	Maintenance	
11	Adaptable to changing design environment	The method is seemingly adaptable to include multiple tools for various engineering principles. This notion of making the method adaptable was not specifically addressed during validation exercises, however.
12	Able to be revised for frequent changes	The iterative process, as well as the ability to update things easily in software, is represented in the method.

Table 19 (continued)

No	Requirement	Discussion
Costs		
13	Can incorporate a dynamic cost database.	Tasks are able to be estimated using a top-down or bottom-up approach. Leveraging a cost database could be implemented using top-down estimation tools with no issues beyond the effort required for integration of additional software tools.
14	Improve the determination of the cost of labor.	The cost of labor is handled in considerable detail during the section describing work estimation tools (Section 2.7).
Schedule		
15	Must not create negative impacts to existing design methods	This was not addressed specifically but could be compared to other estimation methods. This particular comparison is a consideration for future work or development of this cost estimation method.

The primary issue after reviewing the requirements list is the ability to compare the method with other cost estimation methods. This particular validation step is time-consuming and will be considered as an item in potential follow-on work.

Related to the requirements list is the list of assumptions that were used for the method. Some of these assumptions are rather limiting and require discussion to note the limitations that are implied.

One issue is that material estimates are ignored in this method. Because this portion of estimation is overlooked, there can be some issues especially as it relates to prototype development. In some development, particularly prototype developments, a large portion of the cost is incurred by fabricating and assembling systems that have never been built before. There can be considerable uncertainty and consequences associated with these fabrications, yet issues with material estimates were considered outside the scope of this cost estimation method.

Another assumption worth discussing, Assumption 4 from Table 5, is the assumption that all skill sets needed are available. This is not always the case – especially in small organizations. When going outside of the company for additional help there is the added difficulty of task management as well as problems with the protection of the company's proprietary data. The alternative is to train employees to perform new tasks which can be costly, but more importantly will take time. This assumption is stated to ensure the limitation is recognized.

Assumption 7 from Table 5 is related to how requirements definition can be problematic for estimation as discussed in Section 3.1.1. This describes the challenges to estimation as requirements change throughout the design process. This is somewhat addressed by including varying levels of estimates ranging from the Basic Estimate to the Detailed Estimate. The recommendation is to simply revise the estimate as requirements change meaning the estimation needs to be repurposed according to the new requirements.

Not all things are able to be evaluated in projects. For instance, a requirement stating that an object should be aesthetically pleasing may be rather subjective. The assumption stating that all requirements should be demonstrable essentially states that subjective requirements should be limited. This, however, could be viewed as a limitation because some developments may have a large number of subjective requirements making the estimation process difficult.

Assumptions 13 – 15 (See Section 1.4) cover several topics including designer control, corporate management techniques, and the consistency of risk throughout the program. These items can be considered policy related and can be influenced by relationships within an organization or between the contracting organization and the customer. This can be a source of uncertainty, but is not considered in this estimation method.

The previously described limitations capture the perceived weaknesses of the cost estimation method as compared to the initial requirements and assumptions. As future sections focus on application of the method, another critical evaluation will be required to capture the overall performance as demonstrated in example problems. Ultimately, this discussion will address the theoretical performance review of the method described in the Validation Square leading to a decision of whether this method is applicable beyond the example problems covered in Chapter 3 and Chapter 4.

2.9 Reviewing the Intellectual Questions

The second chapter includes a detailed description of the proposed method. The critical evaluation, described in Section 2.8.1, begins to identify any shortcomings of the method that would limit the general application of the method. At this stage of the method development, the tools are in place to apply the method to basic problems. Prior to applying the method the intellectual questions are reconsidered in the context of what research has been done. Table 20 contains each of the intellectual questions with a description of how these questions have been addressed throughout this chapter.

Table 20 is important because it highlights some of the key components that have been highlighted through the initial description of the method in Chapter 2. In addressing the question related to “when is enough information gathered,” the point is made that not only are goals established for the project of concern, but goals are established for the method as well. Additionally, in addressing the question related to uncertainty, the notion of normalization of parameters is yet another key component of the estimation method. One important component that is not evident in evaluating the intellectual questions is the benefit of using design methodologies to the estimation process. Of particular interest is the use of abstraction techniques based upon the work of Pahl and Beitz, which is leveraged in the proposed method. By incorporating this technique into the estimation method a new tool is made available to the estimator to create a more robust design concept in which to base an estimate upon. This improvement in the concept will ultimately lead to a more robust estimate which is one of the primary goals of the cost estimation method.

Table 20: Relevance of Chapter 2 to the Intellectual Questions

Intellectual Question	Section Relevance
1) *When is enough information gathered to generate a robust estimate for the design of prototype systems?*	Although considerable information is provided to the various tools suggested for estimation, a single important check is recommended for this method to address robustness. By setting initial goals for the method and iterating estimation until that goal is met, the goal acts as the definition of robustness for the estimator.
2) *How do you characterize uncertainty in the estimation process?*	Building on the notion of goals set for estimation, the uncertainty is limited by the goals of the estimator. This is captured numerically in the normalized equations described in Section 2.3.1. Uncertainty as it applies to estimation is described in detail in Section 2.3.2.
3) *Why do estimates need to consider interactions between performance, schedule, and cost?*	The numerical example including the normalization effort described in Section 2.3 addresses the importance of this interaction.
4) *Why is the assignment of staff critical to an accurate estimate?*	The section specific to the assignment of staff, Section 2.7, highlights many points as to how the assignment of staff is important during estimation.

The following chapters begin to illustrate how the proposed method applies in example problems enforcing the appropriateness and utility of those example problems. The theoretical example is focused on a representative system and broken into three levels – Basic, Intermediate, and Detailed estimate. The three levels are meant to show the result of incomplete requirements as demonstrated in the Basic Estimate, the result of application of the proposed method as demonstrated in the Intermediate Estimate, and finally different tools that can reduce uncertainty in the Detailed Estimate section.

Chapter 4 progresses into a discussion of a particular application of the proposed method on for work done for the Georgia Department of Transportation. The essence of the Validation Square is captured by progressing from a theoretical evaluation to an empirical evaluation. As this transition is made, the reader is presented with actual examples of the proposed method and more importantly the results of those applications.

CHAPTER 3

Theoretical Example Problem

In order to illustrate how the proposed cost estimation method could be applied an estimate for a robotics development was chosen. Although this example is based upon a robotic design application, the example is theoretical due to simplifications made to exercise the proposed design method. The goal of this particular exercise is to illustrate the relationship between the initial estimated cost and the amount of effort placed on the estimation. Other goals are to show the varying levels of cost estimation that may be applied to a particular problem with a focus on the limitations of those different applications. This chapter will introduce the terms of Basic Estimation, Intermediate Estimation and Detailed Estimation in the context of the proposed method. The terminology describing the complexity of the estimate is similar to that used for the Constructive Cost Model also known as COCOMO created by Barry Boehm [54]. COCOMO and later COCOMO II have been used widely in the estimation of software engineering activities; however, this estimation method does not address multidiscipline activities well.

The Basic Estimate example within this chapter does not incorporate the proposed method (See Figure 4), but is used more as an example of how activities can be underestimated if design activity is limited. The primary focus of this example is to highlight the potential errors that can result from a design that is not properly clarified through the generation of detailed requirements. The Intermediate and Detailed Estimates do include the application of the proposed method at varying levels. These theoretical examples begin to address the empirical structural quadrant of the Validation Square as it is leveraging the proposed estimation method.

Prior to exploring these varying levels of estimation, a problem description is given in Section 3.1. The problem statement provides the reader with the technical background needed to understand the project specific requirements as well as the context in which the engineering specific project tasks are defined.

3.1 Robotic Head Design

Due to past experience with robotic developments, an example was chosen related to the application of the cost estimation method to a robotic head. A particular approach was chosen to use a robotic head that would have a movable neck, eyes, and supporting structure including aesthetic shells. The following sections cover the various approaches that can be taken for estimation, how they can be applied, and the implications of those decisions. The primary subsections are related to varying approaches with basic, intermediate, and detailed cost estimates. The three approaches are explored to gauge the effectiveness of the three varying levels of scrutiny for various situations. These tie back to the assumption made for the method in Table 2 where there is a desire to limit the amount of estimation to 10% of an overall design task. Clearly, to generate more detail in an estimate, more effort will be required.

Prior to discussing the application of estimation methods, a clear understanding of the problem must be established in order to understand the complexity of the system. A robot head design was chosen to exercise use of the estimation method due to the complexity associated with such a design. This complexity translates into a large design space that makes cost estimation challenging.

3.1.1 Challenge of Robotic Head Design

The advent of humanoid robotic systems has led to the need for robotic head design. This is evident as the number of humanoid robots over the past decade has increased substantially [55]. While the number of humanoid robots has been steadily increasing the complexity of these robots has been increasing as well [56].

The estimation examples described in Section 3.3 through Section 3.5 are based upon experience with robotic head design, specifically a prior development where a humanoid robotic head was desired. During this prior development, there were several exchanges of information that led to the development of a humanoid robot head. The exchanges of information were similar to the terms used for estimates of varying detail ranging from basic exchanges of information to detailed information exchanges. The goal of the humanoid robot head platform was to exhibit human like behavior for the purpose of researching the interaction between humans and machines.

During the initial or basic information exchange, a robot was requested that would display general human-like emotions through movement. During these discussions, the robot was requested to: 1) include several moveable axes including eyes, eyelids, a mouth, and a neck, 2) as light as possible, 3) include cameras in the eyes for general vision processing, and 4) contain all controls within the head cavity.

After these discussions, some development was needed prior to fully understanding what was needed for the overall development. These initial fact finding exercises were meant to take various high level requirements and add numerical targets for performance so that the robot could truly exhibit human-like behavior. Many of the fact finding exercises were related to determining realistic performance for various axes like eye and neck movement speeds. Although some research had characterized this behavior on humans, researchers decided to use high speed imaging to determine basic performance values of eye movement and acceleration. Another important exercise was to model this behavior using a simulation with servo parameters to estimate the motor size and power requirements required to execute these movements. Also during this time, industrial design was taking place that would generate the desired shape and form of the robot head. An interesting outcome of the industrial design exercise was that the size of the cameras chosen to be used within the eyeballs set the diameter of the eyeball. This in turn drove the spacing between the eyes, and ultimately influenced the overall diameter of the robot head.

The final design requirements resulted in many additional desires as well as numerical values for the performance of the robot. Table 21 includes the requirements for this final exercise. Note how several axes were added making the total number of axes equal to 19. These axes covered individual ear movement in two rotation angles (2 + 2), two each two-axis eyelids (2 + 2), two rotary eye motions that were linked (1 + 1), the ability for eyelids to blink independently (1 + 1), three rotary joints in the neck (1 + 1 + 1), and four axes to move the mouth (4). Each of these axes was defined by performance parameters including the maximum speed, acceleration, and range of motion. The sensors for the robotic head were limited to two input sensors for cameras in the eyeballs and two multicolored light emitting diodes in the ear cavities to provide information to those interacting via color feedback.

Table 21: Requirements Generated for Humanoid Robotic Head

Humanoid Robot Head Specification			
#	D/W	Description	Revised
1.0		**Performance**	
1.1	D	Maximum number of axes for the head is 19 (See Figure 1 for axis directions) • 2 x 2 eyebrows • 2 x 1 eye • 2 x 1 eye lid • 4 x 1 mouth • 2 x 2 ears or antenna • 3 x 1 neck	
1.2	D	Eye lids to move on top and bottom of eye - this is suggested to be a linked motion with top lid moving more than bottom lid	12-Nov
1.3	D	Overall dimensions of the head shall be 12" wide, 8" high, and 10" deep.	30-Nov
1.4	D	Movement rates for each joint: • eye rotation - 360°/sec with ±45° range • eye lid - 1200°/sec (travel full range in 1/10th second), upper lid w/ more range than bottom lid • neck - should travel full range in ~1/5th second - range left right is ±45-60° and up/down is ±20° • all other axes are less specific - should move entire range in approximately 1/6th of a second	13-Nov
1.5	D	Mouth to show smile, frown, and open	
1.6	D	All control driven by position only • Control will be through serial signal to each axis - likely to be a CAN bus	12-Nov
1.7	D	Control for head of robot (GTRI) to be separate from control of torso and arms (Meka Robotics)	
1.8	D	System to run for no more than 2 hours at a time	
1.9	D	Camera to provide simple blob detection, facial recognition, and visual servo capable - this will be Andrea's responsibility in software	
1.10	D	Firefly MV camera to be used in spherical eyes for vision system • 6mm focal plane for normal, 2mm for wide angle	30-Nov
1.11	D	Relative position feedback for all axes with exception to neck axes - for neck axes, absolute position will be required	
1.12	W	Maximum eye diameter (sphere) is 2.5"	
1.13	D	1" diameter bundle of wires allowed to go from neck into torso	
1.14	D	Head to use no more than 500 watts	
1.15	D	24VDC power supplied to system	30-Nov

Table 21 (continued)

Humanoid Robot Head Specification			
2		**Aesthetic**	
2.1	W	Semi humanoid look with antenna for ears	
2.2	D	Rigid plastic shell to serve for face	
2.3	W	Mouth to use spring or rubber tubing on outside of facial shell	
2.4	W	Face to have muted metallic finish	
3.0		**Integration**	
3.1	D	ICD of neck mount provided to Meka – separate document.	
3.2	W	Meka to provide volume of 3 x 6 x 8" in torso for hardware from head control devices	
3.3	D	GTRI to provide mounting hole locations for facial shield to industrial design department	
4.0		**Environment & Safety**	
4.1	D	Work in room temperature environment	
4.2	D	Only operated indoors	
4.3	D	Appropriate safety switched incorporated into robot (E-stops) at system level	

It is clear from the previously described development that a humanoid robot head design serves as a good multidisciplinary estimation example. The robot head used for this theoretical estimation example will have a limited number of axes to illustrate the interaction among the multidisciplinary teams – these axes will be movable neck and eyes. It is clear that the number of axes to perform these operations must be considered as it affects the overall complexity of the robot significantly. General packaging of custom servo-controlled electronics requires support from mechanical and electrical engineering staff. In addition, the structure and aesthetic pieces will require packaging as well as industrial design experience. Lastly, the software to control the movable joints could be extensive depending on the desired performance of the robot.

3.1.2 Movable Component Design

The two moveable subsystems chosen are the eyes and the neck mechanism. Depending on the desire to accurately match biomechanics of the neck, which the neck alone has been described to have six degrees of freedom [57], the robotic head could have a considerable amount of complexity. For this exercise, the degrees of freedom will be defined as two degrees for the neck (rotation about two axes) and two degrees of freedom for the eyes (rotation about two axes). We will also consider that two axes are required to support blinking for the robot. It must be noted that the reason that only two degrees can be used for the eye is that the assumption can be made that the motion of the eyeballs are dependent on one another. The degrees of freedom are important because there is typically a one-to-one mapping from degrees of freedom to the number of servo-controlled axis requirements. In other words, for each of the six axes previously described a dedicated servo motor, motor controller, electrical power, and control signal will be required to operate a given degree of freedom. Of particular importance is the control signal as this will be the commanded position that will be generated by the control software. Control software can be challenging as it must account for backlash in the system, speed and acceleration limits, and the range and repeatability of the drive components.

This covers the basic electrical and software aspects of the drive design, but there are also a considerable number of mechanical challenges. In order to drive the various systems, a number of variables must be considered. The speed and acceleration required are critical, which are directly affected by the mass of all of the parts. Particular challenges can arise with the design of servo-drive design when the various drives are linked as they are in this system. For instance, the weight of the drives selected for the eye mechanism will have an impact on the performance of the neck system. These interactions can become increasingly complex as more components are added and the mass of one component can ripple through the entire system. The other key mechanical challenge is due to concept selection. Prior to fully investigating the ripple effects of mass and acceleration in a servo-controlled system, the general mechanism concept is often pre-selected.

This simple discussion of the complexity of software, mechanical and electrical packaging is important to raise awareness of an estimator prior to taking on a complex task. An inexperienced estimator in this situation can overlook the major complexities of the system and more importantly the interaction of decisions required by various disciplines of engineering.

3.1.3 Eye Cameras

The use of the cameras in the eyes can be a trivial or daunting task depending on the intended use. If used only for general surveillance of the environment as seen through the eyes of the robot, then the packaging challenge is simply the mechanical mounting and routing of signal and power cabling. However, if more detailed functionality is required such as stereo machine vision, the implications to the drive design can be tremendous. To utilize stereo machine vision, as could be possible through the use of two cameras mounted in the eyes of a robotic head, a clear understanding of dimensional tolerances as it relates to calibration must be considered. This becomes important in the drive design as it can affect accuracy of the servo system through encoder resolution or backlash as well as the mounting of cameras and dimensional “play” that can exist from gaps in the bearings located in the neck and eyeballs. Calibration is also important as a clear understanding of pixel-to-pixel mapping is affected by the selection of the camera sensor and optics. Furthermore, the use of this information could have considerable impacts on the software design depending on the desires of machine vision such as whether simple object detection or more complicated facial recognition techniques would be employed.

3.1.4 Aesthetic Shells and Structure

The last major component is the structure of the robot head as well as the look of that structure. Again, it is important to stress the relationship to drive selection, structure, and mass and can require a number of interactions between several disciplines. A new interaction may be generated by the level of detail placed on the aesthetic components of the robot head. By using the skills of an industrial designer, the shape and look of the exterior surfaces could change drastically forcing a compromise between performance of the drive and structural components and the exterior shells.

3.2 Basic, Intermediate and Detailed Estimate for a Robotic Head

As detailed in the previous sections, the complexity of a robotic head can vary drastically depending on decisions made during the generation of requirements. For example, the decision to implement machine vision in the eye cameras or not could mean the difference of a simple mechanical integration task versus the inclusion of a detailed exercise including machine vision algorithms, increased understanding of camera optics and calibration, and a complex mechanical design. In the context of estimation, consider the implications of this decision compared to the time at which the estimation is made as it relates to uncertainty. If the decision is made prior to this decision point, a high level of uncertainty must be carried in the estimation. Furthermore, a large amount of uncertainty is directly related to the risk level of the estimator. In this case a high acceptance of risk could result in a large loss for the estimator's organization if the incorrect decision is made. Due to these issues as well as limited resources to generate estimates, there is a need for varying levels of estimates to capture the needs of an estimator. Basic, Intermediate, and Detailed Estimates are provided to show how the amount of detail placed on the estimation process will impact the overall uncertainty as it relates to the resulting estimation.

These levels of complexity are presented with increasing amounts of information related to the estimation process. A Basic Estimate refers to the use of basic estimation tools and relies heavily on engineering judgment. This level of estimate is useful for initial estimation purposes and to address questions such as, "Should this effort be pursued or not?" A Basic Estimation has the following characteristics:

- Relies heavily upon engineering judgment
- Contains the potential for high levels of uncertainty
- Can be generated quickly

An Intermediate Estimate builds upon a Basic Estimate by adding a more thorough breakdown to the assignment of tasks and improving the fidelity of the requirements list. The characteristics of an Intermediate Estimate are as follows:

- Includes detailed requirements covering all key multidisciplinary areas
  - Performance related to mechanical, electrical, software, etc.
  - Additional activities such as safety, maintenance, and environmental concerns
- Cost and schedule
- Gantt Chart to track the relationship between tasks and schedule

A Detailed Estimate introduces an approach for quantifying risk as well as the generation of pertinent design details for the estimation process. Characteristics of a Detailed Estimate include those of the Basic and Intermediate estimates with the addition of the following:

- Detailed clarification of tasks including an elaborate requirements list
- Abstraction of the design and initial concept generation
- Generates a mathematical model to consider relationship between cost, performance and schedule
- Incorporates tools to address uncertainty and estimator risk

This tiered approach allows for varying levels of detail to be captured in an estimate. Each of the three types of estimates may be used in a particular estimation process as more information is required by the user of the estimate. A likely outcome is that each of these three types of estimates if the decision to pursue work is made from a Basic

Estimate. In this sequential case, the work products from previous levels of estimates can be leveraged to create a Detailed Estimate.

3.3 Basic Estimate

A Basic Estimate is often used for basic decision making as it relates to whether or not to pursue a various activity. Although with the low amount of detail comes a high level of uncertainty, and this is what is of greatest concern when making decisions based upon limited estimation results. Due to the impact of decisions made early in the design, a considerable amount of resources can be wasted before it is discovered that the uncertainty related to a key task is greater than the risk level of the estimator.

Consider the case where a Basic Estimate is used to make a decision of whether or not to generate a proposal. If the Basic Estimate lacks sufficient detail, then the estimator may decide early on that the potential risks related to pursuing the work are acceptable when perhaps they are not. Let us consider this notion in the context of the theoretical development related to the robot design described earlier. In the initial requirements phase, a system engineer would attempt to capture all major requirements for a Basic Estimate and generate the following list:

1) Incorporate 2 eye axes, 2 ear axes, 2 neck axes.
2) Have cameras in the eyes for stereo vision.
3) Weigh less than 3.5 kg.
4) Be housed in a shell made from rapid prototyping techniques.
5) Shape and size determined by industrial design artist provided within 3 months of design initiation.
6) Tasks include design, fabrication, assembly, and testing of one functional prototype.
7) Schedule not to exceed 16 months.
8) Include motion controls in the head cavity.

After generating this short list of requirements, the task would move to a team of design engineers to capture the cost to complete for each of these tasks. The following is the individual estimate for each of the primary task leaders – mechanical, software, electrical, and industrial design. The hours for the tasks listed in Table 22 through Table 26 are the result of engineering estimates, which are based upon expert judgment. The total estimated cost of the effort is based on the assumption that the average salary of an employee is approximately $65/hour.

Table 22: Mechanical Estimates for Basic Estimate

Task	Labor (hours)	Material
Movable axis design	120	
Custom piece part design (approximately 30 custom parts with drawings)	360	
Packaging of cameras	60	
Shell design	120	
Fabrication of parts	40	$30,000
Assembly	120	$500
Testing	120	$1,000
Subtotal	940	$31,500
Inclusion of 20% uncertainty	1128	$37,800
Total Cost	$111,120	

Table 23: Electrical Estimates for Basic Estimate

Task	Labor (hours)	Material
Servo component selection	200	
Camera selection and implementation	80	
Cabling and power distribution	200	
Assembly support	80	$1,500
Testing support	40	$1,500
Subtotal	600	$3,000
Inclusion of 15% uncertainty	720	$3,600
Total Cost	$50,400	

Table 24: Software Estimates for Basic Estimate

Task	Labor (hours)	Material
Servo control software	180	
Basic movement implementation	320	
Camera control software	240	
Testing software	120	$3,000
Subtotal	860	$3,000
Inclusion of 20% uncertainty	1032	$3,600
Total Cost	$70,680	

The industrial design was simplified to approximately 240 hours with some budget for material ($2,500) resulted in a subtotal of $18,600 without uncertainty and $21,390 with uncertainty assuming a bulk uncertainty level of 15%.

3.3.1 Overview of Basic Estimate

Compiling all of the results and applying an amount of labor for the management of this effort results in the following rollup. A total of 200 hours was estimated as needed for the management task resulting in a cost of $13,000. In the following table, an additional 10% was added as management reserve (MR) making the total effective uncertainty estimated at 30%.

Table 25: Summary of Basic Estimate for Robotic Head

Sub Account	W/o Uncertainty	W/ Uncertainty
Mechanical	$92,600	$111,120
Electrical	$42,000	$50,400
Software	$58,900	$70,680
Industrial Design	$18,600	$21,390
Management	$13,000	-
Subtotal (w/o MR)	$225,100	$266,590
Total cost estimated (with MR of 10%)	$293,249	
Effective uncertainty	30%	

The previous results appear to be reasonable for the theoretical exercise, yet we need to consider the possible outcome based on the decisions made throughout the process. Specifically, let us consider mistakes were made in the generation of requirements as well as errors in a few key tasks under the engineering efforts.

For the requirements, the assumption of number of axes could be incorrect. The customer had actually wanted to have eye lids that could blink individually making the number of axes increase from 8 to 9 while also increasing the complexity of the component design. Another major issue was the request of stereo vision for the eyes. By adding additional packaging challenges around the eyes, the requirement for stereo vision was impacted greatly. The stereo vision requirement was underestimated in that engineers did not plan on having to generate detailed calibration routines as well as fixtures to make sure they would be appropriately linked. Furthermore, the manufacturing tolerances of many components would need to reduce dramatically in order for the stereo vision to work effectively. The last consideration to make is that these changes would add to the weight of the assembly making the weight unwieldy leading to a reduction in dynamic performance as well as requiring larger supporting servo drives for the neck axes that support the weight of the head.

Assuming much of the design was estimated properly, let us consider the impact of the two unknown tasks that arose during development in this theoretical exercise – stereo vision complexity increase and eyelid blinking servo axes addition. The following Table 26 contains the results of the Basic Estimate exercise compared to the potential values that reflect the impact of these two changes in the project. The bottom line of this table is that despite initially having a resulting interval of $247,610 minimum to $293,249 maximum, the total project cost was $358,700 thus exceeding that interval by an additional 22% or $65,451. Additionally, the added weight of the new servo axes did not allow the goal of 4.5 kg to be met and resulted in reduced performance for the customer.

The Basic Estimate example clearly illustrates how the lack of detail in an estimate can prevent a project from meeting original estimates despite what is seemingly an appropriate amount of reserve within the budget. More importantly, this exercise indicates how the experience level of the estimator(s) involved can contribute to considerable variation in the estimation process. Due to a reliance on engineering judgment, the outcome of a Basic Estimation exercise can vary substantially and is prone to non-repeatability.

Other shortfalls highlighted by this example are those related to the design as it resulted from the short list of requirements. By generating more detailed requirements, as demonstrated in subsequent sections, a more thorough design exercise can take place reducing the risk of ignoring tasks on the project. The ultimate goal of the Basic Estimate exercise is to demonstrate that an estimate can suffer from a number of factors that are easily overlooked if little or no structure is applied by the estimator(s).

Table 26: Overview of Results for Basic Estimate Including Uncertainty

Tasks	**Estimated**		**Potential Outcome**	
MECHANICAL	**Labor (hr)**	**Material**	**Labor (hr)**	**Material**
Movable axis design	120		200	
Custom piece part design (approximately 30 custom parts with drawings)	360		360	
Additional parts for eye-lids			180	$ 5,500
Packaging of cameras	60		240	
Camera calibration fixture design/fab			200	$ 2,000
Shell design	120		180	
Fabrication of parts	40	$ 30,000.0	60	$ 32,000
Assembly	120	$ 500.0	180	$ 600
Testing	120	$ 1,000.0	250	$ 1,000
Subtotal	940	$ 31,500.0	1850	$ 41,100
Inclusion of 20% uncertainty	1128	$ 37,800.0		
Total Mechanical Cost	**$ 111,120**		**$ 161,350**	

Table 26 (continued)

Tasks	**Estimated**		**Potential Outcome**	
Electrical	**Labor (hr)**	**Material**	**Labor (hr)**	**Material**
Servo component selection	200		320	
Camera selection and implementation	80		240	
Cabling and power distribution	200		240	
Camera Calibration Support			120	
Assembly support	80	$ 1,500.0	80	$ 1,500
Testing support	40	$ 1,500.0	80	$ 1,500
Subtotal	600	$ 3,000.0	1080	$ 3,000
Inclusion of 15% uncertainty	720	$ 3,600.0		
Total Electrical Cost	**$ 50,400**		**$ 73,200**	
Software	**Labor (hr)**	**Material**	**Labor (hr)**	**Material**
Servo control software	180		240	
Basic movement implementation	320		360	
Camera control software	240		420	
Testing software	120	$ 3,000	180	$ 3,500
Subtotal	860	$ 3,000	1200	$ 3,500
Inclusion of 20% uncertainty	1032	$ 3,600		
Total Software Cost	**$ 70,680**		**$ 81,500**	
Industrial Design	**Labor (hr)**	**Material**	**Labor (hr)**	**Material**
Overall Design	240	$ 2,500	240	$ 2,500
Additional hours for eyelids			80	$ 500
Subtotal	240	$ 2,500	320	$ 3,000
Inclusion of 15% uncertainty	276	$ 2,875		
Total Industrial Cost	**$ 20,815**		**$ 23,800**	
Management	**Labor (hr)**	**Material**	**Labor (hr)**	**Material**
Management	200		290	
Total Management Cost	**$ 13,000**		**$ 18,850**	
Totals	**W/o Uncertainty**	**W/ Uncertainty**	**Actuals**	
Mechanical	$ 92,600	$ 111,120	$ 161,350	
Electrical	$ 42,000	$ 50,400	$ 73,200	
Software	$ 58,900	$ 70,680	$ 81,500	
Industrial Design	$ 18,600	$ 21,390	$ 23,800	
Management	$ 13,000	-	$ 18,850	
Total cost estimated (with MR)	**$ 293,249**			
Actual Total Cost	**$ 358,700**			
Percent Overrun	**22%**			

3.4 Intermediate Estimate

Previously we discussed a Basic Estimate and illustrated the shortcomings of grouping the uncertainty of several items while also showing the issue with lack of attention to requirements generation. The lack of detail in requirements generation is a common problem and an area that requires further discussion. Additionally, an Intermediate Estimate introduces a Gantt chart as a tracking tool to track the relationship between performance, cost and schedule. This relationship is used to generate a mathematical formulation between these three key components of an estimate and improve the overall integrity of the estimation process. Most importantly, the method is followed in this example demonstrating how the proposed method is intended to be applied as well as illustrating the potential benefits.

3.4.1 Step 1 – Is the Method Appropriate for this Work?

For this step, it is important to check if the assumptions used for the proposed method are appropriate. In order to evaluate these criteria, the assumptions listed in Table 5 are used. Table 27 was created based upon Table 5 and was modified to include an evaluation of whether the assumptions were appropriate or not. Only two of the assumptions were not met for this particular application. The first assumption is that for material estimates not being prone to high levels of uncertainty. Because the design for the shape structure of the robotic head was not completed as well as not knowing how stringent movement requirements were leaves an estimator unable to know whether exotic materials would be needed or not. The labor estimate and number of employees was not considered for this particular example either. While both of these assumptions were recognized as not being satisfied, they were not determined to be major issues with proceeding with the use of the method.

Table 27: Assumptions Used for Intermediate Theoretical Example

No.	Met?	Assumption
1	N	Material estimates are not prone to high levels of uncertainty for this case
2	N	Will need to define experience levels to give a correct labor estimate for employee assignments a. 2-5 levels of experience are recommended b. Based upon relevant experience of individuals
3	Y	Assume no conflicts between skill-sets required and time constraints on employee availability
4	Y	Assume 40 hour weeks
5	Y	All skill-sets needed are available and location of engineering resources are irrelevant a. Internal and external resources are available and cost the same b. Example: overseas resources not influential
6	Y	All state of the art engineer tools are available and people know how to use tools a. Stay away from development of tools in this work b. Future work could look into using the method to make decisions on how people will be trained
7	Y	Major requirements defined at the outset
8	Y	Assume constant price of everything
9	Y	Ignore life cycle impact
10	Y	Intellectual property (IP) issues ignored
11	Y	It is feasible to evaluate the performance – in other words, there is a means to validate the performance
12	Y	Functional and working structures can be completed
13	Y	Designer control over all tasks to be estimated
14	Y	Corporate management requirements ignored
15	Y	Risk taken at proposal phase is consistent (not variable)
16	Y	Limits for variance calculations are defined through intervals

3.4.2 Step 2 – Generate Numerical Normalization Parameters

The numerical normalization for this example was decided to have an emphasis on performance and cost with less of a consideration for schedule. The parameters chosen as a preference for the estimator were $P_{pref} = 0.40$, $C_{pref} = 0.45$, $S_{pref} = 0.15$.

Requirements serve as the primary conduit between the sponsor and the design team for sharing technical details and are an important step for the estimation process. This fact is supported by the common measure of how prototypes are evaluated – the performance is typically evaluated by verifying compliance with the requirements at the end of the project as a way to satisfy the sponsor. Despite the existence of rigorous details that may exist in a technical proposal, the design team often has the flexibility to explore the solution space even after a contract has been awarded they are still able to achieve the parameters set forth in the requirements. Furthermore, this is one of the three points that are typically present in a contract where performance, cost, and schedule are specified. The importance of the requirements must be considered carefully in order to prevent misunderstandings such as those highlighted in the previous Basic Estimation theoretical example. Clearly there is a resource penalty paid to increase the fidelity of a requirements list, but instead of spending a small number of hours on requirements definition as was done in the previous example, this Intermediate Estimation uses a detailed requirements list that would take a day or more to generate. The following example of requirements assumes several hours were spent on the generation of requirements with an emphasis placed on sponsor interaction to reduce the risk of misunderstandings throughout the project. This list was generated using a format similar to that recommended by Pahl and Beitz in that it contains a logical breakdown of requirements as well as values that can be quantified as opposed to being notional as they were in the Basic Estimate. Furthermore, the list is prioritized as a set of “demands” or “wishes,” which capture the difference between desires of the customer and parameters that are necessary. A demand refers to a requirement that is compulsory for the designer whereas wishes refer to requirements that should be pursued if there is little added effort or cost to the development. Using this difference, the customer can obtain benefits at little cost to the project while not over-constraining the design with a number of demands.

Table 28: List of Requirements for Intermediate Estimate

<table>
<tr><th colspan="2">Requirements list for Robot Head Design</th></tr>
<tr><td colspan="2">Problem Statement: To determine an appropriate set of parameters to capture performance desires for a humanoid robot head. For these requirements, the Z axis refers to the direction of gravity, and the Y axis would be in the direction from ear to ear.</td></tr>
<tr><th>D/W</th><th>Requirement</th></tr>
<tr><td></td><td>Dynamic Performance and Mechanical Packaging</td></tr>
<tr><td>D</td><td>1. Eyeballs must be able to rotate at 1.0 rad/s in rotation about Z and Y with an acceleration of 1.0 rad/s2. The rotation angle is defined as +20/-30 degrees in the Y axis and +/- 90 degrees in the Z axis.</td></tr>
<tr><td>D</td><td>2. Eyelids must rotate at 2.0 rad/s in rotation about the Y axis with acceleration of 2.0 rad/s2. The rotation angle is defined as +40/-25 degrees in the Y axis.</td></tr>
<tr><td>D</td><td>3. The neck must rotate at .50 rad/s in rotation about the Z axis and .50 rad/s in rotation about the Y axis at 1.0 rad/s2 in each axis. The angles are defined as +/- 90 degrees in rotation about the Z axis and +30/-15 degrees in rotation about the Y axis.</td></tr>
<tr><td>D</td><td>4. The acceptable position error of each eyelid and neck axis is set at 5 mrad, whereas the acceptable position error of each eye position is 10 μrad in order to support high level stereo imaging.</td></tr>
<tr><td>D</td><td>5. All servo drive supporting hardware to reside within the shell of the head.</td></tr>
<tr><td>D</td><td>6. Head volume not to exceed 0.45 m3.</td></tr>
<tr><td>D</td><td>7. Materials shall be able to withstand +/- 3g static loading in each axis.</td></tr>
<tr><td>D</td><td>8. Weight of head shall not exceed 6 kg.</td></tr>
<tr><td>W</td><td>9. Weight of head desired to be 4.5 kg.</td></tr>
<tr><td>W</td><td>10. The robot appearance must be aesthetically pleasing for a broad age of audiences.</td></tr>
<tr><td></td><td>Electrical Performance</td></tr>
<tr><td>D</td><td>11. The frequency of the camera must be greater than 25 Hz with a resolution of 640x480 with 8 bit grayscale pixels.</td></tr>
<tr><td>W</td><td>12. Camera resolution desired to be 1024x768 with 16 bit color pixels.</td></tr>
<tr><td>D</td><td>13. Power consumption of the head is limited to 2 kW with all power being supplied at 24VDC +/- 3 VDC.</td></tr>
<tr><td>D</td><td>14. Position shall be communicated to the head via CANBus serial protocol.</td></tr>
<tr><td>D</td><td>15. Video communications to use a Firewire protocol.</td></tr>
<tr><td></td><td>Software Performance</td></tr>
<tr><td>D</td><td>16. Control software must reside on a single windows based PC.</td></tr>
<tr><td>D</td><td>17. Total boot time of all functions (including calibration routines) within 3 minutes.</td></tr>
<tr><td>D</td><td>18. Total latency related to commands not to exceed 10 msec.</td></tr>
<tr><td>D</td><td>19. Camera calibration only required once during each head setup. Calibration time of eyes not included in total boot time specification.</td></tr>
<tr><td>D</td><td>20. Commanded positions of each axis accessible at a minimum rate of 30 Hz.</td></tr>
<tr><td></td><td>Environmental Requirements</td></tr>
<tr><td>D</td><td>21. Capable of operating in temperature ranges of 0 degrees C to 40 degrees C.</td></tr>
<tr><td>D</td><td>22. Unit designed to function indoors only (no sunlight, minimal dust, and no condensing moisture environments).</td></tr>
<tr><td></td><td>Safety</td></tr>
<tr><td>D</td><td>23. Programmable torque limits on all axes to prevent human injury.</td></tr>
<tr><td>D</td><td>24. Output signal generated for caution light upon activation of any servo axis.</td></tr>
<tr><td>D</td><td>25. Locking pins present to prevent head from falling when unpowered.</td></tr>
<tr><td>D</td><td>26. Emergency stop button to be incorporated into system.</td></tr>
</table>

Table 28 (continued)

D/W	Requirement
	Maintenance
D	27. Shells easily removable for access to servo drives – must be accessible within 5 minutes of disassembly with unit powered down.
W	28. Only tools required for routine maintenance are #2 Phillips adjustable torque screw driver, small flat head screw driver, and lithium grease.
	Cost
D	29. Cost of prototype development, fabrication and initial testing not to exceed $350,000 USD.
	Schedule
D	30. Total time of project not to exceed 12 months.

Notice the detailed nature of the updated set of requirements in Table 28 – each parameter can be measured or verified. If there is no way to verify acceptance through means such as testing, inspection or simulation then there is typically no good reason to include that requirement. However, there are some exceptions for using such requirements such as the requirement in this list that is related to appearance. There is not a good way to measure appearance due to the subjectivity of the meaning from one individual to another. Other requirements that may not be able to be specific are ones that are highly unknown. For instance, a new technology related to lasers may not be reasonable to estimate the output power or efficiency until it is actually fabricated. It is areas such as these that may only be specified as "wishes" due to the amount of uncertainty related to the results. The goal is to capture a list of customer desires as representative as possible.

Another key point to understand in regards to detailed requirements lists is the amount of time involved in generating such a list. To generate meaningful requirements is the result of a greater understanding of the system. For instance, requirements related to the desired motion of the eyeballs for humanoid robotic movement may be determined based on anatomical limitations. This would require searching in anatomical studies for this type of information or even using high speed cameras to measure actual eye movements to determine reasonable values. For this particular example, these values can be important as the implications for the servo design can be great. If the customer decides the eyes are moving too slowly after the robot is made, then significant problems may arise – It may be too costly or impossible to modify the prototype to achieve higher performance. If there is a basis on evidence through testing, this is unlikely to occur. As is the case with most estimation tasks – increased directed effort to understand the problem will lower the uncertainty in the estimate.

To complete the second step of the method, the goals must be explicitly stated by the estimator. These goals are then evaluated at the end of the estimation exercise as a way to include checks and balances within the cost estimation process. Table 29 contains the goals that were determined by the estimator for the project.

Table 29: Goals for Intermediate Theoretical Estimate

Normalization Parameters			
Cost	.45	Performance	.40
Schedule	.15		
Project Limits		**Estimate Limits**	
Cost	$350,000 Max	Cost	<$3,000
Schedule	Completion within 1 year	Schedule	Complete within 2 weeks
Performance	See Table 28	Performance	Cost Uncertainty < 20% Schedule Uncertainty < 30% All Demand requirements met

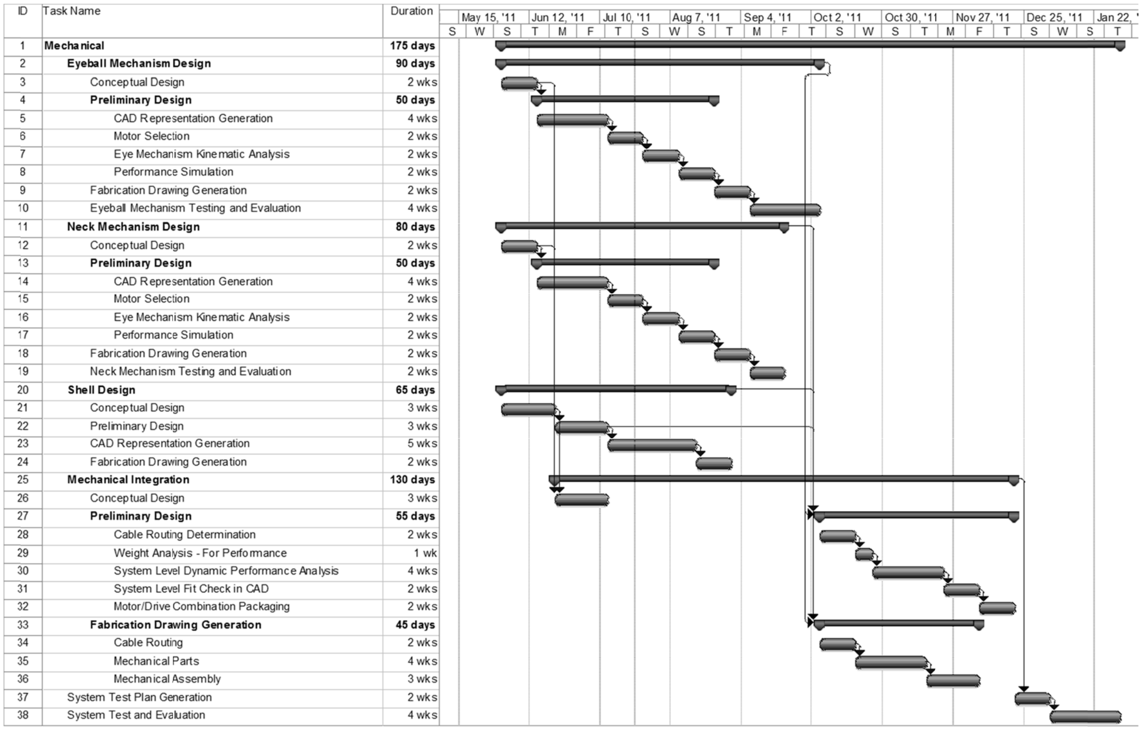
3.4.3 Step 3 – Explore the design space

Exploring the design space is a recommendation for particular subsystems of a development that may are suspected of containing a high amount of uncertainty. One particular component of the robot head was related to the implementation of servo drives for the neck of the robot. Previously in Section 2.5.3, this particular problem was demonstrated for the robot head. In that example, the determination of the servo drive location for the neck was determined to be placed on the torso in order to reduce the mass of the head. This was a result of applying function structures and working principles as recognized in Section 2.5. These types of tasks can help to create a better design base used for the estimation process leading into detailed task descriptions. These task descriptions are needed as the estimator moves into Step 4 of the proposed method.

3.4.4 Step 4 – Generate a Gantt Chart

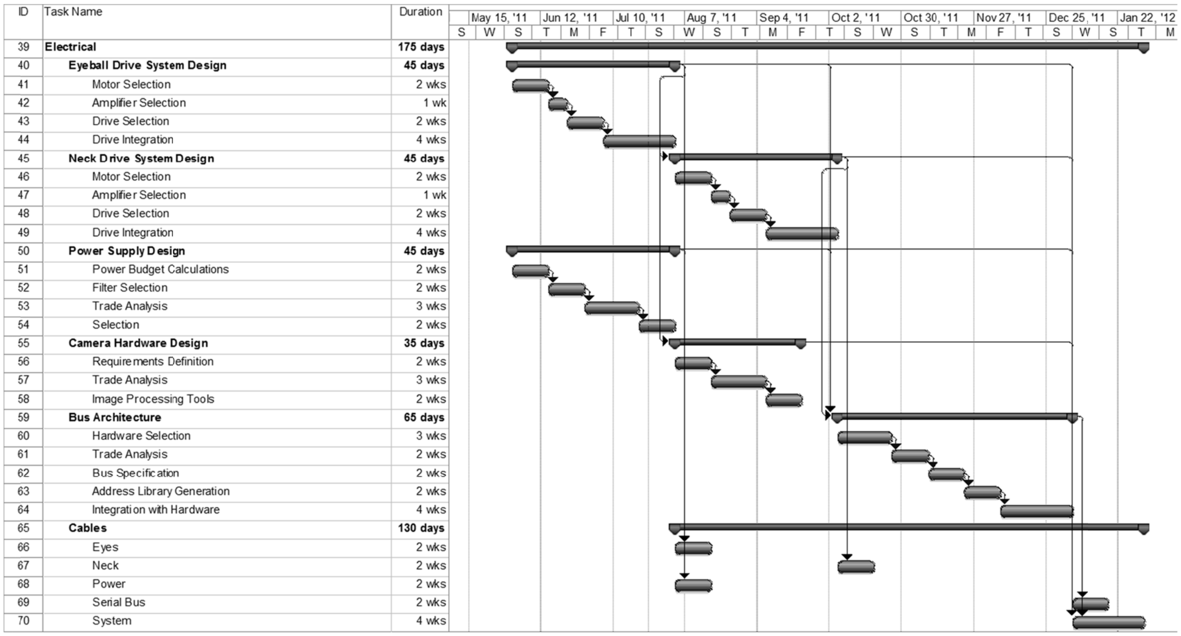
With more detail in a requirements list (result of Step 2) as well as a good conceptual design (result of Step 3) comes the ability to add more detail to the estimation of individual tasks. Given proper parameters, the key task leaders or system engineer is much better prepared to estimate various tasks. For example, having concrete information on the performance expectations of servo drives means that a mechanical estimator can estimate the size of motors required to drive the various axes more accurately. Having more detail at this level reduces uncertainty that flows through the entire system as pointed out earlier. By knowing the approximate drive size, the weight, performance, and cost of the drive selection can be estimated with much a much higher confidence level.

As prescribed by the proposed method, this starts with the generation of a detailed Gantt chart. Each major subtask (mechanical, electrical, and software) has a separate Gantt chart. Interactions between the two areas were limited for this example exercise, but it is clear that interactions would be better captured in a project level Gantt chart as required. The different charts do show a much higher level of detail for the various key tasks and help the estimator to see individual issues especially as more integration tasks are considered. Integration is a task that is often under-estimated in Basic Estimates and the added level of detail highlights the large amount of uncertainty that can arise in these latter portions of the design effort. To clarify what is meant by integration in this context, integration is the term used to describe what effort is needed to combine multidisciplinary tasks. For example after motors, amplifiers, drivers, etc. are available for assembly, one needs mechanical mounting features and brackets, cables and connectors for electrical integration, and processors and software to operate the equipment. Combining these activities and progressing from individual working modules to a working system can be challenging.



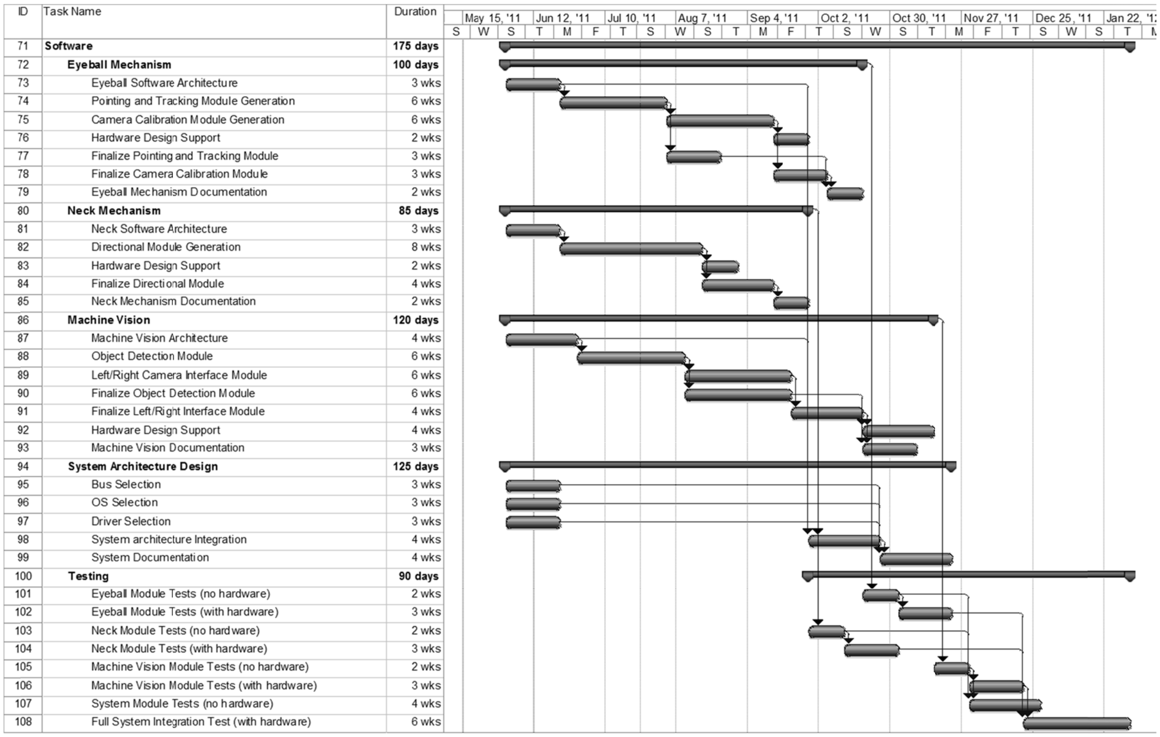
ID	Task Name	Duration
1	**Mechanical**	**175 days**
2	**Eyeball Mechanism Design**	**90 days**
3	Conceptual Design	2 wks
4	**Preliminary Design**	**50 days**
5	CAD Representation Generation	4 wks
6	Motor Selection	2 wks
7	Eye Mechanism Kinematic Analysis	2 wks
8	Performance Simulation	2 wks
9	Fabrication Drawing Generation	2 wks
10	Eyeball Mechanism Testing and Evaluation	4 wks
11	**Neck Mechanism Design**	**80 days**
12	Conceptual Design	2 wks
13	**Preliminary Design**	**50 days**
14	CAD Representation Generation	4 wks
15	Motor Selection	2 wks
16	Eye Mechanism Kinematic Analysis	2 wks
17	Performance Simulation	2 wks
18	Fabrication Drawing Generation	2 wks
19	Neck Mechanism Testing and Evaluation	2 wks
20	**Shell Design**	**65 days**
21	Conceptual Design	3 wks
22	Preliminary Design	3 wks
23	CAD Representation Generation	5 wks
24	Fabrication Drawing Generation	2 wks
25	**Mechanical Integration**	**130 days**
26	Conceptual Design	3 wks
27	**Preliminary Design**	**55 days**
28	Cable Routing Determination	2 wks
29	Weight Analysis - For Performance	1 wk
30	System Level Dynamic Performance Analysis	4 wks
31	System Level Fit Check in CAD	2 wks
32	Motor/Drive Combination Packaging	2 wks
33	**Fabrication Drawing Generation**	**45 days**
34	Cable Routing	2 wks
35	Mechanical Parts	4 wks
36	Mechanical Assembly	3 wks
37	System Test Plan Generation	2 wks
38	System Test and Evaluation	4 wks

Figure 10: Gantt Chart for Mechanical Tasks on an Intermediate Estimate



ID	Task Name	Duration
39	**Electrical**	**175 days**
40	**Eyeball Drive System Design**	**45 days**
41	Motor Selection	2 wks
42	Amplifier Selection	1 wk
43	Drive Selection	2 wks
44	Drive Integration	4 wks
45	**Neck Drive System Design**	**45 days**
46	Motor Selection	2 wks
47	Amplifier Selection	1 wk
48	Drive Selection	2 wks
49	Drive Integration	4 wks
50	**Power Supply Design**	**45 days**
51	Power Budget Calculations	2 wks
52	Filter Selection	2 wks
53	Trade Analysis	3 wks
54	Selection	2 wks
55	**Camera Hardware Design**	**35 days**
56	Requirements Definition	2 wks
57	Trade Analysis	3 wks
58	Image Processing Tools	2 wks
59	**Bus Architecture**	**65 days**
60	Hardware Selection	3 wks
61	Trade Analysis	2 wks
62	Bus Specification	2 wks
63	Address Library Generation	2 wks
64	Integration with Hardware	4 wks
65	**Cables**	**130 days**
66	Eyes	2 wks
67	Neck	2 wks
68	Power	2 wks
69	Serial Bus	2 wks
70	System	4 wks

Figure 11: Gantt Chart for Electrical Tasks on an Intermediate Estimate



ID	Task Name	Duration
71	**Software**	**175 days**
72	**Eyeball Mechanism**	**100 days**
73	Eyeball Software Architecture	3 wks
74	Pointing and Tracking Module Generation	6 wks
75	Camera Calibration Module Generation	6 wks
76	Hardware Design Support	2 wks
77	Finalize Pointing and Tracking Module	3 wks
78	Finalize Camera Calibration Module	3 wks
79	Eyeball Mechanism Documentation	2 wks
80	**Neck Mechanism**	**85 days**
81	Neck Software Architecture	3 wks
82	Directional Module Generation	8 wks
83	Hardware Design Support	2 wks
84	Finalize Directional Module	4 wks
85	Neck Mechanism Documentation	2 wks
86	**Machine Vision**	**120 days**
87	Machine Vision Architecture	4 wks
88	Object Detection Module	6 wks
89	Left/Right Camera Interface Module	6 wks
90	Finalize Object Detection Module	6 wks
91	Finalize Left/Right Interface Module	4 wks
92	Hardware Design Support	4 wks
93	Machine Vision Documentation	3 wks
94	**System Architecture Design**	**125 days**
95	Bus Selection	3 wks
96	OS Selection	3 wks
97	Driver Selection	3 wks
98	System architecture Integration	4 wks
99	System Documentation	4 wks
100	**Testing**	**90 days**
101	Eyeball Module Tests (no hardware)	2 wks
102	Eyeball Module Tests (with hardware)	3 wks
103	Neck Module Tests (no hardware)	2 wks
104	Neck Module Tests (with hardware)	3 wks
105	Machine Vision Module Tests (no hardware)	2 wks
106	Machine Vision Module Tests (with hardware)	3 wks
107	System Module Tests (no hardware)	4 wks
108	Full System Integration Test (with hardware)	6 wks

Figure 12: Gantt Chart for Software Tasks on an Intermediate Estimate

By generating these detailed Gantt charts, the number of tasks increased significantly from approximately 20 tasks in the Basic Estimate to approximately 100 tasks in the Intermediate Estimate. The effort required generating this level of detail increased significantly from about 1 hour to 8 hours, but the ability to describe uncertainty is improved.

3.4.5 Step 5 – Populate Estimation Tools

For each of the major tasks of the robotic head development as identified from the Gantt chart in Section 3.4.4, the expected hours and schedule were estimated using expert judgment. The following tables (Table 30 through Table 33) include the results of the exercise where hours, days, and uncertainty are considered for each individual subtask. The primary discipline areas (mechanical, electrical, and software) were considered to be separate exercises in the Gantt charts so these tasks were assumed to be independent. The result is that only the maximum uncertainty is apparent from these disciplines when considering schedule only as given in Table 34. Uncertainty with hours becomes multiplied by an estimated rate ($65/hr) to generate the base cost parameters.

Table 30: Schedule and Hour Estimate for Mechanical

		Hour	Hours			Schedule	Days		
#	Task	Uncertainty	Lower	Upper	Delta	Uncertainty	Lower	Upper	Delta
1	**Mechanical**	20%	160	192.0	32.0		175		
2	Eyeball Mechanism Design						90		
3	Conceptual Design	30%	60	78.0	18.0	10%	14	15.4	1.4
4	Preliminary Design						50		
5	CAD Representation Generation	15%	40	46.0	6.0	10%	28	30.8	2.8
6	Motor Selection	15%	24	27.6	3.6	15%	14	16.1	2.1
7	Eye Mechanism Kinematic Analysis	15%	40	46.0	6.0	15%	14	16.1	2.1
8	Performance Simulation	15%	60	69.0	9.0	10%	14	15.4	1.4
9	Fabrication Drawing Generation	10%	24	26.4	2.4	10%	14	15.4	1.4
10	Eyeball Mechanism Testing and Evaluation	10%	60	66.0	6.0	10%	28	30.8	2.8
11	Neck Mechanism Design						80		
12	Conceptual Design	30%	40	52.0	12.0	15%	14	16.1	2.1
13	Preliminary Design						50		
14	CAD Representation Generation	15%	40	46.0	6.0	10%	28	30.8	2.8
15	Motor Selection	15%	24	27.6	3.6	15%	14	16.1	2.1
16	Eye Mechanism Kinematic Analysis	20%	24	28.8	4.8	10%	14	15.4	1.4
17	Performance Simulation	30%	60	78.0	18.0	10%	14	15.4	1.4
18	Fabrication Drawing Generation	10%	24	26.4	2.4	10%	14	15.4	1.4
19	Neck Mechanism Testing and Evaluation	25%	40	50.0	10.0	15%	14	16.1	2.1
20	Shell Design						65		
21	Conceptual Design	20%	40	48.0	8.0	10%	21	23.1	2.1
22	Preliminary Design	20%	80	96.0	16.0	10%	21	23.1	2.1
23	CAD Representation Generation	15%	40	46.0	6.0	10%	35	38.5	3.5
24	Fabrication Drawing Generation	10%	24	26.4	2.4	10%	14	15.4	1.4
25	Mechanical Integration						130		
26	Conceptual Design	25%	60	75.0	15.0	10%	21	23.1	2.1
27	Preliminary Design						55		
28	Cable Routing Determination	20%	40	48.0	8.0	10%	14	15.4	1.4
29	Weight Analysis - For Performance	15%	40	46.0	6.0	10%	7	7.7	0.7
30	System Level Dynamic Performance Analysis	25%	80	100.0	20.0	10%	28	30.8	2.8
31	System Level Fit Check in CAD	15%	40	46.0	6.0	10%	14	15.4	1.4
32	Motor/Drive Combination Packaging	15%	40	46.0	6.0	10%	14	15.4	1.4
33	Fabrication Drawing Generation						45		
34	Cable Routing	15%	24	27.6	3.6	10%	14	15.4	1.4
35	Mechanical Parts	15%	24	27.6	3.6	10%	28	30.8	2.8
36	Mechanical Assembly	15%	24	27.6	3.6	10%	21	23.1	2.1
37	System Test Plan Generation	15%	40	46.0	6.0	15%	14	16.1	2.1
38	System Test and Evaluation	30%	80	104.0	24.0	15%	28	32.2	4.2
			1396.0	**1670.0**	**274.0**		**175.0**	**233.8**	**58.8**

Table 31: Schedule and Hour Estimate for Electrical

		Hour	Hours			Schedule	Days		
#	Task	Uncertainty	Lower	Upper	Delta	Uncertainty	Lower	Upper	Delta
39	**Electrical**	20%	160	192.0	32.0		175		
40	Eyeball Drive System Design						45		
41	Motor Selection	15%	24	27.6	3.6	10%	14	15.4	1.4
42	Amplifier Selection	15%	24	27.6	3.6	10%	7	7.7	0.7
43	Drive Selection	15%	24	27.6	3.6	10%	14	15.4	1.4
44	Drive Integration	20%	60	72.0	12.0	15%	28	32.2	4.2
45	Neck Drive System Design						45		
46	Motor Selection	15%	24	27.6	3.6	10%	14	15.4	1.4
47	Amplifier Selection	15%	24	27.6	3.6	10%	7	7.7	0.7
48	Drive Selection	15%	24	27.6	3.6	10%	14	15.4	1.4
49	Drive Integration	20%	60	72.0	12.0	15%	28	32.2	4.2
50	Power Supply Design						45		
51	Power Budget Calculations	15%	40	46.0	6.0	10%	14	15.4	1.4
52	Filter Selection	15%	24	27.6	3.6	10%	14	15.4	1.4
53	Trade Analysis	15%	16	18.4	2.4	10%	21	23.1	2.1
54	Selection	15%	24	27.6	3.6	10%	14	15.4	1.4
55	Camera Hardware Design						35		
56	Requirements Definition	15%	40	46.0	6.0	10%	14	15.4	1.4
57	Trade Analysis	15%	16	18.4	2.4	10%	21	23.1	2.1
58	Image Processing Tools	25%	40	50.0	10.0	15%	14	16.1	2.1
59	Bus Architecture						65		
60	Hardware Selection	15%	40	46.0	6.0	15%	21	24.2	3.2
61	Trade Analysis	15%	24	27.6	3.6	15%	14	16.1	2.1
62	Bus Specification	15%	24	27.6	3.6	15%	14	16.1	2.1
63	Address Library Generation	15%	40	46.0	6.0	15%	14	16.1	2.1
64	Integration with Hardware	25%	60	75.0	15.0	20%	28	33.6	5.6
65	Cables						130		
66	Eyes	15%	24	27.6	3.6	10%	14	15.4	1.4
67	Neck	15%	24	27.6	3.6	10%	14	15.4	1.4
68	Power	15%	24	27.6	3.6	10%	14	15.4	1.4
69	Serial Bus	15%	24	27.6	3.6	10%	14	15.4	1.4
70	System	20%	40	48.0	8.0	20%	28	33.6	5.6
			948.0	**1116.2**	**168.2**		**175.0**	**228.6**	**53.6**

Table 32: Schedule and Hour Estimate for Software

		Hour	Hours			Schedule	Days		
#	Task	Uncertainty	Lower	Upper	Delta	Uncertainty	Lower	Upper	Delta
71	**Software**	20%	160	192.0	32.0		175		
72	Eyeball Mechanism						100		
73	Eyeball Software Architecture	15%	40	46.0	6.0	15%	21	24.2	3.2
74	Pointing and Tracking Module Generation	20%	40	48.0	8.0	20%	42	50.4	8.4
75	Camera Calibration Module Generation	20%	40	48.0	8.0	20%	42	50.4	8.4
76	Hardware Design Support	15%	24	27.6	3.6	15%	14	16.1	2.1
77	Finalize Pointing and Tracking Module	20%	40	48.0	8.0	15%	21	24.2	3.2
78	Finalize Camera Calibration Module	20%	60	72.0	12.0	15%	21	24.2	3.2
79	Eyeball Mechanism Documentation	10%	12	13.2	1.2	10%	14	15.4	1.4
80	Neck Mechanism						85		
81	Neck Software Architecture	15%	40	46.0	6.0	10%	21	23.1	2.1
82	Directional Module Generation	15%	80	92.0	12.0	10%	56	61.6	5.6
83	Hardware Design Support	15%	40	46.0	6.0	15%	14	16.1	2.1
84	Finalize Directional Module	15%	40	46.0	6.0	15%	28	32.2	4.2
85	Neck Mechanism Documentation	10%	24	26.4	2.4	10%	14	15.4	1.4
86	Machine Vision						120		
87	Machine Vision Architecture	25%	80	100.0	20.0	15%	28	32.2	4.2
88	Object Detection Module	30%	80	104.0	24.0	20%	56	67.2	11.2
89	Left/Right Camera Interface Module	25%	60	75.0	15.0	15%	56	64.4	8.4
90	Finalize Object Detection Module	25%	60	75.0	15.0	15%	56	64.4	8.4
91	Finalize Left/Right Interface Module	25%	60	75.0	15.0	15%	28	32.2	4.2
92	Hardware Design Support	20%	24	28.8	4.8	15%	28	32.2	4.2
93	Machine Vision Documentation	10%	40	44.0	4.0	15%	21	24.2	3.2
94	System Architecture Design						125		
95	Bus Selection	15%	24	27.6	3.6	15%	21	24.2	3.2
96	OS Selection	15%	24	27.6	3.6	15%	21	24.2	3.2
97	Driver Selection	15%	24	27.6	3.6	15%	21	24.2	3.2
98	System architecture Integration	15%	80	92.0	12.0	15%	28	32.2	4.2
99	System Documentation	10%	40	44.0	4.0	10%	28	30.8	2.8
			1236.0	**1471.8**	**235.8**		**175.0**	**280.4**	**105.4**

Table 33: Schedule and Hour Estimate for Testing

		Hour	Hours			Schedule	Days		
#	Task	Uncertainty	Lower	Upper	Delta	Uncertainty	Lower	Upper	Delta
100	**Testing**	20%	80	96.0	16.0		90		
101	Eyeball Module Tests (no hardware)	15%	40	46.0	6.0	10%	14	15.4	1.4
102	Eyeball Module Tests (with hardware)	25%	120	150.0	30.0	15%	21	24.2	3.2
103	Neck Module Tests (no hardware)	15%	24	27.6	3.6	10%	14	15.4	1.4
104	Neck Module Tests (with hardware)	25%	120	150.0	30.0	15%	21	24.2	3.2
105	Machine Vision Module Tests (no hardware)	15%	40	46.0	6.0	10%	14	15.4	1.4
106	Machine Vision Module Tests (with hardware)	25%	80	100.0	20.0	15%	21	24.2	3.2
107	System Module Tests (no hardware)	15%	120	138.0	18.0	10%	28	30.8	2.8
108	Full System Integration Test (with hardware)	30%	160	208.0	48.0	20%	56	67.2	11.2
			784.0	**961.6**	**177.6**		**90.0**	**117.7**	**27.7**

Table 34: Schedule and Hour Estimate for Theoretical Project

		Hours				Days		
Task		**Lower**	**Upper**	**Delta**		**Lower**	**Upper**	**Delta**
Mechanical	20%	1396	1670	274		175	234	59
Electrical	18%	948	1116	168		175	229	54
Software	19%	1236	1472	236		175	280	105
Testing	23%	784	962	178		90	118	28
Totals	**20%**	**4364**	**5220**	**856**		**265**	**398**	**133**
Material Estimate (From Basic Estimate)		**$44,275**						
Result with rate of $65/hr		**$327,935**	**$383,549**	**$55,614**				

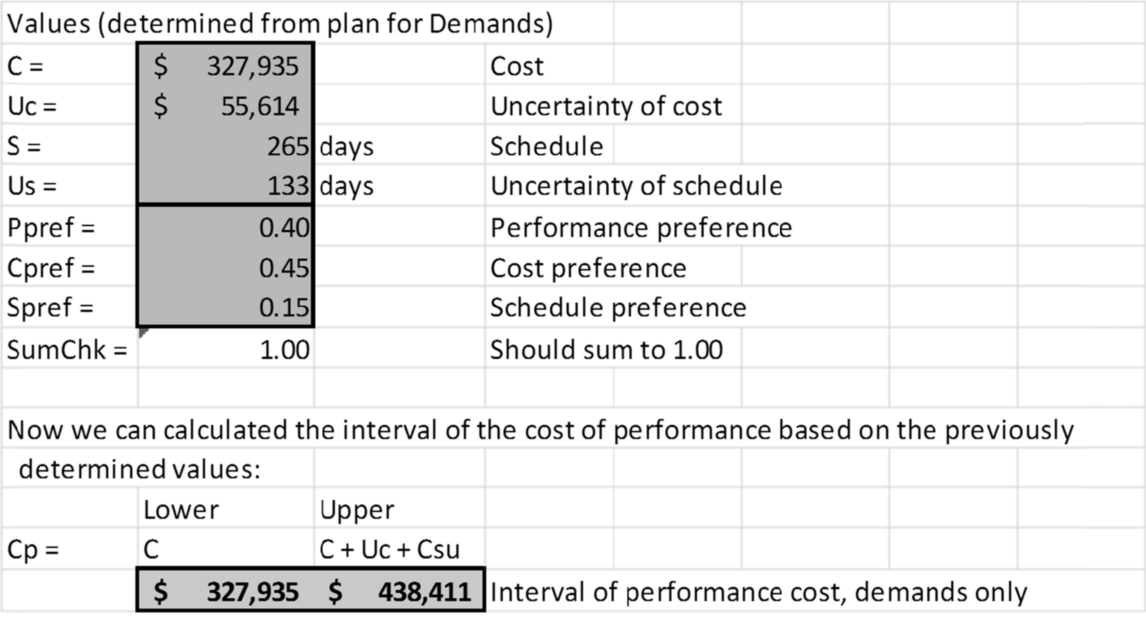
There are several points to be made about the tables within this section. The three disciplines are considered as independent areas in order to simplify the calculation of schedule. A more detailed Gantt chart could capture this, but the separation does not result in a major limitation. For each of the disciplines, an amount of time is considered at the top level to account for management of that particular subtask. Another major consideration is that only the work to address the demanded requirements was considered. If the wishes are to be considered separately, then this activity would have to be completed twice – once for demands and once for wishes. The difference between the two sets of calculations will allow the cost of wishes to be captured separately or what has also been referred to as the uncertainty related to performance in Section 2.3.4. Without having the wishes considered separately, only the interval of cost ($327,935 – $383,549) and schedule (265 days – 424 days) remain. Note that the cost interval includes the material cost used in the previous Basic Estimate. With these intervals now defined, the next step in the estimation method is now possible.

3.4.6 Step 6 – Apply Normalization Equations

With all of the variables in place, the normalization equations developed in Section 2.3.1 can be applied. Table 35 captures the calculation of the cost interval including schedule, uncertainty, and estimator preference. Once the schedule uncertainty is included in context of the normalization parameters, the total cost interval becomes $327,935 to

$438,411. This is more in line with the actual cost anticipated in the previous Basic Estimate section where the actual cost was anticipated to be $358,700.

Table 35: Normalization Equations for Intermediate Estimate



Values (determined from plan for Demands)			
C =	$ 327,935		Cost
Uc =	$ 55,614		Uncertainty of cost
S =	265	days	Schedule
Us =	133	days	Uncertainty of schedule
Ppref =	0.40		Performance preference
Cpref =	0.45		Cost preference
Spref =	0.15		Schedule preference
SumChk =	1.00		Should sum to 1.00

Now we can calculated the interval of the cost of performance based on the previously determined values:

	Lower	Upper	
Cp =	C	C + Uc + Csu	
	$ 327,935	**$ 438,411**	Interval of performance cost, demands only

3.4.7 Step 7 – Compare Results to Initial Goals

In order to compare the results to the initial goals, one must know what the cost of generating the estimate was. Table 36 captures this cost by estimating the cost of each step and applying a rate of $65/hr to those hours. The result of this exercise determines a cost of $4,160 to generate the estimate.

Table 36: Calculation of Cost of Intermediate Estimate

Estimate Task	Hours	Cost
Step 1 - Determine if Appropriate	4	$260
Compare Assumptions		
Step 2 - Numerical Normalization	16	$1,040
Generate Parameters		
Generate Requirements		

Table 36 (continued)

Estimate Task	Hours	Cost
Step 3 - Design Space	8	$520
Decompose Design 1		
Decompose Design 2		
Step 4 - Generate Schedule	16	$1,040
Generate Detailed Task List		
Generate a Gantt Chart		
Step 5 - Populate Estimation Tools	16	$1,040
Generate Skills Needed for Project		
Assign Hours to Each Task		
Step 6 - Apply Normalization Equations	2	$130
Add Values to Spreadsheet		
Step 7 - Compare to Initial Goals	2	$130
Simple Comparison of Values		
	64	$4,160

The next action is to compare all of the results from previous steps to the goals established in Table 29. Table 37 includes the previous goals and calculated results from the previous steps. The results raise several concerns from the standpoint of the estimator. A minor concern is that the estimate cost $1,160 more than initially suggested for the cost of the estimate itself. However, this minor overrun in the estimate has given rise to a much larger concern – the potential to exceed the targeted cost goal by $88,411 when considering the upper bound of the cost. Another concern is the schedule bound which exceeds the goal by approximately 6 months. The variance or uncertainty goals were also exceeded. These overruns are significant and must be weighed carefully between the organization of the estimator and that of the potential sponsor. Although these estimates are well in excess of what was anticipated, the value of this information could prove to be quite beneficial in alarming stakeholders of the potential for exceeding the budget and/or schedule.

Table 37: Comparison of Estimation Goals to Results for Intermediate Estimate

Estimate Task	Hours	Cost
Project Cost Estimate	$ 327,935	Lower Limit
	$ 438,411	Upper Limit
Project Cost Goal	$ 350,000	
Cost Variance	29%	(based on mean)
Cost Variance Goal	<20%	
Project Schedule Estimate	265 days	Lower Limit
	133 days	Upper Limit
Project Schedule Goal	260 days (1 yr)	
Schedule Variance	40%	(based on mean)
Schedule Variance Goal	<30%	
Estimate Cost	$ 4,160	
Estimate Cost Goal	$ 3,000	
Estimate Schedule	10 days	
Estimate Schedule Goal	10 days	

3.4.8 Overview of Intermediate Estimate

The goal of an Intermediate Estimate is to add considerable detail to the overall description of the design activity in order to prevent the issues that can arise if detailed requirements or an understanding offered from a Gantt chart are not present. This intermediate approach can be suitable when the estimator is willing to accept risk or when resources are limited. An example of when this approach is useful is when an updated forecast to complete is needed after an effort has already been funded. The next example provides tools for better understanding risk and uncertainty while also generating a better representation of the conceptual design via design abstraction techniques.

Specific to the Intermediate Estimate exercise is the introduction of detailed requirements generation, use of abstraction techniques, and the use of a Gantt chart for tracking dependencies between schedule and performance. This section builds on the previous section related to Basic Estimation and continues to build on the case that the proposed theoretical exercises are suitable for demonstrating the overall usefulness of the proposed method. The next section offers tools that can be considered if the uncertainty is too high and further investigation is required.

3.5 Detailed Estimate

A Detailed Estimate considers the same level of detail addressed in an Intermediate Estimate while placing more attention to multiple portions of the estimation process. Increases in the number of details associated with requirements, detailed cost estimates on material, and detailed schedules are expected with a Detailed Estimate. Notice these three areas correspond directly with the three major areas of engineering design projects – performance, cost, and schedule. Additionally, other components of the estimate are given more consideration such as the use of abstraction techniques to improve the design concept, generation of a mathematical model to compare cost, schedule, and performance, and assess risk to the estimator. In regards to generating a formal characterization of risk and uncertainty, this enhancement can help to quantify subtasks with a large amount of uncertainty. These subtasks in turn would have additional cost estimating considerations based upon the risk level of the estimator. The primary difference between Intermediate and Detailed estimates discussed here will be in relation to uncertainty or rather a reduction in uncertainty. The following sections describe the various additional steps that could be applied to an Intermediate estimate to better understand uncertainty related to the theoretical example problem.

3.5.1 Characterization of Risk and Uncertainty

An understanding of risk and uncertainty is present in any task, and the two terms are closely aligned for the purposes of engineering cost estimations. In the context of engineering cost estimates, uncertainty is the range of a task not well understood whereas risk is the level of uncertainty an individual or organization is willing to accept moving forward. An example of this can be described by drawing one card from a standard deck of 52 cards and betting upon the chance of this card being a king. Because there are four kings in a deck, the chance of this occurring is 1:13. An even bet would be to place $1 on the chance of this happening with a payout of $13. Doing this hundreds of times would equate to essentially no risk because the chances of having no change over several instances would be certain. Beyond this standard case, there are several other occurrences that may happen that affect the bet – these different situations are described below:

Risk as a function of worth: The bet is only placed once with payout of 1:13. The individual has $1,000 in their pocket and wishes to place $1 on the bet. The risk to the individual is low because the bet is only 0.1% of their belongings. The other case is where the individual has $1,000 in their pocket and wishes to place $500 on the bet. This would be considered an extremely risky bet because the amount wagered is 50% of their belongings.

An estimate of uncertainty is not definitive: The gambler is placing a single bet with a payout of 1:13 as previously described. However, the deck of 52 cards actually included 2 jokers unbeknownst of the gambler, which adds 2 cards to the deck of 52 cards. This would alter the payout ratio from 1:13 to 2:27, which is slightly less. The gambler's assessment of uncertainty was not the actual uncertainty in this example.

Personal risk can differ by individual: Two gamblers sitting beside one another have the same amount of cash in their pocket, $100. Each gambler is placing a bet on the event with the odds being 1:13. Gambler A bets $1 whereas Gambler B bets $10. Gambler B is willing to accept more risk than Gambler A in this case.

Personal risk can differ by situation: A single gambler wages $10 on the previously described bet with odds of 1:13 on a typical day. On a particular day, the gambler had just spoken with an old acquaintance that she had not spoken to in several years. This conversation made the gambler happy and in a good mood. At the time of the bet, the gambler was willing to place a bet of \$20 whereas previously only a wager of \$10 was acceptable. Personal risk can change based upon situations.

These examples were provided to illustrate the relationship between risk and uncertainty with a focus on how changes in the environment, and risk level can affect individuals. The other important example including added jokers to the deck illustrated how uncertainty has an inherent amount of uncertainty as well. This notion of uncertainty with uncertainty is confusing but must be addressed in the context of risk. This is one of the key components of estimation. If the estimate is incorrect even when considering the upper and lower bounds of that estimate, the customer and contractor could both face considerable disappointment if the upper and lower bounds of the initial estimate proved to be far from the actual cost of the development. In regards to the four types of risk previously described, this work will focus on uncertainty with an added level of uncertainty and risk level of an organization. This type of risk was previously described using the phrase, “an estimate of uncertainty is not definitive.”

There is a need to formally characterize the impact of various issues when developing engineering solutions. An accepted approach is to use a risk matrix (see Figure 13) to capture the level of risk based upon the probability of occurrence as well as the consequence similar to that describe in ISO 31000 [58]. There are varying levels of probability and consequence that describe the risk for each major piece of uncertainty in a given development. In many cases this is qualitative, but for the purposes of characterizing risk objectively, this representation must be quantitative. This tool is used when the project is ongoing; however, this tool can also be used to characterize the risk level taken for various design tasks. In Figure 11, it is important to note that the current state of the task is still cautionary meaning there is a chance that the design of the eye motor can be problematic. In order to reduce this risk, additional considerations related to tolerance analysis and/or construction of a prototype is needed. The goal is not to do these activities while generating the estimate, but to understand what risk mitigation is required prior to construction of this component of the system for the purpose of estimating the cost of the effort. Because these additional tasks are needed, these activities will now be considered during the estimation when otherwise; these tasks may have been overlooked if the attention to risk detail had been overlooked.

Notice also the definition of probability and consequence for the risk item described in. Figure 13. For each level of probability and consequence, a unique number is assigned based on that particular risk item. For instance, a probability of Level 1 corresponds to 0.2, with a consequence of Level 1 costing $3,000 with a schedule impact of 2 weeks. Normalization equations must eventually be applied to the consequence as it considers both cost and schedule impacts. There is another aspect to risk – performance. If the risk is associated with a wish as opposed to a demand, it may be chosen to accept the risk based upon achieving or not achieving the objective of the wish requirement. In this case, the wish is considered as uncertainty in performance and can be tracked accordingly. Lastly, even if the performance is a demand, discussion with the customer to redefine the requirement may be necessary to reduce or eliminate the risk. This can occur when a requirement is known to be aggressive or difficult to meet from the beginning of the development.

To demonstrate how uncertainty can affect the performance of the eyeball mechanism, the associated requirements must be described. For this example, the following requirements were chosen to be related to eye motor design risk:

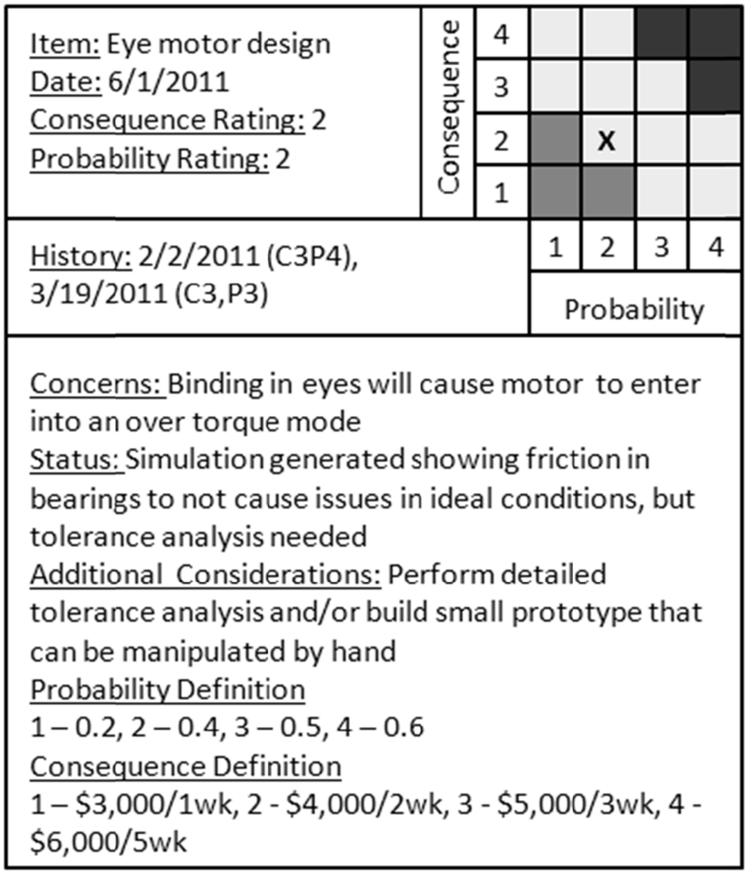
- Requirement #4: Eyeballs must be able to rotate at 1.0 rad/s in rotation about Z and Y with an acceleration of 1.0 rad/s2. The rotation angle is defined as +20/-30 degrees in the Y axis and +/- 90 degrees in the Z axis.

- Requirement #6: The acceptable position error of each eyelid and neck axis is set at 5 mrad, whereas the acceptable position error of each eye position is 10 mrad in order to support high level stereo imaging.

Both of these items are demands meaning that any deviation from these goals must be understood by the customer and thus there is no good way to capture the inability to reach these goals within the framework of this method. However, if we consider these items as wishes, a function could describe the ability to meet the wish as it applies to the current uncertainty. For this case, consider two cases where the performance achievement is nearly inevitable at the expense of probability and consequence risk or where the performance is sacrificed for probability and consequence – this description is in Table 38. Notice that performance uncertainty is negative because it will have a negative impact on the overall desires of the customer.

Table 38: Risk in Regards to Wish Requirements

Performance not met		**Performance met**	
Item	Uncertainty	Item	Uncertainty
Consequence Level 1	\$3,000 2wk	Consequence Level 3	\$5,000 3wk
Probability Level 1	0.2	Probability Level 3	0.5
Performance	-0.2	Performance	0.0



Item: Eye motor design
Date: 6/1/2011
Consequence Rating: 2
Probability Rating: 2

Consequence				
4			■	■
3				■
2	▨	X		
1	▨	▨		
	1	2	3	4
	Probability			

History: 2/2/2011 (C3P4), 3/19/2011 (C3,P3)

Concerns: Binding in eyes will cause motor to enter into an over torque mode
Status: Simulation generated showing friction in bearings to not cause issues in ideal conditions, but tolerance analysis needed
Additional Considerations: Perform detailed tolerance analysis and/or build small prototype that can be manipulated by hand
Probability Definition
1 – 0.2, 2 – 0.4, 3 – 0.5, 4 – 0.6
Consequence Definition
1 – $3,000/1wk, 2 - $4,000/2wk, 3 - $5,000/3wk, 4 - $6,000/5wk

Figure 13: Risk Calculation for Eye Motor Design for Theoretical Estimation

3.5.2 Further Implementation of Abstraction of Design

Previously, the abstraction of design was discussed in Section 2.5 with a short example on the selection of drive placement in the head of a humanoid robot. In this section a more comprehensive arrangement of function structures is discussed to allow an estimator to tackle complicated systems.

The example described in Figure 14 is a representation of functions required for a single eyeball. This representation is important for many reasons. It allows the designer and estimator to gauge the complexity of how the system will be designed. Upon review of this figure, one can see that in order to get signals and power to the eyeball cameras, the routing of cables would be problematic due to how an eyeball would likely be supported in a bearing. Once this image is combined with a second eyeball, it is becomes evident that the up/down and left/right servo mechanisms may be shared between the two eyeballs as well as the eye-position structure. Another benefit from this representation is the ability to estimate the number of mechanical components required for this system. The number of parts in a mechanical system often indicates the complexity associated with packaging thus providing the estimator more information useful for estimating the cost of a task. An abstraction exercise will highlight all of the needed functions in a system limiting surprises in the design process as more details are uncovered. Most importantly however, a detailed abstraction will serve as a building block for the conceptual design of a system as the next step will be to consider working principles associated with accomplishing the functions described in Figure 14.

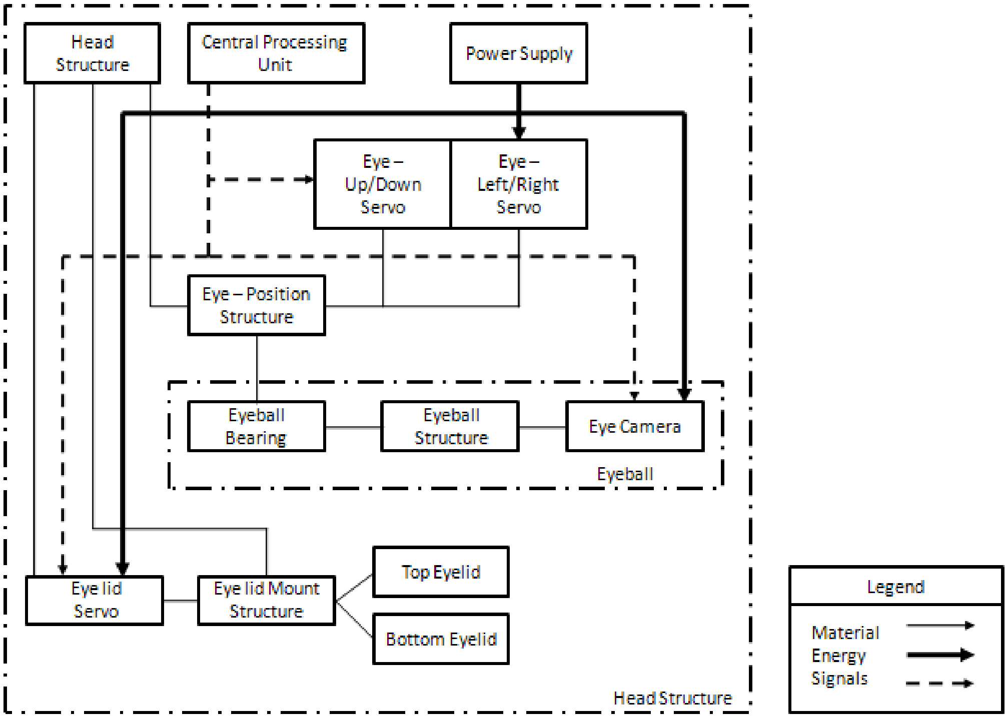


Figure 14: Function Structure of a Single Eyeball Mechanism

3.5.3 Overview of Detailed Estimate

The Detailed Estimate adds useful tools for the estimation process by creating a way to quantify risk as well as capture all of the needed functions of the system through abstraction of the design. The use a more formal risk characterization helps the estimator to have a better understanding of the potential impact of not meeting requirements. By combining these tools with an approach like that discussed in the Intermediate Estimate section, the Detailed Estimate serves as a good estimation tool for prototype systems. Also, the artifacts from generating a Detailed Estimate will be used during the execution of work if the decision is made to move forward with the estimated tasks.

3.6 Discussion of Theoretical Estimate Results

A significant bit of knowledge to take away from this exercise is that as more effort is placed on the estimation process, the level of uncertainty diminishes making the estimate more accurate. This notion is intuitive, but there are some specific points that need to be made that go along with this point. First, a Detailed Estimate is not free – a significant amount of resources can be expended on the estimation process. As demonstrated in this chapter, the Basic Estimate could have been completed in half the time of the Intermediate Estimate, which in turn would be approximately half the time of a Detailed Estimate.

The consideration needs to be made to limit the amount of effort applied to the estimation process in order to prevent a situation where the estimation itself becomes a large part of the overall cost of a given program. This approach may also change as progress is made on various tasks within a program. For instance, when deciding whether or not to generate a proposal or pursue various opportunities, a Basic Estimate can be sufficient. A Basic Estimate may also be suitable for estimating the cost of work performed by a subcontractor prior to generating a statement of work. However, when generating a detailed proposal, it would be prudent to generate an Intermediate or Detailed Estimate depending on the characterization of risk or uncertainty required. This was discussed in more detail in Section 2.3.2 as it was shown that a detailed characterization of uncertainty can prevent large overruns on a program.

Chapter 3 has demonstrated several components of the proposed estimation method. The development of a Basic Estimate shows the need for more detailed estimates and highlights the shortcomings that can appear when not following an estimation method. The Intermediate Estimate described in Section 3.4 demonstrated how the method can be followed explicitly. The Detailed Estimate section described additional tools that may be used to provide more clarification to the estimation process. This becomes more important to reduce the amount of uncertainty or rather the size of the intervals related to the estimate. What was not implemented was the use of work planning tools that are specific to individual engineers. However, in the next chapter an actual application of the estimation method will be discussed in order to demonstrate the impact of engineering resources on the estimation process. Most importantly, the example provided in Chapter 4 is the result of an actual application that provides intermediate evaluations to get a better understanding of what challenges can arise in a practical sense.

A final point about the results of this chapter is to consider the use of the term “effort” as it applies to generating an estimate. Blind effort is not beneficial to any task and it is of utmost importance to apply directed effort in order to achieve the most benefit. This is paramount in order to fully receive the full benefit from a comprehensive estimation method. As mentioned previously, the only way to create a 100% complete estimation is to perform the entirety of the work and capture the cost of the actual design effort. This of course is not cost effective.

CHAPTER 4

Application Example: Crack Sealing for Asphalt Surfaces

This chapter provides an estimator with a practical application of the proposed estimation method. The example problem is the result of applying the method to a particular problem for Georgia's Department of Transportation related to research for automating the sealing of cracks in asphalt. The method is used for the initial estimate and results of the method are evaluated twice during project execution and finally after the project were completed. This chapter is devoted to addressing the usefulness of the proposed method as well as what can be attributed to the application of the method. The case is made that the detail resulting from the estimation process can be attributed to successful demonstration of the automated crack sealing system to GDOT.

Crack sealing refers to operations performed by transportation officials to seal cracks in asphalt surfaces. This practice can prolong the life of roads thus providing considerable savings to the costly process of maintaining roads. GTRI worked closely with GDOT to develop an automated solution to the typical manual operation of filling cracks. The following section describes the details of the system. The complexity of the system is important to understand because of the challenges associated with estimating individual tasks related to the completion of the overall project. Although the complexity of the entire system is discussed, the estimation discussed only applies to the last stages of the project. The remaining tasks within the final six months of the project were addressed as if the project were re-planned at that time.

The content in Chapter 4 begins to link the use of the proposed cost estimation method with positive results due to the application of the method. The topics discussed in this chapter address the empirical performance validity of the Validation Square with the primary goal of showing the reader that the positive results achieved can be attributed to using the proposed method.   This discussion is continued by making the case that the positive results would be evident in similar problems.

4.1 Overview of GTRI Approach

A prototype was designed and constructed to advance research in automated crack sealing operations. This prototype addressed the previously identified challenge of detecting cracks in real time, identified challenges associated with system integration, and provided a demonstration of the system capability on a limited scale.

The prototype, mounted on a trailer, consisted of a single stereo camera, an applicator system, and a means of providing a continuous supply of sealant to both a longitudinal and a transverse distribution system. The transverse crack distribution system consisted of a bank of 12 discreet nozzles spaced evenly across one foot of travel. For longitudinal cracks, a single dispensing nozzle capable of continuous operation was attached to a linear servo axis for tracking cracks while a towing vehicle was in motion. Servo operation is achieved by controlling the position of the longitudinal dispensing nozzle in real time via a command signal generated from the crack map. Controls were implemented for the prototype to permit automated sealing of identified cracks in a 12" wide band of pavement. This prototype was intended to represent one module that could be replicated and joined together to service a full width lane, when supported with a full-scale sealant melting and distribution system. The following figure provides a high-level block diagram describing the interaction between all major components in the system. The configuration of this prototype system was designed to meet the primary goals of detecting and filling a 1/16" wide crack at a speed of 5 mph.

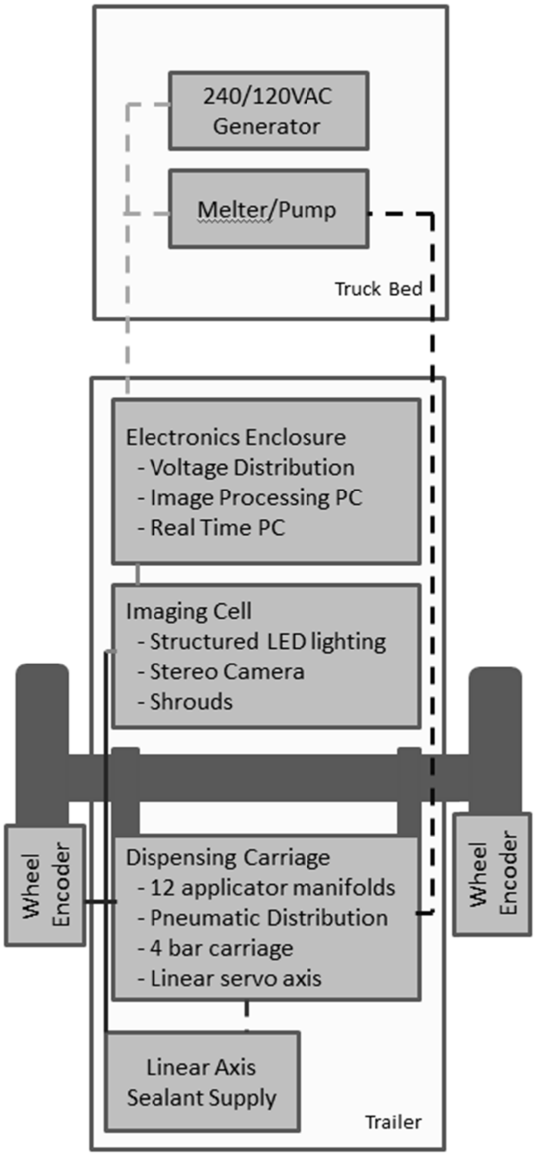


Figure 15: Block Diagram of GTRI Crack Sealing System

4.2 Crack Sealing Hardware

The crack sealing system consisted of a number of components described in the previous section. The demonstration prototype used consisted of a tow vehicle pulling a custom trailer constructed from a T-slot aluminum framing system. The pickup bed had a large generator and a melter/pumping system installed, and a custom trailer housed all other components of the system. The entire system is shown in Figure 16 below. Each of the major subsystems is described in detail in the following sections.

Figure 16: Picture of Prototype Crack Sealing Hardware with Detail of Applicators

4.2.1 Melter/Pumping Units

The integral melter/pumping units were standard items available from hot-melt adhesive dispensing suppliers. These units were sized to provide a continuous flow for the longitudinal crack filling subsystem and the intermittent flow associated with the transverse crack filling subsystem. Both melter/pumping units were outfitted with an additional mixing unit. These small melter/pumping units removed the need of having to operate a large crack sealant kettle in the demonstration unit; however, a much larger sealant unit would be needed to operate a system for the entire lane width.

4.2.2 Electronics

Besides housing general wiring, safety circuits, and voltage distribution, the main electronics cabinet was home to the core image processing computer as well as the real-time operating system. Real-time processing is handled via QNX and controls all real-time functions such as the firing of individual nozzles and navigation and operation of the control signal to the linear servo axis. These functions are guided by crack detection algorithms running on a separate computer.

4.2.3 Camera and Lighting Sub-System

This area of research required unique solutions to allow the system to perform the task of identifying cracks in 100ms. The design of the imaging cell is driven by the need to create two identical images that differ in the direction of lighting required to illuminate both transverse and longitudinal cracks. Two colors of light emitting diodes (LEDs) are projected onto the camera field of view at differing angles to better highlight the respective features of the two primary types of cracks. The two colors are filtered separately and captured by a calibrated stereo camera mounted above a 12x12" field of view. These two differing images are then used for crack detection algorithms. What is achieved by this approach is that each stereo image set already has some features identified, thus simplifying crack detection routines in order to speed up the overall process. The entire system is enclosed in a series of thick rubber sheets that shroud the imaging cell from light in the environment.

4.2.4 Odometers

For navigation of the crack sealing system, it is imperative that the position of the trailer is always accurately known. An encoder assembly was attached to each trailer wheel to monitor wheel position on each of the wheels to not only track overall distance traveled, but to also carefully track the two wheel positions relative to one another when the trailer is turning. Even slight variations in the angle of the trailer can contribute to error in timing of the transverse crack filling subsystem, which drives the need for an elaborate odometer system.

4.2.5 Dispensing Carriage

The dispensing carriage consists of two manifolds with a total of 12 individually addressable nozzles for the purpose of filling transverse cracks while in motion. This carriage also carries a single applicator mounted to a linear servo axis for the purpose of filling longitudinal cracks. Each dispenser in the transverse crack dispensing system is comprised of a pneumatic-operated valve and a spring-loaded accumulator and is housed in a heated manifold. This allows each of the nozzles to be fired individually when commanded by the Navigator as it passes over a crack. The timing of this firing is crucial, and resulted in a detailed timing study, which is discussed in the Testing section. The longitudinal crack system employs one nozzle attached to a high-torque linear servo axis that can be commanded to follow a longitudinal crack as the system is towed. Each of these dispensing elements is supplied with a continuous supply of crack sealant from their respective melter/pumping systems via heated hoses.

The dispensing equipment is mounted to a single structure on casters that is supported by a four-bar linkage tied to the axle of the trailer. This mounting approach allows for the crack filling hardware to follow the surface of the road closely without being damaged by variations on the pavement surface. There is a lift cylinder attached to the entire four-bar mechanism to allow the system to be stowed while the crack sealing system is in tow at highway speeds, but not in operation. The dispensing carriage is shown in the detailed view within Figure 16.

4.2.6 Crack Sealing Software Detail

The software for the crack detection and control system consists of two major sub systems: a vision processing sub system and a real-time control sub system. The vision processing sub-system consists of a camera and a Windows-based processing computer. The control sub system consists of a real-time QNX machine interfaced to wheel encoders and dispensing hardware. This design allows the QNX PC to control and query all of the hardware in real time in order to correlate crack detection with dispensing.

4.2.7 Image Processing and Crack Map Generation

The vision processing sub system handles all crack detection tasks. In addition to running the crack detection routines, this sub system also provides a user interface for control and monitoring of the overall system during operation. The interface allows the user to start and stop the system, as well as view the images and crack maps as they are processed and generated. Figure 17 shows the core operation of the image processing software, which takes a raw image (Image 1) and processes that image into pixels that classify whether a crack is present or not at any given location in the image (Image 4).

The software contains a class for the user interface, acquiring images from the camera, identifying crack segments in images, performing coordinate transformations, and sending the map to the real-time control system. During operation, the image processing software will wait for the stereo image set to arrive from the camera. The image set is reduced to the overlap region, which is limited to the area of the images visible to both sensors.

The crack detection algorithm is contained in the image processor class. This class processes the raw cropped image set independently in the process illustrated in Figure 17. The raw images (1) are flat-fielded to normalize light distribution across the images (2). A threshold is applied to the flat-fielded image to find candidate crack segments (3). Finally, a series of filters is run on the candidate crack segments and a final resulting crack map is generated (4). Once the crack maps are generated for all images, they are sent to the coordinate transformation class.

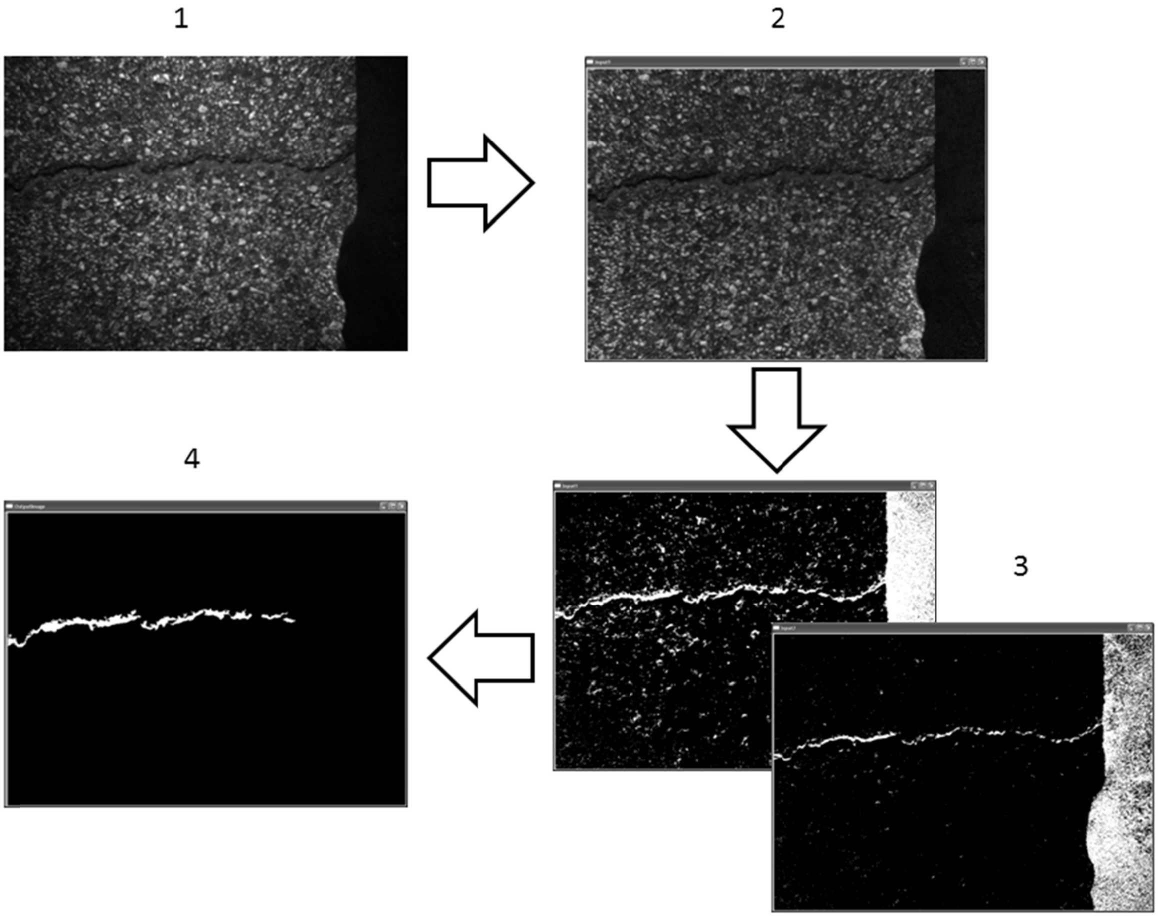


Figure 17: Image Processing Steps

Once in the coordinate transformation class, a mapping is made for both images from image space to a world coordinate frame representing the location on the road surface. The full resolution images are transformed into a single 192x96 pixel image that is associated with the bank of sealant applicator nozzles physically located behind the imaging area. The final step for the image processing component is to send the crack map to the QNX control PC. The crack map is sent via UDP protocol via a physical Ethernet connection between the image processing PC and the control PC.

4.2.8 Real-Time Control

The controls sub system operates on a real-time QNX operating system. This allows processes such as actuating the applicator nozzles, commanding the linear servo mechanism, or sending a hardware trigger signal to the camera to occur in a timely fashion. To put the operation into perspective, at 5 mph the applicators are moving at 88 inches a second meaning a 2 millisecond delay corresponds to .176".

The control PC has physical connections to the camera for image capture, two encoders for position information, and the sealant applicators for actuation. The two encoders (one on each side of the system) allow for tracking of the travel direction and distance with respect to the captured and processed images. The system acquires an image approximately every 11 inches of travel, allowing for a small overlap between subsequent captured images. When a map is received, the control system will then add this map to the current map queue being processed. This map queue represents all the identified cracks on the road surface between the current camera field of view and the actual applicator nozzles.

During the time the system is waiting to receive the new map, it is also concurrently updating the applicator location relative to the current crack maps already in memory using the values reported from the left and right encoders. The system calculates the location of the identified cracks on the road surface relative to the applicator nozzle array. When the applicator approaches a crack on the road surface, the control PC actuates the nozzle, propelling sealant into the crack.

4.3 Application of the Proposed Method

The crack sealing project began in 2003, but has gone through several design iterations and developments during that time. The full system previously described has been in development since 2009. During the latter portion of 2009, changes in the management of the project resulted in a major re-planning effort for the remainder of the design. During this phase of the project, the contract was modified to support a new schedule of work.

This final phase of the program was chosen to be used as an initial test bed to exercise the method, which was proposed in Chapter 2.0. Additionally, many of the tools introduced in Chapter 3.0 have been used during the application of the proposed method on the crack sealing system.

4.3.1 Step 1 – Is the Method Appropriate for this Work?

The first step is to make sure that the proposed method is compatible with the work that we wish to perform. This can be done by considering the assumptions stated for the method in Table 5. Because not all of the items in that table are particularly concerning, only a subset of the assumptions was selected for discussion.

Assumption 2 – Need to define experience levels to give a correct labor estimate;

Assumption 3 – Assume no conflicts between skills and time constraints

Assumption 2 as well as Assumption 3 were of interest for this particular estimate because they are both associated with the use of the work planning tools discussed in Section 2.7. This means that a database needs to be in place in order to apply the work planning tools such that employee skill sets are captured and known for the use of automated planning tools. For the GDOT example, only a limited number of employees were needed to complete the work. Because of this, an employee skill set database was created to demonstrate this capability.

Assumption 7 – All major requirements are defined at the outset

This is an important assumption and may not be as straight forward for other prototype developments. Because the GDOT crack sealing work had been developed for some amount of time, the key requirements had been established previously. The key requirements used are mentioned in Section 4.1. This is important to mention as some level of requirements must be stated by the stake holders prior to determining if pursuing estimation through the proposed method is feasible or appropriate.

Assumption 10 – Intellectual property (IP) issues ignored

This development did contain various components with the potential for intellectual property. At GTRI, however, the costs associated with maintaining IP is often the burden of the organization as opposed to individual projects. If that burden was not held at the corporate level (perhaps for a small business), the concern of where to place these costs would be greater.

Assumption 11 – It is feasible to evaluate the performance; Assumption 12 – Function and working structures can be completed

This is an important assumption to make because it is not always clear the work can be performed. Take for instance cutting-edge research related to developing a new technology. These types of problem may mean either Assumption 11 or 12 may be difficult or impossible. This was not a concern for the GDOT example, but is crucial to determining whether this method is appropriate for other estimates.

Assumption 13 – Designer control over all tasks

Because the project director and the estimator were the same individual for the GDOT example, designer control over tasks was not an issue. If the designer does not have the liberty to go through a proper conceptual design activity, then it must be clear that the method may not be applicable.

There were no major issues with the requirements stated in Table 5 for the GDOT crack sealing work to be performed. Additionally, it was decided the appropriate infrastructure was in place meaning Step 1 of the proposed method had been satisfied. This was decided because GTRI has appropriate tools available to track cost and expenditures related to project work as well as a suitable chain of management to complete research projects.

4.3.2 Step 2 – Generate Numerical Normalization Parameters

It is important to recognize the importance of each estimation parameter (cost, performance, and schedule) at the beginning of the estimation process. The proposed estimation method does this by defining a set of normalization parameters in order to compare the importance of these three parameters.

Setting the initial parameters was rather straight forward due to the way the crack sealing contract was handled with the Georgia Department of Transportation. Because this was a continuation of work (under an existing contract), the end date as well and the cost was defined. This left the importance of the performance slightly less important than the other parameters. The values for the parameters for the crack sealing work chosen were:

$$C_{pref} = .35,\ S_{pref} = .35,\ P_{pref} = .3 \qquad (7)$$

In addition to these three parameters, the goals for the estimation process are required in order to start the estimation process. Because the limits of the cost and schedule were defined contractually, the only definition remaining for the project was the performance, which is captured in requirements (See Table 39). Notice the important distinction to be made between requirements in that they are separated based on whether they are demands or wishes. It is important to make this distinction because demands are compulsory whereas wishes are potential areas that may or may not be completed as cost and schedule change.

Table 39: Detailed Requirements to Estimate Activities on Crack Sealing Program

<table>
<tr><th colspan="2">Requirements List for GDOT Crack Sealing Prototype System</th></tr>
<tr><td colspan="2">Problem Statement: To determine a quantitative set of goals to complete the final phase of a 12” wide crack sealing prototype system.</td></tr>
<tr><th>D/W</th><th>Requirement</th></tr>
<tr><td></td><td>Dynamic Performance and Mechanical Packaging</td></tr>
<tr><td>W</td><td>1. System must work with the dispensing of hot melt adhesive.</td></tr>
<tr><td>D</td><td>2. System must work with the dispensing of bituminous asphalt crack filler.</td></tr>
<tr><td>D</td><td>3. Linear servo system to work with a minimum resolution of 12” / 256 counts.</td></tr>
<tr><td>D</td><td>4. Linear servo system to work over a range of -1 to +13 inches (one inch over on each side).</td></tr>
<tr><td>D</td><td>5. Linear servo system to have a minimum acceleration of 20 in/s2 for the accurate tracking of cracks.</td></tr>
<tr><td>D</td><td>6. Nozzle array capable of dispensing 15-25g of material. Adjustment can be manual.</td></tr>
<tr><td>D</td><td>7. Pressure in large pumping system shall be a minimum of 900 psi.</td></tr>
<tr><td>D</td><td>8. Provisions required for sealant to be heated from melter to dispenser to a minimum of 350 degrees F with temperature control.</td></tr>
<tr><td></td><td>Electrical Performance</td></tr>
<tr><td>D</td><td>9. System must be capable of supplying a minimum of 14 + 4 kW of power. 14kW for large melter and heaters and 4kW for controls and small melter.</td></tr>
<tr><td>D</td><td>10. Real time system response time to be less than 1 msec.</td></tr>
<tr><td></td><td>Software Performance</td></tr>
<tr><td>D</td><td>11. Crack detection algorithms to be able to identify 90% of cracks with no more than 5% false positive responses.</td></tr>
<tr><td>W</td><td>12. Graphical user interface to be generated for the scoring of crack images. Must include ability for multiple users to grade images for statistical grading purposes of raw and processed images.</td></tr>
<tr><td></td><td>Environmental Requirements</td></tr>
<tr><td>D</td><td>13. Capable of operating in temperature ranges of 32 degrees F to 90 degrees F.</td></tr>
<tr><td>W</td><td>14. Capable of operating in temperature ranges of 20 degrees F to 100 degrees F.</td></tr>
<tr><td></td><td>Safety</td></tr>
<tr><td>D</td><td>15. Measures must be taken to protect personnel operating the prototype system.</td></tr>
<tr><td>D</td><td>16. Protective attire must be easily accessible to workers on the system in laboratory as well as field exercises.</td></tr>
<tr><td>D</td><td>17. Personnel must be guarded from high powered dispensing of hot sealant.</td></tr>
<tr><td></td><td>Maintenance</td></tr>
<tr><td>W</td><td>18. Fluid connections must be easily removed and installed for field trials.</td></tr>
<tr><td>W</td><td>19. Wiring must include ability to use shore power for powering unit from cold starts without having to use a generator.</td></tr>
<tr><td></td><td>Cost</td></tr>
<tr><td>D</td><td>20. Cost of activities must be within the fixed remaining budget of $200,000.</td></tr>
<tr><td></td><td>Schedule</td></tr>
<tr><td>D</td><td>21. Work must be completed by December 24, 2010.</td></tr>
</table>

There is yet another important component related to defining goals – setting objectives for the estimation itself. The first parameter to be discussed is cost, which has an interesting association with cost of the project. No additional funds were to be allocated for supporting an internal replanning effort so the cost of the estimate would be taken from the remainder of the budget contained within the contract. Because of this, a goal of $4,000 was provided giving the estimator approximately one full week to complete the estimate. Schedule, similar to cost, meant that any time spent on estimation would come from the remaining time available for the project. A total of 2 weeks was set aside to replan the effort based on this piece of information. Because cost and schedule were set with a slightly higher importance placed upon those parameters in comparison with performance, only the demands were considered essential for the estimate to address. Wishes could be added to the estimation process if additional funds or time were to be seen as available during the estimation process. The result of Step 2 planning efforts is contained in Table 40.

Table 40: Results of Step 2 of Estimation Method for GDOT Example

Normalization Parameters			
Cost	.35	Performance	.3
Schedule	.35		
Project Limits		**Estimate Limits**	
Cost	$87,000 Max	Cost	<$4,000
Schedule	Completion by 12/24/2011	Schedule	Complete within 2 weeks after start
Performance	See Table 39	Performance	Cost Uncertainty < 10% Schedule Uncertainty < 15% All Demand requirements met

4.3.3 Step 3 – Explore the Design Space

This particular step of the proposed method pertains to generating the function structures or working principles of a system. Much of this system had already been designed from the technical perspective with the remainder of the work focusing on integration of various components. There were some pieces of the development that required some attention to detail though such as:

- Longitudinal crack dispensing design and fabrication
- Design of an asphalt mixing unit

These particular items required some amount of conceptual design in order to better understand what tasks would be involved to complete them. For example, if considerable electric power was required to power the asphalt mixing unit, then the cost of adding another large generator may not be feasible within budget allocations. A level of conceptual design is demonstrated for these two subsystems in the following sections.

4.3.3.1 Longitudinal Crack Dispensing Design and Fabrication

To clarify, a longitudinal crack is defined as a crack that is parallel to the travel of traffic on the road. The primary function of the system using actuated nozzles only applies crack sealant on transverse cracks. A longitudinal crack filling system was needed to demonstrate the ability to fill all types of cracks on road surfaces.

Some work had previously been done on the program to estimate the size of a servo system required to power a longitudinal crack sealing device. The primary functions required for that system are shown in the following figure.

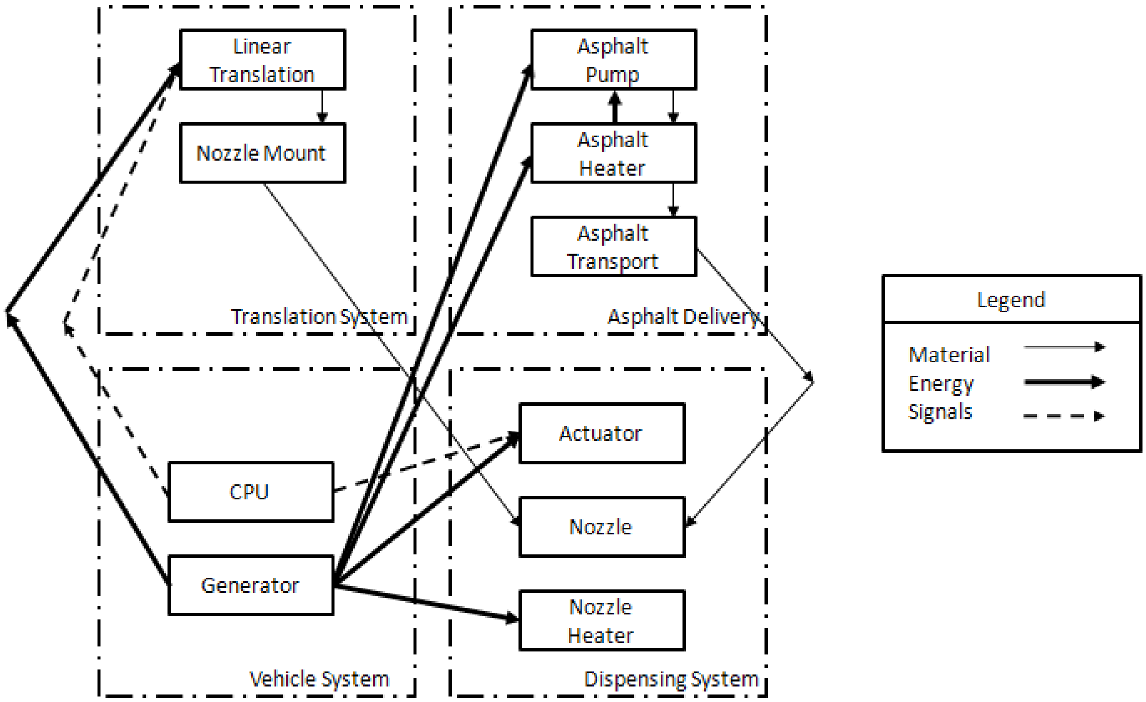


Figure 18: Function Structures Diagram for Linear Asphalt Dispenser

Due to the maturity of the crack sealing system, much of the design flexibility had been removed from the system depicted in Figure 18. The vehicle system already contained provisions for a CPU as well as power generation. Furthermore, the asphalt delivery and dispensing systems were chosen to reuse existing systems being an existing melter/pumping unit as well as an asphalt actuator used in prior research and development activities. The only component requiring design decisions was the translation system.

In order to achieve translation, there are three aspects that need to be considered. The first consideration is a position command that will tell the actuator where to be. The signal was chosen to be generated from the existing computing system meaning the control signal was achieved by generating a digital signal. This could be achieved with a basic input/output device attached to the CPU. Primary energy would come from the generator. Electricity can be used to power many different types of motions based on how it is converted. For example, a pump can be driven for hydraulic/pneumatic energy, or a chain drive may also generate movement. The last component is the physical embodiment of the motion. This portion of the design can become broad because there are so many ways to achieve linear motion. Additionally, a radial arm could be used using trigonometric properties to provide a similarly effective motion. The following table contains the various working principles that can be associated with the aforementioned considerations.

Table 41: Working Principles for Linear Dispensing System

Position Command		**Locomotion**		**Kinematics**	
Approach	Comments	Approach	Comments	Approach	Comments
Analog	Most servo controllers accept analog control signals	Electric Motor	Easy to implement servo control	Belt Drive	Smooth motion with little inertia
Digital	CPU natively supported digital outputs	Pneumatic or Hydraulics	Difficult to implement servo	Chain Drive	High inertia and prone to backlash
				Rack and Pinion	Heavy and difficult to implement
				Radial Arm	Requires trigonometric transfer function as well as a gear box

Based on this assessment, the decision was made to use an electrical motor in conjunction with a belt drive to achieve the linear motion. Additionally, a digital control signal was suggested for the control of a servo motor as this would be easier to implement. These decisions were made on engineering judgment considering things such as the ability to buy off the shelf components such as a purchased linear belt drive and servo/amplifier combination unit. It is important to note, however, that going through this exercise did highlight some unique possibilities such as a radial arm to provide the linear motion. The added complexity of transfer functions and the burden this would place on programming tasks removed this option from consideration.

4.3.3.2 Design of an Asphalt Mixing Unit

Referring to Figure 15, it can be seen that a large melter/pumping unit was required to supply asphalt to the primary actuators. The unit that was already part of the system did not have a large enough reservoir to support extended tests on the road. It was decided that a larger reservoir would be added to the existing melter making it a major design task associated with the crack sealing work.

The function structures for this particular design activity are simpler than that depicted in Figure 18 due to the smaller number of functions. The only function associated with this system is really to mix asphalt and provide an insulated container adapted to the existing melter/pumping unit. The same limits applied for this system such that electrical energy from the generators was the primary source of energy available to operate a mixing mechanism. The general layout of the device can be seen in Figure 19. The real design task became determining the working principles to achieve the motion of mixing of which several designs were considered as depicted in Figure 20.

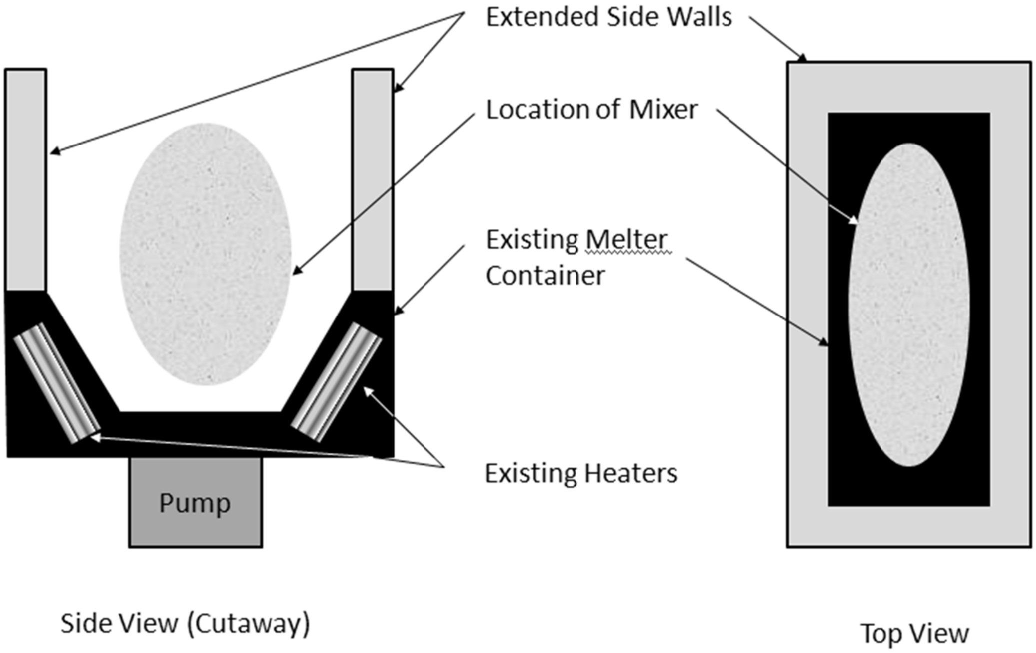


Figure 19: Side and Top Views of Pump/Melter System

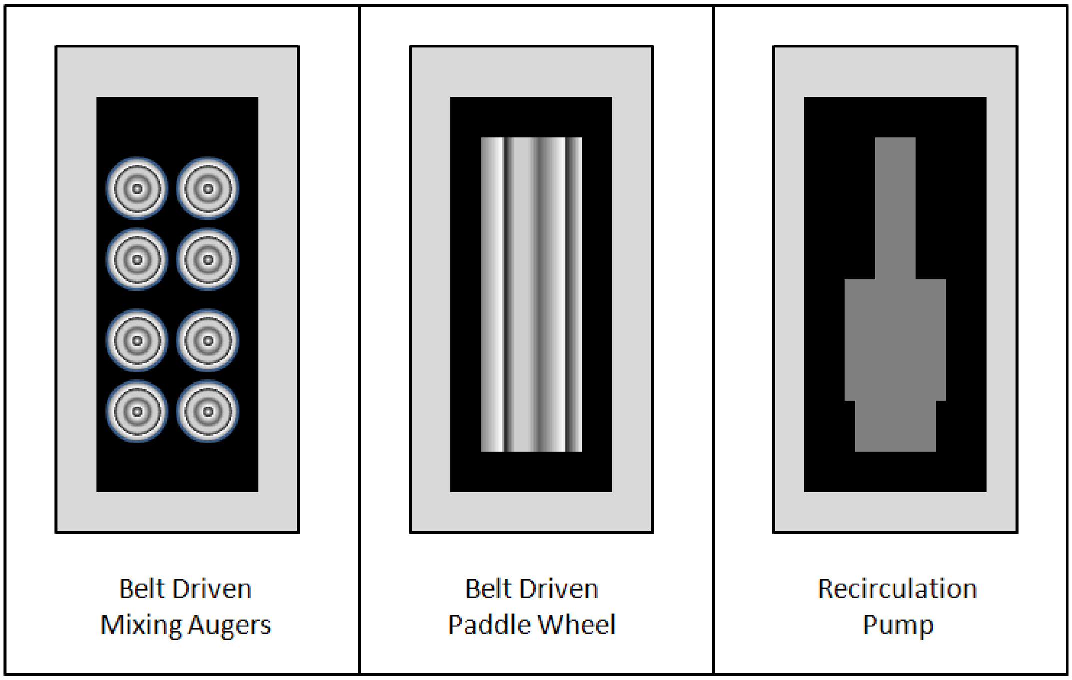


Figure 20: Design Options Considered for Asphalt Mixer (Top Views Shown)

The three options depicted in Figure 20 could vary significantly in implementation. One thing to consider is that each of the mixing options must be capable of surviving in a vat of 400° F crack sealant material and also that the mixing device would not be able to start operating until the sealant had melted after being heated. In the case of the recirculation pump design, the pump would have to be submerged in the container and operate at these high temperatures. In all cases, it was decided that an AC motor be used to drive each system whether a belt drive or shaft drive to a pump.

The belt driven designs had several unknowns associated with them, primarily associated with the mechanical design or embodiment of the drive mechanisms or shape of the mixing element. With the recirculating pump, the design would be as simple as making mounting provisions with the challenge in finding a pump that was suitable for operation in that vat of high temperature sealant. It was this reasoning that led engineers to select the pump option because of the unforeseen challenges associated with the embodiment of the other designs.

The previous two design abstraction examples were provided to show the value of going through design exercises for the purpose of cost estimation. In making these high-level design decisions early in the cost estimation phase of the development, the estimate becomes more realistic and lower risk when such decisions can be made.

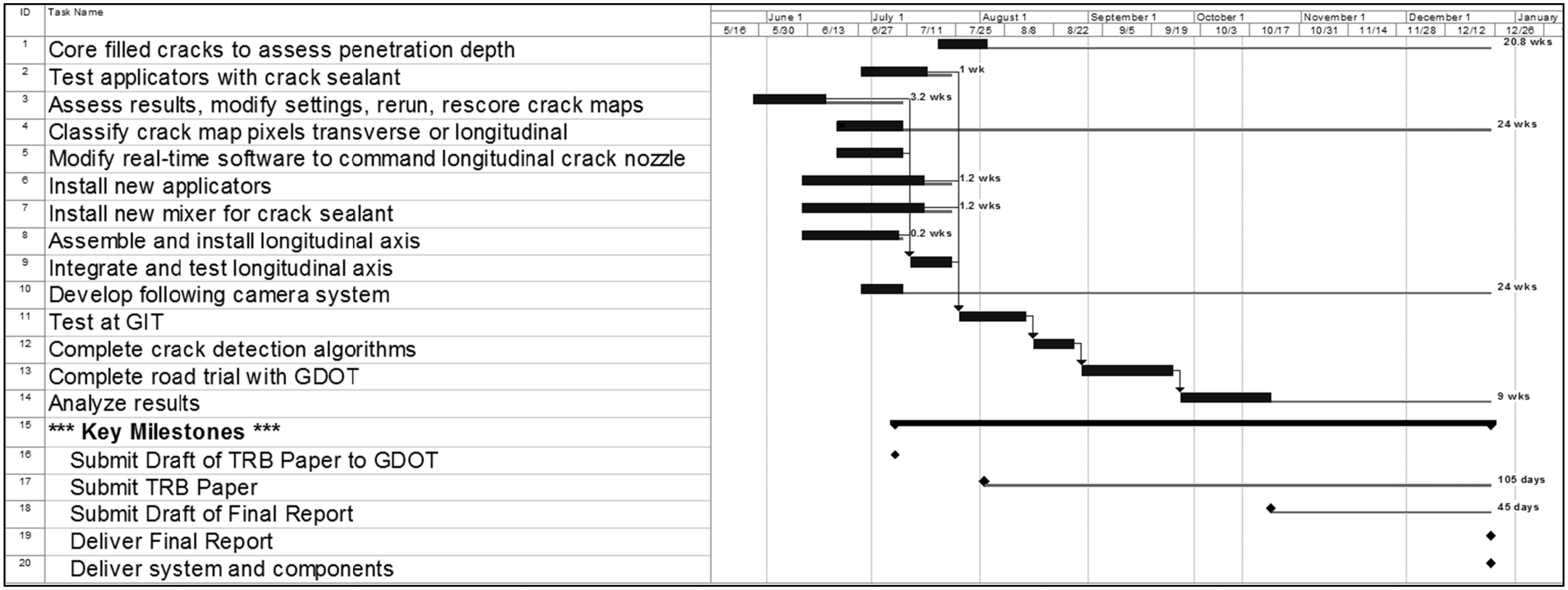
4.3.4 Step 4 – Generate a Gantt Chart

As mentioned previously, a Gantt chart is a task driven schedule that captures the interactions between multiple individual tasks. This planning tool is commonly used for estimation activities and provides the basis for the next step of estimation, which pertains to the assignment of staff and capturing of uncertainty. An abbreviated schedule was delivered to the department of transportation and is provided in Figure 21. This schedule covers a longer timeline because the replanning effort used to support this particular example within this thesis started in August of 2010. Tasks associated with that replanning effort are provided in Figure 22.

The items in Figure 22 cover materials related to finishing integration tasks associated with installing a new applicator manifold containing 12 nozzles and all of the supporting tasks required to complete this major effort as well as test the system. The installation of the new applicator manifold was needed to cover a width of one foot of roadway for transverse cracks. The other major tasks were to install a linear servo guided system that would be able to fill longitudinal cracks. This portion of the system would allow a continuous nozzle to follow cracks running parallel to the direction of travel of vehicles. The linear axis design was discussed in Section 4.3.3.1. These cracks are often generated from heavy loads such as tractor trailers and are predominantly on the right of a lane due to the crown present in asphalt roadways. Although these were the primary hardware tasks addressed in the re-plan effort, the inclusion of these two items involved several other pieces of equipment to be installed such as a large melter/pump system, which was discussed in Section 4.3.3.2. And with any industrial system involving human operators, care was taken to include several safety features to protect workers from the system. The main safety hazard is the crack sealant itself. Because the crack sealant must be heated to 400 degrees F and pumped at 1000 psi, safety for the crack sealing system was paramount.

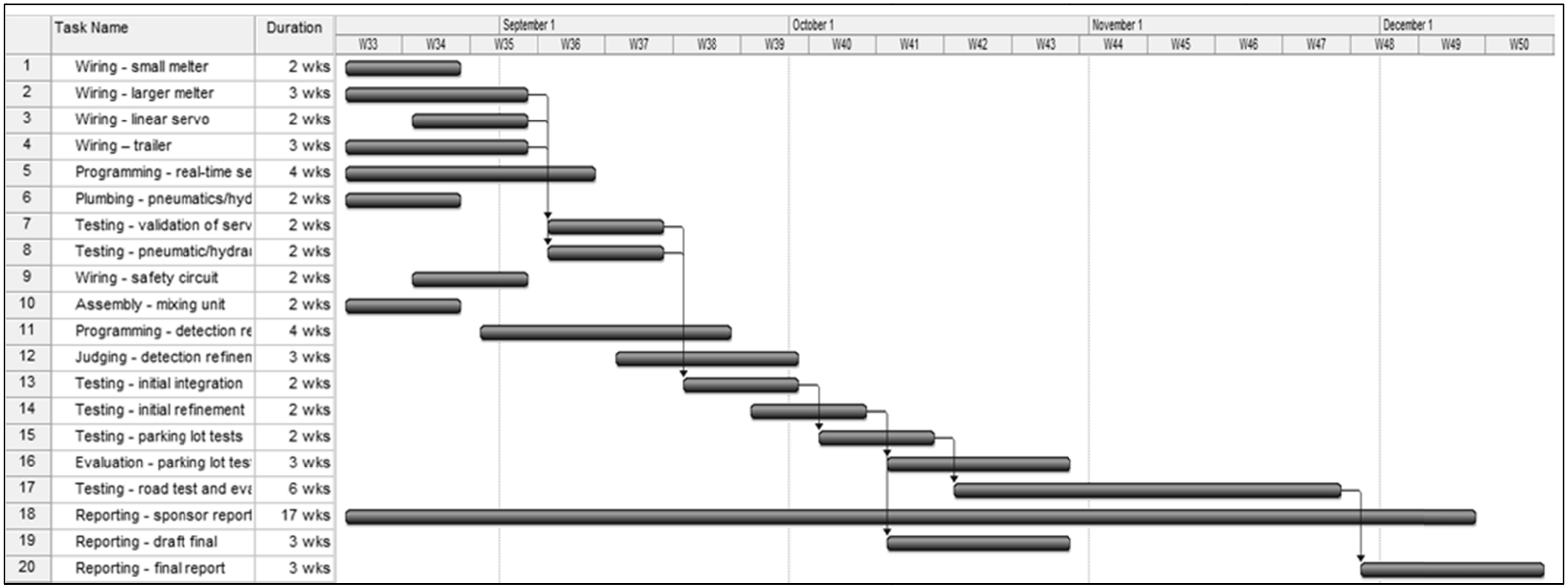
In regards to software, the system required two major developments. The first development was related to the longitudinal crack filling axis. No software had previously been created to differentiate longitudinal cracks from transverse cracks meaning that was an entirely new development. This meant that estimations related to that task included a large amount of uncertainty because it had not been done before. The other task was related to fine tuning the overall effectiveness of the crack detection system. The efficiency of the crack detection algorithm is directly tied to performance of the system and also plays an important role in the economic feasibility of the system. For instance, if the system identified cracks 70 percent of the time, it may mean that operators are still required to follow the system in order to cover the surface of the road entirely. If the effectiveness of crack detection were 97 percent, a following operator may not be required. This led to the additional task of scoring crack detection algorithms to provide an objective measure of detection effectiveness in order to properly state economic viability of the system.

All of this schedule information becomes important as the cost associated with various efforts relates to the ability to meet the stated goals or requirements, which is discussed as the performance parameter. By assigning uncertainty to these tasks the ability to meet requirements as it pertains to both cost and schedule is captured. The next section covers this interaction further tying together the steps of the proposed estimation method.



ID	Task Name
1	Core filled cracks to assess penetration depth
2	Test applicators with crack sealant
3	Assess results, modify settings, rerun, rescore crack maps
4	Classify crack map pixels transverse or longitudinal
5	Modify real-time software to command longitudinal crack nozzle
6	Install new applicators
7	Install new mixer for crack sealant
8	Assemble and install longitudinal axis
9	Integrate and test longitudinal axis
10	Develop following camera system
11	Test at GIT
12	Complete crack detection algorithms
13	Complete road trial with GDOT
14	Analyze results
15	***** Key Milestones *****
16	Submit Draft of TRB Paper to GDOT
17	Submit TRB Paper
18	Submit Draft of Final Report
19	Deliver Final Report
20	Deliver system and components

Figure 21: Plan Submitted to GDOT in June of 2010



	Task Name	Duration
1	Wiring - small melter	2 wks
2	Wiring - larger melter	3 wks
3	Wiring - linear servo	2 wks
4	Wiring – trailer	3 wks
5	Programming - real-time se	4 wks
6	Plumbing - pneumatics/hyd	2 wks
7	Testing - validation of serv	2 wks
8	Testing - pneumatic/hydrau	2 wks
9	Wiring - safety circuit	2 wks
10	Assembly - mixing unit	2 wks
11	Programming - detection re	4 wks
12	Judging - detection refinen	3 wks
13	Testing - initial integration	2 wks
14	Testing - initial refinement	2 wks
15	Testing - parking lot tests	2 wks
16	Evaluation - parking lot tes	3 wks
17	Testing - road test and eva	6 wks
18	Reporting - sponsor report	17 wks
19	Reporting - draft final	3 wks
20	Reporting - final report	3 wks

Figure 22: GDOT Plan Used for Estimation Method

4.3.5 Step 5 – Populate Estimation Tools

The estimation tools used in this method have been implemented in Microsoft Excel to serve as a generic planning tool. Although a generic planning tool exists for project planning as described in this thesis, key elements must also exist in order to properly complete the prescribed planning approach. The items that are project specific include a database of employee skill sets, a detailed task list with skills required of the project, a detailed schedule, and financial values for all staff involved in task completion. This section describes how these parameters have been captured and utilized to combine the data from previous steps in the proposed estimation method to create a viable estimate.

4.3.5.1 Skill Database

Creating a database for employee skills can become a rather daunting task in and of itself. In order to create a proper database, at a minimum the employees planned for the project need to have their skill sets captured for the various skills needed for the project. To properly populate a skill database; however, it must be understood that it become an active database frequently evolving to capture more skill effectively among a set of employees. This database should naturally grow as more efforts are estimated by using the prescribed method. This section covers the application of the skill database material discussed in Section 2.7.1.

For the GDOT example, a limited skill database was created with the intent of capturing necessary skills needed to perform the work required to finish the crack sealing work defined in a Gantt chart (See Figure 22). To do this, each task was considered carefully and the skills needed to address these tasks were estimated as listed in the following table. Table 42 contains two pertinent pieces of data: 1) The skill required for the project, and 2) the level of skill required. This is an important distinction to make as it is clear that an expert in a given field is not required to do every task on a particular project. It is only necessary for the performer to have a suitable level of experience for that given task. Considering this, each expected task for the project was assigned a skill level required. Thinking further down the road, the tasks were grouped into categories in order to make increasing the depth of the database easier in the future.

Table 42: Skills Required to Complete GDOT Crack Sealing Activity

#	Skill	Level	#	Skill	Level
	SYSTEMS ENGINEERING	**3.00**		**PROJECT MANAGEMENT**	**2.00**
1	OVERALL INTEGRATION	3	27	SCHEDULES	2
2	TESTING	3	28	PLANNING	2
	SOFTWARE DESIGN	**2.67**	29	REPORTING	2
3	OPEN CV ARCHITECTURE	3	30	TESTING	2
4	GENERAL CODE MAINTENANCE	2		**AUTOMATION**	**1.83**
5	C++	3	31	MOTORS	2
	MACHINE VISION	**2.50**	32	SENSORS	2
6	STEREO VISION PROCESSING	3	33	ENCODERS	2
7	CALIBRATION AND REGISTRATION	3	34	SIMULATIONS	1
8	MATLAB IMAGE PROCESSING	3	35	AUTOMATION SOFTWARE	2
9	CAMERAS	1	36	CONTROLS	2
	LED LIGHTING	**2.25**		**MEASUREMENT**	**2.00**
10	PULSE WIDTH MODULATION	2	37	COORD MEAS MACHINE	2
11	HEAT SINKING	2	38	STANDARD GAUGES/METROLOGY	2
12	LIGHT EMISSION CHARACTERISTICS	3		**TRANSPORTATION**	**2.00**
13	COLOR FILTERS	2	39	ASPHALT SURFACES	3
	POWER DISTRIBUTION	**2.20**	40	CONCRETE SURFACES	1
14	POWER COMPONENT SELECTION	3	41	ROAD MAINTENANCE	2
15	SCHEMATIC GENERATION	2		**GENERAL MECHANICAL PACKAGING**	**2.00**
16	GENERAL WIRING SKILLS	2	42	PNEUMATICS	2
17	LOW LEVEL ELECTRONIC CONTROLS	2	43	HYDRAULICS	2
18	SAFETY CIRCUIT DESIGN	2	44	NUTS AND BOLTS	2
	REAL TIME PROCESSING	**3.00**	45	CNC MACHINED ELEMENTS	2
19	GENERAL REAL TIME PROGRAMMING	3	46	TOLERANCE ANALYSIS	2
20	QNX	3	47	MECHANISMS	2
	MATERIALS	**2.00**	48	THERMAL ANALYSIS	2
21	ALUMINUM	2	49	STRUCTURAL ANALYSIS	2
22	CARBON STEEL	2	50	ASSEMBLY	2
23	STAINLESS STEEL	2			
24	POLYMERS	2			
25	BI-TUMINOUS ASPHALT	2			
26	HOT-MELT ADHESIVE	2			

The next step was to find the staff required to complete the work. As expected, the staff required would each need a broad set of skills in order for the team to be able to accomplish the planned tasks. The team would also need varying levels of expertise in order to meet the goals. The group of individuals was ranked on a level from 1 to 3 just as the project requirements were ranked so the two sets of data could be compared for the assignment of staff. Table 43 and Table 44 contain the data from this exercise with Table 43 containing tasks 1-26 and Table 44 containing the remainder of tasks. One thing possible after having both the skill database and the project database is performing a simple check to see if the skill sets required for the work are available. The results of that comparison show that a total of five of the skills required were not met: 1) calibration and registration, 2) light emission characteristics, 3) power component selection, 4) general real time programming, and 5) QNX skills. The first three skills missing are not an issue as the mismatch among the skill level was minor and the need for the project was not significant. The lack of real time operating system programming skills, particularly the QNX system, was an issue though. Not having staff able to do this coding would add risk to the program through either training staff to perform activities associated with QNX or to find another employee that could. For the GDOT activities, it was determined that it would be better to find a competent software engineer to learn a new real time operating system language as finding new staff would not be feasible during the time period the skill was needed.

Several potential benefits are seen through this approach to the assignment of staff to a program. The first benefit was identified previously as providing a clear tool that the estimator can determine if the right staff is in place to perform the work. Many of the benefits go beyond individual projects. Having a more complete database makes it clear not only how staff within an organization can be utilized more efficiently, but also to highlight trends in projects or when and where more skills are needed through either hiring or training. Good estimators and/or project engineers often go through these activities in planning to some degree albeit not formally. In doing these planning activities systematically, the estimator is able to do this repeatedly. Additionally, those new to estimation are able to see what interactions need to be considered by following a more systematic approach.

Table 43: Skill Database of Employees Available to Perform GDOT Work (Set 1)

#	Skill	T1	E1	E2	E3	E4	E5	E6
	SYSTEMS ENGINEERING							
1	OVERALL INTEGRATION	1	1	2	1	3	0	2
2	TESTING	1	2	2	2	3	0	2
	SOFTWARE DESIGN							
3	OPEN CV ARCHITECTURE	0	3	1	0	0	2	2
4	GENERAL CODE MAINTENANCE	0	2	1	0	2	3	1
5	C++	0	3	0	0	0	2	1
	MACHINE VISION							
6	STEREO VISION PROCESSING	0	2	0	0	0	1	3
7	CALIBRATION AND REGISTRATION	0	2	1	1	2	1	2
8	MATLAB IMAGE PROCESSING	0	2	0	0	0	1	3
9	CAMERAS	0	2	1	1	1	1	2
	LED LIGHTING							
10	PULSE WIDTH MODULATION	0	1	2	0	1	2	1
11	HEAT SINKING	0	0	3	1	2	0	0
12	LIGHT EMISSION CHARACTERISTICS	0	0	2	0	1	1	2
13	COLOR FILTERS	0	2	2	0	2	1	2
	POWER DISTRIBUTION							
14	POWER COMPONENT SELECTION	2	1	2	1	2	1	1
15	SCHEMATIC GENERATION	2	0	1	0	2	2	0
16	GENERAL WIRING SKILLS	3	1	2	0	2	1	0
17	LOW LEVEL ELECTRONIC CONTROLS	1	0	2	2	2	1	1
18	SAFETY CIRCUIT DESIGN	1	0	2	2	2	0	0
	REAL TIME PROCESSING							
19	GENERAL REAL TIME PROGRAMMING	0	0	0	0	0	1	0
20	QNX	0	0	0	0	0	1	0
	MATERIALS							
21	ALUMINUM	0	0	3	2	2	0	1
22	CARBON STEEL	0	0	2	2	2	0	1
23	STAINLESS STEEL	0	0	3	2	3	0	1
24	POLYMERS	0	0	2	2	2	0	1
25	BI-TUMINOUS ASPHALT	0	1	2	0	3	0	2
26	HOT-MELT ADHESIVE	0	0	2	0	3	0	1

Table 44: Skill Database of Employees Available to Perform GDOT Work (Set 2)

#	Skill	T1	E1	E2	E3	E4	E5	E6
	PROJECT MANAGEMENT							
27	SCHEDULES	0	1	2	1	2	1	1
28	PLANNING	0	1	2	1	2	1	1
29	REPORTING	0	1	2	1	2	1	2
30	TESTING	1	1	2	2	2	1	2
	AUTOMATION							
31	MOTORS	0	0	3	3	3	0	1
32	SENSORS	0	2	2	2	2	2	2
33	ENCODERS	0	0	2	2	3	0	1
34	SIMULATIONS	0	0	1	0	1	0	0
35	AUTOMATION SOFTWARE	0	1	2	2	2	1	0
36	CONTROLS	0	1	2	2	2	1	0
	MEASUREMENT							
37	COORD MEAS MACHINE	0	0	2	0	2	0	0
38	STANDARD GAUGES/METROLOGY	0	0	2	0	2	0	0
	TRANSPORTATION							
39	ASPHALT SURFACES	0	1	2	0	3	0	2
40	CONCRETE SURFACES	0	0	1	0	2	0	1
41	ROAD MAINTENANCE	0	0	2	0	2	0	2
	GENERAL MECHANICAL PACKAGING							
42	PNEUMATICS	0	0	2	1	2	0	0
43	HYDRAULICS	0	0	2	1	2	0	0
44	NUTS AND BOLTS	0	0	3	3	3	0	1
45	CNC MACHINED ELEMENTS	0	0	3	2	3	0	0
46	TOLERANCE ANALYSIS	0	0	3	1	2	0	0
47	MECHANISMS	0	0	2	2	2	0	1
48	THERMAL ANALYSIS	0	0	3	1	1	0	2
49	STRUCTURAL ANALYSIS	0	0	2	1	2	0	0
50	ASSEMBLY	2	0	2	2	2	0	0

4.3.5.2 Defining Task Estimates

Once the skills and staff have been defined for a project, it is necessary to understand how those skills are applied to individual tasks. The proposed cost estimation method is implemented in Microsoft Excel making much of this manual, but providing flexibility for the research contained in this thesis. Also, it is important to note how the assignment of hours to tasks relates to the tables shared in the previous section. The consistent aspect of this estimation is continuing to track the tasks as defined in the Gantt chart (Figure 22) while combining that information with information related to the skills required to complete the GDOT work (Table 42). The result is similar to what was provided in Section 2.7.1.1 where the assignment of work illustrated using information from the GDOT example in Table 16.

Consider another example where this breakdown is provided, similar to Table 16, but also includes uncertainty. In Table 45 the task is broken down into the skill sets required as well as the level of that particular task required. In this particular example, the uncertainty is applied simply as a percentage for the task, yet it is clear this could also be captured by each skill set to further refine the inclusion of uncertainty. Because the number of hours can later have a labor rate applied, these numbers become the cost and cost uncertainty variables (C, C_U) used in the normalization equations. For example, if the average labor rate for the tasks in Task 17 is \$100/hr, then the range of costs for this particular task will be \$4,800 to \$6,000 making that range the cost interval for Task 17. The skill number corresponds to the skill number provided initially in Table 42. Engineering judgment was used for the assignment of hours for many of these tasks, but many other estimation tools could be used. As described in Section 1.2.3, it may be more appropriate to estimate the "C++" skill required on Task 17 using a COCOMO approach because it is a software related task. Once this information is in place for each task, it is possible to now combine this information with the schedule.

Table 45: GDOT Hour Estimate for Tasks 16 and 17 (Including Uncertainty)

Task	Description	Skill #	Skill	Level	Hr,min	Hr,max
16	Evaluation - parking lot tests					
		1	OVERALL INTEGRATION	2	8	9.2
	Task Uncertainty					
	15%	2	TESTING	3	8	9.2
		29	REPORTING	2	8	9.2
		30	TESTING	2	8	9.2
					32	36.8
17	Testing - road test and evaluation					
		1	OVERALL INTEGRATION	2	6	7.5
	Task Uncertainty					
	25%	2	TESTING	2	16	20
		5	C++	2	8	10
		16	GENERAL WIRING SKILLS	2	4	5
		19	GENERAL REAL TIME PROGRAMMING	1	4	5
		41	ROAD MAINTENANCE	1	2	2.5
		50	ASSEMBLY	2	8	10
					48	60

Once the staff are assigned based upon their abilities, then it is a matter of checking availability to ensure staff members are available to complete tasks as defined by the initial schedule. In Table 46, the number of hours is spread evenly over the duration of the task in weeks. As defined by the minimum number of hours. In this way, there can be a calculation of cost per week for the minimum number or hours as well as the maximum number of hours in order to capture the lower and upper limits of the cost interval by week.

Table 46: Schedule for Example GDOT Tasks 16 and 17

Skill #	Skill	1st	2nd	(Weeks)	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
16	Evaluation - parking lot tests			3									▨	▨	▨							
1	OVERALL INTEGRATION	E2	E4		0	0	0	0	0	0	0	0	2.7	2.7	2.7	0	0	0	0	0	0	0
2	TESTING	E4	NA		0	0	0	0	0	0	0	0	2.7	2.7	2.7	0	0	0	0	0	0	0
29	REPORTING	E2	E4		0	0	0	0	0	0	0	0	2.7	2.7	2.7	0	0	0	0	0	0	0
30	TESTING	E2	E3		0	0	0	0	0	0	0	0	2.7	2.7	2.7	0	0	0	0	0	0	0
17	Testing - road test and evaluation			4										▨	▨	▨	▨					
1	OVERALL INTEGRATION	E2	E4		0	0	0	0	0	0	0	0	0	1.5	1.5	1.5	1.5	0	0	0	0	0
2	TESTING	E1	E2		0	0	0	0	0	0	0	0	0	4	4	4	4	0	0	0	0	0
5	C++	E1	E5		0	0	0	0	0	0	0	0	0	2	2	2	2	0	0	0	0	0
16	GENERAL WIRING SKILLS	T1	E2		0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
19	GENERAL REAL TIME PROGRAMMING	E5	NA		0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
41	ROAD MAINTENANCE	E2	E4		0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0	0	0	0	0
50	ASSEMBLY	T1	E2		0	0	0	0	0	0	0	0	0	2	2	2	2	0	0	0	0	0

Now, the cost can be calculated for each of the tasks and is reported in the following table. There is an interesting piece of information that shows up that is related to availability. In order to keep calculation intensity to a minimum, only the primary and secondary staff were used for calculations related to availability. This means that the lowest rate is selected first, with the secondary or next highest rate, calculated next. This results in two different costs making the total cost interval ranging from \$57,882 to \$87,694 considering availability project personnel. Because the assignment of staff will likely be a combination of the two of these staff assignments, the average value of the difference between primary and secondary is used to provide a cost interval from \$57,882 to \$79,320. It is evident that if there are issues with the assignment of staff, the cost can increase drastically as efficiencies diminish.

Table 47: Skill Database of Employees Available to Perform GDOT Work (Set 1)

	First Selection		Second Selection	
Task	Cost	Cost + Unc.	Cost	Cost + Unc.
1	$ 1,440	$ 1,584	$ 2,280	$ 2,508
2	$ 1,656	$ 1,919	$ 2,200	$ 2,552
3	$ 576	$ 662	$ 876	$ 1,007
4	$ 864	$ 994	$ 1,296	$ 1,490
5	$ 5,430	$ 6,860	$ 8,640	$ 10,941
6	$ 576	$ 641	$ 696	$ 776
7	$ 564	$ 620	$ 644	$ 708
8	$ 1,068	$ 1,207	$ 1,144	$ 1,293
9	$ 864	$ 994	$ 1,120	$ 1,288
10	$ 648	$ 738	$ 872	$ 992
11	$ 8,136	$ 9,701	$ 9,468	$ 11,271
12	$ 3,084	$ 3,659	$ 3,288	$ 3,900
13	$ 3,096	$ 4,334	$ 3,960	$ 5,544
14	$ 3,600	$ 4,361	$ 4,920	$ 5,954
15	$ 2,496	$ 2,942	$ 3,384	$ 3,983
16	$ 3,552	$ 4,440	$ 4,424	$ 5,530
17	$ 4,668	$ 5,835	$ 5,772	$ 7,215
18	$ 2,964	$ 3,705	$ 3,192	$ 3,990
19	$ 5,928	$ 7,410	$ 6,344	$ 7,930
20	$ 6,672	$ 8,340	$ 7,056	$ 8,820
Totals	**$ 57,882**	**$ 70,945**	**$ 71,576**	**$ 87,694**

The next portion to address is the schedule. Since the number of weeks was assigned for each task, an uncertainty (separate from cost uncertainty) can be applied to each task. Table 48 contains the results of the schedule planning exercise for the crack sealing example. This table includes a set amount of uncertainty with each task pertaining to schedule represented in number of weeks. Notice some difficult tasks such as “programming real-time servo” have a higher uncertainty than those that are better understood such as “wiring trailer.”

Table 48: Schedule Estimate for GDOT Example (Including Uncertainty)

		Duration	Uncertainty	
Task	**Description**	**(Wks)**	**(%)**	**(Wks)**
1	Wiring - small melter	2	10%	2.2
2	Wiring - larger melter	3	10%	3.3
3	Wiring - linear servo	2	10%	2.2
4	Wiring - trailer	3	10%	3.3
5	Programming - real-time servo	4	25%	5
6	Plumbing - pneumatics/hydraulics	2	15%	2.3
7	Testing - validation of servo	2	15%	2.3
8	Testing - pneumatic/hydraulic check	2	10%	2.2
9	Wiring - safety circuit	2	10%	2.2
10	Assembly - mixing unit	2	25%	2.5
11	Programming - detection refinement	4	20%	4.8
12	Judging - detection refinement	3	15%	3.45
13	Testing - initial integration	2	15%	2.3
14	Testing - initial refinement	2	15%	2.3
15	Testing - parking lot tests	2	20%	2.4
16	Evaluation - parking lot tests	3	20%	3.6
17	Testing - road test and evaluation	4	20%	4.8
18	Reporting - sponsor reports	6	5%	6.3
19	Reporting - draft final	3	5%	3.15
20	Reporting - final report	3	5%	3.15
	Total Weeks	**56**		**63.75**

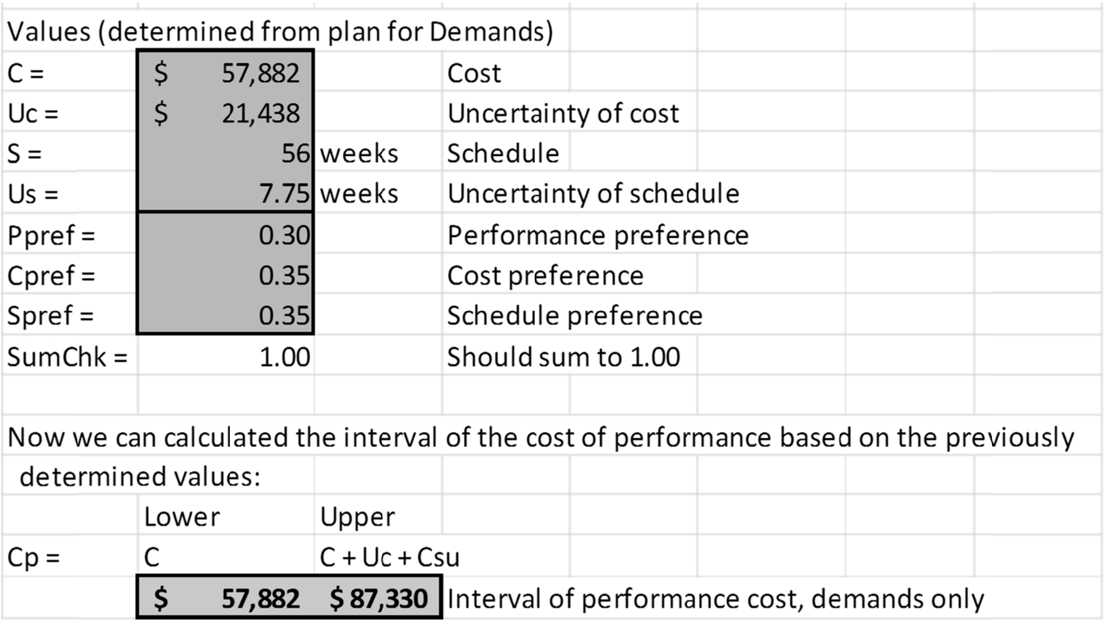
4.3.6 Step 6 – Apply Normalization Equations

With the data in the correct format, the key values needed to do the final estimate calculations are:

- Base Cost
- Cost with Uncertainty
- Base Schedule
- Schedule with Uncertainty

Because the GDOT example only used demands without capturing wishes separately, the values associated with those wishes are not required. Once these values are in place, the interval equations can be applied as previously described in Section 2.3.4. The results are seen in the following table. The total level of uncertainty ranges from $57,882 to $87,330. The next step will focus on whether these numbers meet the initial goals for the program.

Table 49: Results of Normalization Equations for GDOT Example



Values (determined from plan for Demands)			
C =	$ 57,882		Cost
Uc =	$ 21,438		Uncertainty of cost
S =	56	weeks	Schedule
Us =	7.75	weeks	Uncertainty of schedule
Ppref =	0.30		Performance preference
Cpref =	0.35		Cost preference
Spref =	0.35		Schedule preference
SumChk =	1.00		Should sum to 1.00
Now we can calculated the interval of the cost of performance based on the previously determined values:			
	Lower	Upper	
Cp =	C	C + Uc + Csu	
	$ 57,882	**$ 87,330**	Interval of performance cost, demands only

4.3.7 Step 7 – Compare Results to Initial Goals

The data seems to be well within the goals specified initially, but we must consider not only what the end result was but the cost of generating the estimate as well. Because this estimate was generated for the first time meaning all tools were developed as new modules, the actual number of hours spent on the estimate is much higher than what is typically expected to do the estimate. The numbers shown below in Table 50 reflect the number of hours that would be expected for an estimate of this magnitude assuming the construct for estimation is already in place. The estimate uses a value of $100/hr to approximate the cost of each task.

Table 50: Cost of the GDOT Example Estimation

Estimate Task	Hours	Cost
Step 1 - Determine if Appropriate	4	$ 400
Compare Assumptions		
Generate Requirements		
Step 2 - Numerical Normalization	2	$ 200
Generate Parameters		
Step 3 - Design Space	6	$ 600
Decompose Design 1		
Decompose Design 2		
Step 4 - Generate Schedule	16	$ 1,600
Generate Detailed Task List		
Generate a Gantt Chart		
Step 5 - Populate Estimation Tools	8	$ 800
Generate Skills Needed for Project		
Assign Hours to Each Task		
Step 6 - Apply Normalization Equations	2	$ 200
Add Values to Spreadsheet		
Step 7 - Compare to Initial Goals	2	$ 200
Simple Comparison of Values		
	40	**$ 4,000**

Now all of the values are in place to compare the results of the GDOT example exercise to the initial goals set forth in Step 1 of the proposed estimation method. One important piece of information to remember is that the cost of the estimate itself should be added to the overall cost of the work because there is a specified ceiling and the cost of the estimate needed to be covered under that ceiling. This now adds $4,000 to the base cost as well as cost with uncertainty values captured in Table 49. Now the comparison to the goals can be made (See Table 51).

The major point of interest from the goals is the overall cost. The range of cost is from $61,882 to $91,330 with the upper limit being $87,000. Due to the fact of this being an interval, there is no information about the distribution such that one may be inclined to view this as a normal distribution incorrectly. Also, just as discussed in limitations on estimation methods, this particular example is subject to the issues related to a bottom up estimate as well as the fact that it relied heavily upon engineering judgment. The key drawbacks from these approaches being that the omission of tasks can become problematic and the estimator must be experienced to be reliable.

Table 51: Comparison to Initial Goals for GDOT Example

Estimate Task	Hours	Cost
Project Cost Estimate	$ 61,882	Lower Limit
	$ 91,330	Upper Limit
Project Cost Goal	$ 87,000	
Project Schedule Estimate	15.0 Wks	Lower Limit
	17.1 Wks	Upper Limit
Project Schedule Goal	17.0 Wks	
Estimate Cost	$ 4,000	
Estimate Cost Goal	$ 4,000	
Estimate Schedule	1.0 Wk	
Estimate Schedule Goal	2.0 Wks	

The next section takes the results of the GDOT example estimate and provides a realistic look as the actual values are compared to what was estimated. The actual values are compared to those calculated in the estimate as a form of validation.

4.4 Review of GDOT Application Example

Because the work had already been decided to be completed, the execution of tasks began immediately after the estimate was completed. In some of the initial tasks work began before the estimate was complete as work began during Week 33 of the 2010 calendar year. Due to the tools in place at GTRI, the hours charged to the project were recorded for each employee on a daily basis. These hours could then be correlated to the scheduled hours that resulted from the estimation exercise.

Based on the initial estimate performed at the start of the exercise, progress of the project was evaluated two times during completion of the work as well as after it was completed. The first evaluation was performed at Week 40, the second evaluation at Week 46, and then the final evaluation. The first and second evaluation focused primarily on the comparison of planned and actual hours by task whereas the final evaluation was more of a comprehensive analysis including uncertainty.

4.4.1 GDOT Example Evaluation, Week 40

The first evaluation occurred 7 weeks after the project started on Week 40. During this period each task was considered separately compared to the minimum hours scheduled to the actual hours charged. The following table contains the results of that exercise. An important piece of information to highlight is the actual time spent during the reporting period, which was 227 hours. This allows two numbers to be calculated relative to both cost and schedule, which are similar the metrics used in Earned Value Management. The cost performance index (CPI) and schedule performance index (SPI) are simply the actual divided by the plan. For the evaluation at Week 40, the amount of schedule covered equates to 94 hours and the planned schedule is 298 hours yielding a SPI of 0.32. The CPI is calculated by taking the actual number of hours divided by the number of hours scheduled or 227 divided by 298 hours 0.76. It is evident by looking at these two numbers that not only is the project underperforming (SPI << 1.0), but the project is under spending (CPI < 1.0). This variance is due to the fact that needed staff was not available as initially intended and that tasks were taking longer to complete than expected. Keep in mind this was done in comparison to the lower bound of the interval, but the large gap in these numbers is still well outside of the range of the interval for scheduled hours. For comparison, the higher bound of planning resulted in 400 scheduled hours as opposed to the lower bound of 298 hours.

Table 52: GDOT Example Performance Evaluation, Week 40

	Task	Total Hours	% Scheduled	Hrs Performed	Hrs Sched
1	Wiring - small melter	20	50%	10	20
2	Wiring - larger melter	20	25%	5	20
3	Wiring - linear servo	8	75%	6	8
	3/4 complete				
4	Wiring - trailer	12	25%	3	12
5	Programming - real-time servo	45	50%	22.5	45
6	Plumbing - pneumatics/hydraulics	6	25%	1.5	6
7	Testing - validation of servo	6	50%	3	6
8	Testing - pneumatic/hydraulic check	10	0%	0	10
9	Wiring - safety circuit	10	0%	0	10
10	Assembly - mixing unit	8	50%	4	8
11	Programming - detection refinement	72	50%	36	72
12	Judging - detection refinement	30	0%	0	30
13	Testing - initial integration	28	0%	0	28
14	Testing - initial refinement	36	0%	0	18
15	Testing - parking lot tests	24	0%	0	0
16	Evaluation - parking lot tests	32	0%	0	0
17	Evaluation - road tests and eval	48	0%	0	0
18	Sponsor reports	28	10%	2.8	5
19	Reporting - draft final	48	0%	0	0
20	Reporting - final report	48	0%	0	0
	Totals	**539**	**55%**	**93.8**	**298**
	Hours Charged = 227 (@ Week 40)	**Hrs**		**Hrs**	

4.4.2 GDOT Example Evaluation, Week 46

The second evaluation occurred 13 weeks into the 18 week long project. Similar to the first intermediate evaluation discussed in the previous section, only the SPI and CPI were considered based on the lower end of the interval calculated. Calculated as done in Section 4.4.1, the SPI and CPI for this evaluation period are 0.81 and 1.10 respectively. This means the cost project is running behind and overspending, but the extent of this is not extreme (19% and 10%). Of the 525 (lower bound) to 580 (upper bound) hours expected to be spent per the plan, 423 schedule hours were accomplished. However, this was achieved through the charge of 580 hours to the project. As is expected in bottoms up estimates, the occurrence of unforeseen tasks is quite probable. The one considerable task added at this point in the development was related to resolving issues associated with the real time operating system (RTOS), Task 21. The addition of this task brought the scheduled work total to 587 hours as opposed to the initial plan of 539 hours. Ultimately, the schedule was progressing well in terms of the estimate with 160 scheduled hours of work remaining with the lower and upper bound of remaining at 62 and 180 hours.

Table 53: GDOT Example Performance Evaluation, Week 46

	Task	Total	%	Hrs	Hrs
		Hours	Scheduled	Performed	Sched
1	Wiring - small melter	20	90%	18	20
2	Wiring - larger melter	20	100%	20	20
3	Wiring - linear servo	8	100%	8	8
4	Wiring - trailer	12	100%	12	12
5	Programming - real-time servo	45	100%	45	45
6	Plumbing - pneumatics/hydraulics	6	100%	6	6
7	Testing - validation of servo	6	100%	6	6
8	Testing - pneumatic/hydraulic check	10	100%	10	10
9	Wiring - safety circuit	10	100%	10	10
10	Assembly - mixing unit	8	100%	8	8
11	Programming - detection refinement	72	100%	72	72
12	Judging - detection refinement	30	100%	30	30
13	Testing - initial integration	28	100%	28	28
14	Testing - initial refinement	36	100%	36	36
15	Testing - parking lot tests	24	75%	18	24
16	Evaluation - parking lot tests	32	25%	8	32
17	Evaluation - road tests and eval	48		0	48
18	Sponsor reports	28		0	14
19	Reporting - draft final	48	100%	48	48
20	Reporting - final report	48		0	0
	--- Added Tasks ---				
21	RTOS software issues	48	100%	40	48
	Totals	**587**		**423**	**525**
	Hours Charged = 227 (@ Week 46)				**525**

4.4.3 Final Evaluation of GDOT Example

The previous evaluations focused on the hours and the values used to determine cost and schedule performance indexes. The overall cost and schedule performance is critical, but this evaluation adds more emphasis on the uncertainty associated with this exercise. In this case, uncertainty refers to the interval created during the estimation process as it related to the number of hours for the program and the associated cost with those hours.

Table 54 includes data for the duration of the project from 33 to 51 weeks. This first point is important because the initial estimate stopped at Week 50 assuming the program would be complete prior to Week 51. The actual effort went into Week 51 requiring that additional time to complete the last task of delivering a final report. Because the original estimate was organized by employee, the number of hours spent and planned by employee is included in the report. The estimated effective labor rate for those employees is used to determine the total number of dollars for those particular variables. Finally, this is captured at the project level to provide insight on the overall performance of the estimate.

Table 54: Summary of GDOT Example Estimate

		Week																			
		33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	Totals	$
T1	**Actual**	2	0	0	0	1	2	8	0	0	0	0	0	8	1	0	0	0	0	0	22	$ 1,584
	Sched, Low	23	30	16	1	1	0	4	6	2	3	3	3	3	0	0	0	0	0	0	94	$ 6,768
	Sched, High	26	34	18	1	1	0	5	7	3	4	4	4	4	0	0	0	0	0	0	110	$ 7,901
E1	**Actual**	0	8	2	0	1	4	0	6	0	10	8	6	10	11	4	11	15	11	8	107	$ 10,863
	Sched, Low	1	1	17	21	27	27	21	16	4	6	6	8	6	0	0	2	2	2	0	165	$ 16,830
	Sched, High	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	$ 459
E2	**Actual**	14	11	3	12	2	0	0	11	10	16	7	9	11	12	1	5	11	9	10	143	$ 15,444
	Sched, Low	5	7	4	8	6	9	9	5	23	23	23	5	2	0	0	14	14	14	0	172	$ 18,576
	Sched, High	20	25	15	4	13	13	18	14	7	9	9	11	9	0	0	2	2	2	0	172	$ 18,554
E3	**Actual**	0	4	0	0	26	7	0	8	0	0	0	0	9	14	0	0	0	0	0	68	$ 7,560
	Sched, Low	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$ -
	Sched, High	3	5	4	5	3	0	0	1	7	7	7	1	0	0	0	1	1	1	0	46	$ 5,107
E4	**Actual**	16	0	0	0	0	8	4	3	5	22	13	14	28	18	4	21	28	41	2	224	$ 26,904
	Sched, Low	0	0	0	0	0	4	4	4	7	3	3	0	0	0	0	0	0	0	0	24	$ 2,880
	Sched, High	10	12	6	7	5	19	22	13	30	26	26	5	3	0	0	16	16	16	0	231	$ 27,702
E5	**Actual**	0	17	0	0	16	0	1	0	0	15	17	10	15	14	8	0	10	7	8	130	$ 15,990
	Sched, Low	10	10	10	10	0	0	4	4	0	1	1	1	1	0	0	0	0	0	0	52	$ 6,396
	Sched, High	13	13	31	31	18	18	15	15	0	4	4	4	4	0	0	0	0	0	0	167	$ 20,492
E6	**Actual**	0	4	3	1	0	0	0	0	0	0	0	0	9	0	0	0	4	2	0	23	$ 4,523
	Sched, Low	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$ -
	Sched, High	0	0	3	3	3	3	0	0	3	3	3	0	0	0	0	7	7	7	0	40	$ 8,040
A1	**Actual**	0	0	0	23	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	25	$ 1,000
	Sched, Low	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$ -
	Sched, High																					$ -
A2	**Actual**	0	0	0	0	0	0	0	0	0	3	0	0	0	2	0	0	0	0	21	5	$ 250
	Sched, Low	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$ -
	Sched, High																					$ -
Project	**Actual**	32	44	8	36	46	21	13	28	15	63	44	53	102	76	17	37	68	70	28	772	**$ 84,118**
	Sched, Low	39	48	49	42	36	42	42	35	39	39	39	17	12	0	0	21	21	21	0	539	**$ 51,450**
	Sched, High	45	56	58	50	42	53	53	42	48	48	48	21	15	0	0	26	26	26	0	657	**$ 88,256**

The first area to consider is the data by employee. Individual employees are noted by Technicians (T1), Engineers (E1 – E6), and Additional (A1 – A2). These additional employees are those that were not estimated to work on the project but were needed in order to finish the work. Administrative tasks and support from non-technical personnel proved useful, but was omitted from the initial estimate hence the inclusion of "additional" personnel. Viewing any individual employee can raise a few questions such as: Why are the actual hours outside of the range, or why are the lower bound hours higher than the upper bound hours? The first question pertains to the assumption that employees are available for the amount of time needed from the initial estimate. The truth is that employee availability within an organization can fluctuate; meaning that initially employees that were available may not be once their help is needed. The end result of employee availability is that charges by employee may vary significantly with a lesser impact on the overall program. The reason the upper and lower bound by employees is not correct is due to the application of the employee selection criteria in staff assignment. Because staff assignment is selected with a preference for employees with a lower labor rate, the lower bound will have a higher number of lower rate employees. As secondary staff assignments are included in the upper bound of labor as well as uncertainty in hours, the increase in hours is seen in higher rate personnel and decreased on lower rate personnel. Considering these questions, it is clear that the upper and lower bounds are not applicable at the employee level but only the project level.

Beyond employees, the overall project totals carry the most importance in the estimation process. The variance in the estimate ranges from $51,450 to $88,256 and includes the product of labor rate and hours for the primary selection of staff as the lower bound with the upper bound including uncertainty in addition to labor rate and hours for secondary staff selection. With a direct comparison of actual dollars spent, the total of $84,118 falls within the bounds initially stated for the estimate. This is in spite of the fact that more hours were charged than even the upper end of the estimate allowed (772 vs. 657 hours). This was possible because the combination of higher hours with lower labor rate staff did not exceed the higher estimates for higher labor rate staff. Take for instance the upper bound of E6 hours, which were 40 whereas the actual hours expended were 23. This alone accounts for a difference of $3,417. All things considered, the overall cost of $84,118 is contained within the initial estimated range of $61,882 to $91,330 provided a level of validation that the estimation approach used for the GDOT example proved to be useful.

4.5 Discussion of GDOT Example Results

The example provided in this chapter did not fully exercise the method as proposed in the thesis. Omissions were related to the lack of estimation beyond expert judgment, and the use of only what would be considered an intermediate estimate. The goals of the estimate (limited to 40 hours) drove these limitations as generating a more in depth estimate would have required more time spent by the estimator. Likewise, going beyond detail as specified in the Intermediate Estimate example (Section 3.4) would have required more hours than what was initially stated in the estimate goals. The primary objective of this chapter, however, was to rigidly follow the steps of the method and illustrate that application on a real world example, which was achieved. Equally important is the case that can be made that application of the method can be attributed to the success of the GDOT project within the initial goals set forth by the estimation.

4.5.1 Limitations of Reliance on Expert Judgment

As stated in Section 1.2.6, reliance on expert judgment as well as using a bottom up estimation technique is not without risk. The end result of these types of estimates can be non-repeatable due to the fact that the result is reliant upon the estimation skills of only one or a handful of expert estimators. Another potential point of risk is related to the ability to recognize interactions among multiple disciplines in the assignment of tasks. Because a bottom up estimate was used, omission of tasks could result in a largely ineffective estimate. In this example, only one major task was omitted related to the resolution of issues with the real time operating system. This unforeseen task combined with the need for supporting staff did not have a major impact on the overall cost of the project.

An argument can be made as to why an expert judgment was effective for this particular example though. Because this project was fairly mature in comparison to most prototype system estimates, there were far fewer unknowns to be uncovered in the last 18 weeks of project performance as opposed to the previous 5 years of development. This project maturity led to a clearer picture of remaining tasks that could be estimated more easily than a new prototyping estimate. It is for this reason that a reliance on expert judgment is justified for these given estimation circumstances.

4.5.2 Application of Work Planning Tools

The GDOT crack sealing example provided a thorough application of the work planning tools discussed in Section 2.7.1.1. Some items such as staff availability and hour per week limits were not incorporated into the planning tools, but the overall essence of the planning tool was illustrated. After going through the exercise, it was clear that some staff would be needed more than others highlighting potential benefits that could be realized through application among many projects within a given organization. Also, the need for additional staff at the end of the project could be used as a lesson to remember the importance of these activities in future estimation exercises. Although it is clear that the application of these work planning tools would require considerably more effort, the basic benefit is evident in the example problem.

4.5.3 Lack of Consideration of Wishes in GDOT Example

The requirements list for the GDOT crack sealing example (Table 39) was separated into demands and wishes. Demands were considered necessary and the inclusion of wishes was altogether ignored in this example. Wishes were ignored due to the complexity added to the estimation process. The effort related to the application of work planning tools and the assignment of hours to tasks can increase significantly as new schedules and task plans are required to track wishes separately from demanded requirements. This level of complexity was ignored to allow the estimate to fit within the estimation goals set forth in Step 2 of the proposed estimation method. It is important to note this particular omission as it pertains to validation however, as the impact of including wishes in the estimation process are not fully understood in the context of the proposed method.

4.5.4 Choosing the Correct Estimate

Considering the resulting estimate after completed, the best fitting description of the resulting estimate would be considered an Intermediate Estimate as defined in Section 3.4. A Detailed Estimate goes on to include a formal risk assessment, which was omitted in this example estimate making the Intermediate Estimate term more appropriate despite the fact that some amount of conceptual design was applied in the GDOT example. This raises an interesting question to the estimator – What level of estimate is sufficient?

The previous question is discussed in Chapter 3, but it is clearer in the example application how one may make this decision. The goals stated in Table 40 or Step 2 of the proposed estimation method place limits upon resources available to the estimator as well as a time limit. The limit of $4,000 and 2 weeks allows the estimator to have a reasonable amount of time to perform the estimate but also limits the number of estimation activities that can be performed. Table 50 provides a clear breakdown of how the estimate was generated by task allowing the estimator to gain an idea of how much time may be needed to generate a future estimation. For instance, almost half of the estimation effort (40% or 16 hours) is spent on generating a detailed schedule and list of tasks. Given the time spent, one may decide that adding a detailed risk analysis to the estimate may increase the time needed for a similar estimate to 60 hours as opposed to 40 hours for an intermediate estimate. The reliance on expert judgment limited the time spent meaning that the need for a more formal estimation technique may require more time as well.

The key to selecting the correct estimate is the balance between goals established in Step 2 of the proposed estimation method. The estimator must use his/her judgment to determine whether the resources allocated for the estimate are suitable for satisfying the uncertainty goals for cost, performance, and schedule. The balance between resources and uncertainty in this context will determine whether a Basic, Intermediate or Detailed Estimate are appropriate.

4.5.5 Usefulness of the Example and Impact on Results

The previous sections highlight some of the positive and negative components related to the particular example problem shared in this chapter. The various omissions and limits are delineated and the impact towards validation is recognized. These limits are discussed in the final chapter as they are pertinent to the final component of the Validation – the "leap of faith." Despite the existence of these limits, the case has been made that the GDOT example demonstrates the usefulness of the proposed cost estimation method. The detailed set of requirements as well as the detailed level of tasks resulted in only one major task that was overlooked. Because no other "surprise" tasks were evident, the estimate proved valid for the actual work that was performed. The application of work planning tools also helped to enhance the range or uncertainty associated with the resulting estimate.

Because there were several components of the proposed estimation technique that have not been fully explored, it is important for the estimator to be aware of what components are reasonable and what components require additional application. The results of the GDOT example application as well as the logical framework discussed in Chapter 3 are considered in the final chapter as it pertains to validation. Prior to applying the proposed method, one must be fully aware of these limitations prior to implementation.

CHAPTER 5

Closure and Review of the Work

In Chapter 1, the goal of this work was established, which rests on the premise that cost estimation can be improved by leveraging techniques from design methods. In this chapter, the approach taken in this thesis is scrutinized to determine how effective the results of designing a new approach for cost estimation methods are. Chapter 2 established the proposed cost estimation method and also described how the method was designed. Chapters 3 and 4 provide different example problems to exercise the method. The previous chapters were organized such that a cost estimating handbook could be created using the proposed method from Chapter 2 in conjunction with the example problems in Chapters 3 and 4. These chapters are meant to complement one another with the introductory and final chapter focused on the framework in which the estimation method was developed. However, Chapter 5 contains critical information that would also be included in a handbook that specifically states a critical review of the method.

The goal of Chapter 5 is to explain the usefulness of the method while disclosing all of the limitations one must consider if using the method. Section 5.1 discusses how the intellectual questions have been addressed. Section 5.2 describes the results of the cost estimation development in the context of the Validation Square. Section 5.3 covers the limitations of the method with a discussion on how useful the method is beyond the example problems discussed in previous chapters. Section 5.3 is an important section because it also includes benefits specific to GTRI. The thesis concludes with future activities in Section 5.4 and the personal concluding remarks of the author in Section 5.5.

5.1 Discussion of the Intellectual Questions

In general, the findings of this work support the idea that value can be added to the cost estimation process through design of the process using proven design techniques. The design of the process leveraged proven design methods and also employed the use of the Validation Square as a means to qualify the results. The goals of this work were initially structured around a number of intellectual questions, which were introduced in Section 1.1.2. These intellectual questions were formulated such that they addressed challenges faced in estimation for the purpose of research and development.

An important aspect of the thesis is the introduction of intellectual questions and the corresponding work to address those questions. The intellectual questions were introduced in Section 1.1.2 and discussed in each chapter as to how the respective chapter addressed these intellectual questions. In this manner, this document has remained focused on the ability to address these intellectual questions through a detailed description of the problem, the introduction of a logical framework, the relevance of examples and their impact on the intellectual questions. The following sections address each intellectual question individually and provide a critical review of how well they have been addressed by this research.

5.1.1.1 Discussion on Intellectual Question #1

When is enough information gathered to generate a robust estimate for the design of prototype systems?

This particular question is the primary driver in this research presented on cost estimation. The importance of this question is based on three key phrases: 1) "when is enough", 2) "robust estimate", and 3) "prototype systems." The first two phrases are interrelated as the question of "when is enough?" is captured by the term robust. The goal in this case is to understand the point of diminishing return on estimation. This point of diminishing return is discussed in several ways. Table 55 includes particular section numbers that address various ideas surrounding the goal of understanding where the point of diminishing return is.

Another view of "when is enough" is captured by the goals established for the estimation at the beginning of the proposed method. During the GDOT example, goals for the estimate were established in Table 40 setting limits for an estimation exercise. The answer to this question essentially becomes a matter of resources that can be dedicated to the estimation process while simultaneously considering the level of risk the estimator is willing to accept.

Table 55: Sections Addressing Robust Estimating Results

Section(s)	Description	Result
1.2.6, 1.3	Estimator Influence	Although the estimator is often referred to as a single individual an estimator may be a number of individuals or a committee. Depending on the risk taking level of an individual or an organization, robust becomes a goal that is related to this risk level. An example of this could be that a small business may not consider generating a patent for a particular device as robust due to the considerable monetary investment whereas a large organization would consider this a good investment knowing only a portion of patents provide considerable return on investment.
1.2.6, 2.3.2, 2.3.3	Uncertainty in Estimation	A number of estimation tools are discussed in the literature review section. This high level summary of available tools gives the reader a direction to consider the large number of tools described in literature, yet does not serve as an exhaustive search in the public domain. For the proposed method, uncertainty is represented as intervals offering a good representation for phases in the design. As analogous data becomes available to an organization, however, more complete representations of uncertainty could be built upon more accurate historical data – this possibility was not explored.
3, 4	Examples to Demonstrate Relevance	Chapters 3 and 4 present good relevant examples for small prototype design projects. A clear weakness of these example problems is how the ability for the method to address large engineering efforts (10+ employees) has been overlooked. In general, the example applications demonstrated robustness through an application involving representative conditions.

The results discussed in Table 55 indicate a relatively thorough response to Intellectual Question #1. The final representation of the measure of robustness was implemented as a goal specified by the estimator during estimation process described in Section 2.2. By establishing goals for the estimation process, the estimator has defined the level of robustness required to generate what they consider to be an acceptable or good estimate. This does leave a remaining factor of subjectivity to the definition of robust, yet subjectivity is nearly a requirement when considering decisions made by human beings.

5.1.1.2 Discussion on Intellectual Question #2

How do you characterize uncertainty in the estimation process?

Uncertainty was discussed in several sections throughout the thesis (Sections 1.3.1, 2.3, 3.3, 4.3.5) ranging from the definition of the term to its implementation in example problems. For this method uncertainty was captured in interval form for further processing in mathematical calculations. This approach was deemed appropriate due to the inclusion of highly unknown tasks inherent to prototype development. This is due to the fact that intervals do not suggest there is any knowledge beyond the boundaries other than knowing the upper and lower limits to a given boundary. The benefits and drawbacks of such a representation are discussed in Section 2.3.3, but the example problems, particularly the GDOT example in Chapter 4, show how this representation is effective. One limit of the application of the example problems was that these example problems did not fully explore the methods to characterize risk and uncertainty that were uncovered in the literature review described in Section 1.2.6. Future work could focus on characterizing different cost estimation and risk assessment techniques in the proposed cost estimation method.

5.1.1.3 Discussion on Intellectual Question #3

Why do estimates need to consider interactions between performance, schedule, and cost?

A key component of the majority of estimation techniques involves the characterization of cost, performance, and schedule. A considerable amount of research has been performed to characterize these results and these often lead to historical-based databases that describe this relationship. When that information is available, it is well established that parametric models can provide an excellent way to consider these three closely related parameters. By proposing this alternative numerical technique, the estimator is provided a tool to assist in cases where little is known about the development. Intellectual Question #3 goes further to ask why such a tool would be important to the estimator. Section 3.3 touches upon the importance of requirements in the context of estimation planning, which becomes the definition of performance for the purpose of estimation. The primary example focus on the ability to tie in cost with performance, yet the inclusion of schedule is not a primary focus. The result is that Intellectual Question #3 was addressed well when considering performance and cost, and that schedule is not addressed at the level of the other two parameters. This weak point in the research leaves opportunity for a better characterization of all three parameters in future activities.

5.1.1.4 Discussion on Intellectual Question #4

Why is the assignment of staff critical to an accurate estimate?

Section 2.7 addresses a proposed solution to better the assignment of staff in estimation with Section 4.3.5 offering a good application example of the proposed solution. These sections primarily address the question of how to provide solutions to the assignment of staff, but not a strong reason of why to do so. Chapter 4 does highlight some reasons to why the assignment of staff is important. A major driver is that if you assume certain staff can work on a project when you create the initial estimate only to find they cannot do so later, the project may have to pay the price of training another individual or relying on someone not as adept as the individual initially planned on the effort. This can also have an effect if there is a realization that support for a particular tool is thought to be available and is not. For instance, a project may require the use of "CAD Program X" in order to read files when the organization's employees are only familiar with "CAD Program Y." This creates inefficiency that will become evident as an underestimate.

Although much more work could be performed to enhance the response to these intellectual questions, the general result is achieved and demonstrated in the research presented in the thesis.

5.2 Validation of the Results

In order to validate the results of the method, the previous work done to incorporate the Validation Square must be considered. Let us return to the primary goals of the Validation Square from the theoretical structural validity to the theoretical performance validity. This is accomplished through the steps identified in Section 1.5.2. Each of these steps is discussed below in relation to how the validation was supported throughout this work.

5.2.1.1 (1) Accepting the validation of the construct of the method

This portion of the Validation Square is grounded in the literature search captured in Section 1.2. The intent of this section is to leverage previously established methodologies that are proven in industry. In using these previously vetted publications, the method can be developed in such a way that only novel ideas or approaches are used when there is no existing work found to support ideas set forth. This greatly limits the amount of new information injected into the method proposal. By using the Validation Square as an approach to method developments, the design of the method can be thought of as an adaptive design. In this sense, the method is not an entirely new invention but a novel way of combining previously proven approaches.

The first part of this piece of validation was a search on general design methods used in engineering design. The design method proposed by Pahl and Beitz was used a basis for this work. This particular section of validation is not considered to be exhaustive yet the methods discussed remain viable methodologies after years of use despite their respective limitations. Due to this, the Pahl and Beitz approach to manufacturing design was chosen due to the familiarity of the subject with the author and its ability to be used as modular. Furthermore, because estimation is essentially the beginning of the design process, the Pahl and Beitz method offers good design tools early in the design process that assist with the clarification of an effort.

The second piece of validation in this area consisted of a detailed search for tools in cost estimation methods. Due to the large number of cost estimation methods that are available, this particular literature review proved challenging. This challenge was compounded because there are many methods that are unique to various engineering disciplines. Despite these challenges, a representative set of acceptable methods was presented that provided the reader a high level view of what estimation tools are available. During this search, there were no major components uncovered that invalidated the approach of the proposed cost estimation tool.

The last section in the literature search covered tools associated with the characterization of risk and uncertainty. Similar to cost estimation tools, there are a high number of estimation tools in this area. The primary approaches were discussed and a limited number were considered for further use in the proposed method. Due to this approach, the decision of whether to include various risk assessment tools is not considered exhaustive. The idea, however, is not to limit the estimator to certain tools but to describe all of the types of tools available so that their own process can be modified using the tools befitting their organization.

By covering these three areas in the literature search, the thoughts discussed in the proposed method primarily become a matter of how these tools are combined. This portion of validation is considered adequate to support the basis of decisions made for the design of the cost estimation method.

5.2.1.2 (2) Accepting method consistency

In order to accept the consistency of the method, a logical argument must be made to how the method is constructed. This logical argument must include requirements and/or assumptions, a good depiction of the flow of information through the method focused on what inputs and outputs are required at each step, and a final goal of how the proposed method can be realized. Requirements and assumptions were clearly stated and critically evaluated in Section 2.8.1. This section contains the result of how well the proposed method addressed the initial requirements set forth in Section 1.4.2. This final chapter discusses the assumptions needed for using this method after understanding how it applies to example problems. These iterations related to assumptions and requirements provide a solid logical framework on which the method is based.

In regards to explaining the flow of information used in the method, Figure 4 is used to depict each step of the method and how various modules interact with one another. Previous sections explain how this flow of information was designed with the goal of tracking information as the estimator progresses through the estimation process. The sections following the proposed method figure contain detailed descriptions of each step and how they can be applied in theory. Essentially, the entirety of Chapter 2 is meant to address the acceptance of consistency of the method, and this portion of validation is considered acceptable. One component of Chapter 2 that is not as clear as others is that the cost estimation method itself is designed. Section 2.1 covers the design of the cost estimation method using established techniques such as an affinity diagram (results of affinity diagram in Table 6).

5.2.1.3 (3) Accepting the example problems

Example problems are presented at the end of Chapter 2 with Chapters 3 and 4 devoted solely to examples. As far as the chapters devoted entirely to example problems, these examples were considered relevant due to the fact they were based upon actual developments performed by GTRI. These developments are considered to be representative of multidisciplinary research projects including a number of prototype generation support activities. The examples also align well with the requirements generated for the method in Table 3. This is an important point because the consistency of a method development must be made apparent from requirements to results. A significant limitation discussed, however, is the fact that the example problems were not executed using large teams. Because the examples only included a team of <10 individuals, the leap of faith to support acceptance for large teams is difficult to make. The example problems did exercise several parts of the method though:

- Multidisciplinary teams
- Projects with tasks including high levels of uncertainty
- Evaluating performance after the estimate is made to completion of the work

In demonstrating these various points of the method while being based upon actual R&D problems, the example problems are considered acceptable for the purpose of validation.

5.2.1.4 (4) Accepting usefulness of method for some example problems

To address usefulness of the method, an industrial consideration can be made that includes the betterment of affects associated with cost, schedule, and performance. The proposed method was not generated with this in mind necessarily – the goal of the proposed method was to better understand the relationship between cost, schedule, and performance for estimation purposes while improving both precision and accuracy of the resulting estimate. Of course one obvious implication is that the approach should not require significant resources thus increasing the cost and time of a particular development. In other words, the notion of reducing cost and or time cannot be overlooked. Yet the goal was limited to understanding cost and schedule while maintaining performance for this particular method. This is accomplished by stating that the requirements are known at the initiation of the estimation exercise thus solidifying the desired performance of the system.

The method is shown to help the estimator reduce uncertainty and negative consequences by focusing efforts on tasks with a large amount of negative consequences through the example problems. The major limitation related to usefulness is that the method was not directly compared to what is achievable through other estimation means. However in Chapter 2 the case is made that if an organization does not have an existing estimation tool in place such as described by the Basic Estimate, that an Intermediate Estimate could provide well needed improvements.

5.2.1.5 (5) Accepting that usefulness is linked to applying the method

This section is tied closely to the discussion on the example problems in the previous section because usefulness is only achievable if the example problems highlight benefits of using the method. As stated previously, the method does show how uncertainty and the resulting consequence can be reduced through better focusing of engineering resources. This is a key statement that is related to the primary intellectual question of robustness of the method, which implies the estimator is satisfied by the uncertain bounds on cost and schedule at the conclusion of the estimation process. In this sense, usefulness was demonstrated at the project level in the sense that the estimator had already decided to do the work. Utility beyond this would imply that the method could be applied in order to guide business decisions in where and where not to place the company's resources. This is considered a limitation because the ultimate goal of application of this method is to integrate it into the decision making process for R&D organizations. Because some R&D organizations do not have a clear estimation process in place, it was made evident the use of this method would be beneficial if compared to a loosely defined method as evident in the descriptions of the Basic Estimate and the Intermediate Estimate in Chapter 3. Chapter 4 provided a successful implementation of the proposed cost estimating method and demonstrated that the method provided value by allowing the estimator to capture all but one of the tasks avoiding surprises in the development. This is important when bottom-up estimates are made because the omission of tasks is the major risk when using bottom-up estimation approaches.

5.2.1.6 (6) Accepting usefulness of method beyond example problems

Accepting usefulness beyond the example problems can be referred to as the "leap of faith" made to extend the method beyond examples. At this point in validation one must ask, "Has the application of the method to the example problems illustrated how it can be used beyond the examples and what are the limitations?"

The example problems were chosen to be representative of a hardware packaging and integration problem faced by an R&D organization. This brings up an obvious limitation – the example problems primarily focused on hardware integration problems. This focus is considered negligible because the actual tasks involved skills covering industrial design, computer science, electrical engineering, and mechanical engineering. Due to the plethora of information related to estimation of software tasks, one could argue that R&D projects only involving software could be better estimated using existing software estimation tools. This argument is true as the method is considered more to focus upon multidisciplinary teams. The limit of application to primarily multidisciplinary R&D projects is not considered a barrier to the usefulness of the method though as a number of R&D projects consider multidisciplinary integrations. Another limit is the use of small teams in the examples, which makes a broader acceptance of the method for large design teams difficult.

The leap of faith is then considered effective for small teams tasked with multidisciplinary integration R&D projects. The reason the term "R&D projects" is needed is because the utility has only been demonstrated for projects that contain high levels of uncertainty. For instance, it was stated in Section 1.2.3.1 that top-down estimation approaches may be the best approach when considering tasks with little uncertainty. Additionally, the use of the term suggests that there may not be considerable information available to perform analogous or parametric cost estimation because a good statistical collection of previous work may not be available to an R&D organization. Ultimately, "the leap of faith" is relevant in the context of the critical review of the method in the following section. Once the estimator has been made aware of the limitations and benefits described in Section 5.3, the proposed cost estimation can be applied with confidence.

5.3 Critical Review of the Method

A thorough critical review of any newly proposed method is essential for understanding the possible improvements while carefully noting the limitations of that method. The first portion of the critical review focuses on the requirements established for the method in Chapter 1. After this discussion, the key limitations and benefits are discussed individually while considering the points raised in Section 5.2 related to validation.

5.3.1 Review of Method Requirements

Prior to discussing the important points that resulted from the method development, let us revisit the requirements established in Section 1.4.2. Below is a listing of each of the initial requirements with a short discussion on how and if the method has addressed these requirements.

1. Adaptable for all engineering principles – The example problems demonstrated the method is appropriate for multidisciplinary teams. This was achieved by using example problems that included mechanical, electrical, and software tasks.

2. Incorporate tools to account for uncertainty in the estimation process – Uncertainty was handled by the inclusion of intervals that captured the lower and upper bounds of cost. These intervals were the result of uncertainty defined by the estimator at the task level.

3. Incorporate checks and balances throughout the process – The primary check incorporated in the method is that of setting goals at the beginning of the estimation method and reevaluating those goals at the end of the estimation process. This is an important check that provides guidance to the estimator and other stakeholders involved in the results of the estimation process.

4. Adaptable to meet the needs of designing prototypes in a research environment – The example problems chosen contained prototype developments in a R&D environment. The use of these problems has demonstrated the proposed method is appropriate in these areas.

5. Create normalization terms to compare cost, schedule and performance – The use of cost as a normalizing basis in the estimation method helped to include the estimator preferences while providing a repeatable framework in which the estimation is performed.

6. Easily communicate within organization – The result of the thesis has essentially become a document in which the method can be shared. Chapter 2 contains the general form of

the proposed method while Chapters 3 and 4 provide clear examples that can be leveraged by future potential estimators.

7. Must incorporate safety considerations throughout the process – Stated as a wish, this particular requirement was not addressed. Currently, the way safety would need to be incorporated would be at the task level. The method does not prescribe any particular steps to address safety, which may be viewed as a limitation in some developments.

8. Must be organized and written such that a college graduate can understand the methodology – Similar to the answer for Requirement 6 on communication, the thesis document has been written for a comparable potential estimator to understand.

9. Must be articulated clearly to allow for transmission of ideas through standard documentation – The method is executed in two simple software tools – MS Excel (Estimation tools) and MS Project (Gantt charts). These tools were chosen due to their commonality in many organizations and have made the method calculation tools easy to transfer among divisions and organizations.

10. Accuracy of references for readers to check content – References in the literature section were checked for consistency.

11. Adaptable to changing design environment – The literature review section in Chapter 1 contained several cost estimation methods that can be used in the proposed estimation method. The proposed method serves as a construct to break down a problem into tasks while applying uncertainty in a framework where terms are normalized to cost. Many other cost estimation methods could be infused into the same context making it applicable in many design environments.

12. Able to be revised for frequent changes – The proposed method allows for the expansion of detail with a focus of reducing uncertainty in the revision of estimates.

13. Can incorporate a dynamic cost database – Similar to the discussion made for Requirement 11, the method becomes a construct that can accept inputs from several sources. If historical cost data is desired for some tasks then it is simple to insert that set of information.

14. Improve the determination of the cost of labor – The example described in Chapter 4 for the asphalt crack sealing system contains a module that helps to automatically assign staff based on availability and skill set. This tool is seen as a potential improvement related to determining the cost of labor.

15. Must not create negative impacts to existing design methods – This is not addressed directly, but in generating a set of goals, the estimator is guided by an initial cost goal for the cost of the estimation itself. However, there were no direct comparisons to other estimation methods meaning this requirement was not satisfied.

The review of the initial requirements indicates the method has addressed the requirements well with one major drawback – lack of comparison to existing estimation methods. Because there was not a detailed head-to-head comparison to existing estimation methods, it is impossible to determine whether this method has created a positive or negative impact on the estimation process. This is an area of concern and would be of keen interest to an organization when comparing to their existing estimation process. For organizations that do not have a strict estimation method already in place, this development has demonstrated that the prescriptive estimation method does provide a benefit.

5.3.2 Review of Method Assumptions

After applying the method to the example problems in Chapter 3 and Chapter 4, several limitations became evident. These results have been summarized in the following table to as a new set of assumptions that must be considered prior to implementation of this method. In this table, the initial assumptions are captured. There is a third column added to capture either revised assumptions denoted by an "R," delete assumption denoted by a "D," or new assumptions denoted by a "N."

Table 56: Final Assumptions Prior to Using the Proposed Estimation Method

No.	Description	R/N
1	Material estimates are not addressed by the method	R
2	Method can consider an experience level in labor estimates	R
3	Assume 40 hour weeks for a given employee	
4	All skill-sets needed are available and location of engineering resources are irrelevant	
5	All state of the art engineer tools are available and they know how to use tools	
6	Assume constant price of everything	
7	Intellectual Property issues are ignored	
8	It is feasible to evaluate the performance	
9	Functional and working structures can be completed	
10	Designer control over all tasks to be estimated	
11	Corporate management requirements ignored	
12	Limits for uncertainty calculations are defined through intervals	
13	No more than approximately 10% of total effort dedicated to estimation	R
14	The total size of the team is no larger than approximately 10 staff members	N
-15-	The estimate must not have a negative impact on existing methods.	D

For each of the revised, deleted, or new assumptions a more detailed explanation of each item is shared below.

Assumption 1: ***Material estimates are not addressed by the method***

Assumption was modified to make it clear the method development never addressed the cost of material in depth. Some other method for material estimates must be incorporated, but were not specifically addressed in the proposed estimation method.

Assumption 2: Method can consider an experience level in labor estimates

This was rewritten to make this assumption optional. The Intermediate Estimate detailed in Chapter 3 did not include a review of experience level whereas the asphalt crack sealing example in Chapter 4 did. This now is recommended as an option to the estimator.

Assumption 13: No more than approximately 10% of total effort dedicated to estimation

This assumption was slightly modified to include the term "approximately." This is important, because the estimator really does not know what the total estimated result is until performing the estimation. This means that this limit is only recommended when defining the initial goals for the estimation method.

Assumption 14: The total size of the team is no larger than approximately 10 staff members

This assumption is made because there was no validation research performed on teams larger than this. Because of this, the ability for the proposed cost estimation method cannot be easily extended into large teams where the dynamics begin to increase the complexity of estimation exercises. Scaling up the method may not be an issue in many cases, yet as added levels of management will be present when task leaders are required the new layer of management may become costly.

Assumption 15: The estimate must not have a negative impact on existing methods.

There was no direct comparison to other methods in the thesis. This lack of discussion in the thesis means this assumption has been deleted.

The modified table above, Table 56 , now serves as the final set of assumptions to guide an estimator when applying the method in the future. It is clear that Assumption 15, which has been deleted, really belonged as a requirement as opposed to an assumption.

5.3.3 Limitations of the Proposed Method

Progressing through the critical review for this method we consider the material covered in Section 2.8.1 as well as the previous sections related to requirements and assumptions. Building on these evaluations, as well as an evaluation of the Validation Square in Section 5.2, the following items highlight key limits of the method.

5.3.3.1 Better methods may exist for different teams

A minor potential limitation to the method is that it was only applied to systems related to electro-mechanical developments. Other problems with a more singular discipline focus may invalidate the utility of the method beyond these types of multidisciplinary teams. For example, a design team working on software tasks only may rely on software estimation tools that have been well established in literature and industry. These tools may serve the estimator better for pure software engineering related tasks in R&D. This is a minor critical point because the general prescriptive approach of the proposed cost estimation method lends itself well to the inclusion of other estimation tools. The general form where estimation goals are established and abstraction of designs still hold the potential for benefits.

5.3.3.2 Project teams larger than ten individuals may not work well with the method

Large project teams can bring many new challenges such as additional layers of developments including multiple estimators to the estimation tasks. These effects were not explored due to the limited resources for this particular method development. The use of manpower planning tools, however, could greatly improve how estimation progresses on large programs in regards to the staffing of labor. These arguments can only be made in speculation though as they were not tested in this work.

5.3.3.3 When highly uncertain tasks are not present in the project other estimation methods may be more suitable

The use of the term “prototype” was intended to capture the fact that highly uncertain tasks were present on a project. In areas where these high levels of uncertainty are not present it may be better to simply use expert judgment or other top-down techniques. This particular limitation is discussed in further detail in section, Section 5.2.

5.3.3.4 The separation of wishes and demands may have benefit

The separation of these two types of requirements was not fully explored. A method for handling the separation of these requirements by using uncertainty of performance was discussed but not rigidly demonstrated in the two major example problems. This approach appears to have merit at first glance, but the work performed in the thesis did not validate the use of this particular module of the proposed method.

5.3.3.5 Work planning tools discussed may present significant human resource related barriers

A work estimation tool for the management of staff was discussed in Section 2.7. During this section, the use of databases capturing the skills of employees in concert with capturing skills required of a project was used to assign staff to a project. In this approach, it is postulated that staff assignments can be greatly improved by having the appropriate individuals working on tasks such that highly valued resources of an organization are not misplaced. The benefits seem obvious, but the challenges to acceptance by employees as well as their employers could be substantial. These challenges cannot be addressed in this work as they are based upon perception and could differ among organizations or even cultures.

5.3.4 General utility of the proposed cost estimation method

To finalize the critical review of the method, a discussion on the overall utility of the method is in order. Despite the number of limitations discussed, the ideas and tools proposed were demonstrated to offer a good potential for improving the estimation of prototype systems in a R&D environment. When working within the known limitations stated in prior sections, the ability to reduce uncertainty in an estimate offers benefits between the customer and the estimator. The improvements go beyond the method alone and extend into the better understanding of estimation particular to estimation in a research environment. The background information provided also serves as a good primer on cost estimation techniques for those not familiar with the vast amount of information available surrounding this topic. The following text contains a description of the contributions which can be attributed to the method:

5.3.4.1 Incorporating project and estimation goals

A good result from the method development is the inclusion of incorporating project and estimation goals into the estimation process. This is described in the various example problems in Chapters 3 and 4 and results in a set of values that can be reevaluated at the end of the estimation process to determine whether the estimator has achieved acceptable amounts of uncertainty as well as whether too much time is being spent on the estimation itself. This means that as historical databases are developed that not only past project estimates are available, the cost of generating estimates for those projects will be available as well.

5.3.4.2 Including abstraction techniques in estimation can reduce uncertainty

The discussion of the Intermediate Estimate in Chapter 3 demonstrated that added detail at the task level can reduce uncertainty while improving the overall cost of the estimate. These improvements translate to improvements in both accuracy and precision of the estimate. As demonstrated in the example problems, these improvements can be attributed to including more design details at the task level which was the result of abstraction techniques.

5.3.4.3 Detailed requirements improve the estimation process

The clarification of tasks is achieved through the generation of detailed requirements. Although the generation of requirements is time consuming and may involve additional customer interaction, the resulting list of requirements serves as an anchor of which the estimate is based upon. The differences between the Basic Estimate and the Intermediate Estimate captured in Chapter 3 discuss how a lack of requirements can become a major contributor to error in the estimation process. This idea is critical as developed in the method of Pahl and Beitz, and offers an important step that some cost estimation methods glaze over.

5.3.4.4 Incorporating work planning tools can add organization specific benefits

By applying engineering resources directly to tasks in from the estimation process, an estimator can begin to account for organizational limitations that are a part of estimation. For instance, a task can cost significantly more of the right individual is not present to perform the work. Adding work planning tools, such as those applied to the crack sealing example in Chapter 4, to the estimation process can help to alleviate some of these challenges. By linking tasks to skill sets of individuals within an organization, the ability to make the estimation process more integral to an organization has been demonstrated.

5.3.4.5 Explaining the Relationship Between Uncertainty and Consequence

Uncertainty is meaningless if consequence is not considered. Take for instance an example of the estimation of a task to cut a piece of material for use in the construction of a prototype system. There may be several options to cut the material such as sawing with a band saw, cutting with a numerically controlled machine, or several others. The cost of this cut may vary significantly from a few dollars to $100 based on the decision made. The uncertainty is extremely high for this particular cut as considered in this example, yet without considering the effect on cost or consequence, the risk to the estimate is meaningless. If these particular cuts only need to be made twice during the entire project and the expected overall cost of the work is $1M, then the consequence related to a large amount of uncertainty for this particular cutting task is miniscule. Sections 2.3.2 and 3.3 provide more examples of how this relationship between uncertainty and consequence can affect the overall results of an estimate.

5.3.4.6 Enough information is available when goals are satisfied

This addresses the primary research question of the thesis – "*When is enough information gathered to generate a robust estimate for the design of prototype systems?*" A way to address this is through the use of goals for the project and the estimation process, specifically the incorporation of uncertainty. By including uncertainty calculations as well as goals in the estimation process the tools to capture the desires of the estimator are made available in the proposed method.

Several beneficial statements can be made about the use of the proposed method; although it is not evident these results would be better than any other method. The contributions of this method must be considered carefully as there are a number of limitations and assumptions that must be considered prior to using this recommended approach. This section serves as a guide to educate a potential estimator as to whether this method is appropriate for their particular needs.

5.3.5 What Do the Results Mean for GTRI

The Georgia Tech Research Institute, or GTRI, is an applied research and development organization that has serviced a number of government and industry customers since 1934 [59]. GTRI is considered an integral part of the Georgia Institute of Technology (Georgia Tech). Because GTRI deals in the area of applied research and development, there are a vast number of program types within their project portfolio. Projects range from basic research in the design of nano-materials to be used in solar collectors to large scale hardware integrations for the department of defense (DoD). Because of this broad range of products in addition to the focus of research and development, GTRI often faces the challenge of designing prototype systems for the purpose of technology demonstrations for their customers. In this type of research and development environment, the design and creation of prototypes is a common product. This thesis has considered cost estimation in the context of prototypes as a key characteristic in order to provide assistance to various cost estimation activities at GTRI, the employer of the author.

The first point of discussion is simple and can be expressed in a question: What findings have been generated to provide a direct benefit to GTRI? The following sections highlight a number of points that are beneficial to the organization of GTRI.

5.3.5.1 Gaining a better understanding of prototype estimation

Section 1.3.1 provides the definition of the term prototype and discusses the meaning of this term in research and development. In regard to cost estimation, the point is made that prototype developments contain at least one major task or sub-task that contains a high level of uncertainty. This is because the meaning of prototypes implies that at least one part of the system has not been performed before. Furthermore, this implies that a portion of the development contains an original or adaptive design.

The method described in Figure 4 includes a step related to the exploration of design space. During this step, the notion of abstraction of the design through the generation of function structure breakdown as well as exploring potential working principles is discussed. This discussion is considered beneficial and this benefit was demonstrated through example problems in Section 2.5.3 and Section 3.5. These benefits can be summarized by noting how decisions made early in the estimation effort can greatly affect the overall cost of the system. By going through a high level conceptual design including representation of the design in abstract form, certain challenges become evident to the estimator thus preventing a large miscalculation during the estimation process.

5.3.5.2 Uncertainty in Estimation

The previous section, Section 5.3.5.1, concluded with a discussion preventing large miscalculations through better exploration of the design space. This can be one area where uncertainty can be reduced and was demonstrated in the GDOT example in Section 4.3.3. Yet the uncertainty was not quantified during the example problem. In order to do this, an estimate would have to have been created prior to going through a rigorous conceptual design exercise. The GDOT example only contained a few minor conceptual design exercises.

Because of this, the conclusion cannot be drawn with certainty that this step will reduce uncertainty. Further uncertainty discussions had been covered in detail in Section 2.3.2 with tools to reduce or understand uncertainty covered in Section 2.4. These sections address uncertainty and tools for the reduction of this uncertainty in the estimation process.

The uncertainty that was covered in the example problems was related to the uncertainty of hours and schedule by task. This particular type of uncertainty was covered by selecting a low and high number for any given task based upon a percentage that was generated using expert judgment. This range was then carried through the estimation process as an interval resulting in a low and high expectation for the overall cost (See Section 4.3.7). This particular characterization of uncertainty proved useful as the final project cost was within the bounds initially estimated. More advanced techniques, such as Monte Carlo Analyses, can represent uncertainty and can be included in existing cost estimation methods such as Activity Based Costing [22]. It is clear that the characterization of uncertainty is directly related to the quality of the estimation, which in turn offers benefits to a research organization.

5.3.5.3 Work Planning Tools

One component of estimation is the assignment of staff to support the research effort. The assignment of staff can be a daunting task due to the dynamics of a multidiscipline effort as well as requiring managers to keep track of the considerable details associated with the staff they are responsible for. Section 2.7 describes a tool that can be used by managers to staff projects based upon the needs of a project as well as the skills of their employees. There are a number of details that would need to be addressed prior to implementing such a technique at an organization such as GTRI, yet the case is made how such a tool could be used to improve the estimation process. Possible implementations for GTRI could result in improvements in work load forecasting at the organizational level while the availability of employees could help project management at the task level. To accomplish this within the current organizational structure would be difficult though.

5.3.5.4 Relevant Examples

The examples described in the thesis in Chapters 3 and 4 are all related to work that was performed by GTRI. Because GTRI specific examples were chosen, the benefits discussed in those sections can be considered to be directly applicable to GTRI as an organization. In the case of the asphalt crack sealing example (Chapter 4), the results are captured at multiple points throughout the process to provide multiple instances of performance to the estimator.

5.3.5.5 Summary of GTRI Benefits

It is clear from the previous discussion that there are tangible benefits applicable to GTRI. The use of relevant example problems as well as demonstration of how the removal of uncertainty can improve estimation could serve to improve GTRI's estimation process. These potential improvements are discussed in further detail in Section 5.4.

5.4 Future Activities

Several potential future activities have been discussed in previous sections. The key items of interest are as follows:

- Continued application of the method with larger teams
- Exploring the impact of estimating demands and wishes separately
- Comparing the proposed method to other methods in a controlled fashion
- Building a limited work planning tool for initial evaluation in practice
- Better understanding the dynamics between the organization and the designer

The opportunity for further application will be explored in the context of the limitations and benefits provided in the previous section. In the context of these limitations, the thesis as it stands can be used to form a general handbook for estimation. The plan to generate a handbook would leverage the final chapter, specifically Section 5.3 as a way for the estimator to become familiar with the potential limitations and benefits of the method. The next portion of the handbook would be the proposed method from Chapter 2. The sections on method development would not be needed, but the general framework of the method would be used. Chapter 3 could be condensed to focus primarily on the Intermediate and Detailed Estimate tools while Chapter 4 could essentially be used in its current format. Leveraging this plan, the thesis can be transformed into a handbook that could have an immediate impact to GTRI or other similar organizations.

5.5 Concluding Remarks: the "I Statement"

This is the point of the thesis where I, the author, have made several observations throughout the development of this work. This exercise greatly influenced how I view estimation. An interesting idea that occurred early on was the thought that the only accurate estimate is one that completes the work prior to generating the estimate and reinforces the common reference of estimation as being an attempt to predict the future. I still feel this is true, yet have a much better understanding of how one could limit the uncertainty in estimation and generate a "good" estimate provided a sound method is followed.

Another bit of learning is that I have come to understand the relationship between the estimator and the customer much better. Because there is always uncertainty in estimation it is a matter of risk taking between the two parties as to who will pay for the cost of the uncertainty. This can be influenced by the type of contract that is in place and becomes an interesting facet of estimation only seen through experience. From either standpoint, a better characterization of uncertainty is desired to limit the negative impact that can result from the estimation process.

A very important thing I have taken away from my thesis studies is my understanding of how estimation is more closely related to design than is typically recognized. My literature search revealed that there are not many formal connections between these two areas of study, yet there is no reason this should be the case. The estimation process is essentially a high level design exercise that must take place prior to making a good estimate. Portions of cost estimation incorporate this idea, but the focus on design can be lost. Although only touched upon lightly in this thesis, a case for improving estimation by linking these two areas has been made.

The Validation Square is a unique tool in that it serves as a logical framework to evaluate the performance of a proposed method. The Validation Square focuses the work related to designing a method on the generation of a method that will be effective in a given environment. The use of this technique proved to be extremely useful because this was my first time really generating a method from a clean sheet of paper. I had preconceived notions of what needed to be a part of the method, but rigorously following the Validation Square prevents the designer, of a method in this case, from overlooking important steps in the generation of that method. The prescriptive format ensures the designer addresses all logical questions that can arise and most importantly results in a set of assumptions that limit the use of the method. If these assumptions are not explicitly stated, then it is easy to misuse a method expecting a result that may not be achievable given how the user is applying the method. The use of the Validation Square also served as a roadmap to make the reader aware of the objective of any given section within the thesis while also helping to focus my own work. I think this is point becomes increasingly important as a document becomes larger because it cannot be easily read or internalized in one continuous reading. The bottom line is that the Validation Square is exceedingly helpful to force a strong logical framework to any engineering argument.

The previous anecdotes of learning are important pieces of information to take away from this thesis development. Although, to provide more value to a potential estimator I feel it would be more useful to generate a list of tips that will help those that may use this methodology in the future:

The proposed method should be changed to meet your needs

The proposed method should not be considered the final solution. It requires some improvement as stated previously, but more importantly the method needs to be tailored to the needs of the estimator that is using it. I recommend using the tools that are familiar to the estimator, but recognizing the real benefit of applying the core components of the method. The core components being checks and balances by establishing goals, recognizing the importance of requirements, abstraction of designs, and the consideration of using work planning tools.

The proposed method is not literal – it is an attention directing tool

Many engineering tools are incorrectly viewed as a final word or solution when they are not. Most engineering tools are attention directing tools for engineers or in this case, estimators. This notion is something that should be considered carefully. If the initial goals are exceeded by 3%, then maybe the solution is still valid. Users of this method must be careful in how they use it and understand there are external factors that can affect the end result. Estimation can be very subjective and the proposed method is a way to reduce that subjectivity, but at the same time retain some flexibility by the estimator.

The importance of requirements cannot be overstated

Requirements, thresholds, objectives, demands, etc. – many terms can be used for the same piece of information which in all cases is the article resulting from clarification of the task. A more familiar way of stating this perhaps is that, “garbage in equals garbage out.” Lacking appropriate details in requirements can result in large variations related to the estimate. This problem is oftentimes preventable and an estimator really needs to consider the potential for negative impacts by trying to take short cuts during this portion of estimation.

Work planning tools need to be used carefully

As stated in the thesis, work planning tools refer to a set of tools developed in this thesis that assist the estimator in assigning engineering resources in a methodical fashion. This idea was not explored in depth, but there are several major benefits that could be realized at an organizational level if this notion was implemented properly. Prior to doing this, an organization needs to address the human resource challenges primarily related to misuse of such tools. If these challenges are not addressed, a level of distrust could form within the staff creating more harm than good.

I consider the previous statements to be very important to future implementations of this method and recommend careful consideration of these four statements prior to doing so. If used as intended, I feel this method could grow into a nice standalone estimation tool for prototype system developments.

As always, I strive to improve the efficiency of organizations that I am a part of and hope to do so at the Georgia Tech Research Institute (GTRI). I feel the results of this document can form the basis for a handbook or manual that may be useful among the various estimators within GTRI – especially those generating estimations with less experience in estimation. My goal is that the personal learning I have taken away from generating this thesis be passed along to others at GTRI and beyond. As natural resources begin to diminish in this world, we must learn to be more efficient through better use of technologies. This is one small effort of contribution towards that goal.

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