Trade Study Methodology for a Helicopter Modernization Program

By

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Abstract

An emerging trend in the aerospace industry is the increasing tendency towards refurbishment, upgrading, or enhancement of existing platforms. Several factors have influenced this trend, the most influential being that the gestation period from initial design concept to an operational aircraft continues to increase over time, the norm now extending over 20 years. With respect to projected trends in the military helicopter sector, it is forecasted that by the year 2007 more than 21% of the world helicopter market will consist of remanufacture programs, up from 8% in 1998 [Veloc1999a]. As a result, a significant portion of the military helicopter business in the foreseeable future will be derived from the refurbishing or modernizing of current helicopter platforms. The issues of structuring a helicopter modernization program so that the aircraft remains a viable platform for several decades requires an orderly and comprehensive trade study analysis of both the product and the process by which the product is remanufactured. Trade studies performed during the preliminary design phase play an integral role in determining the configuration of the helicopter modernization effort.

This thesis proposes a system engineering methodology for performing preliminary design trade studies for a helicopter modernization program. Specifically, it addresses the issues of how to evaluate candidate upgrades for a helicopter modernization program using an example from the UH-60A (BLACK HAWK[1]) Modernization Program as a case study.

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[1] BLACK HAWK is a registered trademark for the UH-60A helicopter.

Biography

The author, Mike Ambrose, is a Senior Design Engineer in the Advanced Design and Business Development department at Sikorsky Aircraft. My responsibilities in Advanced Design include performing preliminary design trade studies for new concept helicopters and modernization alternatives for existing helicopters. Past assignments at Sikorsky Aircraft have included Airframe designer and supervisor. While in Airframe Design, I had the privilege of working on many different helicopter platforms, including helicopters for the Royal Australian Navy, the United States Coast Guard, and a prototype light attack helicopter for the United States Army. In addition, I served as the technical point of contact with a Japanese partner during the prototype development of a commercial helicopter. During my 15-year career at Sikorsky, I have received two engineering recognition awards and currently have a patent-pending for a sliding door mechanism. I graduated Summa Cum Laude with a B.S. in Mechanical Engineering at the University of New Haven in 1984. While at the University of New Haven I set seven school records in track and was selected to the University's Athletic Hall of Fame in 1991. I will receive my Masters of Science in System Design and Management from the Massachusetts Institute of Technology in February of 2000.

Acknowledgments

This thesis work would not have been possible if not for the support given by my family, friends, coworkers, Sikorsky Aircraft, United Technologies, my classmates, and the SDM staff. However, there are some people that I would like to specifically thank. First and foremost, I would like to thank my wife Diana and children Adrian and Sarah for not giving up on me through some very difficult times. You definitely deserved better than what I gave you over these past two years. It will be a fantastic feeling to be a father and husband full-time again. I would like to remember Pete Fox who encouraged and lobbied for me to apply for the SDM program. Even though you are retired now, you can still share in my accomplishment. I would also like to acknowledge my supervisors and company advisors, Chris Van Buiten and Keith Mcvicar. Their insight and passion for helicopters has truly been an inspiration. In addition, the patience and understanding they showed towards me while I tried to juggle work, school, and home enabled me to keep some of my sanity over these past two years. Of particular mention is my thesis advisor, Charlie Boppe. The diligence and thoroughness you have consistently provided to me over the past year has enabled me to produce quality research and a quality thesis.

After having been out of formal schooling for 13 years, I was very apprehensive about undertaking the challenge of going back to school at an institute of MIT's caliber. However, with the encouragement and support of the people mentioned here, I have been able to not only survive the program, but take with me an immense sense of achievement for what I have accomplished. This thesis is a culmination of my studies at MIT. It is my hope that the body of work enclosed will prove to be a valuable reference for preliminary design engineers for years to come.

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Introduction

The aerospace industry today is characterized by the astronomic development costs associated with creating a new platform, particularly with respect to military aircraft. The helicopter industry is no exception to this phenomenon, with the cost of developing a new helicopter platform being several billion dollars. Resultantly, the U.S. military has no new helicopter platforms planned until the Joint Transport Rotorcraft (JTR), which is scheduled for production in the year 2020. The large startup costs have forced the U.S. military to look towards refurbishment or modernization programs of existing helicopter platforms to extend their useful life well beyond the initial objectives.

A distinction needs to be made between a pure refurbishment program and a modernization program. For the purposes of this thesis, a refurbishment program refers to the reconditioning of a helicopter airframe to extend its useful life without consideration for enhancing the performance or capabilities beyond what the structure was originally designed for. A modernization program on the other hand goes beyond a refurbishment program. A partial list of recent and current helicopter modernization programs is shown in Table 1. In a modernization program the capability and performance of the aircraft is enhanced to meet the projected requirements over the expected life extension of the aircraft.

Helicopter	Customer	Manufacturer
VH-3	Marines / U.S. President	Sikorsky
CH-47	U.S. Army	Boeing
SH-60B	U.S. Navy	Sikorsky
HH-60G	U.S. Air Force	Sikorsky
UH-1	U.S. Army / Marines / Air Force	Bell

Table 1: Partial List of Recent & Current Helicopter Modernization Programs

Of course there are trade-offs to consider when determining how much an aircraft can be altered during remanufacture to meet all the projected requirements over the expected life extension, which could extend 20 years or more. Selecting a countermeasures system to protect against future threats, a cargo hook capability to meet future external lift requirements, or a propulsion and blade configuration to meet projected range and speed requirements are all constrained by the architecture of the existing aircraft platform. Unlike a new platform design that essentially starts with a clean sheet of paper (or blank computer screen), a modernization program is constrained by physical constraints imposed by a platform that was designed several decades ago. Often the platform was designed to requirements and mission scenarios that are out-dated or inadequate to meet future needs. In addition, the cost of the modernization program is also constrained since the cost of an upgraded aircraft is usually bounded by the cost of new aircraft. The schedule is usually driven by the age of the fleet and also by the need to maintain a minimum percentage of fleet availability.

In order to produce an upgraded helicopter that is capable of being a viable platform several decades into the future and meet cost and schedule objectives, a comprehensive trade study methodology is necessary. Trade studies exist in many different forms and are performed in every phase of project. However, the basic structure of all good trade studies follows an orderly, efficient, and quantifiable process. This process or methodology should be tailored to meet the unique characteristics of a project. In the case of a helicopter modernization program, the trade study methodology is tailored to work within the constraints of an existing architecture. This limits the design trade space and influences the prioritization of the customer needs among other things.

Of particular importance are the trade studies performed during the preliminary design phase. The decisions made during the preliminary design phase have the greatest impact on life cycle costs of any product phase. This is the case because preliminary design engineers have the responsibility of capturing the voice of the customer and translating their needs into quantifiable design characteristics. The design characteristics establish the requirements for the product designers to perform detail design.

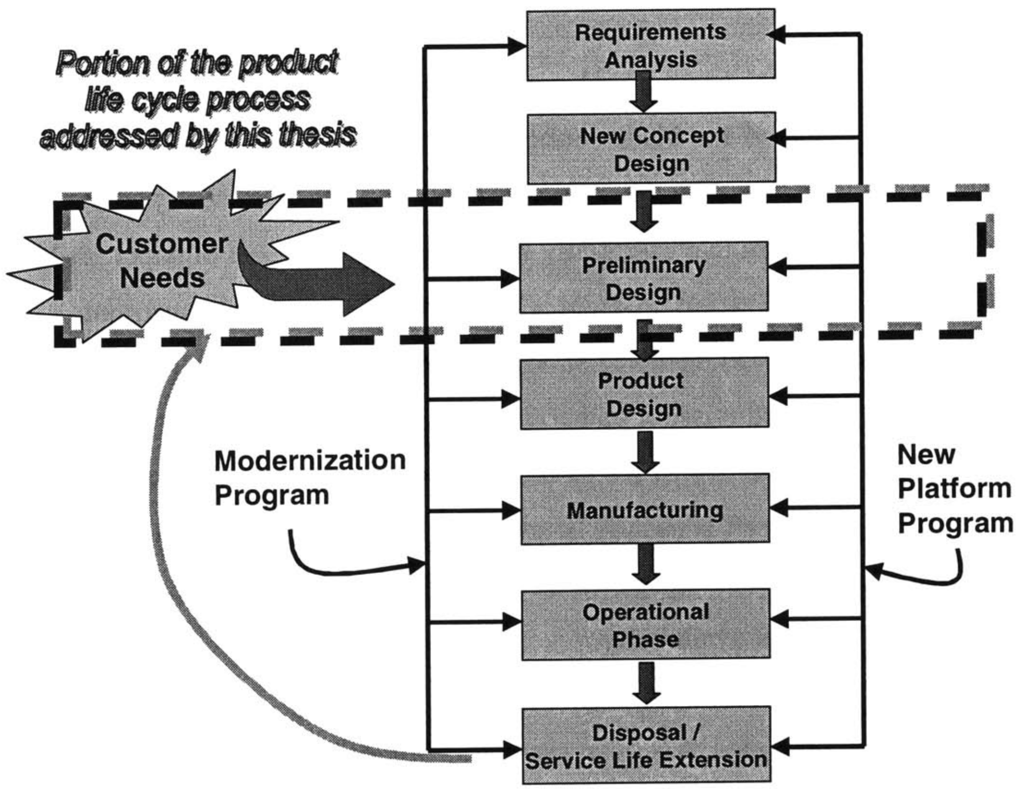


Figure 1: Portion of Modernization Project Product Life Cycle that is Studied in this Thesis

Recognizing the importance of the decisions made during the preliminary design phase, this thesis attempts to define a comprehensive trade methodology that is general enough to be used for all types of projects. The fact that the trade methodology is applied to a helicopter modernization program is an acknowledgement of the complexity and large number of criteria / constraints that are associated with this type of project. The criteria and variables are too numerous for a designer or even a team of designers to visualize in their heads, let alone conceptualize viable alternatives. Therefore, a structured approach based on proven techniques are required to ensure that the voice of the customer is properly captured in the product design requirements for a helicopter modernization program.

The modernization project chosen for this thesis is the U.S. Army UH-60A (BLACK HAWK) helicopter. The first BLACK HAWK's are scheduled to reach the end of their useful life by the year 2002. Preliminary design engineers at Sikorsky Aircraft are currently working with the U.S. Army to define the configuration for a modernized UH-60A (commonly referred to as the UH-60L+). This thesis examines how the proposed trade study methodology was applied to a subsystem trade study as part of the preliminary design effort for the BLACK HAWK modernization program.

It is the expectation of the author that this thesis will accomplish the following main objectives:

- To provide a systematic approach for conducting large-scale preliminary design trade studies.
- To provide tailored system engineering tools for qualifying and quantifying preliminary design trade studies.
- To demonstrate how this systematic approach for performing trade studies can be applied to a helicopter modernization program.

With these customer's objectives in mind, and the realization that customers needs are becoming increasingly more complex and demanding, it is necessary for preliminary design engineers to embrace a structured approach for conducting trade studies. The methodology that follows is a means by which preliminary design engineers can execute complex trade studies such as the one analyzed in this thesis.

Finally, even though the methodology is tailored for helicopter modernization programs, it can easily be modified to for all types of preliminary design trade studies. The basic structure and methodology can serve as a roadmap and example of how to use system engineering tools to comprehensively analyze complex trade studies.

Thesis Statement

This thesis proposes a general methodology for performing preliminary design trade studies as they apply to helicopter modernization programs, describing each of the phases that encompass a comprehensive trade study. Written from the perspective of a design engineer, this thesis is intended to articulate the steps that a designer needs to perform in order to conduct a comprehensive trade study. In addition, the designer is faced with the challenge of understanding the interaction between the numerous attributes associated with a complex product, which drives the designer to search out for a formal methodology to assist in the trade study evaluation. The primary objective of this thesis is to provide the design engineer with a structured, yet flexible methodology to use as a 'roadmap' for performing preliminary design trade studies. A helicopter modernization program was selected as the focus for the thesis because of the trend towards extending the useful life of today's existing helicopter platforms. Modernization programs contain many unique issues that distinguish them from a new design and therefore it is one of the intentions of this thesis to address these unique characteristics.

Utilizing Quality Function Deployment (QFD) as the foundation for the trade study methodology, the thesis describes how to sequentially capture the 'voice of the customer' to produce a trade study recommendation that best meets the needs of the customers. In the context of a military helicopter modernization program there is usually one primary customer; however, this 'customer' is in actuality many different customers that have conflicting needs. Deciding how to integrate the various customer requirements into the design process is a major objective of this thesis.

Validation of the methodology will be through an analysis of the Sikorsky UH-60A (BLACK HAWK) Modernization Program, using one of the sub-systems as a case study for the validation. The sub-system to be used as the case study was the cabin section of the airframe. It was selected because of its high level of complexity and potentially large impact on the cost, weight, and schedule of the BLACK HAWK modernization effort.

Overview of the Methodology

Overview

The methodology proposed for evaluating upgrades for a helicopter modernization program combines Pugh's [Pugh1991a, pg.74, 75] method of controlled convergence as applied to concept generation with Quality Functional Deployment (QFD) techniques as defined by Hauser and Clausing [Hause1988a]. While basically adhering to the guidelines of the classical QFD process, the methodology proposed has been tailored to meet the unique structure of a helicopter modernization program and is summarized by the six-phase process described below:

1. **Data Collection (Identifying Customer Needs)**
2. **Data Structuring and Prioritizing**
3. **Building the QFD Product Planning Matrix**
4. **Trade Alternative Evaluation**
5. **Risk Benefit Analysis**
6. **Implementation Strategy**

The methodology proposed provides a 'big picture' framework to contain and control the design trade space. As described by Pugh [Pugh1991a pp.74, 75], the controlled convergence method as applied to concept generation recognizes the natural convergent (analytic) and divergent (synthetic) tendencies of the concept generation and evaluation process. By implementing a framework of controlled convergence into the trade study, it is easier for the design team to recognize and plan for the iteration that is inevitable in the design process. In addition, the controlled convergence methodology is structured to 'carry' design alternatives far into the development process, while allowing for new alternatives to emerge. Because the method is iterative, continued iteration alternately expands and contracts the matrix until such time as the best concepts emerge, and one has converged as the preferred concept.

An important feature of the methodology is that the QFD process feeds the downstream phases. Specifically, the attributes and the technical characteristics, along with their corresponding relationships and interactions, are used as the basis for alternatives generation and subsequent trade alternative evaluation. In addition, the technical characteristics derived from the QFD process are used to identify candidate metrics for the risk / benefit analysis. In this respect, the QFD process indeed forms the foundation for the methodology.

Figure 2 depicts the trade study methodology proposed for the helicopter modernization program.

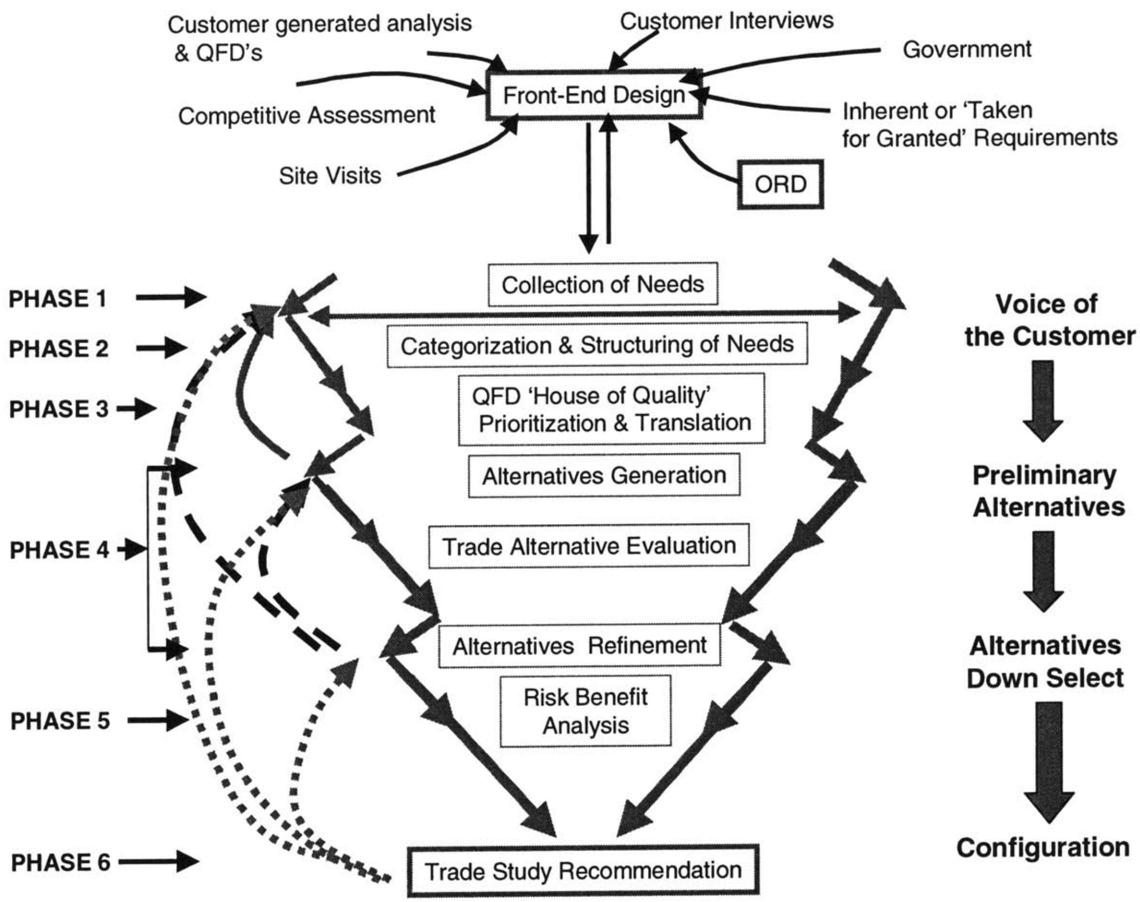


Figure 2: Controlled Convergence Approach Applied to the Product Planning Phase of a Helicopter Modernization Program

Phase One: Data Collection Phase

Overview

Phase One (Data Collection) is critical to the ultimate success of the program and involves collecting the needs and requirements of the various customers. In this context, the customer is not just limited to the primary end user of the helicopter. This viewpoint is supported by Hauser and Clausing [Hause1988a] who stated that "not all customers are end users," also Tseng and Jiao [Tseng1997a] who described 'customers' as including anyone downstream of the design team in the product realization process. With respect to a system as complex as a helicopter, these additional customers include potential end users other than the primary customer, manufacturing, R & D, logistic support, and suppliers among other stakeholders. A legitimate question that may be asked is: "Why should these other stakeholders also be considered customers?" In the case of a military helicopter modernization program, there is usually one primary customer who is paying for the program. However as will be explained later, in terms of providing the best overall product, it is crucial to consider the input of as many stakeholders as feasibly possible. Even the primary customer can in actuality be a conglomerate of many different customers, each with their own priorities and objectives. In the case of the U.S. Army, some of these constituent customers are shown in Figure 3.

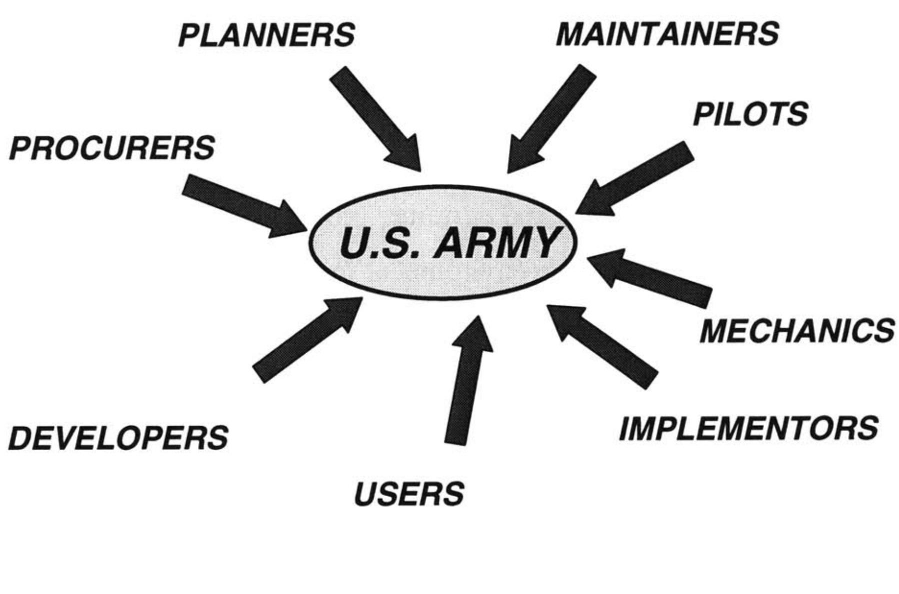


Figure 3: U.S. Army Constituent Customers

Some of the sources from which customer needs are derived for a helicopter modernization program include:

- Requirement Documents (ORD), System Performance Specifications (SPS)
- Customer Interviews
- Observation (site visits, media, publications)
- Competitive Assessment

Requirement Documents

The requirement documents are synonymous with military programs and provide the starting point for the product planning process. The requirements document in the form of an Operational Requirements Document (ORD) contains the customer's initial characterization of the objective and threshold requirements for a particular project. The ORD development is often an iterative process that gets refined as the customer acquires feedback from suppliers and users.

Customer Interviews

Customer interviews often provide a clarification and/or substantiation for the information provided in the ORD. Additionally, customer interviews in the form of working meetings can be particularly beneficial because they often bring out underlying reasons for some of the customer requirements. Customer interviews can also help define acceptable upper and lower bounds for meeting objective requirements. The Internet has provided new ways of soliciting customer information that complements the customer interview process. On-line surveys and customer product design tools (see Van Buiten, [VanBu1998a]) create an interactive environment for customers to communicate with suppliers through a website, thereby minimizing the cost of conducting on-site interviews and also providing the customer with a valuable tool for articulating their needs.

Direct Observation

Direct observation of the customer is a marketing research tool often used by consumer product manufacturers. Observing the customers in action can be a very effective tool for extracting ambiguous or poorly articulated customer needs. As applied to a helicopter modernization program, observation in the form of field visits can provide a level of insight into customer issues that can not fully be captured in the ORD, or even through customer interviews. Direct observation is also an excellent method by which latent customer needs are uncovered. Observing the product in use can be an eye-opening experience for a supplier, since often the product is used and /or maintained in ways that were not predicted or understood adequately through documentation or interviews. For example, observing how a particular customer uses their helicopters, and in what type of environment, can shed insight into why their helicopters have higher maintenance costs than other customers using the same helicopter.

Competitive Assessment

Ulrich and Eppinger [Ulric1995a] recommend that competitive assessment of related products can reveal existing fixes or approaches that have already been implemented to solve a particular problem, in addition to providing a rich source of ideas for both the product and process development of the new product. They further state that competitive assessment is performed in support of the specification activity as well as in support of concept generation and concept selection. With respect to a helicopter modernization program, competitive assessment provides the opportunity to acquire lessons learned from similar programs, while at the same time providing some level of benchmarking for cost and scope of work comparison. In fact, competitive assessment of similar in-house products can be the most significant source of data when it comes to estimating cost and scope of work estimates for a new product. Competitive assessment can also be beneficial where precedence can function as a point of reference when the team might have difficulty deciding on a particular direction.

Phase One Summary

The Data Collection phase provides the best opportunity for a company to collect the various stakeholders' needs. Once the subsequent phases have begun, adding or modifying customer needs will result in rework of already completed efforts. In order to mitigate this possibility, an effort should be made to encourage the customers to re-evaluate and better conceptualize their needs as more data is collected. To facilitate the effectiveness of this process, it is necessary for the design team to solicit customer needs from as many sources as possible. During the data collection phase, a conscious effort must be made to avoid formulating concepts to meet specific customer needs. One method for minimizing the potential to bias the data collection is to assign different engineers to collect the data than the engineers who will do the subsequent phases.

Phase Two: Data Structuring and Prioritizing

Overview

Phase Two (Data Analysis and Prioritizing) of the process is the phase in which customer needs are categorized, through decomposition and aggregation, and ranked in order of importance. It is also the first opportunity to consider the risks associated with various needs. In some respects this the most difficult stage because of its potential for subjective decisions. The major benefit of this phase is that by screening the data before the creation of the QFD 'House of Quality' it is possible to obtain a better understanding of how the customer needs map into technical requirements. Often customer needs conflict with one another, or the needs of one customer might complement the needs of another. Another factor to consider is that while QFD can be a valuable tool for correlating perceived customer attributes into appropriate technical requirements, care must be taken in interpreting the various customer needs. By screening, categorizing, and ranking the customer needs, the QFD process is more likely to yield an accurate translation between key customer needs and the product definition.

Several publications written about the QFD process also agree that a preprocessing of the customer needs can be very useful for preparing for subsequent efforts [Griff1993a], [Matzl1998a], [Porta1990a]. By preprocessing the customer needs before entry into the QFD matrix it is possible to structure the customer needs to allow for a partitioning and decomposition of the needs into categories. This subsequently permits an analysis into trends and conflicts within the customer needs that could potentially be resolved before the creation of a QFD matrix. It also provides a level of assurance that the customer needs are captured at the right level of quantification. [Porta1990a] provides an illustration of how a Product Planning QFD matrix had to be regenerated because the customer needs were interpreted at such a detailed level that they were actually design requirements (the '*HOW's*' instead of the '*WHAT's*'). There are several tools for accomplishing this structuring effort, with affinity diagrams and clustering techniques being among the most popular.

Affinity Diagramming Process

Affinity diagramming is essentially a group consensus process where the objective is to get group buy-in to the structuring of the customer needs. This process is the most popular technique for structuring needs since it doesn't require as large an investment as other techniques. The process works in a brainstorming environment where a group first segregates the customer needs into similar-themed 'piles', and then consolidates the duplicate and comparable need statements into representative topics. The process continues until the group has segregated the topics into distinct and descriptive categories. The objective of this process is get the group to agree on the partitioning of the customer needs and also to come to a consensus on what is needed with respect to the voice of the customer. Care should be taken during this process to ensure that the group is capturing '*WHAT*' is desired in terms of the customer and not '*HOW*' the need is to be obtained.

One potential disadvantage to a group consensus process is that there is no guarantee that the resultant characterization of the customer needs actually represents how customers perceive their needs or make decisions. Figure 4 shows a portion of the affinity diagram created for the case study used in this thesis. Note that the customer requirements listed are purposely vague but correspond to '*WHAT*' is required in terms of customer needs. Also note that the needs are partitioned into specific groups representing similar-themed items.

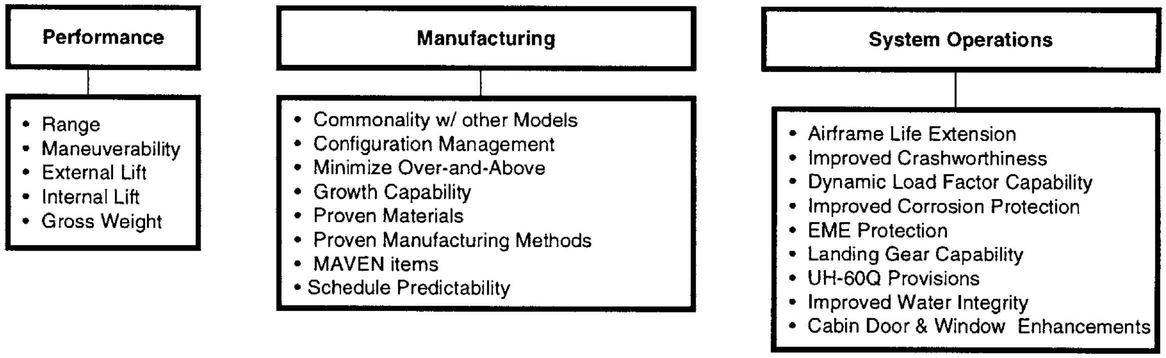


Figure 4: Partial Example of an Affinity Diagram

Customer-Sort and Cluster Process

Another method for structuring customer needs is called the customer-sort and cluster process. It is based on clustering techniques [Griff1993a]. This process is similar to the group consensus affinity diagramming process except the customers do the structuring. This method is used more often with consumer type products such as household appliances where one-on-one interviews and focus groups have proven to be an effective means of collecting customer needs.

The way in which this process works is that customers sort the need statements into 'piles' consisting of similar needs with each pile differing from the other piles in some way. No restriction is placed on the number of piles and the interpretation of how similarity is defined is left unspecified. After the customer completes the sort, a single representative need is selected from each pile, called an exemplar. After all of the customer sorts have been completed the results are analyzed to determine co-occurrence. Typically this is done by creating a co-occurrence matrix in which the number of customer respondents who placed a need *i* in the same pile as need *j* are tabulated. Also the number of times each need was chosen as an exemplar is counted.

Studies conducted at MIT [Griff1993a] have demonstrated that a customer sort aggregation provided a better mapping to the 'customer's voice' while the group consensus affinity diagramming produces a good system-engineering description of the problem. Qualitatively, the affinity diagramming method structured the customer needs in terms of an engineering view and the customer sort structured the needs to reflect product use.

While the customer sort process has proven to be an effective means for capturing the customer's voice with consumer products [Griff1993a], there appears to be very little data on its application to products as complex as a helicopter. In addition, when using this type of process for structuring customer needs for an application where there is a clear dominant customer, consideration should be taken into applying a weighing factor for determining the partitioning of the needs. This is certainly not a trivial decision and could easily bias the results in an inaccurate manner. Another interesting aspect to consider is the cultural issue of applying a technique that is most associated with consumer products and using it in a military environment. Obviously, getting a large sampling of customers is advantageous to capturing the voice of the customer. However, in a military environment is it possible to get to the right customers in sufficient quantity to produce meaningful results? In all likelihood, worthwhile data could only be obtained through a major undertaking by the team performing the survey. Whether this effort could fit within the schedule and scope of the trade study are the primary concerns to be considered by the evaluation team.

Types of Customer Needs / Requirements

Regardless of the method used for structuring and prioritizing customer needs and their corresponding product requirements, it is important to differentiate the types of customer needs into a logical partitioning. Matzler [Matzl1998a] distinguishes three types of product needs that influence customer satisfaction in different ways:

- Threshold or 'Must-Be' Needs
- Objective or 'One-Dimensional' Needs
- Attractive Needs (i.e. implied, unarticulated, unexpected)

Matzler describes that by partitioning the customer needs into the discrete categories listed above, it is easier to measure how the various needs influence customer satisfaction. Figure 5 shows a graphical description of how the various types of needs are correlated with customer satisfaction. The partitioning of needs works very well in a helicopter modernization program and is an effective starting point for the structuring of the needs.

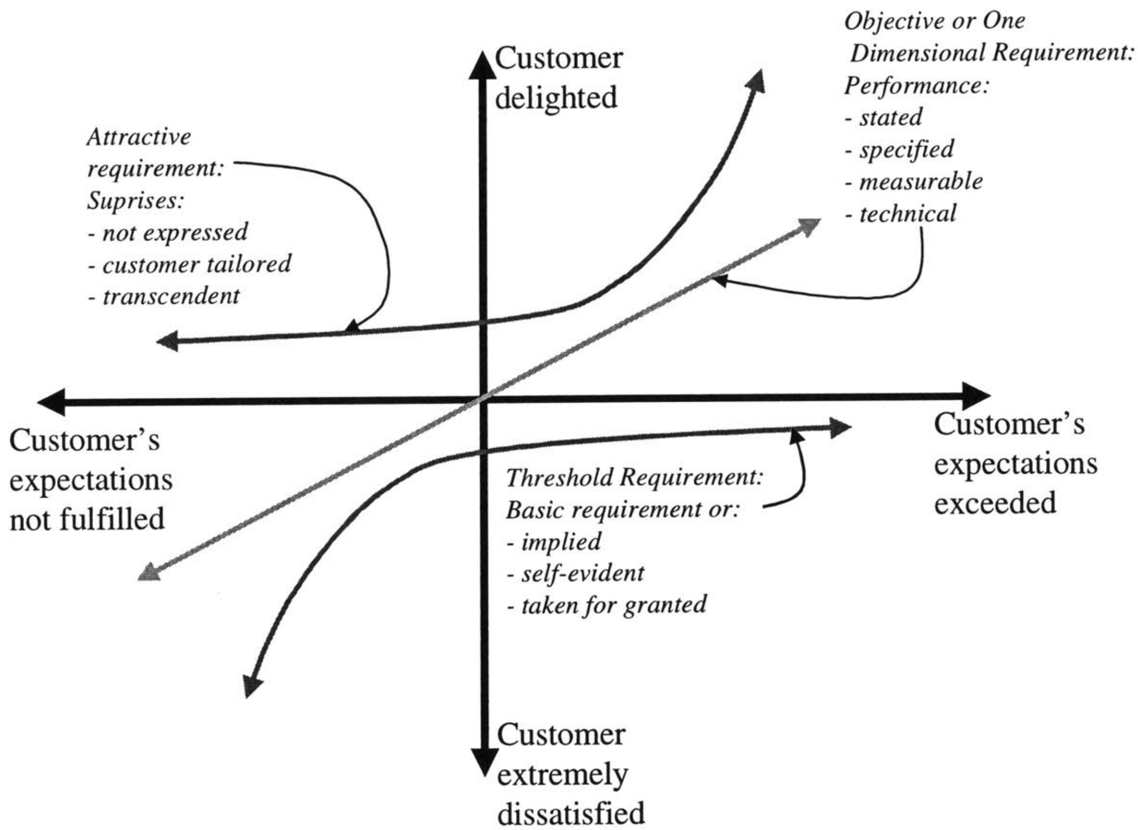


Figure 5: Correlation Between Customer Needs and Customer Satisfaction Kano's Model of Customer Satisfaction [Berge1993a]

Threshold Needs

Threshold needs are criteria that the customer deems required for the acceptance of a product. An example of a threshold requirement could be that an aircraft must be capable of flying 150 NM while carrying an external load of 9000 lbs. in ambient conditions of

95 degrees F at 4000-ft altitude. This requirement is non-negotiable and therefore in many respects becomes a constraint on the structuring and prioritizing of the customer needs. Matzler [Matzl1998a] states that the customer regards the 'must-be' requirements as prerequisites and that fulfilling them will not usually increase the customer's level of satisfaction. Resultantly, fulfilling the 'must-be' requirements only leads to the customer being 'not dissatisfied'.

Objective Needs

With respect to objective needs, Matzler [Matzl1998a] says that customer satisfaction is proportional to the level of fulfillment – the higher the level of fulfillment, the higher the level of customer satisfaction. The ORD usually contains many of the objective requirements for a military project. Because objective needs are so 'one-dimensional' they are often in direct conflict with other customer needs.

Attractive Needs

Matzler [Matzl1998a] describes attractive needs as "product criteria which have the greatest influence on how satisfied a customer will be with a given product. Attractive requirements are neither explicitly expressed nor expected by the customer." Resultantly, these needs are often latent in nature and fulfilling them will lead to more than a proportional level of satisfaction. Interestingly, if these needs are not met, there is no feeling of dissatisfaction. Attractive needs can also encompass product or service features that exceed customers' expectations thereby enhancing the level of satisfaction or perceived value of a particular need. Often, fulfilling attractive needs can result in an added level of differentiation with competing products or alternatives. An example of an attractive need with respect to a helicopter modernization program is involves the incorporation of high speed machining (HSM) technology to save weight and cost in the airframe structure. While HSM technology in itself is the means through which threshold or objective requirements are achieved, the implementation of HSM technology could also result in the fulfillment of attractive needs being met. For instance, reduced corrosion through the elimination of faying surfaces would not be the primary benefit of using HSM technology but provides an attractive incentive that would not be readily obvious at first glance.

Summary of Structuring Techniques

In summary, there are inherent benefits and shortcomings with both the affinity diagramming process and the customer sort process. The affinity diagramming process encourages company buy-in to the structuring of the needs and usually aligns better with the product development structure. In addition, a company probably has a more 'global' perspective of the product needs than any one customer does because of the interaction with numerous stakeholders. While it has been largely accepted that the customer sort process is better at capturing the voice of the customer, with respect to a complex product it might be impractical to integrate and weigh all the various stakeholder needs. In an ideal environment, both the affinity diagramming and customer sort techniques done in parallel would probably yield the best mapping between the voice of the customer and structuring of the needs.

With respect to a helicopter modernization project, where feasible, the most practical approach is to use the affinity diagramming process and substantiate it with stakeholder feedback. The emphasis will be on carefully selecting stakeholders who best represent the voice of the customer for a particular need. Ideally, this process would include face-to-face meetings between the various stakeholders and the team responsible for structuring the needs. The expectation of this phase is that by analyzing the customer needs in a deliberate and ordered manner it will be possible to develop a hierarchical structure of the customer needs for later use in the QFD 'House of Quality'.

Determining the Relative Importance of the Needs

Deciding how to prioritize the customer needs is the final task that must be performed prior to creating the QFD matrix. The process of prioritizing the customer needs imposes a discipline on the design team that yields insight into the relative importance of the needs as they relate to each other. The prioritization of needs is essential for three primary reasons:

1. To determine which customer needs most heavily influence a customer's perception of the product.
2. To determine which customer needs require the greatest allocation of the design team's resources.
3. To guide the design team when forced to make a trade-off between competing customer needs.

The prioritization or ranking of the customer needs must be done as objectively as possible. Because this task has the potential to be so subjective and therefore bias the results, it is crucial to carefully strategize how it will be carried out. Every stakeholder from the customer, designer, manufacturing engineer to the various managers has some perception of what needs are most important and how they should be implemented. Therefore, even though the team may think they are using a common basis for evaluation, in actuality they are not [Wrigh1998a]. In order to minimize the amount of subjectivity that creeps into the ranking process, it is recommended that a set of ground rules for ranking decision criteria be established before this effort is started. Recommended ground rules are described below:

- Where possible, let the customer suggest the ranking order.
- Always make sure that the ranking correlates back to 'what' is desired in terms of customer needs.
- Suggest an impartial third party review the rankings (here is where experience helps).
- Achieve group consensus on the top one or two needs that will most influence the architecture of the product.
- The ranking is re-evaluated if the primary customer needs change.

The rationale behind the ground rules is that they help a design team to better focus on the task at hand with the expectation that following them helps to mitigate the inevitable politics and diversions that can emerge during this phase. Not adhering to the ground rules for ranking needs might lead to a bias caused by pre-conceived perceptions and/or incorrectly ranked needs.

Of all the ground rules, probably the most significant is the importance of obtaining group consensus on the top one or two needs. Because these needs will be weighted more heavily than the other needs, agreement on these will provide some degree of anchoring to the data structuring. Often it is only a few key attributes that drive a product architecture. Examples of attributes that typically have a significant impact on the architecture are low observable and air transportability requirements. Key attributes such as these could influence everything from the overall shape of the helicopter down to the materials selected for detail components.

Numerical Weighting Techniques

There are numerous quantitative techniques that have been developed [Griff1993a], [Matzl1998a] for ranking customer needs. However, most popular techniques utilize some form of relative weighting system [Cross1994a], [Hause1988a], [Pugh19991a], and [Ulric1995a]. Pugh [Pugh1991a pg. 92, 93] describes a convential weighting technique as follows:

> "The basic form is organized in a matrix format where criteria are placed in order of merit and each is given a weighting factor, which is usually based on a 1-5 or 1-10 scale; the higher the weighting factor, the greater the relative importance of the criteria. The order of the criteria and the values allocated to them are matters of judgement. Next, the alternative concepts are rated in turn against the criteria, and, as with the weighting numbers, are allocated a value on a sliding scale. The concepts that satisfy the criteria best, on a relative basis, are given the highest numbers- again, these are arrived at by judgement. The criteria weighting values are multiplied by the rating values to give a total score for each alternative. The concepts having the highest scores are those that appear to best satisfy the criteria. The main reason for using rating and weighting is that it allows numbers to be allocated to some non-quantifiable parameters – aesthetics, materials,

compatibility, maintenance, etc. – and thus provides a base to which the various types of criteria can be reduced."

The design team must exercise great caution when considering whether to use a numerical weighting technique. While a convential weighting technique can be beneficial in getting the design team to think about the relative importance of the customer needs, care must be taken in treating the results as absolute. The use of weighting techniques commonly leads to a false sense of confidence because the results have a value assigned to them, an assumption that is often ill founded. Griffin [Griff1993a] attributes much of the blame on the self-selection bias that is inherent in a numerical weighting technique. It is important for the design team to remember that this technique relies heavily on the selection of criteria, the relative merits of which must be questioned when working with new technologies or a lack of experience with a particular product or process. [Pugh1991a, pg. 99] cites examples where a rating/weighting technique was used on products that had previously been designed through controlled convergence many years prior. Even when given the final solution, never once did the rating/weighting technique yield up the chosen solution.

Numerical rating and weighting is most useful where a strong correlation can be made to an existing product and where the 'voice of the customer' has evolved through the Product Development Specification into a repeatable set of conditions. For example, if the customer or user always rates reliability above cost, cost above appearance or appearance above complexity, and relationships between criteria become fixed and justifiable then a numerical weighting technique is more effective.

Relative Weighting Techniques

In lieu of using a strict analytical technique for ranking customer needs, this thesis recommends a technique described by S. Pugh [Pugh1991a, pg.98] where the needs are neither rated nor weighted (numerically). Instead, the theory of controlled convergence as applied to concept generation and selection is utilized whereby the needs are graded into categories of importance. Pugh recommends this procedure for concept down select; however, it is equally applicable to weighting customer needs. By ranking the needs into categories (i.e. top, high, medium, low), much of the absolute connotation associated with conventional weighting techniques is removed. This is particularly important when there are many needs that must be ranked. It also alleviates much of the petty disputes over what need should be ranked ahead of another. In summary, the two most important criteria that the team must remember when developing a framework for prioritizing needs are:

1. Agree on what needs are the overwhelming drivers on the architecture and then bracket the needs from there.
2. Make sure that any criteria considered in establishing a relative importance ranking is correlated back to the customer needs.

Phase Two Summary

Phase Two of the helicopter modernization trade study methodology involves taking the customer needs and then sequentially categorizing and ranking them in order of importance. It is suggested to first segregate the customer needs into different types of customer needs as recommended by Matzler [Matzl1998a] and then performing the ranking of the needs. Two techniques for ranking needs were described: numerical weighting and relative weighting techniques. Numerical weighting techniques are best utilized when there is a clear understanding of the customer needs and ranking of importance. Otherwise, relative weighting techniques are a more effective means of ranking the needs.

Phase Three: Building the Quality Function Deployment (QFD) 'House of Quality'

Introduction to QFD Matrices

Once the needs have been structured and classified it is then possible to build the QFD matrices. Portanova and Tomei [Porta1990a] have described QFD "as a method for systematically analyzing a customer's perceptions of what constitutes a highly reliable and operable system and functionally breaking down those attributes to identify the critical characteristics that determine an efficient end product." In applying the principles of QFD, a series of matrices or charts are developed with emphasis on the one commonly known as the "House of Quality" (because of the roof-like format), which identifies and translates the most critical information. Hauser and Clausing [Hause1988a] describe four key types of matrices that effectively convey the voice of the customer from product planning through manufacturing. The four basic types of matrices are:

1. Product Planning
2. Part Deployment
3. Process Planning
4. Production Planning

While the focus of this thesis with respect to the QFD process is on creating the product planning matrix, it should be mentioned that the objective of the linked "houses" is "to develop a process whereby the '*HOWs*' of one stage become the '*WHATs*' of the next" [Hause1988a]. In fact, a future thesis could explore the continuation of the work performed in this thesis by carrying the QFD process through manufacturing for a helicopter modernization program.

Tailoring the QFD Matrix for a Product Subsystem

When developing a QFD 'House of Quality' matrix for a subsystem of the product, the design team must be careful to recognize the boundaries and interfaces of the subsystem to the overall product. In addition, care must be taken to prevent optimizing a subsystem at the expensive of the overall product. In order to alleviate this possibility a thorough understanding of system boundaries, system elements, and system interfaces is required. In the case of a helicopter airframe subsystem, Figure 6 identifies some of the boundaries, elements, and interfaces that encompass the airframe subsystem. The airframe subsystem has been further decomposed into elements representing the major assemblies of the fuselage. This is a convenient partitioning in that each major assembly can be evaluated on its own merit because each assembly is actually a separate product. Even though this figure represents only a small portion of the interfaces, functions, and boundaries associated with a helicopter airframe; it does provide an illustration of how different subsystem elements cross boundaries and interact with other subsystem elements and functions. For example, if a QFD product planning matrix was being developed for the cabin subsystem, the design team would need to be cognizant that increasing the fuel capacity in the cabin section might require changes in the tail cone and tail pylon sections in order to maintain an acceptable center-of-gravity. In addition, the cabin fuel configuration affects such system attributes as performance, survivability, and ballistics.

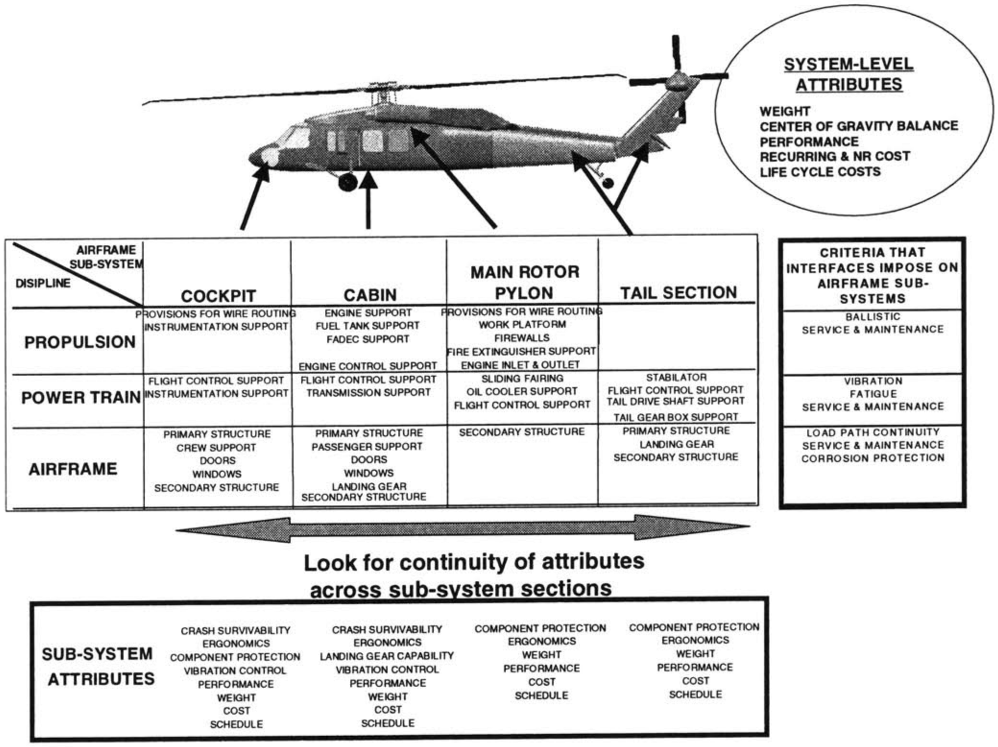


Figure 6: Helicopter Airframe Structure System

Typically the design team will evaluate the relative influence of the various sub-systems on the overall product. What is important is that the team performing the sub-system trade is aware that there are other trades going on and therefore it is critical to understand the interactions between the sub-systems and how they influence the overall product.

The QFD 'House of Quality' Matrix

There are many different approaches that have been developed for applying the principles of the QFD process. Figure 7 shows the QFD 'House of Quality' matrix template used by Portanova, et al. [Porta1990a] for the product planning for an Advanced Launch System (ALS).

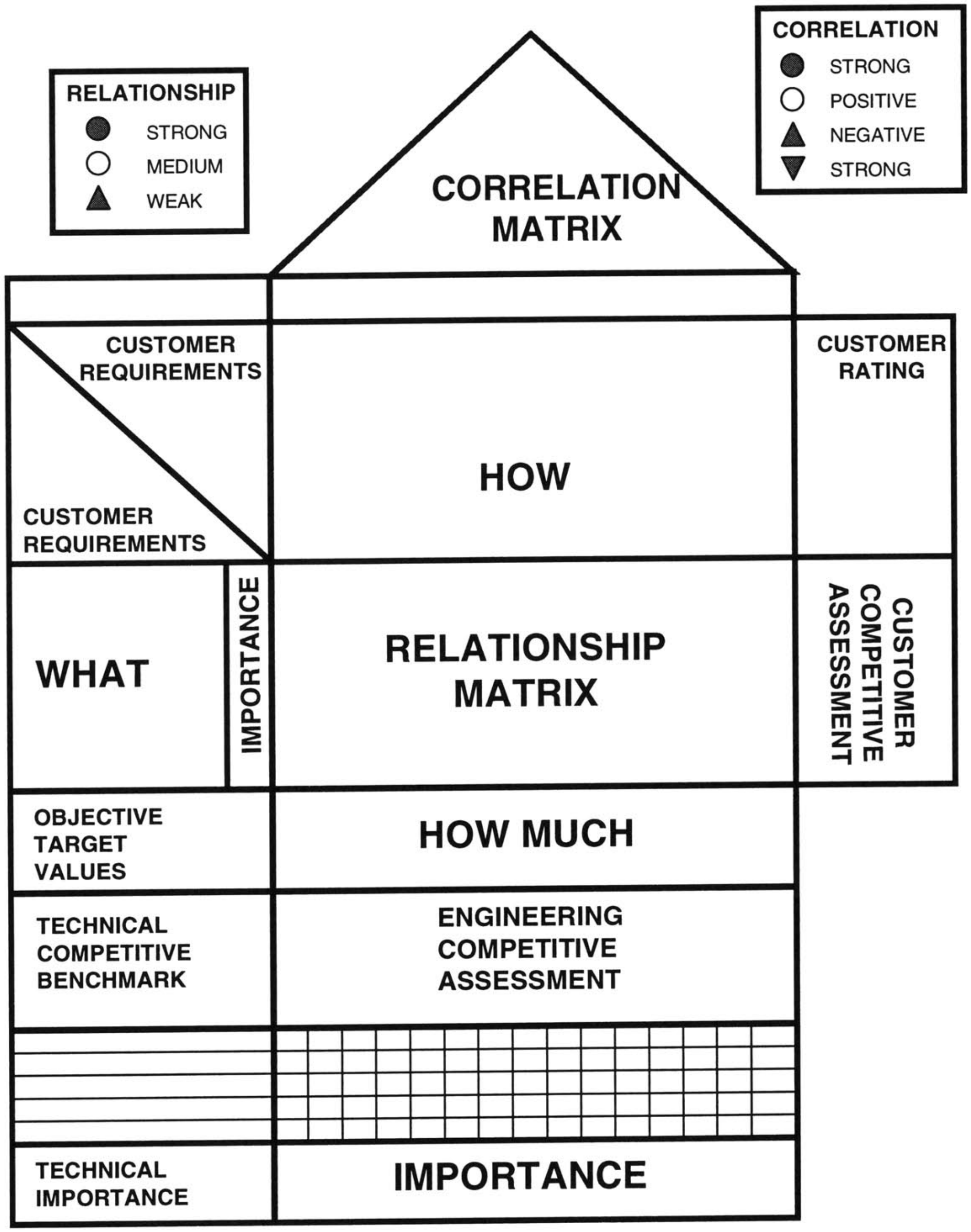


Figure 7: Quality Function Deployment Product Planning Matrix

Source: Quality Function Deployment in Launch Operations [Porta1990a]

Documenting Customer Needs

The first input into the QFD process is the listing of the *WHATs* or 'Voice of the Customer'. Phase One and Phase Two of the trade methodology form the foundation for this list. Care should be taken to maintain the top level character of the *WHATs* at this stage in order to encourage more thorough decomposition later in the trade study.

Establishing Design Requirements

This is the first opportunity for the design team to begin articulating how the customer needs are mapped into a product. This mapping is accomplished by identifying a list of *HOWs* so that there is at least one *HOW* for each *WHAT*. This process ultimately translates each of the customer needs into technical design requirements. Typically, some of the design requirements will affect more than one customer need and may even adversely affect others.

Relationship Matrix

The Relationship Matrix graphically identifies the relative relationships between the *WHATs* and *HOWs*. More specifically, it specifies the customer needs in terms of a product's design characteristics that relate to the needs. Resultantly, the objective of the relationship matrix is to identify those engineering characteristics that satisfy or influence in any way the customer needs. In a helicopter system, the rotor blade configuration and the structural airframe load factor will influence its 'maneuverability' capability.

With respect to creating the matrix, the design characteristics must be real, measurable characteristics which the design team has some degree of control. Note that not all of the engineering characteristics affect all of the product attributes. The relationship between particular attributes is defined at the intersection of the rows and columns that represent the *WHATs* and *HOWs* along with the strength of the relationship. Symbols are used to represent the degree of influence a need has on a design characteristic (i.e. strong correlation, medium, weak, or no correlation). This technique provides a simple graphical interpretation for understanding the complex interrelationship between customer needs and product features.

Portanova, et al [Porta1990a] states that the relationship matrix serves two purposes: "one is establishing a baseline of relative merit for each factor, and the other was fostering a fresh look at the interaction between requirements." Usually this process requires iteration because as the design team gains a better understanding of how the customer needs interact with design characteristics, new perspectives on the need-to-characteristic relationships are extracted. Often new design requirements are identified during the iterations and then added to the technical characteristics.

Technical Requirement Correlation Matrix

Once the relationship matrix is created the next step is to develop an understanding of the correlation between the various technical characteristics. This correlation matrix is added on top of the technical requirements (*HOW's*) section and is characterized as a triangular-shaped 'roof' (hence the basis for the term 'house of quality'). It is in the correlation matrix that the respective technical requirements are compared with each other to graphically depict the degree of correlation (i.e. degree of positive or negative influence). The correlation matrix is also used for identifying potential trade candidates. The design team should take care to remember that often assumptions are made about the final design concept when filling out the correlation matrix. Therefore, if the concept evolution results in the contradiction of any assumptions, the design team must re-evaluate the interactions in the correlation matrix.

Establish Target Values for Design Requirements

In this step, target values are assigned to the measurable parameters of the design characteristics. For the helicopter modernization program these target values are the threshold and objective values that satisfy the customer requirements or improve the helicopter over its competitors or similar internal programs.

Competitive Assessment

When dealing with competitive assessment it is important to know what values the competitors or similar internal projects can achieve for the design characteristics, usually this requires a detailed investigation. With respect to competitor helicopter products, obtaining accurate competitor data is often very difficult. Reliable sources for obtaining competitor data on helicopters include the Farnborough and Paris air shows, trade magazines such as *Vertiflite* and *Rotor and Wing* , and the American Helicopter Society publications and journals. In addition, the Internet can provide a wealth of relevant information, in particular, websites maintained by the DOD, military branches, and manufacturers often contain relevant information on helicopter programs. One of the most valuable sources of information when it comes to a helicopter modernization program is the internal resources of similar or legacy projects. Internal projects can be invaluable sources of data when attempting to quantify values for cost, level of effort, risk, and complexity. The competitive assessment can also function as a sanity check for the target values assigned to the design characteristics.

Summary of QFD Product Planning Matrix Development

The aim of the QFD product planning matrix is to set targets to be achieved for the technical characteristics of a product, such that they satisfy customer requirements [Crossn1994a]. However, as will be demonstrated in the next phase of the methodology, the QFD product planning matrix also helps to identify the trade space for the sub-system trade studies. The development of the QFD product planning matrix can be summarized as follows:

1. List the customer needs as identified in the data collection and sorting phases, assigning relative importance to the needs.
2. Perform a competitive assessment of competitor and similar internal products. Assign performance scores and list them with a corresponding customer need.
3. Create the relationship matrix, defining technical design characteristics that correlate to the customer needs. Where possible, select technical design characteristics that can be quantitatively measured.
4. Establish the relative correlation between the technical design characteristics and customer needs within the body of the relationship matrix. It is recommended that the relative correlation be indicated by a symbol instead of a number since weighted number values often result in over confidence.

5. Create the 'roof' of the matrix, identifying the interactions between the various technical characteristics. This matrix identifies both complementary and contradictory requirements, which represent potential subjects for appropriate trade studies [Porta1990a, pg. 24]. Note that the interactions between the design characteristics can be affected by future changes in the design concept and therefore should be re-evaluated for accuracy.
6. Define measurable target values to the design characteristics. Use competitor assessment and similar internal products as sanity checks for these values.

Phase Four: Performing the Trade Alternatives Evaluation

Overview of the Trade Alternatives Evaluation

The role of the trade alternative evaluation is to achieve a product design that effectively balances the system design with respect to the cost, schedule and performance evaluated across the entire process and product life cycle. A trade alternative evaluation involves a quantitative and qualitative analysis of the design characteristics from the QFD product planning matrix. Metrics are established and sensitivities are studied to see how changes in a technical characteristic influence other characteristics and the product as a whole. The objective is to maximize characteristics that have a positive correlation with a corresponding customer need and minimize those characteristics that have a negative correlation with a corresponding need. The roof portion of the QFD product planning matrix is used to identify design characteristics that are affected by other characteristics, both positively and negatively. The alternative evaluation takes all these factors into account and establishes weightings based on their importance to the customer. When characteristics positively affect other characteristics, opportunities are searched to link these characteristics in the trade alternatives so to maximize (or minimize) their impact on the configuration.

When working with many trade studies as is typical of a helicopter modernization program it is advised to standardize the trade alternative evaluation process. The reason for a standardized process is two-fold:

(1) Documenting the steps and criteria so that all the trades are performed in a similar fashion ensures that there is continuity across the trade studies. This makes it easier for the design team and customer to understand and interpret the various trade results.

(2) A standardized process facilitates the trade alternative evaluation thereby reducing the amount of time required to complete the trade. This is possible because the designers are already familiar with the process and don't need to create a new process for each trade study.

The standardized format used for the helicopter modernization trade studies encompasses the following elements:

<u>Helicopter Modernization Trade Alternative Evaluation Process</u>

1. Document Relevant Requirements
2. List Assumptions
3. Define Relevant Measures
4. Concept Generation ('Developing the Trade Space')
5. Evaluate Metrics & Impact of Related Trades
6. Risk Assessment
7. State Closing Criteria
8. Document 'Revisit' Criteria

While every trade alternative evaluation will contain some unique structure that requires modification of the standardized format list above, a trade alternative evaluation at the very least should attempt to address each of these items.

A generic trade alternative evaluation process is illustrated in Figure 8. Of particular note is that the process is evolutionary in nature and the information needed to develop the trade alternative design space comes from the QFD product planning matrix. Also note that the result of the trade alternative evaluation is usually a recommendation and not a definitive solution. Even if a trade study yields the best technical approach from the perspective of the applicable metrics, there are often other considerations that must be accounted for in addition to the trade study recommendation. Often there are political, strategic, and other extraneous factors that could influence the ultimate trade decision.

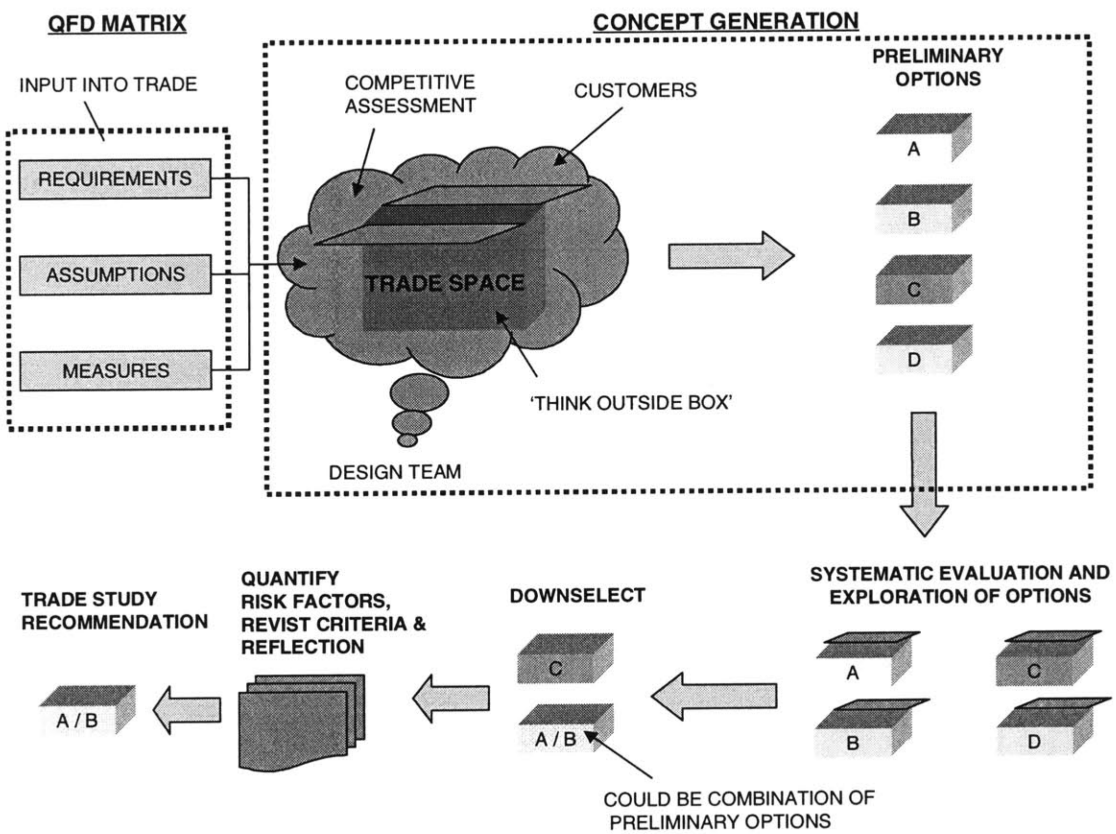


Figure 8: Trade Alternative Analysis Process Flow

Document Relevant Requirements

This is a sub-set of the voice of the customer as it applies to the specific trade study. In the case of a helicopter modernization program, the relevant requirements were obtained during the Data Collection phase and were listed in the QFD product planning matrix.

The primary purpose for documenting the relevant requirements for a trade study is to ensure that the design team maintains a clear focus on the customer needs.

Document Trade Alternative Evaluation Assumptions

Listing the trade alternative evaluation assumptions will help anchor the trade space and is usually required in order to get the trade alternative analysis initiated since the design team usually doesn't have all the parameters defined when the trade alternative evaluation starts. Therefore it is often necessary to make reasonable assumptions and then revisit the assumptions periodically to make sure they are still valid.

Define Relevant Measures

The relevant measures are obtained from the QFD product planning matrix and include target specifications for each measure. Typically this includes comparisons with competitor and/or similar products. Typical metrics that can be measured for a helicopter program include performance, lift, cost, schedule, percent commonality, and weight.

Concept Generation

Ulrich and Eppinger [Ulric1995a] state that " the degree to which a product satisfies customers and can be successfully commercialized depends to a large measure on the underlying concept" and it is through concept generation that the product is derived. Even though the concept generation phase is just one facet of the overall methodology it is among the most important. The objective of the concept generation phase is to explore as many feasible design alternatives as possible early in the design process so that the entire design space is defined. The rationale being that early identification of the design alternatives lessens the chance that the design team will develop a better concept late in the design process or that a competitor will produce a superior product.

Ulrich and Eppinger [Ulric1995a] describe some common dysfunctions exhibited by design teams during the concept generation phase as including:

- Consider only one or two alternatives, often proposed by the most assertive members of the team.

- Failure to consider carefully the usefulness of concepts employed by other firms or other internal products.
- Involvement of only one or two people in the process, resulting in lack of confidence an commitment by the rest of the team.
- Ineffective integration of promising partial solutions.
- Failure to consider entire categories of solutions.

Just as there is a recommended format for performing trade studies, the helicopter modernization program utilized a standardized approach to generating concepts. The standardized concept generation approach developed was intended to minimize the likelihood of some of the pitfalls described by Ulrich and Eppinger and to encourage participation of all the team members including the customer.

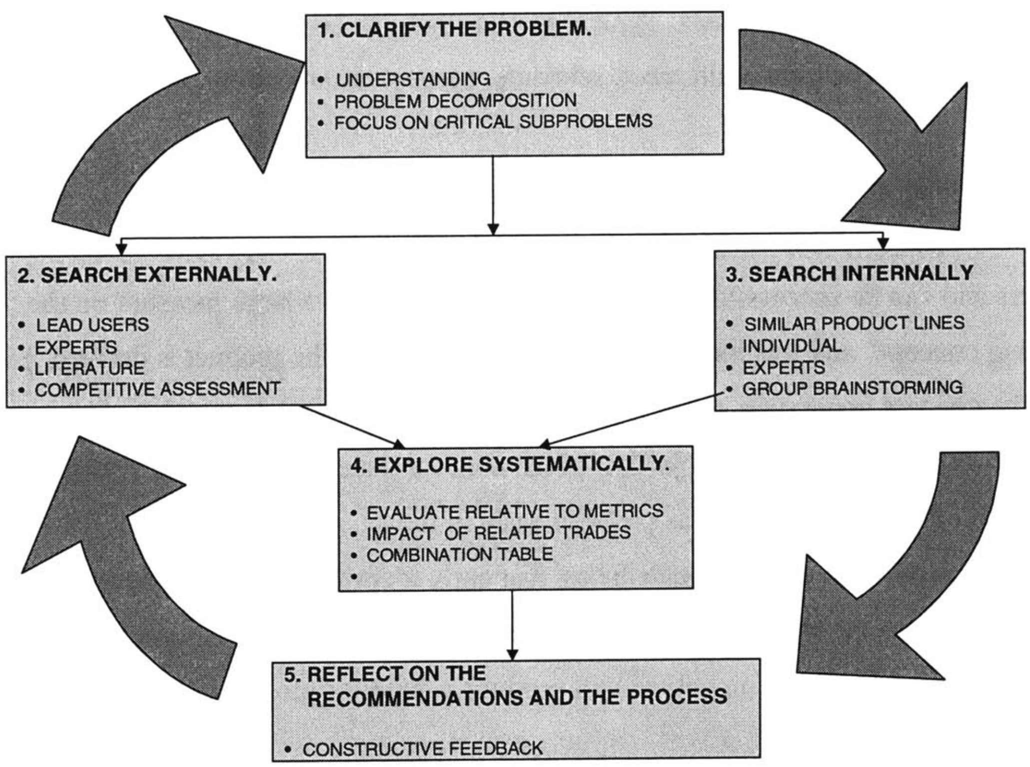


Figure 9: Concept Generation Methodology

(Based on Ulrich and Eppinger Methodology [Ulric1995a]

The arrows in Figure 9 indicate the iterative nature of the concept generation process, whereby each decision should be evaluated for correlation with the previous steps. Note that the process begins with the clarification of the problem. By further clarifying the problem it is easier to quantify the objective of the trade study. Cross [Crossn1994a] states that "often the problem or trade is ill defined or vague," thereby leaving it up to the design team to clarify the trade objective. In the case of a helicopter modernization program, there could easily be dozens of trade studies that need to be performed, deciding what the objective of each trade study is critical to defining the overall system in a timely and cost-effective manner.

Techniques used to explore the trade space and develop preliminary concepts include:

- Performing group brainstorm sessions
- Soliciting external and company internal experts
- Performing patent searches
- Examining trade literature
- Discussing with lead users
- Performing competitive assessment of external and internal products

With the exception of patent searches, each of the techniques listed was used in developing concepts for the helicopter modernization case study. While the role of patents can be beneficial regardless of the type of trade, it was not used in the case study due to the limited resources available. As for how to utilize these techniques, Wright [Wrigh1998a] comments that the creative performance of individuals and teams can be improved substantially by the use of appropriate methods. I will defer to Wright [Wrigh1998a] on how to develop training methods for improving the creative performance of the design team.

Ultimately, the concept generation process involves a great amount of creativity, innovation, and perseverance in order to generate a concept that best balances the design parameters. Creativity and innovation are an inherent part of the product development process. While some individuals may be more creative than other individuals, a diverse team will usually add strength to the concept generation process. Additionally, Bakerjian [Baker1992a] identifies some barriers to innovation that could potentially stifle the creative process.

These barriers include:

1. Fear of Failure
    - Risk must be accepted to move forward
    - Often rooted in company or departmental culture
2. Organizational Style Constraints and Communication Protocols
    - Organizational attitude rigidity- 'that's not how it's done here' , 'not invented here' syndrome
    - Inflexibility in organization responsibility hierarchy
    - Supervision authority effect
3. Need for Speed and Productivity
    - Imposing time constraints compromises incubation period typically required for innovation
4. Environment
    - Exposure to variety, attitudes, surrounding events
5. Limits or Inflexibility in Viewing Problems

The design team must be cognizant of these barriers and actively pursue methods and policies that facilitate the techniques mentioned previously for creative concept generation.

Evaluation of Metrics & Impact of Related Trade Studies

"It is pointless producing brilliant concept solutions to design problems if incorrect decisions are made in choosing the best idea to develop into a product [Wrigh1998a]." In the previous phase, concepts were generated based on their potential to satisfy customer needs. The next step is to evaluate the remaining concepts with respect to the metrics derived from the QFD product planning matrix. During this process some of the concepts are systematically tossed aside as not practical based on face value or some might be merged with other concepts to create a new hybrid concept. This phase can often be the most time consuming and frustrating portion of the trade alternative analysis since obtaining data and optimizing configurations is often difficult to estimate before beginning the trade alternative analysis. Ultimately, the trade alternative analysis must be completed within resource and schedule constraints. With this in mind, it is important to utilize a structured approach for evaluating the concepts against the various metrics.

Wright [Wrigh1998a] recommends the basis for evaluating the metrics should be an evaluation matrix. He states that "the construction of an evaluation matrix forces the design team to seek agreement on the extent to which each concept meets all of the criteria. It is not the completion of the matrix itself that facilitates concept choice, but the discussion which precedes it."

Wright proposes a standardized evaluation matrix format that relies on a utility ranking for determining the best concept. When developing the evaluation matrix it is important to concentrate on 'configuration' drivers. Configuration drivers are those design requirements that most influence the trade alternative analysis. Examples of configuration drivers are cost impact; number of parts affected, schedule implementation, and weight. This is where the QFD product planning matrix can be very beneficial since the top customer needs should have been identified and ranked in order of importance. Therefore it is the metrics that correlate to the top customer needs that should be analyzed in the most detail, with the ancillary requirements evaluated as time and budget permits. However, some amount of sensitivity analysis should be conducted for the ancillary requirements because their cumulative effect might add up to create a significant impact on the trade alternative evaluation.

A portion of the evaluation matrix used in the case study is shown in Figure 10. The attributes and objectives listed in the evaluation matrix were taken directly from the QFD product planning matrix. In this particular matrix, two concepts were evaluated for their ability to meet the customer requirement for a service life extension of 25 years for the airframe. Ideally the weighting values for the various attributes should be derived with the concurrence of the customer. In the case study, the values assigned to the weights were reviewed and accepted by the primary customer.

Attribute	#	Objective	Weight	Parameter	Concept A			Concept B		
					Magnitude	Score	Weight Value	Magnitude	Score	Weight Value
Service Life Extension	1	Affordable remanufacture of airframe	0.325	Procurement cost	Higher when enhancements are factored in	2	0.65	Enhancements are included in base price	3	0.975
	2	Lower maintenance costs	0.02	Reduce likelihood for unscheduled maintenance	Higher likelihood	1	0.02	Lower likelihood	4	0.08
	3	Reduce technical risk	0.05	Reduce likelihood of technologies not being available	Less likelihood	4	0.2	Moderate chance (High speed machine)	3	0.15
	4	Stay on schedule	0.03	Reduce likelihood of slipping schedule	Higher likelihood	1	0.03	Lower likelihood	3	0.09
	5	Minimize weight growth	0.09	delta weight over baseline configuration	Mod kits are heavier than new builds	3	0.27	New build can be optimized	4	0.36

Figure 10: Partial Trade Alternative Evaluation Matrix

During the evaluation of the metrics it is not uncommon for the preliminary concepts to be refined or new concepts emerge as the trade alternative evaluation matures. This is usually the result of the designer gaining knowledge about how the design requirements interface with the system. In the case of the helicopter modernization program, incorporating external stores provisions for extra fuel into the refurbishment of the cabin section requires an investigation into what the manufacturing impact will be. Once this information is obtained, recommendations can be made on labor hours, material costs, schedule, and weight. The conclusion reached might lead the design team to propose a hybrid concept that was not part of the original trade space.

When performing a trade study it is necessary to evaluate the interrelationship between related trades. Related trade studies are trade studies being performed by separate IPT's that either directly impacts or potentially influences another IPT trade study. As an example of how to graphically correlate the relationship between trade studies a spreadsheet matrix was developed for the thesis case study. The spreadsheet consists of an N x N matrix listing all the potential trade studies that could impact the specific trade alternative evaluation (see Figure 11). The body of the related trade study matrix contains symbols that indicate how a trade decision on the vertical axis impacts another trade decision on the horizontal axis; each correlation is evaluated with respect to the specific trade alternative analysis. For example, in the case study for this thesis two of the primary related trade studies to the cabin remanufacture trade study were the increased structural load factor and the service life extension trade studies. These trade studies were highly coupled and both had a significant impact on the other one as well as the cabin remanufacture trade recommendation. By identifying this coupling and documenting it in the related trades matrix, the design team had a qualitative understanding of the affect of these related trades on each other and the cabin remanufacture trade study.

INSTRUCTIONS FOR READING MATRIX: WITH RESPECT TO CABIN CONFIGURATION, MATRIX SHOWS RELATIVE AFFECT OF ROW 'A' TRADE DECISION ON COLUMN 'B' TRADE DECISION.

LEGEND CODE
S = STRONG AFFECT
M = MEDIUM AFFECT
W = WEAK AFFECT

A \ B	BASIC REFURBISHMENT	412 FUEL CELL	10k CARGO HOOK	EXT. RESCUE HOIST	TUB PENETRATIONS	3.6 NZ LOAD FACTOR	38 FPS @ L+ PMGW	TROOP SEATING	EME	CORROSION	9 FPS LANDING GEAR	WATER INTEGRITY	GROSS WEIGHT EXPANSION
BASIC REFURBISHMENT	X	S	S	S	W	M	M	M		W	M	TBD	S
412 FUEL CELL	S	X	S		W				S	S			
10k CARGO HOOK	M	W	X		S	W							W
EXT. RESCUE HOIST	S			X						W			M
TUB PENETRATIONS	M	W	M		X			W					
3.6 NZ LOAD FACTOR	W		M			X		M					M
38 FPS @ L+ PMGW	W						X				S		
TROOP SEATING	W		W		W			X					
EME		W						W	X				
CORROSION	W	M		W						X		W	
9 FPS LANDING GEAR	W						S				X		
WATER INTEGRITY	TBD									W		X	
GROSS WEIGHT EXPANSION	M		W	W		M							X

Figure 11: Related Trade Study Matrix for UH-60L+ Cabin

Perform Risk Assessment

Once the metrics and related trades have been evaluated and quantified, it is now possible to perform a risk assessment for each of the trade options. Wright [Wrigh1998a, pg. 159] states that when performing the risk assessment it is important to distinguish between two factors: the probability of failure, and the consequences of the failure. At this stage of the trade study process it is sufficient to identify the risks along with a qualitative analysis of the risks associated with each trade option. The qualitative analysis should include the identification of risks, the likelihood of occurrence, and the potential severity of their consequences.

In a helicopter modernization program the primary risks are schedule, cost, and technology, although the design team should solicit other potential sources of risk. Ultimately, only the top 3-5 risks should be analyzed for each of the trade options. Once the risks have been identified, the severity of the risks can be assigned. The assignment of the severity of the risks should be at a high enough level so that the risks are partitioned into simple categories (i.e. high, medium, low). Simple high/medium/low segregation allows for easier consensus within the design team and reinforces the qualitative nature of the risk assessment. The same process is used is assign the relative probabilities of occurrence for each risk factor. Wright [Wrigh1998a, pg. 170] proposes plotting the probability of failure versus the severity of the risk in a risk mapping diagram as shown in Figure 12.

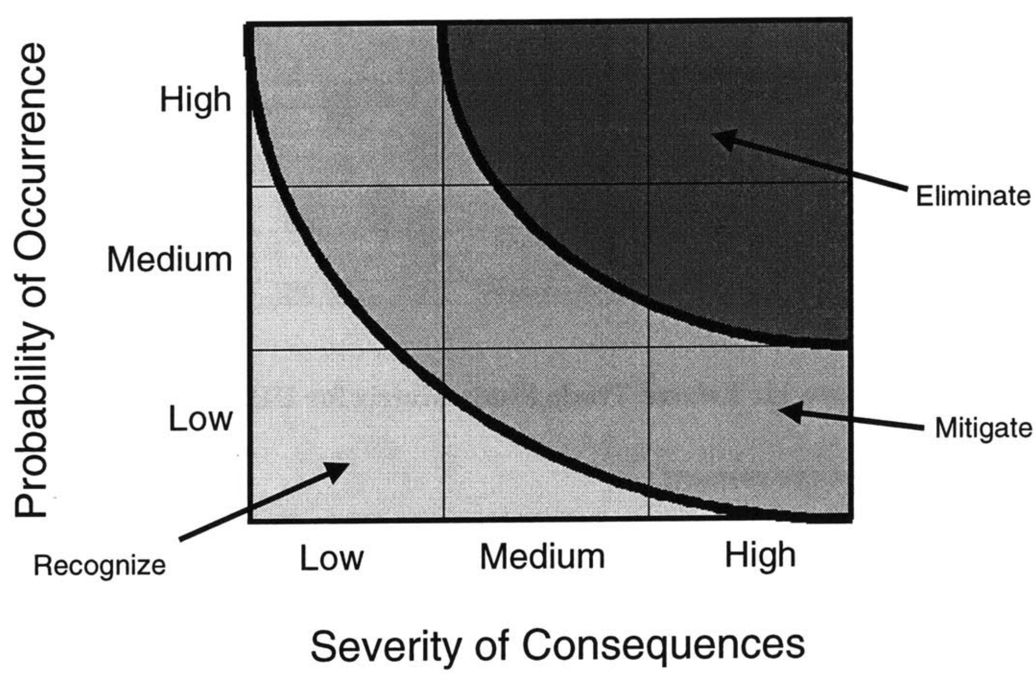


Figure 12: Risk Prioritization Mapping

Risk mapping as shown in Figure 12 helps to establish a 'triage' mechanism for identifying areas of concern and opportunities for risk mitigation. Often, trade study options can be eliminated from consideration at this stage based on their risk mapping. For example, if Figure 12 represents the schedule risk associated with a particular trade option and the design team ranking falls in the upper right quadrant then that trade option should be evaluated much closer. If the probability and/or severity associated with that particular trade option could not be reduced, then that trade option should be eliminated from further consideration. Eventually those trade options that fall into an acceptable risk region will be evaluated more thoroughly during the risk / benefit quantitative analysis.

It should be noted that depending on the industry there are varying degrees of acceptance of risks. The helicopter industry is particularly risk-averse as compared to most industries due to the complexity, cost, and length of time it takes to develop a new platform. Concerning the primary risk factors (schedule, cost, and technical) associated with a helicopter modernization program, the following situations should serve as a guideline for the qualitative risk assessment:

- If a trade option could not possibly meet the schedule requirements even with risk mitigation factors considered it should be removed from consideration. For example, if the trade option requires the purchase of capital equipment for fiber placing composite material that will cause the trade option to miss the schedule, a risk mitigating approach might be to use a hand lay-up process until the fiber placement equipment is on-line. The part will not be as light or as inexpensive using a hand lay-up process but it will be identical to the fiber placement part in terms of form, fit, and function and could meet the schedule. If such an alternative did not exist then the trade option should be removed from consideration.
- When cost is the risk factor there are usually few options for risk mitigation. Sometimes it is possible to leverage the cost of a development project by combining it with a similar project that requires the same technology thereby spreading the non-recurring cost and increasing the learning curve. Another option might be to out-source the item that is causing the high cost risk. Keep in mind that changing an

assumption could result in new and unexpected risks that could also require mitigation.

- Technical risk factors are often hard to quantify even at a rough order of magnitude level. Resultantly, technical risks must always have a comprehensive mitigation plan since the probability of failure is high.

Document the 'Revisit' and Closing Criteria

The last two steps in the trade study phase are inserted for documentation purposes. The closing criterion is needed to prevent what is often called 'engineer's syndrome'. This occurs if the design team is allowed to iterate without some sort of milestone or criteria for signifying the end of the trade study. On the other hand, there are a variety of reasons why the 'revisit' criteria should be documented. Reasons to revisit a trade study include a change in customer priorities, a change in a related trade, or a change in one of the technical assumptions. In the event one of the underlying assumptions changes, the design team has a 'checklist' that they can reference to see what is impacted and must be revisited. Both of these criterions are beneficial in the event the trade study needs to be resurrected or used as a reference at some future date.

Phase Four Summary

By the time the trade study analysis has been completed the concept options should be reduced to the one or two most attractive candidates. These candidates will be evaluated further in the risk / benefit analysis phase. However, before proceeding to the next phase it is important to reflect on the decisions and recommendations made to date. Some factors for the design team to consider at this point are:

- Are the trade study recommendations consistent with the data output from the QFD product planning matrix?
- Are the underlying assumptions still valid?
- Have the customer needs changed or been clarified as a result of conducting the trade studies?

In order to objectively answer these questions it is beneficial to bring in impartial experts to review the trade study recommendations with a 'fresh set of eyes'. Only after the design team and the review team have reached concurrence on the concerns listed above should the trade study recommendations be carried forward to the next phase.

Phase Five: Risk / Benefit Analysis Phase

Introduction

During the previous phase a qualitative risk assessment was performed to identify mitigation opportunities and weed out high risk options. This next phase describes a framework for performing a quantitative risk / benefit analysis of the remaining trade options. While past experiences can lead to an intuitive measure of the probability and potential severity of a particular risk, it is important to quantify the risk even it is on a relative and not absolute level. Moghissi [Moghi1987a, pg. 2] states that a comparative risk assessment is one of the most powerful tools in risk management because it evaluates trade options from a relative perspective. This is particularly useful in preliminary design trade studies where engineers might not have complete pricing and life cycle cost information or a comprehensive manufacturing scheme to accurately perform a risk analysis at an absolute level. However, by emphasizing the primary cost drivers, it is possible to develop a high level risk / benefit analysis that identifies the relative risks / benefits of the trade alternatives.

The case study in this thesis evaluated three types of quantitative risk/benefit analysis that were of particular interest to management and the customer.

1. Weighted expected value calculation for schedule risk associated with the trade alternatives.
2. Cost risk if the customer decides to add enhancements to the baseline configuration.
3. Net Present Value (NPV) analysis based on a decision tree matrix of the trade alternative decisions.

Schedule Risk Evaluation

An important consideration when evaluating trade options for a helicopter modernization program is the schedule risks associated with each trade option. The schedule risk has three implications: fleet availability, rate of aircraft modernized, and cost overruns.

In the case of the UH-60 BLACK HAWK the proposed schedule calls for the remanufacture of 60 aircraft per year. In the proposed remanufacture program, aircraft will be taken out of service for a period of approximately one year. As a result, the overall availability of the fleet is reduced by the number of aircraft undergoing remanufacture. Variations in the condition of the aircraft can lead to large schedule variances depending on the trade option selected. Depending on the remanufacture method more aircraft might need to be taken out of service (more work in progress) to feed the critical path than other remanufacture methods. Resultantly, depending on the manufacturing process required for the various trade options, there will be varying degrees of schedule risk that are manifested by work in progress (WIP) and eventually in aircraft availability.

The rate at which aircraft are modernized is also a function of schedule risk. If the trade option selected has the potential for wide schedule variability then the possibility exists that fewer aircraft are remanufactured per year than planned. Over time, this could result in a significant percentage of the fleet that is not able to perform at the required system performance level. From a strategic and political perspective this could have severe ramifications on the congressional support of the program which leads to the third implication of schedule risk: cost overruns.

Cost overruns can come from numerous sources but one of the most prevalent reasons why helicopter remanufacture programs overrun costs is 'over-and-above' or unplanned work due to the variability in the condition of the aircraft to be refurbished. Usually the customer allocates a budget to address the 'over-and-above' work. However, 'over-and-above' work is difficult to estimate from a cost perspective and does not lend itself to a very efficient manufacturing process. Resultantly, in order to maintain schedule for the worst condition aircraft, more resources and material must be available than would be required if the variability of 'over-and-above' work was minimized.

Method for Evaluating Schedule Risk

One method for evaluating schedule risk is to use a weighted expected value analysis. In a helicopter modernization program there is often historical data available to validate assumptions made in assigning probabilities for the expected value analysis. The process for evaluating schedule risk in a helicopter remanufacture is as follows:

- Step 1: Establish the assumptions.
- Step 2: Analyze the manufacturing process.
- Step 3: Determine the 'bottle-neck' control points for each trade option.
- Step 4: Define the risk factors at the 'bottle-neck' control points for each trade option.
- Step 5: Check to see if other control points have higher risk factors that might change the 'bottle-neck'.
- Step 6: Assign probabilities to the risk factors, preferably based on historical data.
- Step 7: Perform expected value analysis.
- Step 8: Check results against historical data.

The validity of the results obtained from this process depends to a large extent on the fidelity of the assumptions, the structuring of the manufacturing process for each trade option, and the availability of historical data to derive probabilities from. The less 'guessing' or estimating that the design team has to do when performing the risk analysis the more credibility there will be in the results.

Cost Risk Associated with Different Trade Options

Another important task that should be performed is a cost sensitivity of the baseline assumptions and related trade study outcomes for each trade option. The primary question that needs to be addressed is: "Does the rankings of the trade options change significantly if the assumptions and related trade study outcomes change?" If so, this needs to be identified as a significant risk factor. In the case study, the impact of changing the outcome of related trade studies was evaluated for each trade option. It should be noted that the evaluation of cost risk is often done in phase four as part of the risk assessment and is included in the evaluation matrix.

Net Present Value (NPV) Analysis

While net present value (NPV) or present worth calculations are commonly performed at the system level, they are not always performed at the sub-system trade study level. As observed by Wright [Wrigh1998a, pg. 161], reliable NPV calculations are based on numerous factors resulting in a high level of uncertainty in the decision-making process itself. In addition, depending on the particular sub-system, it could be misleading to quantify the NPV for a sub-system trade independent of the over-all system NPV. As a result the design team should be very careful in quantifying the NPV at the sub-system level, particularly in the preliminary design stage.

A logical starting point in developing an NPV analysis is to create a decision tree. A decision tree is the graphical representation of the mutually exclusive decisions that will need to be made when exploring the trade space for a particular trade study. Specifically, each 'branch' of the decision tree represents a separate decision that needs to be made. Following that branch through subsequent decision branches will trace a cost flow path correlating to a particular trade alternative. Therefore, by creating a decision tree, the design team can better understand the life cycle costs associated with all the trade alternatives on a relative basis. Another important feature of the decision tree is that it is an excellent tool for soliciting new opportunities or alternatives. As demonstrated in the case study, graphically documenting the decision branches sometimes encourages the design team to look at the trade space from a different perspective, in particular from a cost perspective.

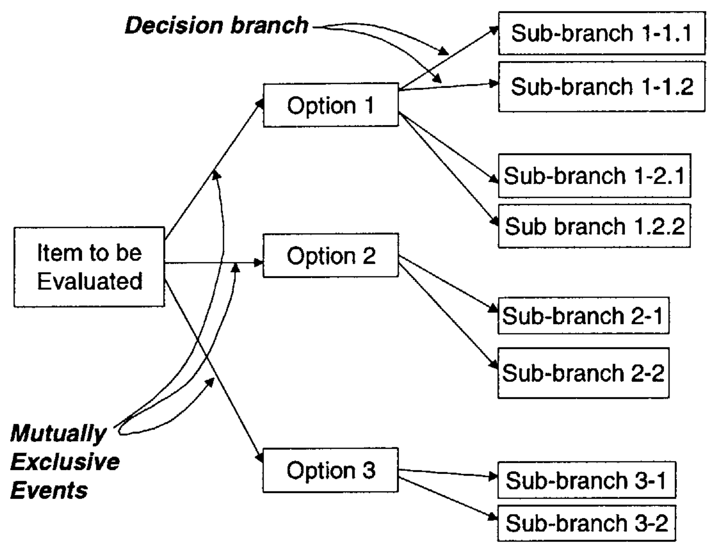


Figure 13: Generic Decision Tree

Once the decision tree has been created, a cash flow diagram as shown in Figure 14 can be created that graphically illustrate the annual cash flows associated with a decision branch. The cash flow diagram also helps in setting up a spreadsheet to calculate the present worth of the various decision branches.

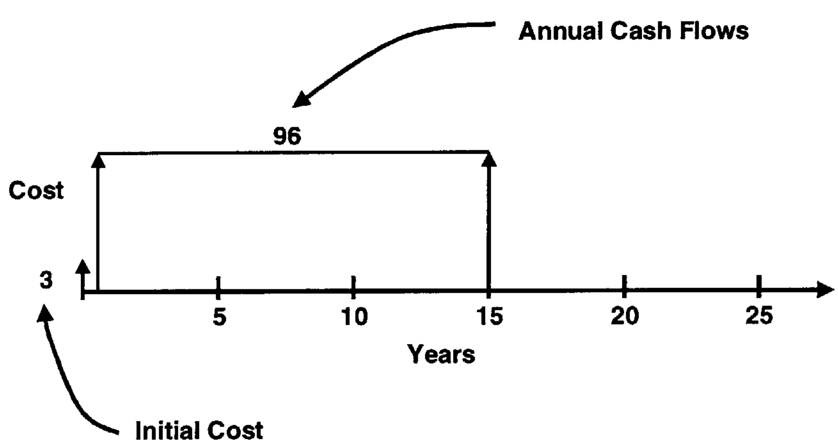


Figure 14: Generic Cash Flow Diagram

The present worth values calculated in the spreadsheet are often presented to management and the customer to evaluate 'what-if' scenarios. Because of the relative ease with which these spreadsheets can be manipulated, present worth analysis is a powerful management tool for quantifying the life cycle costs associated the trade alternatives. By adjusting the spreadsheet inputs, managers can get a quick understanding of the relative magnitude and timing of the major cost drivers.

Phase Five Summary

The output of this phase is the quantification of the risk / benefit factors identified in phase four. Usually by this stage a clear alternative has emerged as the best candidate among the trade options. Quantifying the risk factors enables the design team to focus more precisely on mitigating potential trouble areas for the best trade alternative. In addition, quantitative risk / benefit analysis provides management with a simple, yet powerful, tool for measuring the relative worth of each of the alternatives. The fact that the risk / benefit analysis can be easily summarized in one graph or chart makes it a popular tool for management evaluation of the trade alternatives.

While there are numerous methods for quantifying risk/benefit factors, this section described three methods that were effectively used in the helicopter modernization program. A schedule risk evaluation based on a weighted expected value calculation can be performed to quantify the likelihood that trade option can meet the schedule. A cost sensitivity can be performed to quantify the cost risk associated with changing assumptions and the outcome of related trades. Finally, a net present value analysis can be performed to quantify the present worth of the trade alternatives.

Phase Six: Implementation Phase

Sanity Check

Once the risk / benefit analysis has been completed there is still one task left in the trade study methodology. While it is sometimes overlooked, taking the time to review the results of the trade study and then propose a plan for implementation can pay large dividends as the product goes into detail design and manufacture. After exerting a tremendous effort, not to mention resources, in performing a well-structured trade study, the design team must now reflect on their results and make sure that:

(1) The results still map to the customer needs.
(2) Any assumptions made during the trade study are still valid
(3) The trade study results are defendable.

The first two actions listed are performed as a sanity check. It is possible that a fair amount of time has elapsed since the customer needs and assumptions were first recorded and the design team might not beware of changes occurring while the QFD product planning matrix and trade alternative evaluation were being performed. The last suggestion is often a necessary action and this is not meant in a negative connotation. If the trade study results are controversial or have more risk (schedule/cost/technical) associated with them than some other alternative, then the design team will need to substantiate and defend the results with quantifiable data.

Sometimes a trade study result is not universally accepted as the best approach for very legitimate reasons. Developing an implementation plan based on the decision tree created from the previous phase is an excellent method for convincing skeptics that the trade study has been thoroughly prepared and that the entire spectrum of life cycle issues has been addressed. Additionally, the implementation plan provides a road map for downstream and upstream departments to begin working on a product configuration derived from the trade study decision tree.

Final Thoughts

The proposed trade study methodology is intended for use in helicopter modernization programs, although it can easily be adapted to most other types of helicopter programs. Some of the major concepts to take from the methodology just described include:

- Every facet of the trade study must be traceable back to a customer need. The QFD process is a valuable tool for capturing the voice of the customer and translating it into characteristics that can be quantified and analyzed throughout the trade study. The methodology is sequential in the respect that each phase builds on the data developed in the previous phases, with the QFD process forming the foundation for the methodology. It takes the voice of the customer and transforms it into the attributes and technical characteristics that define the trade space, which in turn forms the basis for the metrics used during the trade alternative and risk / benefit analysis phases.
- Structure is important for performing a comprehensive analysis. A flexible approach as proposed by Pugh [Pugh1991a pg.74, 75] is recommended in order to tailor the methodology to a specific application. A conscious effort is required by the design team to simultaneously encourage new ideas while staying within the structure of the QFD process.
- Risk assessment and risk / benefit analysis are important tools for quantifying the relative values for trade alternatives and are therefore valuable management aids for ranking the alternatives.

While not addressed in this thesis, updating and carrying the QFD matrices through the design and manufacture of the helicopter modernization program is recommended and could be the topic of another thesis. What follows is a case study applying the methodology just described to an actual trade study from the BLACK HAWK Modernization Program.

Application of the Trade Study Methodology

Overview

In order to illustrate and assess the trade study methodology proposed in this thesis, an application of the methodology is exercised in a specific application. The case study is taken from the UH-60A BLACK HAWK Modernization Program and focused on the remanufacture of the cabin section of the fuselage. Figure 15 and Figure 16 show the cabin section of the UH-60A fuselage, which actually encompasses both the cabin and transition sections. The cabin section shown is considered a major assembly from a manufacturing perspective because it is built as a separate component. It is chosen as the case study for three primary reasons.

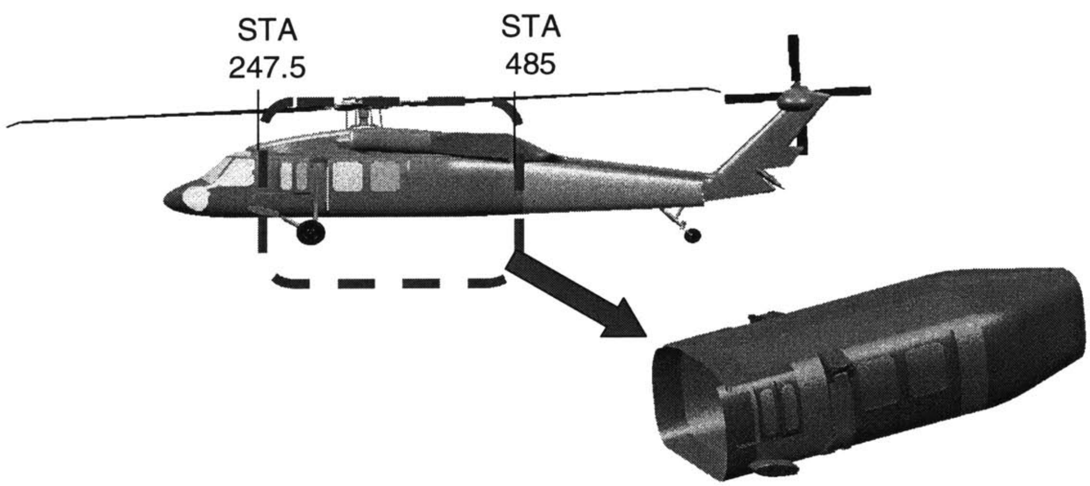


Figure 15: UH-60A Cabin Section

The first reason for selecting the cabin section is that based on past remanufacture programs the cabin has been the section of the fuselage that requires the most service life extension focus. This is due to the fact that the cabin section has several interfaces that eventually translate into more fatigue, damage, and corrosion related issues than the rest of the fuselage. Among the more prevalent issues are the vibratory and dynamic loads introduced by the main gearbox into the upper portion of the fuselage, reactive loads introduced through the external stores support and cargo hook, and corrosion problems caused by trapped water under the floor and fuel sections.

The second reason for selecting the cabin assembly section for the case study is the high number of interfaces within the cabin. The complexity caused by all these interfaces necessitates a structured methodology for capturing the relationships between the interfaces and their effect on the remanufacture decision.

Thirdly, the modernization of the cabin section has historically represented the highest cost among structural items in past remanufacture programs. This coupled with the fact that the cabin section can be partitioned separate from the rest of the fuselage readily lends itself to a stand alone trade study.

To better understand the background for this case study it is important to understand the history of the UH-60A BLACK HAWK helicopter along with a brief overview of the BLACK HAWK Modernization Program. This information is contained in the Appendix.

Cabin Trade Study

Overview

The UH-60L+ cabin trade study followed the methodology proposed in this thesis. It was the largest and most complex of the 57 trade studies performed for the UH-60L+, and was very much affected by many of the these other trade studies. In addition, due to the dynamic interaction between the design teams and the primary customer, the priority and understanding of the customer needs evolved as the trade studies were being performed. Changing priorities of the customer needs in addition to the effect of the related trades had a significant impact on the cabin trade study and confirmed the importance for having a flexible trade study framework as proposed by Pugh [Pugh1991a pp. 74, 75].

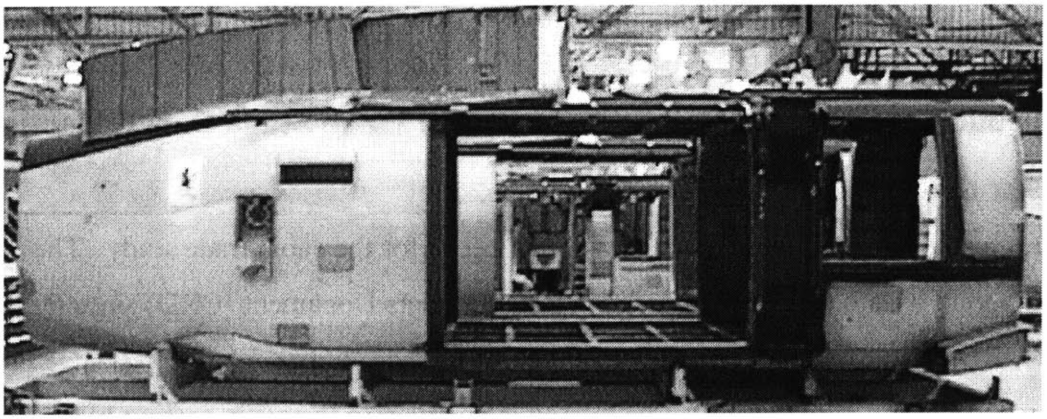


Figure 16: UH-60 BLACK HAWK Cabin Assembly

Cabin Trade Study Design Team

The Sikorsky core team assigned to the cabin trade study consisted of the following representatives:

- Two representatives from the advanced design and business development team. One representative had twelve years of experience in airframe design; the other had six years of experience in materials and process engineering.
- Structural analyst with ten years of experience on the BLACK HAWK and BLACK HAWK derivatives.
- Industrial engineer with several years of experience in industrial engineering, but no prior experience on the BLACK HAWK.
- Manufacturing engineer with twenty years of experience on the BLACK HAWK.
- Airframe design engineer with several years of experience in aircraft design, and three years of experience in airframe design.

In addition, a team of structural engineers was assigned by the Army to oversee all of the structural design trade studies for the UH-60L+ and worked very closely with the Sikorsky team described above. The Sikorsky core team also solicited input on an as needed basis from manufacturing, configuration management, the BLACK HAWK program office, the electronic mock-up group, and advanced research and development group.

Application of the Trade Methodology: Cabin Trade Study Data Collection

UH-60X ORD

Several methods were used to solicit customer needs for the cabin trade study. The starting point was the UH-60X Operation Requirements Document (ORD) since the UH-60L+ ORD was not available in time to support the trade studies. The UH-60X ORD was researched for any item that might be related in any way to the cabin section of the fuselage. While the UH-60X ORD was written for a different objective than the UH-60L+, the majority of the threshold objectives were directly applicable to the UH-60L+ program. Meetings and interviews were conducted with a user representative, who was involved in the generation of the UH-60X ORD, to get clarification and quantification on sections of the ORD that were not clearly understood by the trade study team.

Site Visits

Members of the trade study team, including members of the Army team conducted several site visits as part of the data collection effort. The purpose of the site visits was to observe first hand the condition of the aircraft to be refurbished and conduct interviews with the mechanics responsible for repairing the aircraft.

The trade study team visited the following sites as part of their research:

- FT Campbell
- FT Rucker
- Davis Monthan AFB
- California AVCRAD
- Wheeler Army Air Field
- Mississippi AVCRAD
- Corpus Christi

Corpus Christi is the primary location for overhaul and repair of the UH-60A fleet. The AVCRAD centers are regional repair depots. The forts and bases have limited repair facilities but offered the opportunity to observe first hand the aircraft in use. In addition to conducting interviews, the site visit team took digital photographs and recorded notes concerning general airframe condition, geographic specific observations, corrosion issues, and usage observations. In total 50 aircraft were observed by the site team. An example of a typical consideration affecting airframe issue is shown in Figure 17. In addition to this data being used to identify customer needs, the information collected would be used later to help define the baseline for the service life extension configuration.

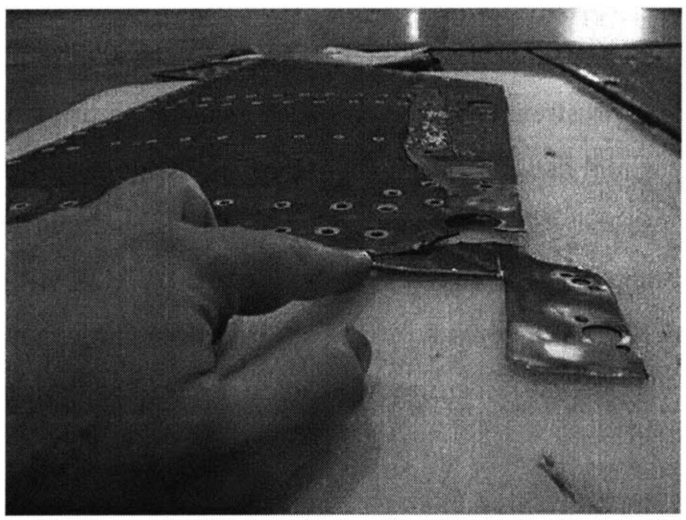


Figure 17: Photograph of UH-60A Skin Crack

Customer Interviews: Primary Customer

Several meetings were held with various departments within the Army, including the BLACK HAWK program office, the Army Advanced Technologies Division (AATD), and user representatives. Each of these customers was briefed at various stages of the cabin trade study, with feedback and input solicited at each meeting. These observations were captured in the customer needs list in addition to being used for the data prioritization.

Some of the more significant observations that came from these interviews were:

- The importance of range capability.
- A sense of what the customer felt was required for refurbishment.
- A latent need for a higher external cargo carrying capability.
- The importance of maintaining cost and schedule goals.

Customer Interviews: Internal Customers

In addition to the interviews with the primary customer, other interviews were conducted with internal departments at Sikorsky Aircraft. The objectives of these interviews were to collect a list of lessons learned and understand what some of the internal customer needs are. A total of approximately ten interviews were conducted with representatives from the internal departments. The BLACK HAWK has been in production for twenty years. As a result, downstream departments such as manufacturing had a long 'wish list' of items that they would like to see in a BLACK HAWK modernization effort. Ultimately, eight of the 'wish' list items made the UH-60L+ Cabin Trade Study customer list. Some of the suggestions were more applicable to a BLACK HAWK replacement instead of a BLACK HAWK remanufacture effort. These particular suggestions were archived for the UH-60X customer needs database and will be revisited at a later date if necessary.

Competitive Assessment: CH-47 Chinook Modernization Program

The Chinook CH-47F modernization program was chosen for a competitive assessment because in many respects it is very similar to the BLACK HAWK modernization program. Even though it is much larger than the UH-60A BLACK HAWK, the Chinook is designed with a similar technology, faces many of the same modernization issues, and has the same primary customer as the BLACK HAWK.

The CH-47 Chinook (Figure 18) is a Vietnam-era heavy lift helicopter manufactured by Boeing Helicopters for the United States Army (see Table 2 for aircraft characteristics and performance). More than 600 are currently in service internationally with approximately 433 "D model" Chinooks in the Unites States Army inventory. It's primary mission is movement of troops, artillery, ammunition, fuel, water, barrier materials, supplies and equipment on the battlefield. Secondary missions include medical evacuation, aircraft recovery, fire fighting, parachute drops, heavy construction, civil development, disaster relief and search and rescue. It has a maximum gross weight of 50,000 lbs. versus the UH-60L maximum gross weight of 22,000 lbs. The average flyaway cost of a CH-47D is approximately $23 M versus approximately $8.5 M for an UH-60L.

Figure 18: CH-47D Chinook [Boein1999a]

The Army is expected to spend approximately $2.4 billion to upgrade 302 CH-47D Chinook helicopters into a CH-47F configuration by the year 2015. This modernization program is expected to add another twenty years to the operational life of the Chinook. It will replaced by the joint technology rotorcraft (JTR) in about the year 2020 [Phili1998a].

The primary objective of the Chinook modernization program is to extend the operational life of the CH-47 to approximately the FY 2020 timeframe (total life of the CH-47 would be over 70 years when the last aircraft is retired in 2033) [Kande999a]. A majority of the enhancements in the CH-47F are being funded as part of the Improved Cargo Helicopter (ICH) program. The ICH program encompasses the following components: extending the life of the CH-47D through the remanufacture of the airframe, reducing operation and support costs (O & S) through vibration reduction, and supporting the Army XXI battlefield by providing a digital communications and situational awareness capability [Smithr1999a]. Upgraded T55-L714A engines that will provide additional lift for high/hot conditions (4000-ft altitude, 95 degree F) are funded through a separate contract. Other items that are being paid for through funding outside of the ICH program are extended-range fuel tanks and low-maintenance rotor heads. The Engineering and Manufacturing Development (EMD) effort is scheduled for completion in July 2002 and the first production aircraft is scheduled for delivery in FY 2003. See Figure 19 below for further description of the CH-47F upgrades:

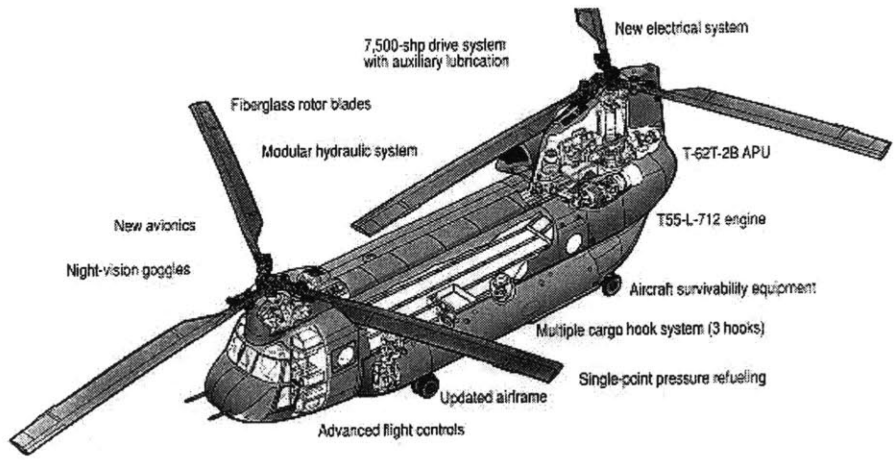


Figure 19: CH-47F Upgrades: source Boeing Website [Boein1999a]

Competitive Analysis Research

Even though the CH-47 is not a direct competitor of UH-60 in terms of mission and performance, it is a competitor in the sense that the UH-60 will be competing with the CH-47 for Army funding allocation during roughly the same time period. With this in mind, it is important to benchmark some of the key attributes of the CH-47 modernization program that could be applied or compared to the UH-60 modernization program. In addition, the competitive assessment of the CH-47 could provide new ideas for the UH-60 modernization program.

Some of the key areas to be analyzed in the CH-47 modernization program that could potentially apply to the BLACK HAWK cabin upgrade are:

- Cost Information

- Structural Approach
- Schedule Information

Cost Information from the CH-47F Modernization Program [Kande1999a]:

• Total cost of upgrade effort per aircraft (Represents about 1/3 the cost of a new aircraft):	$7.5 million
• Cost of structural and avionics improvements:	$6.5 million
• Cost of new engines:	$1 million
• Cost of a new cockpit structure as compared to a remanufactured structure:	10-15%
• Expected reduction in O & S costs:	22%
• Cost of EMD effort:	$76 million

Schedule information pertaining to the CH-47F Modernization Program [Phili1998a]:

- EMD program duration: start - 1998; finish - 2002
- Production Modernization program duration: start – 2002; finish – 2015
- Production rate: FY02 – 12 aircraft, FY03 – 18 aircraft, FY04 & FY05 – 26, FY06 through FY15 – 218 aircraft

Approach to CH-47F Structural Refurbishment [Kande1999a]:

- The structural refurbishment is planned primarily to stiffen the airframe and eliminate historically trouble-prone structures (determined by analyzing maintenance databases).
- The structural refurbishment was partitioned into primary structure and secondary structure. Six primary structure areas such as transmission frames and seventeen secondary structural areas such as cowlings and tunnel closures will be either modified or replaced. Total weight added to stiffen the structure is about 120 lb.

- The structural refurbishment is also addressing vibration reduction. This *will* require replacing the CH-47 cockpit. Total weight savings is about 150 lb. less than a remanufactured structure with about 70 lb. coming from eliminating a vibration absorber.
- Repairs normally done by Army's Corpus Christi, Texas maintenance facility will not be handled by ICH contract. Instead, they will be billed separately because they vary from aircraft to aircraft. To eliminate disputes, members of the Defense Contract Management Command will be available on the shop floor to help determine which aircraft components to save and which to scrap.
- Redesign of the aft pylon system to allow for quicker air transportability in a C-5. The changes will reduce the time it takes a CH-47F to be disassembled and ready for shipment from about 5 hours down to 2.5 hours.

Table 2: CH-47 Performance and Specification [Boein1999a]

CH-47D Specifications
Powerplant and Transmission: Two Textron Lycoming T55-L712 Engines Engine Rating: 3,750 shp Transmission Rating: 7,500 shp
Rotor System: Three blades per hub (two hubs) Fiberglass construction Speed: 225 rev./min Manual folding blades
Performance: Max. cruise speed: 160 kt. Rate of climb: 3,130 ft/min. Max Range: 1279 miles Useful load: 30, 615 lbs. Forward and aft cargo hooks: 19, 958 lbs. Center cargo hook: 27, 942 lbs.
Crew: Cockpit-crew seats: 2 Cabin-troop seats/litters: 33/24
Weights: Max gross weight: 50, 000 lbs. Empty weight: 23, 401 lbs.

Observations from CH-47 Chinook Competitive Assessment

With respect to the BLACK HAWK cabin trade study, a number of key observations can be derived that will be of benefit for the trade study phases to follow. Among the observations that will be of most use are:

- The partitioning of the structural items into primary and secondary structure.
- The incorporation of vibration reduction into the customer needs as a means of lowering weight and increasing the life of the structural components.
- The method by which repairs and 'over-and-above' work is addressed during the remanufacture process.
- The methods by which structural refurbishment candidates were derived (maintenance databases) will also be used to substantiate the BLACK HAWK cabin refurbishment candidates.
- Finally, the data obtained on the cost comparison between a new cockpit structure and a refurbished cockpit structure for the CH-47F will be archived and used for comparison during the trade alternative evaluation phase.

Documentation of the Customer Needs

After collecting as many customer needs concerning the UH-60A cabin as time and resources permitted, the list of customer needs were documented and compared with the UH-60X ORD requirements. The results were tabulated and references to the source of the need and whether it was considered a threshold or an objective need was also documented. The results of this effort are listed in Table 3.

#	Customer Needs	Threshold / Objective	Source	Targets
1	Extend useful life of airframe beyond yr 2025.	Threshold	ORD para 3, SES70070	Airframe service life extension (SLEP).
2	Provide tactical air movement of troops	Threshold	ORD para. 4a.1a	Carry 11 troops @ 290 lbs. each
3	Enhance aircraft survivability	Threshold & Objective	ORD 4a.5	Provide sufficient capabilities for crashworthiness & self-protection.
4	Reduce operations and support costs (O & S).	Threshold & Objective	ORD para. 3f	Redesign to result in lower O & S costs.
5	Improve lift capability	Threshold & Objective	ORD para. 3a, 4.1c	Lift light-weight artillery. Lift HMMWV @ 4K/95F
6	Improve reliability & maintainability (R&M)	Threshold & Objective	ORD para 4b.1.6.2	Meet or exceed maintenance ratio and unscheduled maintenance thresholds.
7	Improve range capability	Threshold & Objective	ORD 4a.1.a	Meet mission requirement
8	Exploit aircraft maneuvering performance	Objective	ORD para 4a.1.5.3d	Operate throughout operational flight envelope without exceeding structural or other limitations.
9	Provide extended range fuel system capability	Threshold	ORD para 4c.1b	Meet or exceed self-deploy range
10	Provide shipboard compatibility	Objective	ORD para 4c.2	Airframe corrosion protection for sustanined operations in vicintiy of salt water.
11	Provide easier access to cabin door handle	Objective	ORD para 4c.4a	Redesign cabin door handle to allow for rear most seated occupant operation.
12	Prevent inadvertant jettison of emergency window exit handle	Objective	ORD para 4c.4b	Redesign/reposition emergency exit handle.
13	Improve heated air distribution system	Objective	ORD para 4c.4c	Ensure consistant heated air (4degrees C, to ambient temp. down to -54degrees C throughout entire cabin.
14	Improve water integrity	Threshold	ORD para 4c.4d	Protect mission equipment packages.
15	Accommodate design growth	Threshold	ORD para 4c.6	Provide sufficent margins and capability for systems growth.
16	Operate in NBC environment	Threshold	ORD para 4c.8	Tolerate material damaging effects of NBC contaminants.
17	Provide configuration management control of SLEP aircraft & new build	Objective	Interview w/ program manager	Develop electronic mockup (EMU).
18	Improve assembly of airframe components	Objective	Interview w/ manufacturing	Consider using S-92 & Comanche technology to better coordinate tooling to drawings.
19	Leverage existing parts & tools	Objective	Several internal interviews	Utilize CH-60 components were feasible.
20	Use standard and environmentally safe materials	Objective	Interview with M.E. IPT	Establish candidate list of parts that might require material changes.
21	Shipboard Compatability: Electric Magnetic Emmisions (EME)	Objective	Derived	Provide sufficient EME protection of aircraft systems.
22	Provide capability for MEDEVAC systems	Threshold	Program	External rescue hoist, aft avionics shelves, aft transition door, additional cabin tub penetrations for harnesses.
23	Eliminate all after-refurbishment carry-forward repairs	Objective	Interview with customer PM staff	Account for over-and-above repairs in refurbishment.
24	Develop architecture that provides growth path to UH-60X	Objective	Interview with PEM	Identify opportunities to incorporate next generation requirements into refurbishment.
25	Must be affordable	Objective	Several sources	Decisions must be made with cost as key variable.
26	Update user spectrum	Threshold	Interviews with structures IPT, SES70070	Update user spectrum to account for higher mission weight and consider operational changes.
27	Incorporate MAVEN team enhancements	Objective	Internal interviews	Consider feasibility of incorporating MAVEN enhancements (I.e. improved drip pan, transmission gear box damping)

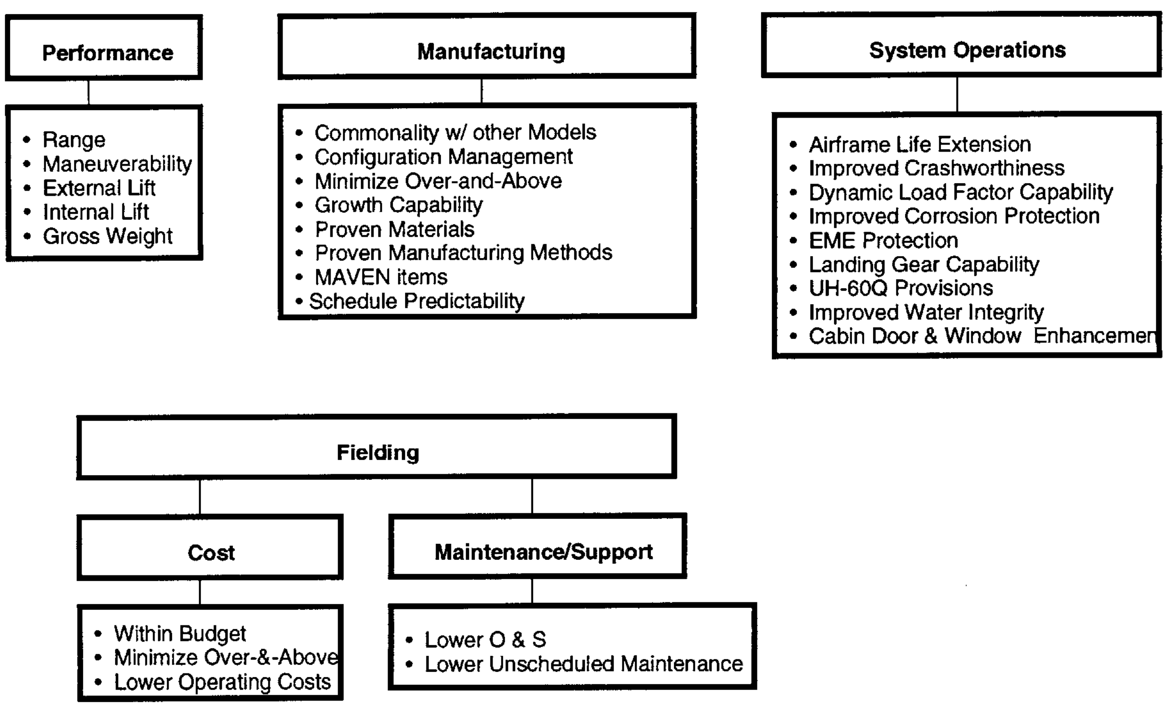
Table 3: UH-60L+ Cabin Trade Study Customer Needs List

Application of the Trade Study Methodology: Data Structuring and Prioritizing

Overview

Affinity diagramming was used to initiate the structuring and prioritization of the customer needs. Using this process, the customer needs were segregated into similiar-themed 'piles', with any duplicate and / or comparable need statements consolidated into representative topics. The resultant affinity diagram for the UH-60L+ cabin trade study is shown in Figure 20. Note that the diagram captures the '*WHAT*' attributes in terms of the customer and not '*HOW*' the need is obtained. Even though the design team was unable to experiment with a customer sort and cluster process due to time constraints, various end customers did have a significant voice in identifying customer 'exempliers' or priorities.

Figure 20: UH-60L+ Cabin Affinity Diagram for Customer Requirements



In order to ensure that the design team had characterized the customer needs in line with how they were perceived by the various customers, follow-up interviews were conducted with the customers throughout the trade study and checked against the structuring described in Figure 20. In retrospect, while customer sorting was not used in the case study it might have reduced some of the iteration that came about during the prioritization phase.

Categorizing and Structured the Customer Needs

Once the affinity diagram was created the data was then categorized by the type of customer need and then structured. First, the needs were categorized as a threshold, objective, or attractive need. Then the relative importance of each need was determined based on the information obtained during the data collection phase and subsequent interviews with the customers. Interestingly, during the process it became apparent that some of the supposed '*WHAT'S*' in the affinity diagram where actually '*HOW'S*'. For example, improved corrosion protection and improved electro-magnetic emissions (EME) protection where actually ways of achieving shipboard compatibility. Any items that fell into this category were removed from the customer need list and archived for later use to be consideration as technical metrics in the QFD product planning matrix.

The structuring of the customer needs was largely driven through meetings and discussions with the various customers. The design team collected the viewpoints and opinions of the customers and attempted to categorize the needs in terms of overall priority to the UH-60L+. Particular attention was given to those needs that could potentially have a large impact on the cabin configuration. For example, range, acquisition cost, and airframe useful life all emerged as high priorities by the customer. Unfortunately, none of these needs was quantified very well at the time the affinity diagram was created. However, knowing that these three needs had emerged as the most important would help structure the trade studies to be performed in the later phases.

Table 4 lists the customer needs partitioned by type with a corresponding priority assigned for each need.

Type	Need	Category	Priority
Performance	Range	Threshold	H
	9K External Lift	Threshold	H
	Internal Lift	Threshold	H
	10K External Lift	Objective	M
	Maneuverability	Threshold	M
System Operations	Airframe Useful Life	Threshold	H
	Crashworthiness	Objective	M
	Shipboard Compatibility	Objective	M
	Hard Landing Capability	Objective	M
	UH-60Q Commonality	Objective	M
	Water Integrity	Objective	L
	Cabin Door Enhancements	Objective	L
Fielding	Low Acquisition Cost	Threshold	H
	Low O & S Cost	Objective	M
	Low Unscheduled Maintenance	Objective	M
Manufacturer	Low Aircraft Variability	Objective	H
	Aircraft Commonality	Objective	H
	Growth Capability	Attractive	M
	MAVEN items	Attractive	L
	Proven Materials	Attractive	L
	Proven Manufacturing Methods	Objective	L

Table 4: Data Structuring and Prioritizing

The needs were classified into high, medium, and low priorities as described in the methodology. Classifying the needs by priority helped reduce the scope of work in the next phase because only the medium and high priority items would be carried forward into the QFD matrix. Based on interviews with the customers, the highest priority needs were determined to be the airframe useful life, low acquisition cost, range and lift. Other important needs that emerged were aircraft commonality and low aircraft variability (which translated into schedule). The low priority items were analyzed in just enough detail to prescribe a plan of action for when the project goes into the product design phase. This information was provided to the customers (both primary and internal) for concurrence. Once agreement was reached on the disposition of the low priority items, the trade study for that particular need was considered complete. For the purposes of the cabin trade study, this helped lock in the configuration from a weight and cost perspective. For example, Figure 21 shows the disposition of the cabin door / emergency exit enhancement. The needs were to provide rear-most occupant access to the cabin door egress handle and 'Murphy-proof' the emergency jettison handle so the it wouldn't inadvertently released. A concept was developed that met the objectives of the ORD, but weighed fifteen lbs., which was determined to be too much by both the design team and the customer. A second concept was developed that met the intent of the ORD but was less elegant. This concept weighed less than one pound. Therefore it was determined that the second concept would be the most practical and would be evaluated further during detail design.

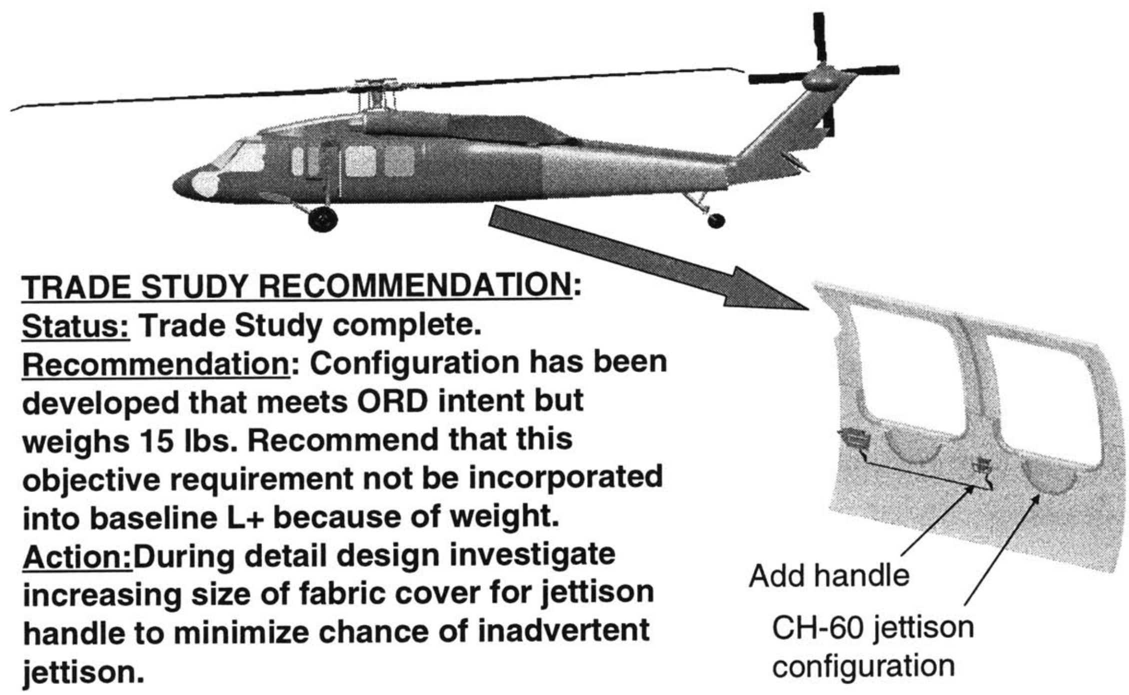


Figure 21: Disposition of the Cabin Door Enhancement Need

Application of the Trade Methodology: Building the QFD Product Planning Matrix

Overview

The quality function deployment (QFD) product planning matrix created for the case study was tailored for a helicopter modernization program. A significant difference between the classical QFD matrix and the cabin trade study matrix was that absolute numbers were not used to quantify the priority of the technical characteristics. Instead, ranges were identified that separated the technical characteristics into three categories. This enabled the technical characteristics to be categorized, but at an abstract level. By prioritizing the technical characteristics into ranges of priority, it was still possible to identify the highest priority characteristics for trade study evaluation without introducing possible misconceptions between closely ranked characteristics. At this stage in the methodology, assigning an absolute numerical ranking to the technical characteristics was premature and could lead to spurious conclusions.

Concurrent to the cabin trade study effort a separate product development team in conjunction with the customer systematically researched the prioritization of the customer attributes. The results of this separate effort were used in the subsequent trade alternative analysis. An evaluation matrix was developed that applied weighted values to the customer attributes. These weighted attributes where then applied to each of the technical characteristics associated with the specific trade alternatives.

Another difference with the classical QFD matrix was that the competitive assessment block was not included in the case study QFD product-planning matrix because in the foreseeable future the BLACK HAWK does not have any direct competitors for the U.S. Army mission. However, the data obtained from the CH-47 modernization program was used throughout the trade study for comparison and as a source for concept ideas.

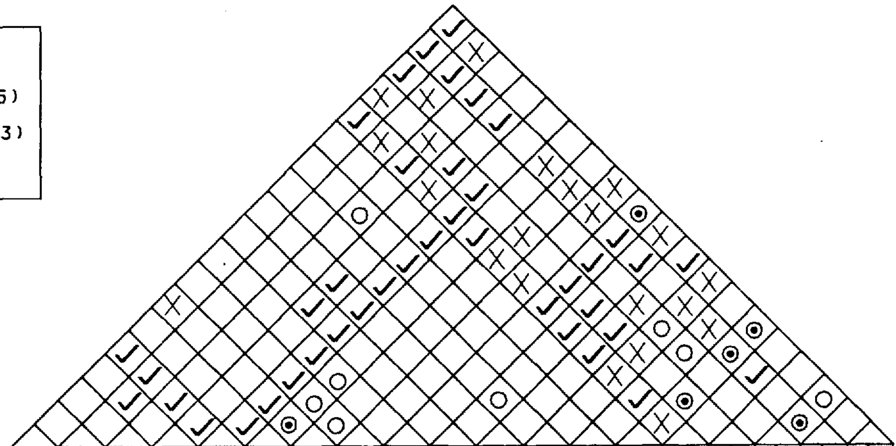
The QFD product-planning matrix generated for the cabin trade study is shown in Figure 22.

RELATION MATRIX

- ◎ - STRONG RELATIONSHIP (5)
- ○ - MEDIUM RELATIONSHIP (3)
- △ - WEAK RELATIONSHIP (1)

ROOF MATRIX

- ◎ - STRONG POSITIVE AFFECT
- ○ - POSITIVE AFFECT
- X - NEGATIVE AFFECT
- ✓ - STRONG NEGATIVE AFFECT



TYPE	WHAT'S \ HOW'S	IMPORTANCE	INCREASE FUEL PROVISIONS	DYNAMIC LOAD FACTOR CAPABILITY	ELECTROMAGNETIC EMISSIONS HARDENING	STRUCTURAL LIFE CRITERIA	LOW EMPTY WEIGHT	AIRFRAME CRASH CAPABILITY	LANDING GEAR LIMIT LOAD	STRUCTURE HARD LANDING LIMIT LOAD	INCREASED CABIN VOLUME	EXTERNAL LIFT CAPABILITY	EXTERNAL FUEL PROVISIONS	CABIN HARNESS PROVISIONS	AVIONICS ACCESSIBILITY	LEVEL OF CORROSION PROTECTION	LOW COST REMANUFACTURE METHOD	LOW MAINTENANCE COSTS	COMMON ASSEMBLY TOOLS	COMMONALITY WITH UH-60L	OVER & ABOVE REPAIRS
			↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓	↑	↑	↓
PERFORMANCE	RANGE	5	◎			○	◎				◎	○	◎				△				
PERFORMANCE	EXTERNAL LIFT	5	◎			○	◎					◎					◎				
PERFORMANCE	MANEUVERABILITY	3		◎		○	◎					○	◎				◎				
PERFORMANCE	INTERNAL LIFT	5	◎			○	◎				◎						△				
SYSTEM OPERATIONS	AIRFRAME USEFUL LIFE	5		◎		◎				◎		○				◎	◎				
SYSTEM OPERATIONS	CRASHWORTHINESS	3	△			△	◎	◎	◎	◎							◎				
SYSTEM OPERATIONS	SHIPBOARD COMPATIBILITY	3			◎					○	○					◎	◎				
SYSTEM OPERATIONS	HARD LANDING CAPABILITY	3	△			△	◎	◎	◎	◎							◎				
SYSTEM OPERATIONS	UH-60Q COMMONALITY	3	○		○	◎		△	△		◎	○	◎	◎	◎	○	○			△	△
FIELDING	LOW AQUISITION COST	5	○	◎	◎	◎	◎	○	○	○	◎	△	◎	△	△	○	◎	○	◎	◎	◎
FIELDING	MEET SCHEDULE	5	◎	◎		◎	◎	◎	◎	◎	◎	◎	◎				◎		◎	◎	◎
FIELDING	O & S COST	3		○	△	◎			△	○	◎	△	◎			◎	◎	◎		○	◎
FIELDING	UNSCHEDULED MAINTENANCE	3				◎		△	△	○	○	△	◎		△	◎	◎	◎			◎
MANUFACTURER	AIRCRAFT VARIABILITY	5		◎		◎				◎		◎	◎	○	△	◎	◎	△	△	◎	◎
MANUFACTURER	AIRCRAFT COMMONALITY	3	◎	◎	○	◎		○	◎	◎	◎	◎	◎	◎	◎	○	◎	△	◎	◎	◎
MANUFACTURER	GROWTH CAPABILITY	3	◎	◎	○	◎	◎	○	○	○	◎	◎	◎	○	○	△	○	○	◎	◎	○
	TARGETS		> 360 GAL	3.7 G	ADS-37	25 YRS	< 1025 LBS	> 38 FPS	9 FPS	9 FPS	UH-60L	9,000 LBS	YES	YES	YES	> UH-60L	= TO FWD FIT	< UH-60L	= UH-60L	> 75%	MINIMIZE
PRIORITY	<100			X	X			X	X					X	X			X	X	X	
PRIORITY	100 - 200		X				X			X	X	X	X			X					X
PRIORITY	>200					X											X				

Figure 22: UH-60L+ Cabin QFD Matrix

Analyzing the Results of the QFD Product Planning Matrix

The QFD product planning matrix shown in Figure 22 proved to be an excellent method for capturing the voice of the customer and correlating to the technical requirements for the cabin section. Among the benefits derived from the UH-60L+ Cabin QFD product-planning matrix were:

- Mapping of high and medium priority customer needs to technical characteristics. This effort effectively transformed the voice of the customer into technical characteristics that could be measured and evaluated.
- Established a baseline of relative merit for each technical characteristic. This helped identify priorities for the subsequent trade alternative evaluation.
- Provided insight into the interaction between technical characteristics. This helped identify potential tradeoffs that would need to be evaluated in the trade alternative evaluation phase.
- Identified target values for the technical requirements. These values were used in the concept generation process to help develop alternative configurations.

The selection of some of the technical characteristics in the cabin QFD matrix revealed a unique feature of a helicopter modernization program, which was that some of customer needs already have a desirable solution. When the QFD product planning matrix was originally created for this case study, some of the technical characteristics selected were actually product design requirements; in other words they described the solution instead of the characteristic. An example of this was that avionics accessibility was originally listed as the aft transition avionics access door in the product planning QFD matrix. The aft transition avionics door is certainly too detailed a description to be considered a technical characteristic, so obviously this was an oversight in the original matrix. However, the source of the confusion was that the aft transition avionics access door is a means by which avionics are accessed in the aft transition and has been installed on over

200 BLACK HAWK derivatives. It is a desirable configuration that has been time-tested; so in reality, the solution to the avionics access has already been found. In order to maintain consistency in the QFD matrix intact, this particular technical characteristic was changed to a more abstract description called 'avionics accessibility'. This rewording recognized the possibility that there might be other ways of meeting this particular customer need.

As previously described, the technical characteristics were ranked into three separate categories. The categories allowed for a convenient partitioning of the characteristics and eliminated any biases that might have occurred between two closely ranked characteristics. Any characteristic that achieved a priority value of over 200 was placed in the highest priority category. Structural life criteria and low cost remanufacturing method were the only two characteristics that made it into this category and therefore were determined to be the highest priority characteristics. These two characteristics would become the primary metrics to be evaluated during the trade alternative analysis. The second category consisted of those characteristics that achieved a score of between 100 and 199. This is the category that contained the majority of the characteristics with increased fuel provisions, decreased empty weight, and external hard points ranking the highest among them. Resultantly, these items were given a higher priority during the alternative generation process than the other lower ranked characteristics. The last category was those characteristics that obtained a value of between zero and 99. While not as highly ranked, the design team had to be cognizant of these characteristics during the alternatives generation and subsequent evaluation.

Among the most important observations to be taken from the matrix in Figure 22 is that there is strong relationship between performance enhancing technical characteristics such as external hard points (for additional fuel) and the acquisition cost. A pattern emerged that helped define some of the parameters to be used in the trade alternative evaluation. Because the performance enhancing characteristics have a strong correlation to both the remanufacture method and the acquisition cost, a logical sensitivity analysis was to test how the cost of the various trade alternatives are affected by incorporating the various performance enhancing characteristics. Likewise, the performance enhancing characteristics have a strong negative correlation with the empty weight of the UH-60L+. These correlations triggered analyses during the trade alternative evaluation.

Analyzing the Correlations between Technical Characteristics

Several key observations were derived from the roof matrix of the product planning matrix. The most significant being the negative correlations between characteristics such as acquisition cost and empty weight, and the performance and system operation related characteristics desired by the customers. In fact, the performance and system operation related technical characteristics were combined into a new category called performance enhancements. What is worth noting is that even though the correlations were intuitive to an extent, this exercise substantiated the importance of two key metrics, cost and weight. The correlation between these particular metrics and the performance enhancements listed in the QFD matrix became the major discriminators between the trade alternatives in the cabin trade study.

With respect to positive correlations, the most important finding from the roof matrix was the importance of using common assembly tools and minimizing 'over-and-above' repairs. Common assembly tools means that the fixtures and processes used for the cabin remanufacture are the same ones used for the new build production aircraft. This has important implications for cost, schedule, and space allocation on the assembly line. These repairs can vary greatly from aircraft-to-aircraft. As a result they can have a negative impact on the schedule and cost because they are so difficult to predict. In fact, 'Over-and-above' repairs played a significant role in the risk assessment phase because of the variance associated with the condition of the fleet to be remanufactured.

Establishing the Target Values for the Technical Characteristics

Most of the target values assigned to the technical characteristics were obtained from the data collection phase, either from the UH-60X ORD or through interviews, observations, and/or research. In some cases, threshold and objective target values were identified and later used as a metric in trading off alternative concepts. Some of the technical characteristics such as 'over-and-above' repairs and acquisition cost could not be quantified, so relative values (i.e. minimize 'over-and-above' repairs) were assigned to these particular characteristics. Interestingly, it is the technical characteristics that can not be quantified that often require the most work to substantiate during the trade study phase. With this in mind, the design team to made every effort to avoid assigning relative target values; in the very least, an attempt was made to bound target value limits.

Summary of UH-60L+ Cabin QFD Matrix

The UH-60L+ cabin QFD product planning matrix forms the foundation for the phases to follow. It contains the technical characteristics and corresponding target values that will shape the alternative concept generation development. Priorities established in the matrix identified which technical characteristics are the most important to the customer. In addition, the QFD product planning matrix graphically depicts the correlation between the various technical characteristics. This information will be used in the evaluation of tradeoffs between the trade alternatives.

What is apparent from performing the QFD product planning matrix is that it establishes a communication path that extends from the voice of the customer to a trade study recommendation. Even though this thesis did not address product development phases beyond the preliminary design phase, it is possible to use the work done in this case study to further continue the QFD process into downstream development phases.

Application of the Trade Methodology: Performing the Cabin Trade Alternative Evaluation

Establishing the 'Baseline' for the Alternative Evaluation

The information necessary to perform the alternative evaluation for the cabin trade study was derived from the QFD product planning matrix and the customer needs list. The primary inputs into the alternative evaluation are the relevant requirements, the starting assumptions, and the design characteristics and their corresponding target values. Of particular importance are the relevant requirements that are considered configuration drivers. With respect to the cabin trade study, the following primary technical requirements were determined by the Sikorsky design team and the Army team of structural engineers assigned to the project.

- Airframe Service Life Extension
  - ORD paragraph 3
- Structural Life Criteria
  - SES 700700
- Usage Spectrum
  - SES 700700

Each of these requirements was taken from the customer needs list (Table 3, items # 1, 4, 5, 26) and is directly traceable back to the airframe useful life technical characteristic that was ranked the highest priority in the QFD product planning matrix. These requirements helped establish the criteria required to satisfy the customer need to extend the useful life of the airframe beyond the year 2025. The usage spectrum was important because it contained the governing criteria for the dynamic load factors, mission gross weights, and number of ground-air-ground interactions. Each of these criteria has a significant impact on the useful life of the airframe, the sensitivities of which are analyzed later in the alternative evaluation.

In order to find what the drivers are for the structural life criteria of the UH-60L+, it was necessary to first determine the current condition of the fleet and projected utilization of the aircraft. This information was obtained from data records kept by Sikorsky field representatives and is shown in Figure 23. Based on the current utilization rate for the

UH-60A's, a cumulative flight hour projection was mapped for the UH-60A fleet and is shown in Figure 24.

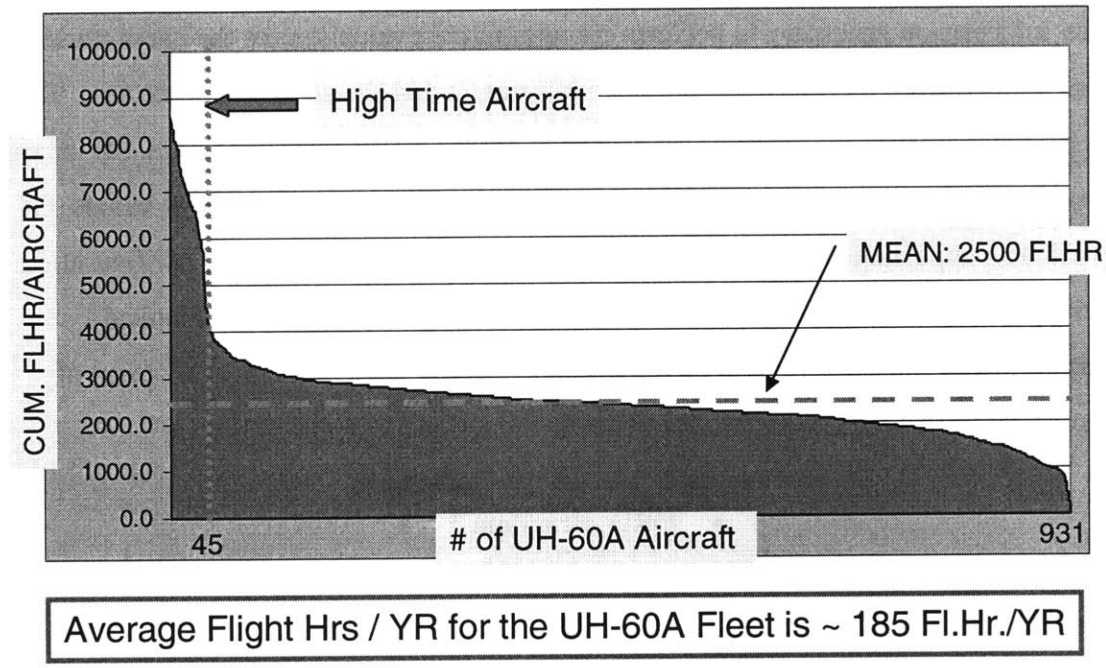


Figure 23: Cumulative Flight Hours / Aircraft for the UH-60A Fleet

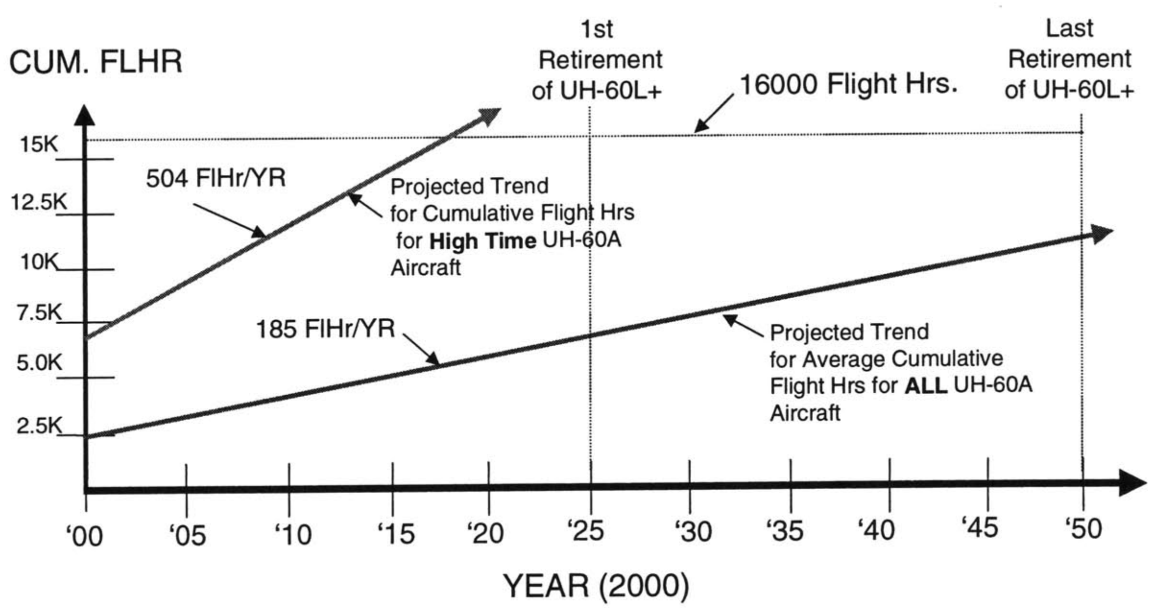


Figure 24: Projected Flight Hours / Aircraft for the UH-60A Fleet

The current UH-60A was designed to have a structural life of 8000 flight hours under the usage spectrum defined in SES70000. As seen in Figure 24, the projected fleet flight hours based on the current utilization will not reach 8000 hours until after the year 2025. This observation in part substantiated the BLACK HAWK program management's decision to recommend that the airframe service life extension be achieved through the refurbishment of the existing cabin airframe instead of through a remanufacture.

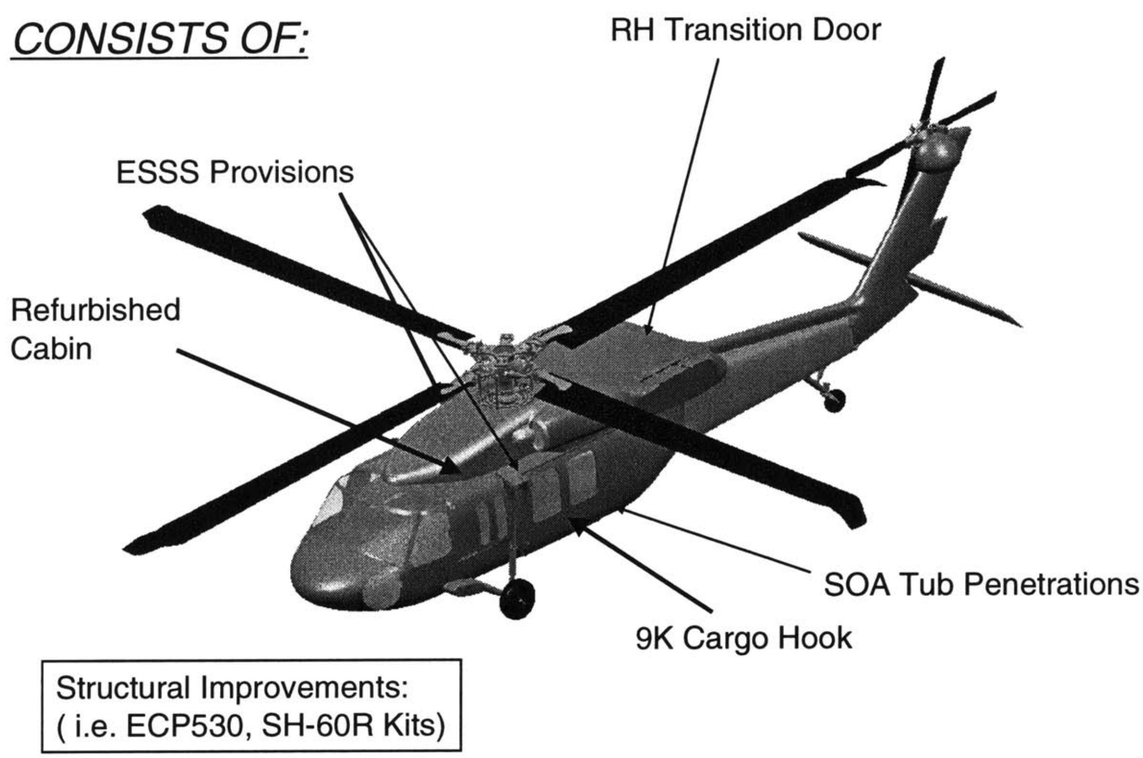


Figure 25: UH-60L+ Cabin 'Baseline' Configuration

Figure 25 contains the recommended 'baseline' configuration as it pertains to the UH-60L+ cabin section and represents the customer's first pass at addressing the primary customer needs. In addition, it was considered the starting point for the trade alternative evaluation. The fact that the customer provided a baseline configuration did not mean that they were not open to alternative configurations. Instead the baseline configuration was interpreted as a barometer for understanding the customer's priorities.

Before starting the concept generation process the objectives, relevant measures, and assumptions for the cabin trade study were recorded. These criterion all were traceable back to the voice of the customer via the QFD product planning matrix as described below:

Objective of Cabin Trade Study:

- Provide an affordable modernization plan that ensures a robust cabin airframe platform for the next 25 years (ORD paragraph 3 and QFD product planning matrix).

Cabin Trade Study Decision Enablers:

- Meet defined UH-60X ORD threshold requirements.
- Provide best performance and most capability while recognizing cost, weight & schedule constraints (reference QFD product planning matrix).
- Where feasible, provide growth path capability to UH-60X objective requirements from Table 3 (i.e. 10K external lift capability as listed in QFD matrix).
- Where practical, identify candidates for separate engineering change proposals (ECP's) as was done in the CH-47 modernization program.

Cabin Trade Study Relevant Measures (as derived from the QFD product planning matrix):

- *Potential* impact of related trades on entire airframe system (i.e. fuel growth, crashworthiness, cargo hook capability, dynamic load factor increase, etc).
- Schedule risk and aircraft variability.
- Life cycle costs and in particular the acquisition cost.
- Empty weight impact.
- Commonality with future new build UH-60L+ aircraft.

Cabin Trade Study Assumptions:

- Airframe shall have a useful life of 25 years (source: UH-60X ORD).

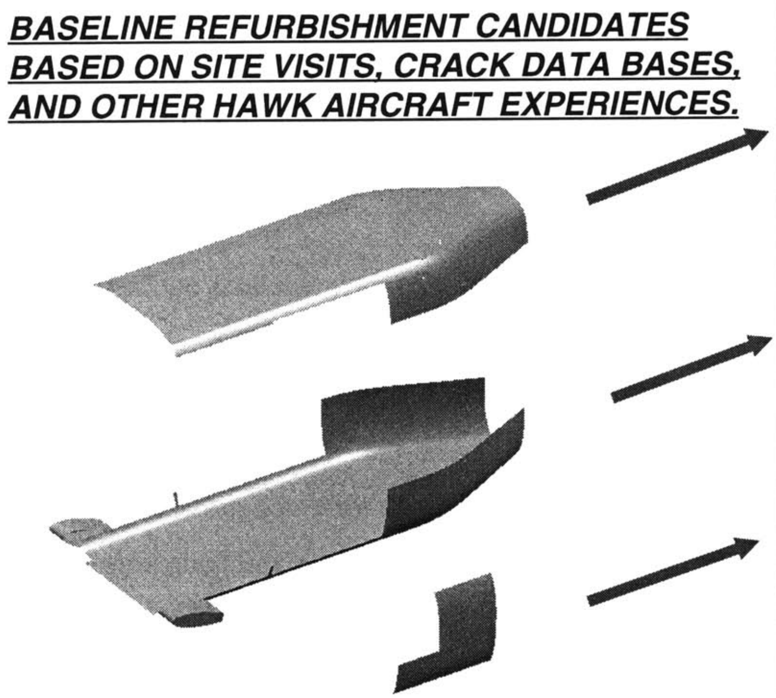
- Remanufacture plan calls for 60 UH-60A to L+ deliveries per year (source: customer plan).
- Remanufacture plan shall consider commonality with future new build UH-60L+ aircraft (source: Table 3, Customer Needs).
- Structural life criteria is the same for all UH-60A aircraft, including high-time aircraft (reference Figure 25, source: Army structural IPT).
- Primary mission gross weight has increased to 19412 lbs. from 16864 lbs. (based on customer baseline configuration).
- Remanufactured airframe must account for growth blade (source: Army structural IPT).

Using the criterion and enablers just described, the design team had sufficiently established the inputs necessary to begin the generation of alternatives.

Generation of UH-60L+ Cabin Alternatives

The generation of UH-60L+ cabin alternatives followed the guidelines outlined in Figure 8 of the trade methodology. This effort started with the information developed in the QFD product planning matrix including the assumptions, design enablers, and the baseline refurbishment configuration recommended by the BLACK HAWK Program Management. Using this information, several techniques were utilized to identify potential cabin concepts. Among these were internal interviews and brainstorming sessions with R & D, engineering, manufacturing operations, and preliminary design. In addition, meetings were held with the Army structures IPT and the user representatives to solicit additional trade alternatives. Finally, the competitive assessment performed on the CH-47 modernization program provided ideas on how to partition the trade space into separate features or capabilities.

In consideration of the baseline recommendation provided by the Program Management, the design team's first task was to define what were the minimum structural upgrades needed to satisfy the baseline refurbishment. The baseline refurbishment was determined by analyzing data obtained from various crack databases maintained by Sikorsky aircraft and from the site visits conducted by members of the structural IPT. These crack databases contain the known structural issues from all the various BLACK HAWK derivatives. Figure 26 shows the resultant baseline refurbishment candidate. One important note was that it was felt by the design team that regardless of what the ultimate structural life criteria was, that it would be necessary to incorporate at least the baseline refurbishment candidates just to get the airframe to 8000 flight hours. Establishing a baseline refurbishment was critical to the trade alternative generation for two reasons: (1) It established the lower bound for satisfying the customer threshold for the amount of structure that needed to be upgraded. (2) It established a starting point for looking at ways to partition the cabin structure.



Cabin Section	REFURBISHMENT CANDIDATES
Upper Deck	1. Fire Walls / Upper Deck Structure
	2. FS 360 Transmission Frame
	3. Servo Beam Rails
	4. Upper Deck Skins FS327-360
	5. BL 16.5 Transmission Beams
	6. FS 295, 308 Splice
	7. FS 308, 327, BL 34.5 Lngn
	8. Oil Cooler, TRDS Support Bracket
Lower Tub	1. FS 379 @ WL206 Splice Doubler
	2. 9K Cargo Hook Provisions
	3. Fs 379 Frame Splice at WL 245
Aft Transition	1. RH Transition Door
	2. Vapor Barriers
	3. FS 485 Tension Fittings
Side Module	1. Side Skin FS 247-265
	2. Gunner's Window Box
	3. Beaded Skin FS 295-308
	4. FS 379 Frame Splice at WL 245
Other Items	1. IR Supressor Interface
	2. Roll Absorber
	3. Drag Beam

Figure 26: Baseline Refurbishment Candidates

The partitioning of the cabin section played a significant role in the generation of concepts. Ways in which the cabin could be partitioned were:

- To look for major configuration changes during the lifetime of the UH-60A
- To look at different ways the structure can be divided into smaller chunks.

The importance of partitioning was that it could lead to different trade alternative concepts that might not otherwise have been considered. This effort necessitated a thorough review of the major engineering change proposals (ECP's) that had been incorporated into the UH-60A fleet. Table 5 shows some of the major partitions that were uncovered as part of this study.

Table 5: Potential Partitioning of the Cabin Structure

Partition	# of Aircraft Affected
Aircraft that don't have external stores supports (ESSS).	427 of 935
Aircraft that do not have an UH-60L level of corrosion prevention.	500 of 935
Partitioning the cabin airframe by manufacturing sub-assemblies (see Figure 26).	935 of 935

ESSS provisions were added to the 428th UH-60A and subsequent aircraft. The addition of this feature was determined to have the single greatest impact of all the ECP's incorporated into the UH-60A fleet. This was due to the amount of structure affected and the impact on the fatigue lives of the airframe structure in the cabin top deck (see Figure 26). ESSS is primarily used to carry 230 gallon external fuel tanks in the UH-60A aircraft, although a few aircraft had weapons mounted to the external stores.
The first several hundred UH-60A aircraft did not have the same level of corrosion protection as aircraft # 500 through 935. This seemed to be a logical partitioning because of the potential for a major rework to bring all the UH-60A aircraft to the same level of corrosion protection.

Another partitioning that was considered was to divide the cabin section into chunks coinciding with the manufacturing sub-assemblies of the cabin. These sub-assemblies are shown in Figure 26. By dividing the structure into sub-assemblies, it might be possible to consolidate design characteristics and their corresponding customer needs into specific sections of the cabin. The expectation was that a large number of design characteristics could be lumped into a few sub-assemblies and therefore these sections could be treated differently than the rest of the fuselage. Note that the largest number (8) of refurbishment candidates affected the top deck section, some of which would require significant rework to implement as refurbishments.

In parallel with the partitioning effort, the design team pursued other alternative concepts for consideration. For example, the R & D department was tasked with coming up with a concept based on the incorporation of new technologies such as high speed machining and composite automated fiber placement. The expectation was that a high technology cabin would be significantly lighter and less expensive than the current cabin. In addition, one of the objectives of the new technology cabin was to look for opportunities to establish a growth path to the UH-60X if possible. Another concept that was generated was to leverage the latest BLACK HAWK derivatives such as the UH-60Q and the CH-60 and combine them into a common BLACK HAWK cabin. Features that were unique to a specific customer would be incorporated through a build-to-order bill of materials. The objective of this approach was to develop a common assembly line for the entire HAWK family.

Listing of the Concept Alternatives

The alternatives generated using the process described above are listed in Table 6. The concept alternatives are divided into refurbished options and remanufactured options. The remanufactured options necessitate the removal of the old cabin from the rest of the fuselage and replacing it with a new cabin section as described in Table 6. Note that the concepts listed represented the first iteration in the concept generation process. It was determined that the corrosion partition would be treated as a sub-trade study since further research had uncovered methods for applying corrosion preventive compounds to the old UH-60A cabins that would not require the removal of fasteners and/or structure.

Table 6: First Pass at UH-60L+ Cabin Alternatives

#	Concept
	Refurbished Options (Modification Kit Approach)
1	Baseline Refurbishment + ESSS fittings for those aircraft that don't already have it.
2	Baseline Refurbishment only (aircraft that already have ESSS fittings).
	Remanufacture Options (New Build Approach)
1	Remove & Replace with UH-60L cabin section.
2	Remove & Replace with a 'common' HAWK cabin section based on the CH-60.
3	Remove & Replace with a 'new technology' cabin section.

Analysis of Concept Alternatives: Refurbishment Concepts

With respect to the QFD product-planning matrix, even though the refurbished options address two of the customer's primary needs (service life extension and range), they do not include the incorporation of many of the performance enhancing needs. What became apparent to the design team was that it would be necessary to trade performance against cost and schedule risk for each of the concept alternatives. However, before the design team created the evaluation matrix, a closer analysis of the different options was performed to measure the validity of each alternative and also to look for other potential concepts.

Adhering to Pugh's method [Pugh1991a pg.74, 75] for controlled convergence as it applies to concept generation and selection, one last concerted effort was made to ensure all possible combinations of alternatives were considered. Concentrating on the refurbished options first, the design team went back to the sub-assembly partitioning and discovered that it might be more cost effective to replace the top deck portion of the cabin and refurbish the remainder of the cabin with modification kits. In order to confirm this assumption, a thorough labor and material cost estimate was generated for each of the refurbishment concepts.

The design team partitioned the cost estimates into the following components:

- Material Cost
- Recurring Labor
  - Detail Parts
  - Disassembly
  - Inspection
  - Over and Above (unscheduled repairs)
  - Assembly

The design team was able to benchmark each of the components listed above by using data obtained from either the UH-60L program or other similar programs. A particular challenge was estimating the amount of unscheduled repairs. These repairs are often referred to as 'over and above' repairs and are negotiated separate from the contracted work on an aircraft-by-aircraft basis. Because the condition of the airframe varies from aircraft to aircraft, over and above repairs are inherently difficult to estimate. Fortunately the design team was able to use legacy data from the SH-60B SEAHAWK[2] SDLM program that was currently being performed at the Sikorsky plant. Using a database generated from the 21 aircraft and correlating the data back to the UH-60A, the design team was able to estimate an anticipated impact of over and above repairs for the UH-60L+ refurbishment. The methodology for determining the over and above repairs is illustrated in Figures 27 and 28.

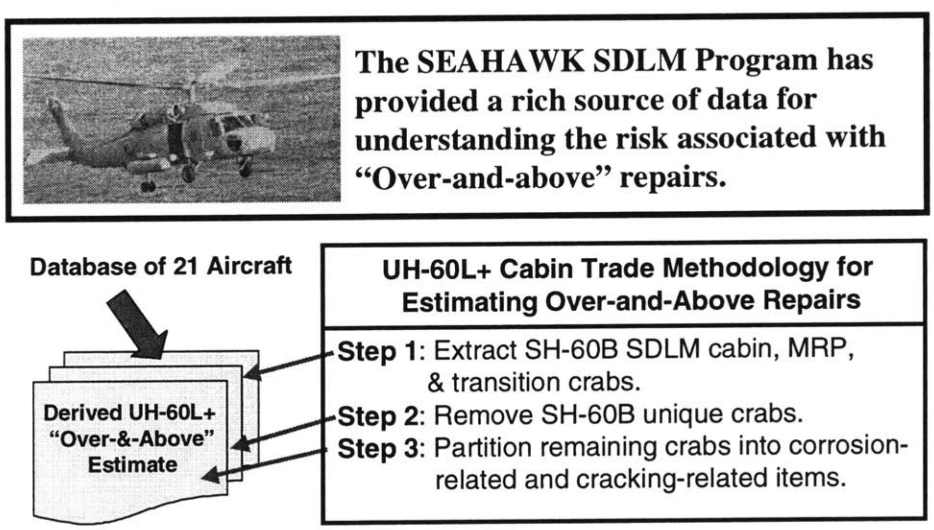


Figure 27: 'Over and Above' Repair Estimate Methodology (Part A)

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[2] SEAHAWK is a registered trademark for the U.S. Navy SH-60B helicopter.

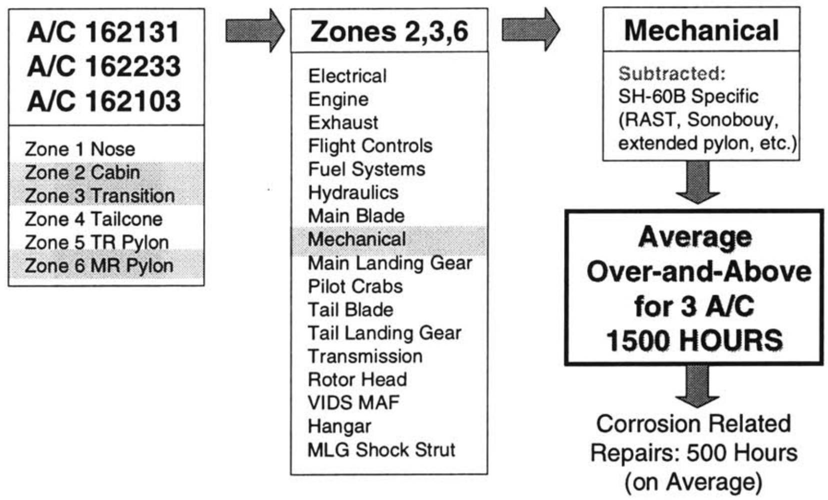

Figure 28: 'Over and Above' Repair Estimate Methodology (Part B)

The estimated hours derived from using the methodology described above was converted to dollars and used in the refurbishment option estimate. A normalized comparison of the cost estimates for the refurbished options is shown in Figure 29. Note that the cost estimates reflected recurring costs only and were normalized to the cost of the hybrid option (new top deck with the remainder of the airframe refurbished by modification kit).

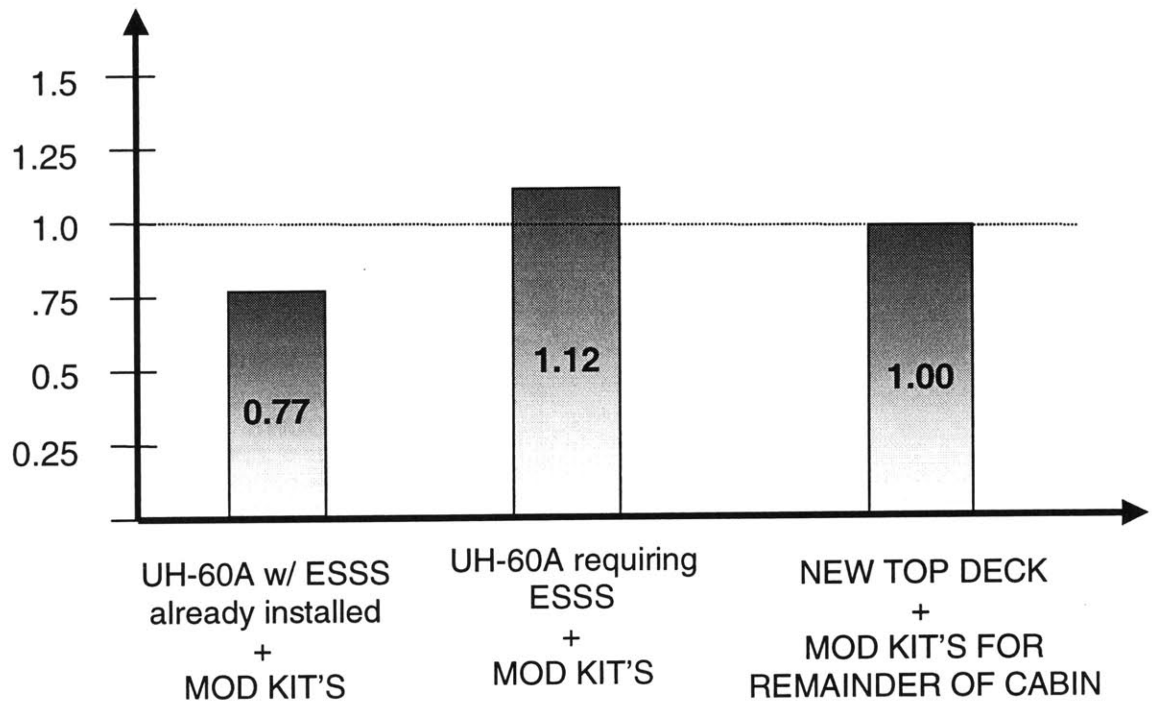

Figure 29: Normalized Cost Comparisons for Refurbished Concepts

Some interesting observations can be derived from the analysis just performed on the refurbishment options. At first glance the partitioning of the UH-60A fleet into aircraft based on whether ESSS is installed makes sense considering the large cost difference between the two approaches. However, the cost estimate performed only included the effort to incorporate the 'baseline' refurbishment candidates (Figure 26). A review of the QFD product planning matrix shows that even if performance enhancing needs are not taken into consideration; there are other needs such as schedule, aircraft commonality, and maintenance costs that are also worthy of evaluation.

Since a majority of the refurbishment occurs in the top deck section, the hybrid refurbishment option that combines a new top deck with the remainder of the cabin upgraded via modification kits appears to be an excellent compromise between mitigating schedule and cost risk, and providing a common configuration. In order to get a sensitivity of the risk associated with the primary customer needs described above, a qualitative risk mapping was performed for each of the refurbishment concepts. The risks that were evaluated included cost, schedule, empty weight, and technology. Technology risk included any risk associated with integrating a new process or material. In the case of the new top deck option this included high speed machining. Of particular concern was the risk associated with the field repair of high speed machined parts because there was so little field experience. The risk-mapping diagram generated for the refurbishment options is shown in Figure 30.

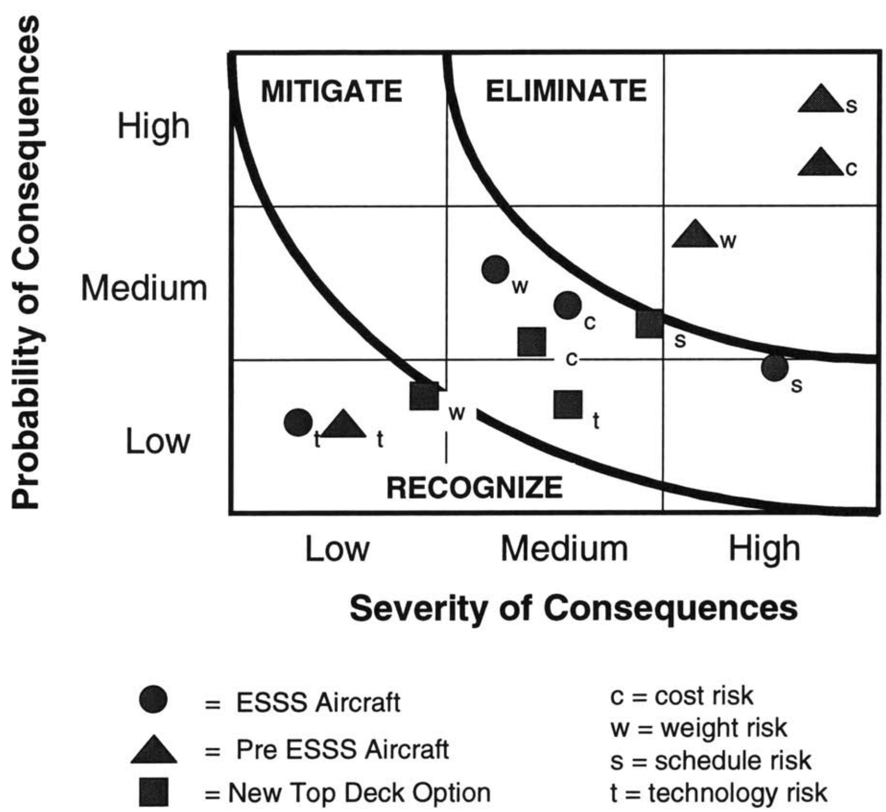

Figure 30: Risk-Mapping Diagram for Refurbished Cabin Concepts

As shown in Figure 30, the refurbishment of the Pre-ESSS aircraft option carried considerable risk that could dramatically affect the cost and schedule estimates for the refurbishment effort. Even the aircraft that already had ESSS hard points installed were judged to have a more than acceptable amount of schedule and cost risk, largely due to the number of baseline refurbishment candidates impacting the top deck. Minimizing risk was a top customer need as identified in the QFD product planning matrix. Additionally, a desire to maintain a common configuration for all the refurbished aircraft was another important consideration. While this was not identified as one of the higher priority customer needs, it carries with it significant logistics issues that might not be readily apparent. Ultimately, the combination of risk and a desire to have a common configuration for all the refurbished aircraft influenced the design team to down-select to the hybrid refurbishment option that consisted of a new top deck with the rest of the cabin upgraded via modification kits. The recommended refurbishment concept is described in Figure 31.

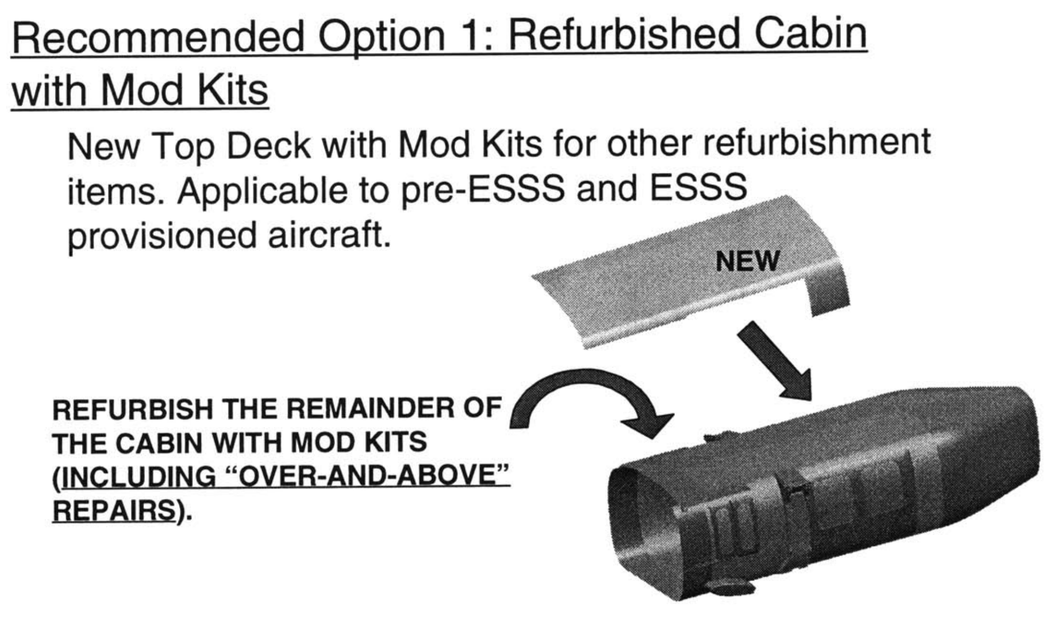

Figure 31: Recommended Refurbishment Concept

Analysis of Concept Alternatives: New Build Alternatives

A similar analysis was performed on the new build concepts listed in Table 7 below.

Table 7: New Cabin Build (Remanufacture) Alternatives

1	Remove & Replace with UH-60L cabin section.
2	Remove & Replace with a 'common' Hawk cabin section based on the CH-60.
3	Remove & Replace with a 'new technology' cabin section.

The recurring cost estimate for the new build concepts consisted of the following components:

- Material Costs
- Labor Costs
  - Disassembly and removal of the old cabin section.
  - Build of the new cabin section.
  - Joining of the new cabin section.
  - 'Over and above' repairs during the joining of the new cabin to the existing fuselage.
  - The R & D group parametrically estimated the cost estimate for the 'new technology' cabin.

The recurring cost estimates for the new build alternatives were normalized to the cost of removing the existing cabin and replacing it with the current UH-60L cabin. The result of this effort is shown in Figure 32.

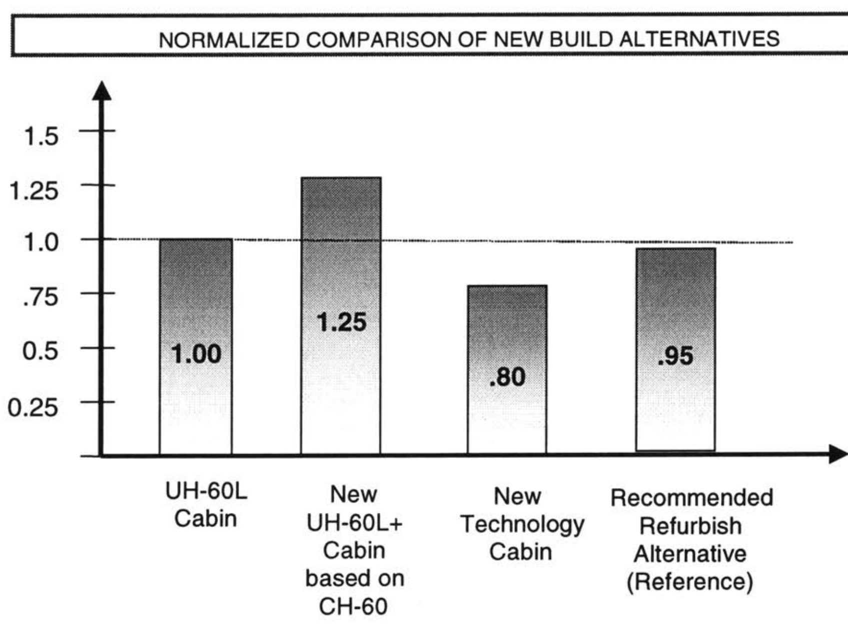

Figure 32: Normalized Cost Comparisons for New Build Alternatives

After generating the cost estimates and comparing the configuration for each of the new build alternatives with the baseline refurbishment, the design team made the following recommendations:

- The UH-60L alternative was rejected from further consideration because it did not satisfy many of the baseline refurbishment candidates (Figure 26).
- The UH-60L+ cabin based on the CH-60 cabin was determined to be too expensive. Further investigation indicated that the CH-60 did not have as much in common with the UH-60L+ as first hoped. In effect, an UH-60L+ cabin based on the CH-60 would have been burdened with extra weight and cost plus-ups that did not correspond to any of the customer needs. Resultantly, the design team elected to modify this particular alternative to an UH-60L+ that was similar to a CH-60. This meant that wherever practical the UH-60L+ cabin would incorporate CH-60 enhancements, otherwise the UH-60L+ cabin would be unique. The long-term objective was that the UH-60L+ cabin would implement a build-to-order bill of materials so future derivatives could more easily be accommodated. The revised cost estimate for the UH-60L+ concept was lowered from 1.25 of the UH-60L cabin to 1.20 of the UH-60L cabin.

Once the new build alternatives were down-selected, a risk-mapping was performed on the remaining two new build alternatives. The risk-mapping diagram is shown in Figure 33.

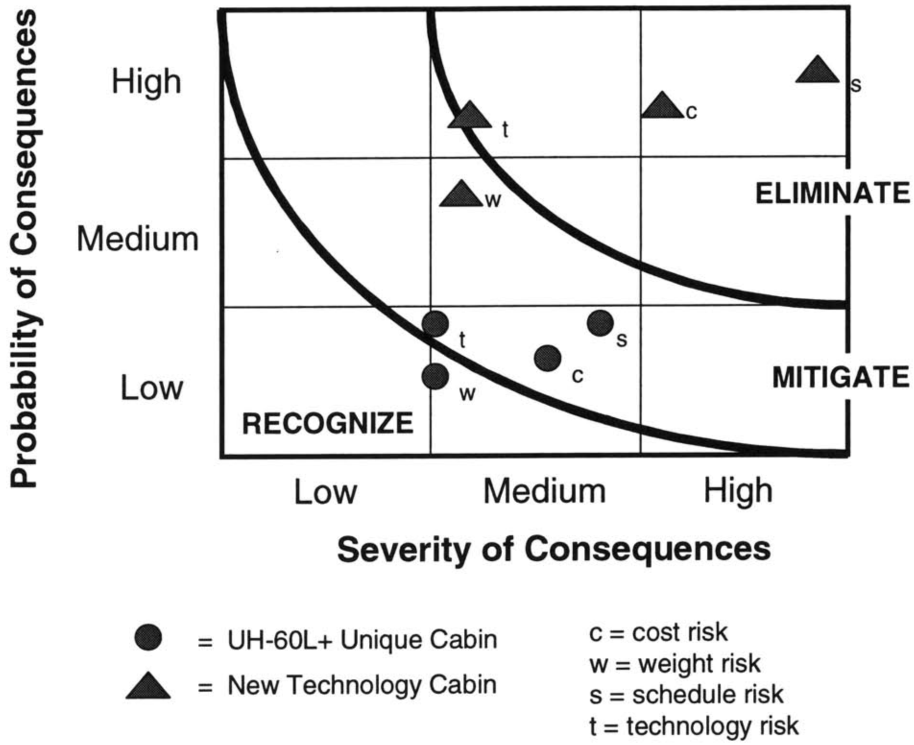

Figure 33: Risk-Mapping Diagram for New Cabin Build (Remanufacture) Alternatives

It was obvious to the design team that the new technology concept carried too much inherent risk to be a viable option for the UH-60L+ program. Some of the technologies required for the new technology approach would not be available in time for the start of the UH-60L+ program. Likewise, the cost and schedule risks were determined to be too great considering the low risk approach desired by the customer. However, the effort put into developing the new technology concept was not wasted since these technologies are directly applicable to the future UH-60X program.

In mapping the qualitative risk factors for the UH-60L+ cabin, it was determined that the risks factors associated with the UH-60L+ unique cabin could be mitigated sufficiently to merit keeping this alternative in the trade space.

Cabin Trade Alternatives Evaluation Matrix

By this point in the trade study the cabin alternatives had been down-selected to the most viable concept from the refurbished and new build alternatives. These alternatives were the hybrid option consisting of a refurbished cabin with a new top deck (concept A) and a new UH-60L+ unique cabin section (concept B). Once the trade space was narrowed to two candidates an evaluation matrix was developed to analyze the relative value of each alternative. All of the attributes and objectives contained in the evaluation matrix are directly traceable back to the QFD product-planning matrix.

As previously explained during the development of the QFD matrix, a thorough quantitative analysis of the relative merit for technical characteristics was deferred. It was felt at the time that assigning an absolute numerical value to the ranking of the technical characteristics might lead to spurious observations. By the time the alternatives had been generated and down-selected, the System Requirements PDT working in concurrence with the primary customer had assigned numerical weightings to the technical characteristics. It could be possible to evaluate all the alternatives simultaneously in the evaluation matrix. However, the other candidate alternatives in this trade study were able to be eliminated based on qualitative measurements. If a clear distinction between the alternatives did not exist then they would have been included in the evaluation matrix also. In addition, it has been the experience of the author that the complexity increases and the objectivity decreases considerably as the number of alternatives are added to a comparison matrix. It is usually easier to differentiate on a relative scale between two alternatives than it is between several options. Therefore, whenever possible, down selecting by a qualitative means not only reduces the amount of analysis required, it also permits an increase in the fidelity of the evaluation matrix.

The evaluation matrix created for the UH-60L+ cabin trade study is shown in Table 8.

Attribute	#	Objective	Weight	Parameter	Concept A			Concept B		
					Magnitude	Score	Weight Value	Magnitude	Score	Weight Value
Service Life Extension	1	Affordable remanufacture of airframe	0.325	Procurement cost	Baseline configuration	5	1.625	Baseline configuration	3	0.975
	2	Minimize weight growth	0.09	delta weight over baseline configuration	Mod kits are heavier than new builds	2	0.18	New build can be optimized	5	0.45
Performance	1	Increase external lift capability	0.02	Provide structural provisions for 10K external lift	Accept fallout capability	0	0	10K external lift can be designed into new build	7	0.14
	2	Increase maneuver capability	0.05	Provide structural capability to accommodate wide chord blade	New top deck provides most of capability	5	0.25	New cabin can accommodate higher dynamic load factor	7	0.35
Range Extension	1	Increase range	0.09	Increase Fuel Capacity	Modifications require replacement of transition section	0	0	Increased fuel capacity can be incorporated into new build	7	0.63
Crash Worthiness	1	Protect occupants in crash	0.05	Maximize fps crash capability	Changes are prohibitive, accept fallout capability	1	0.05	Potential to incorporate enhanced crash capability in new build	7	0.35
Risk	1	Technical Risk	0.05	Use proven technologies	Use existing prod mod kits	6	0.3	High Speed Machine has not been proven in production	3	0.15
	2	Producibility	0.04	Use common tools & processes	rework nature of concept will limit common tools	2	0.08	Use existing production tools	5	0.2
	3	Interfaces	0.01	Minimize impact of new interfaces on remanufacture	aircraft variability will affect repeatability	3	0.03	Interfaces can be accounted for in new build	5	0.05
	4	Schedule	0.03	Likelihood of remanufacturing 60 A/C per year	aircraft variability will affect schedule	2	0.06	New build concept is very similar to current production	5	0.15
	5	Cost	0.03	Likelihood of meeting cost target	aircraft variability could result in O.T. Enhancements will drive up cost	1	0.03	New build is more predictable, variability will be in joining aircraft	5	0.15
Supportability	1	Common Configuration	0.03	Commonality between refurb.aircraft & forward fit aircraft	No commonality with forward fit	2	0.06	Common configuration for all cabins	7	0.21
	2	Lower maintenance costs	0.02	Reduce likelihood for unscheduled maintenance	Higher likelihood	4	0.08	Lower likelihood	6	0.12
TOTAL			0.835		CONCEPT A:	=	2.745	CONCEPT B:	=	3.925

Table 8: UH-60L+ Cabin Trade Study Evaluation Matrix

The evaluation matrix shown in Table 8 illustrates quantitatively the relative overall benefit of each alternative, in addition to providing insight into the strengths and weaknesses of each alternative. Before analyzing the results of the matrix it is necessary to first explain some of the data and rationale used in generating the evaluation matrix. As previously mentioned the weighting values are generated by the System Requirements team working in conjunction with the customer. Also previously stated, was that the evaluation matrix in some respects is an extension or evolution of the QFD product planning matrix. While the QFD matrix assigned a range of priorities to avoid premature or biased conclusions, by the time the evaluation matrix was developed the trade study had matured to the point where the design team had more confidence in assigning weightings to the technical characteristics. In addition, with an evaluation matrix the magnitude or score for each technical characteristic could be applied to a concrete alternative, thereby further enhancing its fidelity.

A quick review of Table 8 shows that the total sum for the weightings only add up to 0.835 instead of 1.00 as might be expected. This was due to the fact that only those attributes that impacted the cabin were included in Table 8. The remainder of the attributes being measured at the systems level were mostly software or avionics related. Another note concerning the structure of the evaluation matrix was the use of a rating scale ranging from 1 through 7. Experience has shown that using a scale of 1-7, instead of a scale of 1-5 or 1-10, reduces the likelihood that the rating values will gravitate to the midpoint.

The first observation to be taken from Table 8 is that the affordable refurbishment of the airframe is by far the most important attribute, accounting for almost 40% of the total weighting. Concept A scored higher than concept B in meeting this need based on the cost estimates performed on each concept. The customer's interpretation of this need is represented by the baseline refurbishment shown in Figure 26. Taken by itself, the importance and visibility placed on affordable refurbishment reinforces the customer's baseline recommendation. However, when all of the other attributes listed in Table 8 are included, Concept B actually ranked significantly higher than Concept A. This illustrates the importance of accounting for all of the technical requirements listed in the QFD product planning matrix and not just the most visible.

The evaluation matrix is not the end-all for the trade study. Even though the objective of the evaluation matrix is to quantify the benefits of the alternatives, there is still some amount of subjectiveness in the weighting and rating of the needs. The alternatives will be evaluated further in the risk /benefit analysis phase in an attempt to solidify the results recorded in the evaluation matrix.

Before closing out the trade alternative evaluation phase, the 'revisit' criterion was documented based on the analysis performed up to this point in the trade study. The 'revisit' criterion that was identified for the cabin trade study was defined as follows:

- Revisit the Cabin Trade Study Results if any of the following events occur:
  - There is a significant change in the 'baseline' refurbishment.
  - There is a change in the structural life criteria assumptions.
  - New technologies become available earlier than expected.
  - There is a significant change in the assumptions used for estimating the cost of each of the concepts. For example, a more cost-effective means of handling 'over-and-above' repairs is discovered.

Trade Alternative Analysis Summary

Using the QFD product planning matrix as the foundation for generating alternative concepts, several candidate alternatives were derived. Each of these candidates was qualitatively evaluated for risk assessment. It was this qualitative risk assessment process that led to the down select of the trade space to the two most viable alternatives. These alternatives were identified as a refurbished cabin with a new top deck and a remanufactured cabin consisting of new build UH-60L+ unique cabin. Next, an evaluation matrix was created that assigned numerical weightings to the attributes and technical characteristics listed in the QFD product planning matrix. Each of the two remaining alternatives was ranked and scored against each of the attributes. The results of this evaluation showed that if only service life extension was considered then the refurbished cabin was the preferred alternative. However, as performance enhancements and risk factors were added to the evaluation, the remanufactured or new build cabin obtained a higher score. This set the stage for the next phase of the methodology, the risk / benefit analysis, where the alternatives would undergo further quantitative analysis of the highest priority technical characteristics.

However, before proceeding onto the risk /benefit analysis, a sanity check was performed on the trade alternative analysis. Specifically, the following questions were addressed:

1. Is the evaluation matrix consistent with the data in the QFD product-planning matrix?
2. Does the analysis make sense?

With respect to the first question, all of the attributes and objectives used in the evaluation matrix were derived from the QFD matrix. With respect to the second question, a review of the trade alternative analysis showed a clear trend that was consistent with the analysis from the previous phases of the trade study and also information supplied by the customer. Additionally, it was clear that the primary customer need was to ensure an affordable modernization of the airframe that enabled the BLACK HAWK to function for the next 25 years; even it meant downscaling the amount of performance enhancing needs included in the UH-60L+. The conclusion that was derived from the alternative analysis was that the refurbished cabin option (concept A) met the customer's highest priority need of affordable modernization better than a new cabin (concept B). However, the potential impact of risk was not fully quantified, particularly if the customer should decide in the future to incorporate some of the performance enhancing needs. The quantification of these risk factors was performed in the next phase of the trade study.

Application of the Methodology: Risk / Benefit Analysis

Overview

Continuing the sequential analysis of the remaining trade alternatives, a quantitative risk / benefit analysis was performed to further substantiate the results derived in the trade alternative evaluation matrix. Specifically, the risk / benefit analysis addressed the following concerns and scenarios:

1. A quantification of the schedule risk associated with the manufacturing process used for each concept.
2. A quantification of the cost risk associated with adding performance enhancing design characteristics to each concept.
3. A present worth analysis comparing the life cycle costs associated with each alternative.

Quantification of Schedule Risk

The objective of the schedule risk evaluation was to determine how the manufacturing method associated with each alternative impacted the ability to deliver 60 upgraded UH-60L+ aircraft per year. Following the step-by-step methodology described below, the potential schedule impact of the manufacturing processes was estimated for each option.

1. State assumptions concerning resources and process flow.
2. Identify risk areas associated with each station:
   - Aircraft variability.
   - Where and how each control point is performed (i.e. Is the same party responsible for disassembly and assembly?).
3. Assign probabilities for the likelihood of risk event occurring (based on SEAHAWK SDLM & previous experience).
4. Assign estimates for the impact to schedule if the risk event occurs (based on SEAHAWK SDLM & previous experience).
5. Chart change in aircraft delivered per year assuming manufacturing flow remains constant.

Schedule Risk Evaluation Assumptions

The following questions concerning the resource and process flow associated with each alternative had to be answered to support the schedule risk evaluation:

- How many hours can be allocated per aircraft to meet the yearly delivery requirement?
- How many workers can productively work on the aircraft at a particular control point?
- How many stations are required at the risk control point to meet schedule?

Using data obtained from the cost estimates generated in the trade alternatives phase and interviews with personnel familiar with the manufacturing processes associated with each concept, an analysis was performed to answer the questions listed above. Figures 34 and 35 summarize the results of this analysis.

• Scheduled number of UH-60A aircraft to be refurbished per year:	60
• Number of work weeks per year:	÷ 50
• Number of aircraft per week:	1.2
• Number of production shifts assumed:	2
• Number of hours per shift per week:	x 40
• Number of hours available per week:	80
• Number of hours required per aircraft to meet schedule is:	80 hrs/ week / 1.2 aircraft / week
Number of hours allocated per aircraft to meet delivery requirement:	**66.6 hr**

Figure 34: Manufacturing Assumptions for Schedule Risk Quantification (Part A)

• Maximum number of mechanics able to productively work on cabin section:	5
• Number of production shifts assumed:	x 2
• Total number of workers per day:	10
• Assumed efficiency rate of workers:	x 0.75
• **Effective workers / day used for manufacturing flow calculations:**	**7.5**

Figure 35: Manufacturing Assumptions for Schedule Risk Quantification (Part B)

Figure 34 indicates that assuming a normal scheduled work calendar (no overtime, holidays, or weekend shifts) and a requirement to deliver 60 upgraded aircraft per year, that cycle time for each aircraft is 66.6 hours. This implies that an aircraft can not be in any one control point longer than 66.6 hours without impacting the schedule delivery. For the purposes of this evaluation, it was assumed that the resources and available time are held constant. In reality, measures would have been taken to get the aircraft back on schedule, but these measures would have resulted in additional costs to the program.

Figure 35 identifies the workers that could operate productively on the aircraft in any particular control point. What this means is that 7.5 workers per day can effectively work on the UH-60 cabin in a particular control point at one time.

The methodology used in estimating the number of stations at the risk control point is described as follows:

- A process flow diagram for the two remaining concepts was generated along with estimated hours for each control point. The process flow diagram and estimated hours were taken from the cost estimate analysis done in the trade alternatives phase.
- The risk control point was identified for each concept using the control point hour estimate.

- A process flow calculation was generated for the risk control point using the assumptions listed above.
- The value obtained from the process flow calculation was compared with base assumption that an aircraft must be moved from a control point every 66.6 working hours.

The results of this calculation for each of the two remaining concepts are shown in Figures 36 and 37.

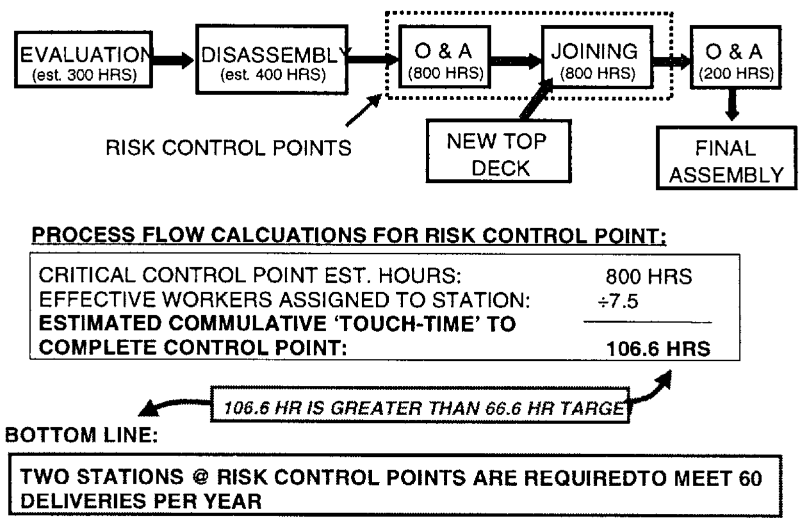

Figure 36: Number of Work Stations Required at the Risk Control Point (Refurbished Option)

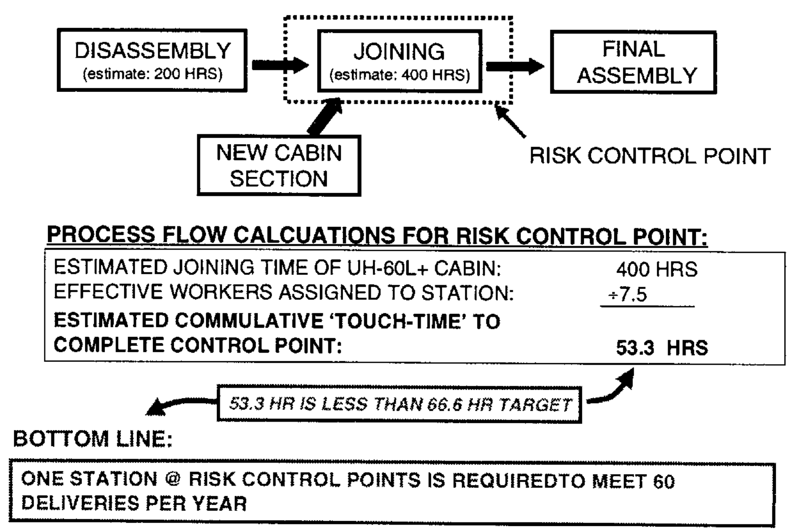

Figure 37: Number of Work Stations at the Risk Control Point (New Cabin Option)

Implied in the calculations just performed is that two stations are required at two different control points for the refurbished alternative (concept A), while only one work station is required at each control point for the new cabin alternative (concept B). The fact that more work stations are required for concept A versus concept B means that more aircraft are needed in the process flow, which means that less aircraft are in service at any particular time.

Weighted Risk Estimates for Each Alternative

This process involved two steps. First, the design team assumed that the hour estimates generated for the risk control points were average expected hours, then the design team estimated the probability that an event occurred would result in the actual hours being greater than average. Then if this event occurred, the design team estimated the corresponding impact on schedule. Furthermore, assuming that the base assumptions did not change (no overtime, weekend, or holidays), the design team estimated the corresponding impact on the number of aircraft delivered per year. As a benchmark, the design team performed a weighted expected value calculation on schedule risk based on actual data obtained from the SEAHAWK SDLM program. Figure 38 and 39 shows the corresponding risk factors, their probability of occurrence based on the manufacturing method used, and the potential impact on schedule if the event occurs.

Risk Factor	Relative Probability	Probable Cause	Potential Impact on Schedule if Event Occurs	Risk Mitigation
Difficulty aligning new top deck structure with cabin if top deck is removed by second party.	HIGH (.75)	1. Lack of process control. 2. Lack of coordination between disassembly process and joining process. 3. Variability between aircraft. 4.Ownership of process concerns.	HIGH (80 HRS)	1. Process improvement possibly requiring shop aids and tools. 2. Make same party responsible for disassembling and joining cabin.
Difficulty aligning new top deck structure with cabin if top deck is removed by same party.	MEDIUM (.5)	1. Lack of process control. 2. Variability between aircraft.	MEDIUM (40 HRS)	Process improvement possibly requiring shop aids and tools.
Variability in Over & Above	HIGH (.75)	1. Age of aircraft. 2. Unique Issues. 3. Location of base where aircraft was stationed.	+ HIGH (160 hrs) - LOW (20 hrs)	1. Look for trends and have parts in inventory. 2. Identify potential problems during evaluation and have fixes ready by the time cabin goes into O & A.

Figure 38: Risk Factors and Probabilities for Refurbished Cabin Alternative

Risk Factor	Relative Probability	Probable Cause	Potential Impact on Schedule if Event Occurs	Risk Mitigation
Difficulty aligning cockpit structure with new cabin if cabin is removed by second party.	HIGH (.75)	1. Lack of process control. 2. Lack of coordination between disassembly process and joining process. 3. Ownership of process concerns.	MEDIUM (40 HRS)	1. Process improvement possibly requiring shop aids and tools. 2. Make same party responsible for disassembling and joining cabin.
Difficulty aligning cockpit structure with new cabin if cabin is removed & joined by same party.	LOW (.10)	1. Lack of process control.	MEDIUM (40 HRS)	Process improvement possibly requiring shop aids and tools.
Misalignment of tailcone to cabin (assumes new tailcone).	LOW (.10)	1. Lack of process control.	LOW (20 HRS)	Provide coordinated tooling between mating fittings at STA 485.

Figure 39: Risk Factors and Probabilities for New Cabin Alternative

In all likelihood, mitigation actions would be taken to eliminate the problems described in Figures 38 and 39. However, the purpose of this exercise is to bring to light the inherent risk associated with each alternative and establish a relative comparison between the two alternatives. The risks described in Figures 38 and 39 were used to calculate the potential 'high' estimate for each alternative. These calculations are shown in Figure 40.

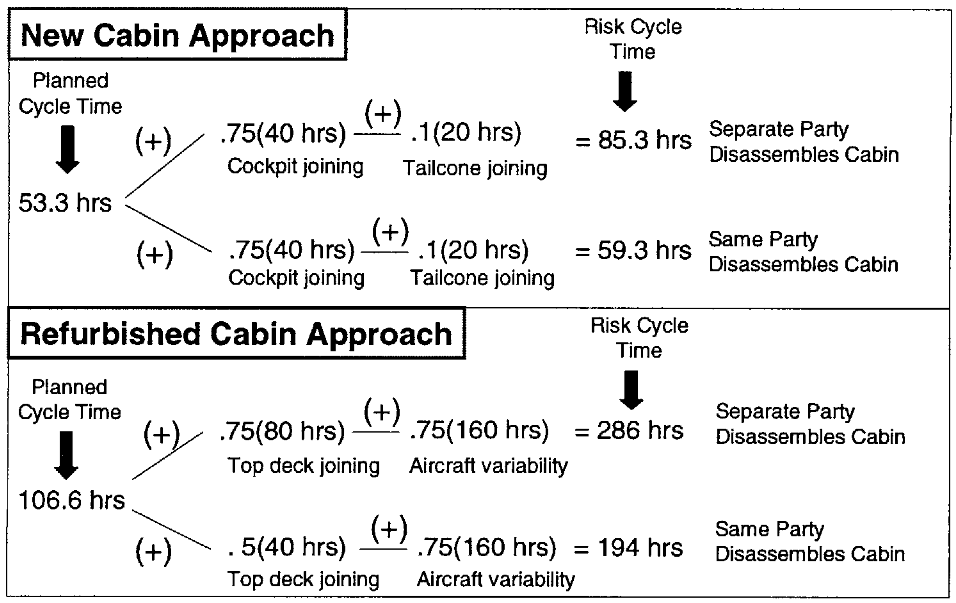

Figure 40: Weighted Expected Value Calculation for 'High' Estimate

The analysis performed above revealed some interesting observations. Based on the assessment of the design team, both the manufacturing method employed and the responsible party performing the different stages of work caused wide variations in the cycle time. Variability that is caused by the condition of the airframe can occur for many different reasons.

Among the more prevalent reasons include the location of deployment (salt-water environment), whether the aircraft saw combat, age of the aircraft, and the primary mission of the aircraft. Variability resulting from different parties performing the disassembly versus the assembly is not entirely intuitive. There are several reasons for this type of variability, including insufficient knowledge transfer from the disassembler to the assembler, shifting of the airframe during transport, and different manufacturing processes used by the disassembler versus assembler.

The analysis performed to quantify the potential schedule risk caused by aircraft variability and method of manufacture was put into a graphical format (Figure 39) to better illustrate the relative contributions of each type of risk.

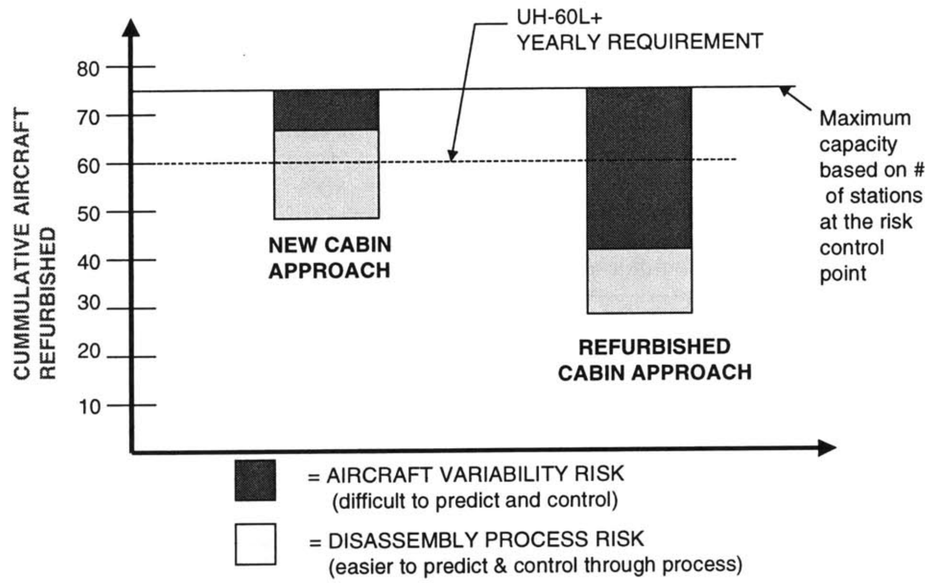

Figure 41: Schedule Risk Comparison

Referring to Figure 41, the maximum capacity of 75 aircraft per year is derived from the assumptions stated earlier. Figure 41 shows an 'apples-to-apples ' comparison of the schedule risk associated with each alternative based on an equivalent production capability. The lower limit of the bars shown in Figure 41 represent a worst case scenario where for a one year duration all of the aircraft are in poor condition and separate parties disassemble and assemble the airframe sections. A major message from Figure 41 is that inherently there is a much greater risk with the refurbished approach versus the new cabin approach. Additionally, a large percentage of the schedule risk associated with a refurbished cabin comes from the variability in the condition of the aircraft to be modernized; something the manufacturer has little control over. The manufacturing process risk, something that can be controlled and mitigated over time causes most of the risk associated with the new cabin approach.

As a sanity check, the design team decided to benchmark the refurbished approach results shown in Figure 41, based on actual schedule data obtained from the SEAHAWK SDLM program. The data used to determine the schedule probability was taken from the actual hours needed to refurbish 21 SDLM aircraft over a three-year period. Figure 42 shows the results of this benchmark.

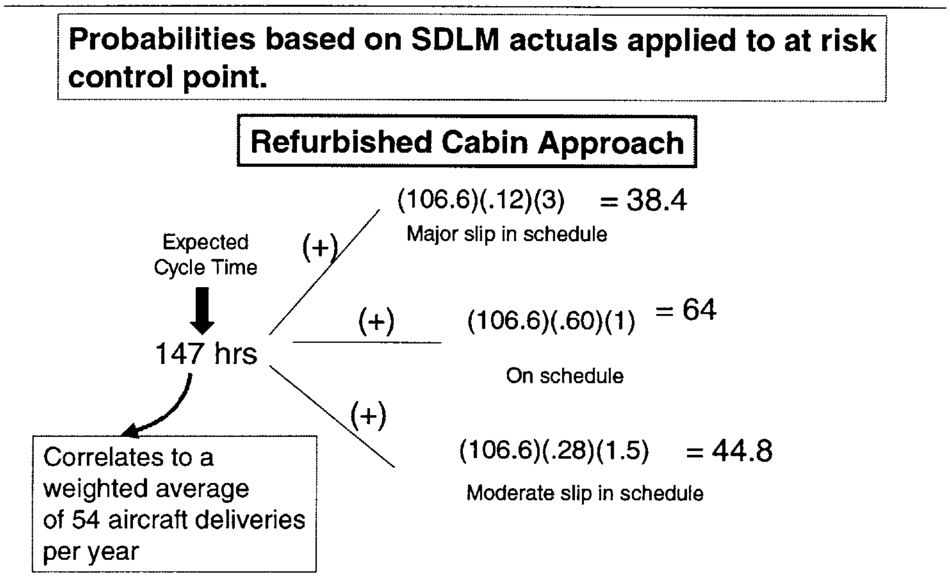

Figure 42: Benchmark for Schedule Risk Associated with Refurbish Alternatives

This benchmarking indicated that if the actual dates from the SDLM program where correlated to the estimates developed for the UH-60L+ refurbished cabin concept that the weighted expected average for yearly deliveries would be 54 aircraft. This falls approximately at the midpoint of the expected deliveries for the refurbished approach (Figure 41). It should be noted that the SDLM data included corrective measures such as overtime and weekend work were not included in the UH-60L+ schedule risk; so in retrospect, the SDLM benchmarking should have been adjusted. Even still, the conclusion of the benchmark was that the assumptions and analysis performed to quantify the schedule risk could be considered representative of the expected outcomes for each alternative.

Quantification of Cost Risk

The objective of the cost risk analysis was to quantify the recurring cost risk associated with the incremental addition of performance enhancements to the cabin alternatives. The cost analysis performed in the trade alternative evaluation phase was based on a common baseline that did not include any of the performance enhancements. Once performance enhancements are included into the cost estimate of each alternative an interesting observation is noted. While the recurring cost associated with the refurbished cabin increases substantially when performance enhancements are included, the recurring cost of a new cabin did not increase when performance enhancements were included. This is because the number of parts and processes associated with adding the performance enhancements to a new cabin build does not change very much when compared to the baseline configuration. However, the recurring costs associated with incorporating modification kits, removing, and then adding structure causes the recurring cost of the refurbished approach to rise considerably. Note that the non-recurring design and tooling costs are not included in this estimate since these costs can be amortized over 930 aircraft and therefore are small compared with the recurring costs.

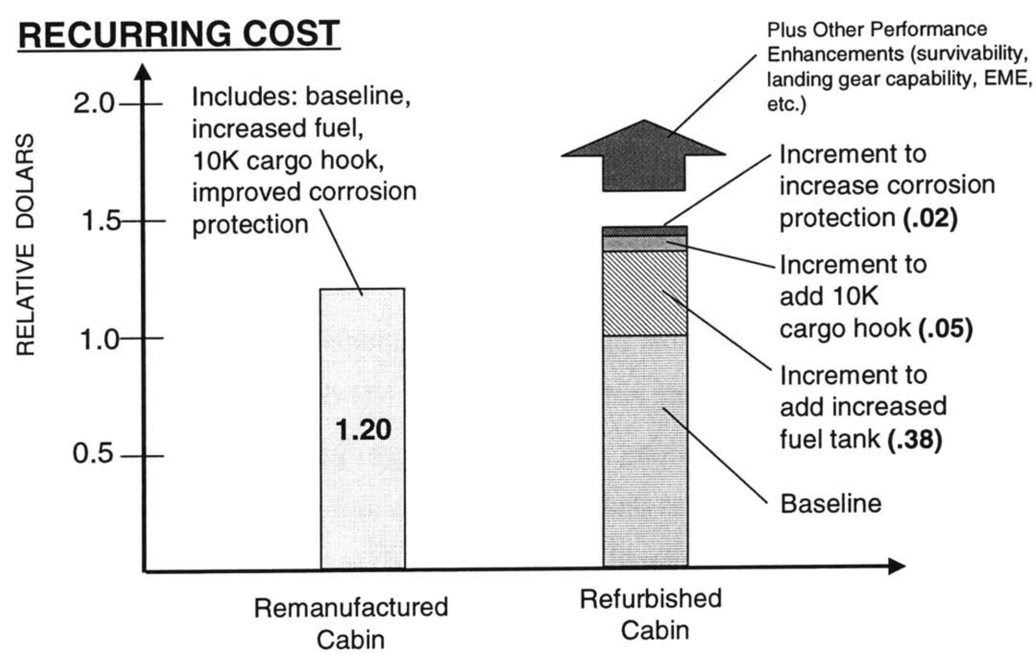

Figure 43: Impact of Performance Enhancements on Cabin Alternatives

The results of the UH-60L+ cabin alternatives cost risk analysis is shown in Figure 43. Note that the cost of a remanufactured cabin is 1.2 times the cost of a refurbished cabin if only the baseline requirements are addressed. However, if provisions for a larger fuel tank is included on top of the baseline refurbishment, the cost of the refurbished alternative is approximately 1.38 times the cost of the baseline refurbishment, while the recurring cost of the remanufactured cabin remains at 1.2 times the baseline refurbished cost. As shown in Figure 43, when other performance enhancements are added to the refurbished alternative, the recurring cost continues to increase.

The cost risk analysis is the quantification of the tradeoff between cost and the performance enhancements that were defined in the QFD matrix and also described in the evaluation matrix. This analysis shows the importance of establishing a configuration that will take into account the future requirements of the UH-60L+ over the next twenty-five years. One of the implications of this analysis is that a modernization plan that is driven by short term constraints might in the cost more as performance enhancements are added incrementally during the life time of the UH-60L+. This scenario will be studied in more detail in the next phase of the methodology.

Quantitative Net Present Value (NPV) Analysis

To understand how the cost risk analysis just performed manifests itself in life cycle costs, a present worth analysis was performed for various alternative scenarios. Deciding whether to include performance enhancements to the cabin section is just one decision that needs to be made that influences the total life cycle costs of the UH-60L+. Other decisions include what to do with the removed top deck or cabin section, how long is the useful life of the UH-60L+ if performance enhancements are not included, and what are the life cycle maintenance costs associated with each alternative? To better illustrate some of the life cycle cost drivers, a decision tree was developed to document some of the key decisions. The UH-60L+ cabin decision tree is shown in Figure 44. While this decision does not include all of the cost decisions, it does contain most of the major cost drivers and therefore serves as a road map for performing present worth analysis for different scenarios.

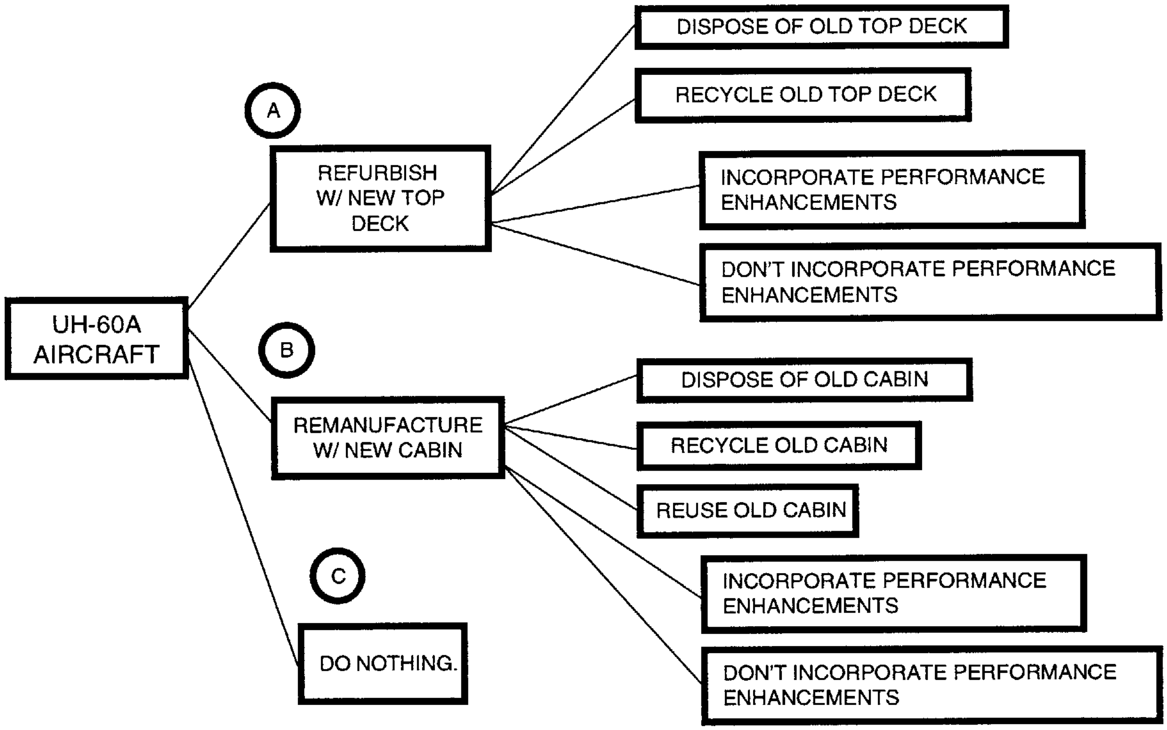

Figure 44: UH-60L+ Cabin Decision Tree

The decision tree is partitioned into three major decision branches: (1) how to upgrade the cabin sections, (2) what to do with old components, (3) whether to incorporate performance enhancements and how this impacts the useful life of the UH-60L+.

Once the decision tree was established, a cost matrix was created that took each of the branches listed in the decision tree and identified a corresponding relative cost for non-recurring, annual recurring, and salvage value for each of the decisions. The cost values were normalized to the cost of a cabin refurbished to the baseline configuration. For the purposes of this study, an assumption was made with respect to the useful life of the various alternatives. These assumptions are based on the fact that the UH-60A was upgraded into an UH-60L thirteen years after it's initial delivery for performance related reasons. A valid argument could therefore be made that if performance enhancements are not included into the modernization program, that the useful life of the UH-60L+ could very well be less than the 25-year target for the airframe planned life. The example presented postulated that the UH-60L+ would need to be replaced 5 years before it reached its 25-year target. This implies that a new upgraded UH-60L+ (UH-60L++?) aircraft will need to be purchased 20 years into the modernization program to replace the first refurbished UH-60L+ aircraft if performance enhancements are not included in the configuration. Of course, sensitivity analysis can be performed to see how this decision affects the life cycle costs of the alternatives.

The decision tree cost matrix used in this study is shown in Figure 45. The values shown in the decision tree matrix where normalized to the cost of a cabin refurbished to the baseline configuration shown in Figure 26. These costs represent the annual expected cost to the customer associated with modernizing 60 aircraft per year. All of the relative dollar values are assumed to be in constant dollars using a discount rate of seven percent. This discount rate was determined to be a consistent with the discount rate used for determining the present worth of government projects [MIT1999a]. Non-recurring costs were included in the matrix because they varied depending on what the approach was and whether future new build UH-60L+ aircraft could be used to leverage the non-recurring costs.

One of the most important features of a decision tree analysis is that it presents the opportunity to analyze the alternatives from a different perspective. This often leads to creative new possibilities. With respect to what to do with old cabin sections, the original plan was to either dispose of or recycle the cabin section. By going through the thought process of documenting the decision branches, a third option emerged that offers wide-ranging potential. As shown in the Figures 46 and 47, the third option is to reuse the old cabin section. This option would entail the manufacturer buying back not only the old cabin section, but other old components as well; including gearboxes, controls, and blades. The manufacturer would then assemble these components into a kit that could be used for creating a low-cost, slightly used BLACK HAWK for possible international sales. While this option would require extensive research beyond the scope of this trade study. The possibility that the customer can sell a portion of the used aircraft to either lower the cost of the overall modernization program or use the proceeds to buy performance enhancements is an intriguing alternative that was only recognized through the analysis of the decision branches.

ALL VALUES HAVE BEEN MULTIPLIED BY 60 TO CORRESPOND TO NUMBER OF AIRCRAFT REQUIRED PER YEAR					
ASSUME A DISCOUNT RATE OF 7%					
Concept	**Decision**	**One-Time Cost (Relative $)**	**Annual Cost (Relative $ / Yr)**	**Expected Life (Yrs)**	**Salvage Value (Relative $ / Yr)**
1. CONCEPT A: REFURBISH APPROACH					
Top Deck Decision					
	Dispose of Top Deck	N/A	1.2	1	0
	Recycle Top Deck	N/A	0.6	1	0
Performance Enhancement Decision					
	Incorporate Performance Enhancements	N/A	96	25	12
	Do not Incorporate Performance Enhancements	N/A	60	20	12
Non-Recurring (Future UH-60L+ New Build Leverage)					
	Non-Recurring if Common Top Deck with UH-60L+ New Build	1.1	N/A	N/A	N/A
	Non-Recurring if No New UH-60L+	1.7	N/A	N/A	N/A
Replacement Cost					
	Replacement Cost for Future UH-60L+ Cabin	N/A	90	N/A	N/A
2. CONCEPT B: REMANUFACTURE APPROACH					
Old Cabin Decision					
	Dispose of Old Cabin	N/A	2.4	N/A	N/A
	Recycle Old Cabin	N/A	1.2	N/A	N/A
	Reuse Old Cabin	N/A	-12	N/A	N/A
Performance Enhancement Decision					
	Incorporate Performance Enhancements	N/A	72	25	12
	Do not Incorporate Performance Enhancements	N/A	72	20	12
Non-Recurring (Future UH-60L+ New Build Leverage)					
	Non-Recurring if Common Cabin with UH-60L+ New Build	0	N/A	N/A	N/A
	Non-Recurring if No New UH-60L+	4	N/A	N/A	N/A
Replacement Cost					
	Replacement Cost for Future UH-60L+ Cabin	N/A	540	N/A	N/A

Figure 45: UH-60L+ Cabin Decision Tree Matrix

Once the costs associated with various decision branches were identified, the cash flow scenarios for the various trade decisions were developed. The cash flow scenarios for the decision branches shown in Figure 45 were illustrated as cash flow diagrams as shown in

Figures 46 through 47 to provide a timeline perspective on the annual cash outlays associated with the decision branches.

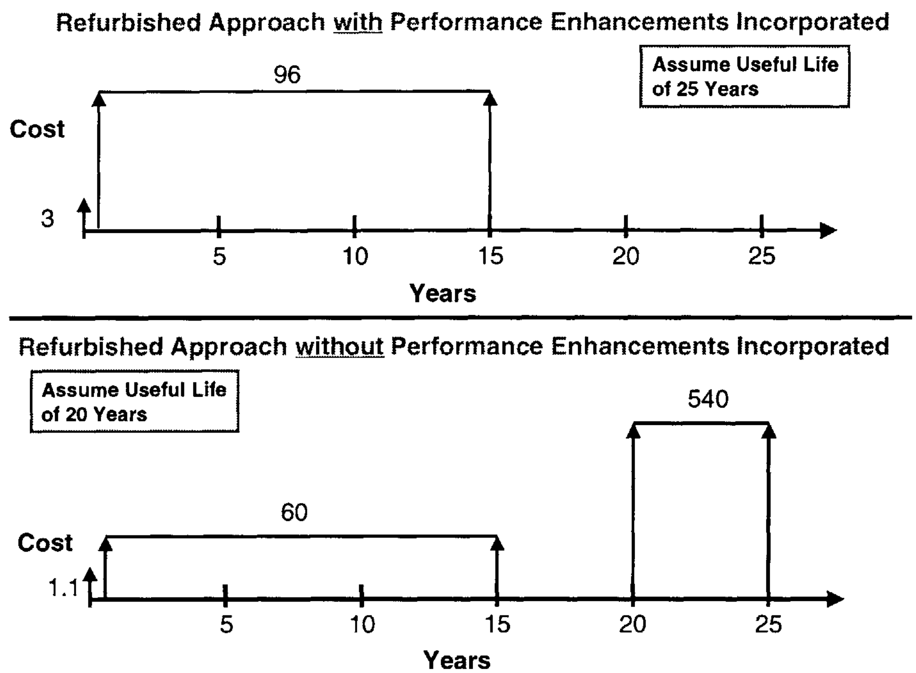

Figure 46: Cash Flow Timelines for Refurbished Approaches

The cash flow diagrams for the refurbished approach shows the annual cash flows with and without the addition of performance enhancements. The 'Do Nothing' scenario was not modeled since this would entail replacing the UH-60A aircraft with a new aircraft beginning in year one. As previously stated, an assumption was made that the useful life of the UH-60L+ was only 20 years if performance enhancements were not added. Because the majority of the capability needed to incorporate the performance enhancements are contained within the cabin section, the argument is made that if performance enhancements are not included, then the full burden of replacing the aircraft must be accounted for in the present worth analysis. This scenario is represented in Figure 47 by the 540 relative dollars associated with replacing 60 refurbished UH-60L+ beginning in the 20th year of the modernization program.

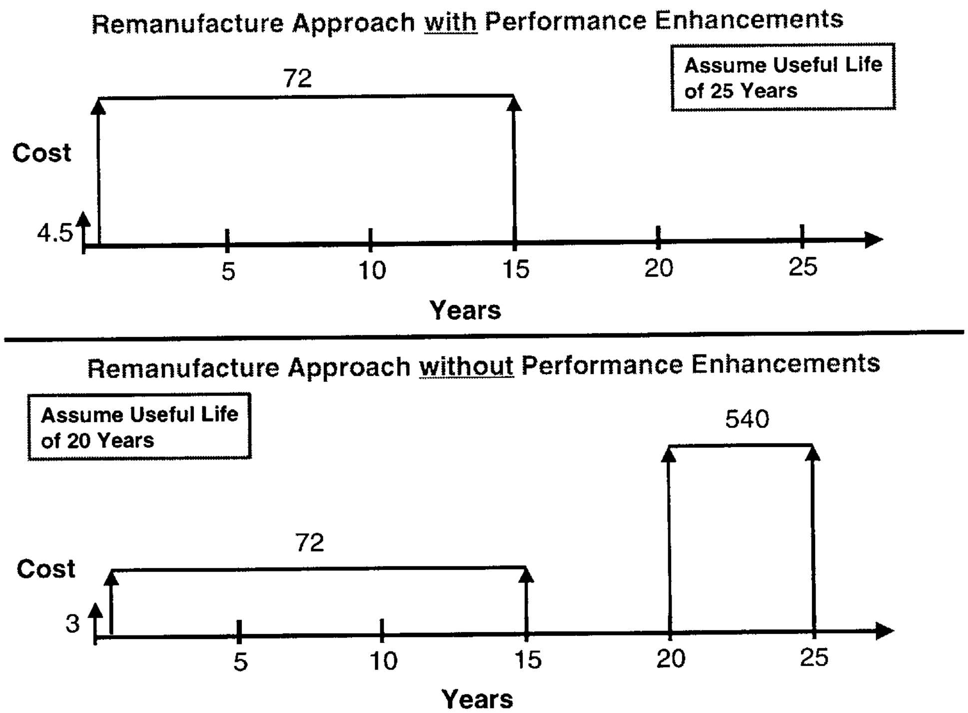

Figure 47: Cash Flow Timelines for Remanufacture Approaches

Figure 47 shows the annual cash flows associated with the remanufacture approach decision with respect to performance enhancements. Similar to the refurbished cash flow diagram, the useful life of the remanufactured configuration without performance enhancements is 20 years. Using an Excel spreadsheet, tables of the expected present worth for each alternative were created. These tables, which are shown in Table 9 & 10 show the various costs associated with pursuing different decision branches on a yearly basis. The NPV of for each scenario has also been tabulated using the seven percent discount rate previously explained. Table 11 contains a summary comparison of present worth for each scenario.

Year	Dispose of Top Deck	Recycle Top Deck	Incorp. Perf. Enh.	Do Not Incorp. Enhan.
1	1.2	0.6	96	60
2	1.2	0.6	96	60
3	1.2	0.6	96	60
4	1.2	0.6	96	60
5	1.2	0.6	96	60
6	1.2	0.6	96	60
7	1.2	0.6	96	60
8	1.2	0.6	96	60
9	1.2	0.6	96	60
10	1.2	0.6	96	60
11	1.2	0.6	96	60
12	1.2	0.6	96	60
13	1.2	0.6	96	60
14	1.2	0.6	96	60
15	1.2	0.6	96	60
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
20	0	0	0	0
21	0	0	0	540
22	0	0	0	540
23	0	0	0	540
24	0	0	0	540
25	0	0	0	540
NPV	**$11**	**$5**	**$875**	**$1,160**

Table 9: Excel Spreadsheet Cash Flow for Refurbished Approaches

Year	Dispose of Old Cabin	Recycle Old Cabin	Reuse Old Cabin	Incorporate Performance Enhancements	Do not Incorporate Performance Enhancements
1	2.4	1.2	-12	72	72
2	2.4	1.2	-12	72	72
3	2.4	1.2	-12	72	72
4	2.4	1.2	-12	72	72
5	2.4	1.2	-12	72	72
6	2.4	1.2	-12	72	72
7	2.4	1.2	-12	72	72
8	2.4	1.2	-12	72	72
9	2.4	1.2	-12	72	72
10	2.4	1.2	-12	72	72
11	2.4	1.2	-12	72	72
12	2.4	1.2	-12	72	72
13	2.4	1.2	-12	72	72
14	2.4	1.2	-12	72	72
15	2.4	1.2	-12	72	72
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
20	0	0	0	0	0
21	0	0	0	0	540
22	0	0	0	0	540
23	0	0	0	0	540
24	0	0	0	0	540
25	0	0	0	0	540
NPV	**$22**	**$11**	**($109)**	**$660**	**$1,269**

Table 10: Excel Spreadsheet Cash Flow for Remanufacture Approaches

Decision Branch	Present Worth (Relative $)
1. Refurbished Alternative Options	
Do not Incorporate Performance Enhancements	548
Incorporate Performance Enhancements	875
Do not Incorporate Enhancements and Replace Aircraft after 20 years	1160
2. Remanufacture (New Cabin) Alternative Options	
Do not Incorporate Performance Enhancements	657
Incorporate Performance Enhancements	660
Do not Incorporate Enhancements and Replace Aircraft after 20 years	1269

Table 11: Summary of Present Worth of Costs Associated with Modernization Options

Table 11 presents some very interesting scenarios for both the customer and manufacturer to consider. Two of the scenarios that need to be considered are:

- Even though the baseline refurbishment approach costs less than the remanufacture approach, a decision must be made concerning the future mission requirements that might necessitate the need for performance enhancements. If the consensus is that near-term needs and constraints result in following the refurbished approach without performance enhancements, then long-term planning should incorporate the possibility that the UH-60L+ might need to be upgraded or replaced before the end of its planned life. As shown in Table 11, this could raise the total life cycle costs by almost a factor of two when compared with incorporating the performance enhancements from the beginning.
- If it is determined that incorporating the performance enhancements via the new cabin approach is the desired approach, the customer must decide whether they can afford the higher annual costs. While this might appear to be a shortsighted approach,

budget limits and near term needs might outweigh the long-term benefits of reduced life cycle costs. For example, there could be political pressure to keep the modernization cost below a certain dollar amount if the program is to get accepted by Congress. In this case, creative alternatives might be developed to address the budget constraints.

- With regards to the new cabin approach, the difference between incorporating performance enhancements and not incorporating them is the cost of the non-recurring. However, if the performance enhancement characteristics are not incorporated from the beginning, the life cycle costs skyrocket in comparison with the other alternatives making this options the most expensive. The message from this scenario is that if a decision is made to modernize with a new cabin, then as many performance enhancements as could be afforded should be incorporated from the beginning.

One option for addressing potential near-term budget constraints is to revisit the decision branch that looks at what to do with the old cabins. The cash flows for the different scenarios are shown in Figure 48.

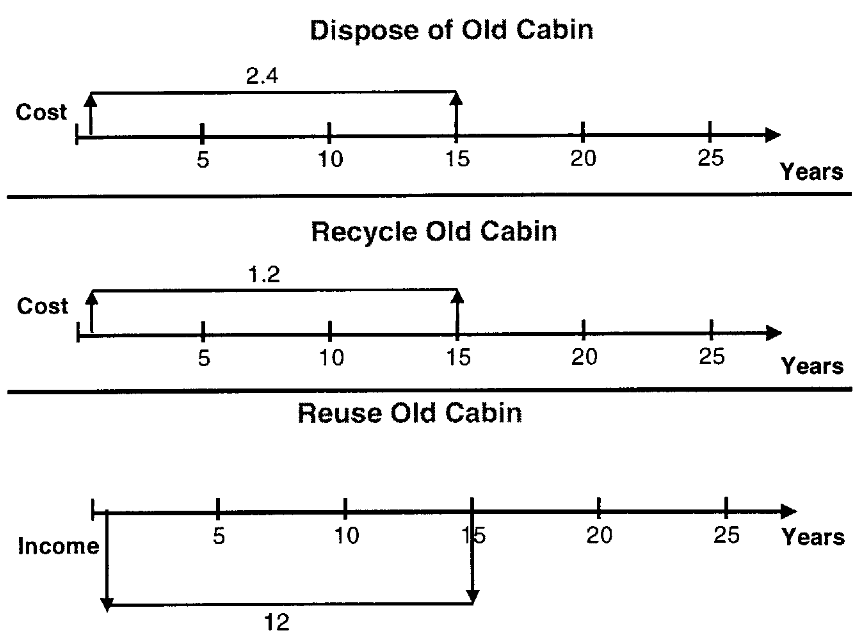

Figure 48: Cash Flow Timelines for Costs Associated with Old Cabin Section Options

The values shown in Figure 48 represent the best guesses of the design team without hard substantiation. The design team believes that either disposing of the cabin or recycling the cabin material will cost the manufacturer money. Probably the most significant cost driver is how to remove or neutralize the primers and corrosion protection compounds from the old cabin without imposing an environmental threat. The third alternative is to reuse the old cabin as the basis for creating low cost helicopter kits. As previously described, in this scenario the manufacturer would buy back components of the old aircraft from the customer. The old airframes, for the most part, are still in good condition and could easily be refurbished to meet the needs of a lower gross weight, less capable aircraft than the UH-60L+ that would be more than adequate for most international customers. The cash returned to the customer could potentially be used to pay for the performance enhancements that would extend the useful life of the UH-60L+. While the quantification of this scenario is beyond the scope of this thesis, mainly because of the political and strategic issues that would need to addressed, it does present an option that addresses the customer needs while acknowledging cost constraints.

In summary, the objective of the present worth risk / benefit analysis is to provide both the customer and management a quantitative cost sensitivity on the alternatives down-selected in the trade alternative evaluation phase. A simple and clear way to communicate the results of the present worth analysis is to show the results graphically so that management can grasp the conclusion of the study without digging too far into the details. The present worth of each of the alternatives shown in Table 11 are illustrated graphically in Figures 49 and 50. These figures explicitly show the potential magnitude of what happens if the UH-60L+ does not reach its planned life expectancy.

Figure 51 graphically illustrates how reusing the old cabin offers the potential to lower the near-term annual costs and makes the new cabin approach more attractive from a cost perspective. In fact, following this scenario it is possible to lower the cost of the new cabin approach to be comparable with that of the refurbish approach with performance enhancements.

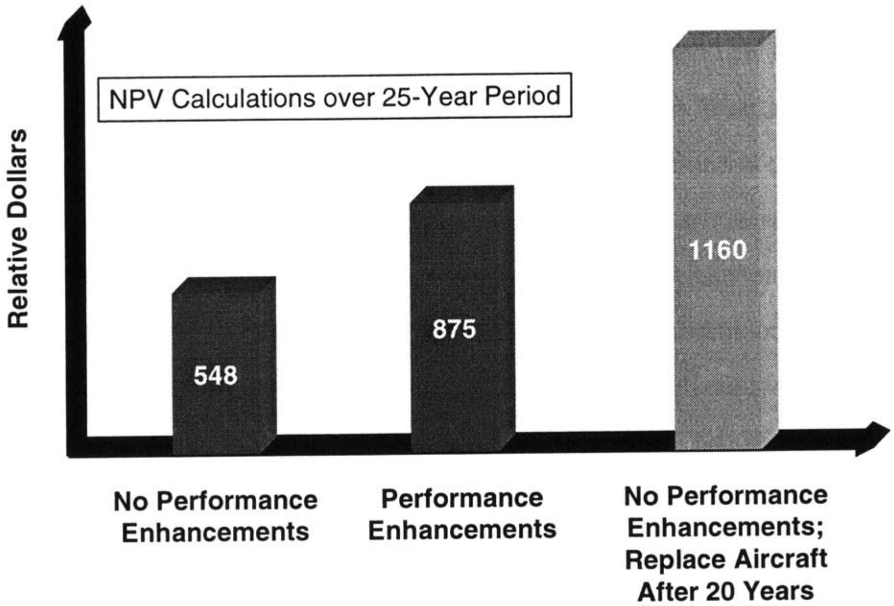

Figure 49: Present Worth of Refurbished Alternatives

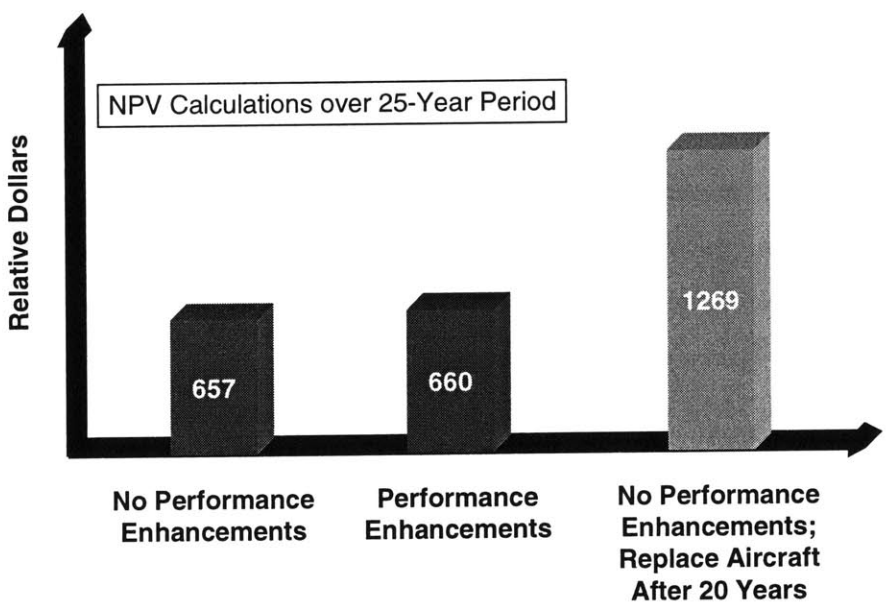

Figure 50: Present Worth of Remanufactured Alternatives

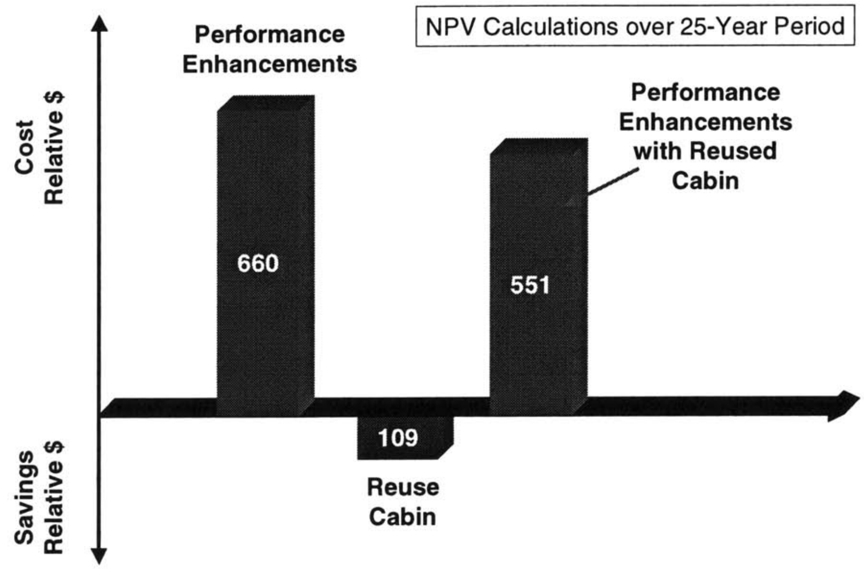

Figure 51: Present Worth of Remanufactured Alternative with Performance Enhancements & Reused Cabin

Application of the Methodology: Implementation Phase

Wrapping up the Trade Study

Once the risk / benefit analysis was completed, a sanity check was done to make sure that results of the trade alternatives and risk / benefit analysis phases still mapped back to the customer needs. As could be expected, the design team observed that the customer needs in many respects evolved and solidified as the trade studies were performed. In particular, low risk implementation of the structural life criteria and low cost emerged as the primary drivers in the configuration. This was interpreted as the minimal modernization necessary to ensure that the cabin airframe is structurally sound for another 25 years (reference cabin trade study objective on page 83). The trade alternative that best meets this description was the refurbished cabin alternative with no performance enhancements incorporated.

The dilemma presented to the design team is that the trade alternative evaluation and the risk / benefit analysis showed that in the long-term the refurbished cabin approach with no performance enhancements was potentially higher risk and more costly than the new cabin remanufacture with performance enhancements. This raised the concern that the design team missed the mark and misinterpreted the customer needs.

In order to check the validity of the trade study results, the design team reviewed the assumptions with the customer and discovered that there was confusion and concern about some of the assumptions made with respect to the proposed structural life criteria for the UH-60L+. The feeling was that some of the assumptions addressing the structural life requirements for the UH-60L+ were too conservative and therefore biased the results towards a more extensive structural change than might otherwise be needed. Referring back to the data shown in Figures 23 and 24, it became clear to the design team that the some of the original assumptions concerning the structural life requirements were in fact too conservative. However, the design team also discovered that even after adjusting the structural life assumptions, the magnitude of the expected structure changes did not change the results. The rationale for this observation was based on experience with BLACK HAWK derivatives that showed most of the expected fatigue issues would occur before the aircraft reached 8000 flight hours. The conclusion is that structural changes proposed for the UH-60L+ were still valid and that the assumptions for the structural life criteria needed to be modified to reflect the anticipated flight hours and usage spectrum for the UH-60L+ fleet. In the end, making this change strengthened the validity of the trade study recommendation.

With respect to mapping the trade results back to the voice of the customer, it was clear that the performance enhancements were highly desirable features that the customer wanted, but might not be able to afford. As a check, the entire trade study was reviewed to see if the results traced back to the voice of the customer. Here is an overview of that check:

The voice of the customer was captured through various means, including written operational requirement documents, site surveys, interviews, and competitive assessment. This data was structured and prioritized using the affinity diagramming process. Through the QFD process, the high and medium priority customer needs were transformed into technical characteristics as part of the QFD product planning matrix development. These characteristics were ranked by priority and analyzed for correlation with each other. The highest priority characteristics were judged to be structural life extension and low cost modernization method. In addition, from this analysis emerged specific performance enhancement related characteristics. These characteristics would eventually be the primary discriminators in the trade study analysis.

Continuing with the trade study methodology approach, the alternatives generated were qualitatively evaluated for risk. Using the highest ranked technical characteristics as criteria for the qualitative risk assessment, the alternatives were down selected to two candidates, one from the refurbished options and one from the remanufactured cabin options. An evaluation matrix was developed that quantitatively ranked each of the two remaining alternatives. The weighting was established with customer concurrence and the attributes and parameters used in the evaluation matrix were directly traceable back to the QFD product planning matrix and therefore the voice of the customer. An analysis of the evaluation matrix indicated that the new cabin approach was more attractive when performance enhancements were included in the evaluation, otherwise the refurbished approach ranked higher at meeting the highest ranked attributes of low cost and structural life extension.

Finally, a risk / benefit analysis was performed using much of the same criteria used for the qualitative risk assessment. Three types of risk / benefit analysis were performed including a schedule risk assessment, a cost risk assessment associated with incorporating performance enhancements, and a net present worth analysis on each of the potential options. The schedule risk assessment used the SEAHAWK SDLM program as a benchmark and the results of this study indicated that the refurbished approach carried a much higher inherent risk than the new cabin approach. The net present worth analysis was based on a decision tree that contained all the potential options with regards to the two remaining alternatives. While the results of the NPV analysis showed that the refurbished approach was much less expensive than the new cabin approach if no performance enhancements are considered, several issues came to light about life cycle costs. For example, the possibility exists that the aircraft might have to be replaced before the end of their planned life if performance enhancements are not included. With service life extension being one of the primary customer needs, this observation lent itself to a scenario analysis. In the scenario analysis it was assumed that if performance enhancements were not incorporated that the useful life of the aircraft was only 20 years instead of 25 years. This meant that aircraft would have to be replaced five years earlier than planned. Calculating the NPV for this scenario clearly showed that the new cabin approach with performance enhancements had the lowest life cycle costs.

The costs associated with this approach were higher than the refurbished approach without performance enhancements. A conventional method for reducing the cost of the new cabin approach includes evaluating offload of some of the work to lower cost subcontractors. However, using the decision tree as a concept tool, a more creative potential solution to this problem was discovered. By reusing the cabin to create kit aircraft offered an opportunity to offset the additional cost of incorporating the performance enhancements and bring down the cost of the new cabin approach to be inline with the refurbished approach. Although beyond the influence of the design team, it was felt that alternative strategies such as cabin reuse would enable the incorporation of performance enhancements into a new cabin remanufacture and result in the lowest life cycle costs for the UH-60L+ program of all the alternatives.

The conclusion of the UH-60L+ trade study can be summarized as follows:

1. The alternative that best met the voice of the customer was the new cabin approach with performance enhancements incorporated.
2. While the refurbished cabin approach was the alternative that best met the customer's highest ranked needs of structural life extension and low cost manufacturing approach, the risk / benefit analysis indicated that there was significant schedule and life cycle cost risks associated with this approach.

3. A potential solution to lower the cost of the new cabin approach was generated. By reusing the old cabins, it would be possible to use some of them to make low cost helicopter kits for sale in the international market.

Epilogue

The case just evaluated represented a thorough application of the trade study methodology proposed in this thesis. It will provide management and the customer with the information necessary to make informed decisions based on quantitative analysis that is derived directly from the voice of the customer through the QFD process.

With respect to areas that are worthy of further analysis, certainly carrying the QFD process through subsequent product development phases would be an excellent candidate. Also, another area that was only touched upon was how to use the trade study methodology at a higher systems level. The case study was performed on a sub-system and therefore did not fully integrate some of the system level issues like center-of-gravity. Finally, the methodology proposed was tailored for a helicopter modernization program; however, with some modifications the methodology could easily be applied to generic preliminary design trade studies. Tools and methods utilized in the case study that could be applied to a generic trade study include:

- Voice of the Customer Data Collection
- Affinity Diagramming
- QFD 'House of Quality'
- Related Trade Matrices
- Competitive Assessment
- Evaluation Matrices
- Qualitative Risk Assessment Diagrams
- Weighted Expected Value Calculations
- Net Present Value Analysis

In conclusion, it is the expectation of the author that the methodology presented in this thesis and validated through the case study will become a model for future preliminary design trade studies.

Appendix

History and Description of UH-60 (BLACK HAWK) Helicopter

Figure 52: Sikorsky UH-60A BLACK HAWK

The UH-60A (BLACK HAWK) helicopter was developed in response to the U.S. Army's requirement for a Utility Tactical Transport Aircraft System (UTTAS) in the early 1970's. A significant factor in the formulation of the requirements for the UTTAS was the crucial role that the helicopter played during the Vietnam War. Even though the Vietnam War was commonly referred to as 'The Helicopter War', it was clearly evident to the Army Aviators of the time that the helicopters used in the campaign were inadequate in terms of performance, survivability, and reliability. In response for the need to improve these attributes the UTTAS program was initiated by the United States Army to develop the next generation medium utility helicopter with Sikorsky Aircraft and Boeing Vertol Corporation being the prime contenders.

As described by Pember [Pembe1998a pg. 59, 60], the production award was largely influenced by competitive maintenance and operational evaluations conducted during 1976 between two Sikorsky prototypes and two Boeing prototypes. A memorable event took place during the fly-off that helped create the BLACK HAWK's renowned reputation for survivability and durability. Once during a night evaluation flight with a full squad of soldiers on board, one of the Sikorsky prototypes developed severe vibration and was forced to make a night landing in a dense pine forest. Amazingly, none of the soldiers was seriously injured, and other than broken rotor blades, the aircraft received only superficial damage. After replacing the rotor blades and conducting a thorough inspection, the aircraft was able to fly off and resume its evaluation testing. Sikorsky eventually won the fly-off and received contracts to a production go-ahead in 1976.

The primary mission capability of the UH-60A is tactical transport of troops, supplies, and equipment. Secondary missions include training, mobilization, and support of disaster relief. The UH-60A was designed to be combat survivable and air transportable. Ultimately, the air transportability requirements, and in particular the requirement to fit two UH-60's in a C-130 air transport plane had a major effect on the final configuration and size of the UH-60 helicopter.

Largely driven by Army Aviation's expansion role for the BLACK HAWK, the UH-60L was introduced in 1989. New mission requirements called for improved performance in all ambient conditions, particularly operations conducted at high altitudes (4000 ft) and hot temperatures (95 degrees F). The new requirements also required operational capability at higher gross weights than the UH-60A [Pembe1998a pg.62-64]. UH-60L incorporated upgraded T700-GE-701C engines with digital electronic fuel control, upgraded main transmission, external fuel stores mounting, and improved flight controls. The increase in performance between the UH-60L and UH-60A was significant and is summarized below [Pembe1998a pg. 64]:

- Maximum cruise speed in all conditions improved by as much as 12 kts.
- Vertical rate of climb at sea level improved from 2,200 fpm to over 3,000 fpm.

- Vertical rate of climb at hot temperatures improved from 390 fpm to over 1,550 fpm.
- Maximum gross weight improved from 20, 250 lb. To 22,000 lb.
- Engine horsepower increased from 1,560 hp to 1, 940 hp per engine.
- The external load capability was improved so that the UH-60L could transport an M1036 HMMWV (Humm-Vee).

Dimensions		
	Main rotor diameter:	53 ft 8 inches
	Tail rotor diameter:	11 ft 0 inches
	Overall length with rotors turning:	64 ft 9 inches
	Maximum height to top turning tail rotor:	16ft 9 inches
	Width fuselage:	7 ft 9 inches
Weights		
	Empty weight:	11,780 lbs.
	Mission gross weight:	16,864 lbs.
	Maximum gross weight:	22,000 lbs.
Engines		
	Two turboshaft engines:	General Electric T700-GE-701 C
	Power:	1,940 shaft horsepower
	Transmission rating:	3,400 shaft horsepower
	Internal fuel:	360 US gallons (1,360 litres)
	External auxiliary fuel tanks on ESSS system:	460 US gallons (1740 litres)
	Endurance on internal fuel:	3 hours 5 minutes
	Maximum endurance with auxiliary fuel:	7 hours 21 minutes
Performance: @ 16,864 lbs. Missions Gross Weight		
	Maximum Cruise Speed at 5,000:	162 kts
	VNE (not to exceed speed):	190 kts
	Service ceiling:	19,000 ft
	Hover ceiling, out of ground effect (OGE):	10,600 ft
	Maximum range at 5,000 ft:	304 nautical miles

Table 12: UH-60L Technical Data

To date, over 1,500 BLACK HAWKs have been delivered to the U.S. military. The UH-60 has also served as a platform for the S-70 derivative series helicopters. The use of the term platform is not entirely accurate, since the majority of the S-70 series helicopters required major modifications to the base UH-60 configuration in order to meet specific customer requirements. Ultimately, it was the specificity of the customer requirements that drove the need to have a derivative instead of a platform architecture for the S-70 series. There are approximately 40 derivatives of the S-70 series helicopter that can be found in over 20 nations throughout the world. Over 500 BLACK HAWK variants have been sold to international customers.

Description of UH-60 Systems and Architecture

The airframe for the UH-60 can be divided into six structural sections as described by [Holme1998a, pg.17 and 18]. The main rotor has four blades made of titanium/fiberglass. The drive train consists of a main transmission, intermediate gearbox and tail gearbox with interconnecting shafts. The propulsion system has two T700-GE-700 engines operating in parallel. The nonretractable landing gear consists of the main landing gear and a tail wheel. The airframe consists of mostly aluminum semimonoque construction with composite secondary structure. Several kit options have been developed for the UH-60L over its lifetime including range extension fuel tanks, rescue hoist, infrared suppression, blade anti-icing, blackout devices, winterization and static/rappelling kits. For a more comprehensive description of the various systems and architecture that make up the UH-60 BLACK HAWK refer to Holmes [Holme1998a, pp. 17 - 47].

Description of BLACK HAWK Modernization Program

The BLACK HAWK Modernization program as defined by the U.S. Army is intended to develop an improved version of the BLACK HAWK that meets evolving warfighting concepts and addresses known operational deficiencies to ensure a system that is equipped and capable of meeting battlefield requirements through the 2025-2030 timeframe [Gantc1998a]. The BLACK HAWK fleet is scheduled to begin meeting its service life goal of 25 years in the year 2002. In order to keep the BLACK HAWK fleet operationally effective through the 2025-2030 timeframe; the aircraft will need to undergo a major life-extension program. This life-extension process is planned to include the inspection, refurbishment, and modernization of approximately 935 UH-60A BLACK HAWK aircraft.

Primary modernization areas for consideration include: increased lift, advanced avionics (digital communications and navigation suites), enhanced aircraft survivability equipment (ASE), increased reliability and maintainability (R & M), airframe service life extension (SLEP), and reduced operations and support (O & S) costs. The Operational Requirements Document (referred to as the ORD) for the UH-60 BLACK HAWK modernization program identifies the customer needs and requirements for the modernization program.

The BLACK HAWK Modernization Program is actually divided into two separate programs: the near-term UH-60L+ that addresses the impending service life extension concerns and the future UH-60X program that addresses long term Army battlefield range and payload requirements. A significant increase in the mission radius capability of up to 300 km and increased external lift capability, up to 10,000 lbs. is desired for the UH-60X program.

The UH-60X program is being paced primarily by the development of a new engine technology called Joint Turbine Advanced Gas Generator (JTAGG). The JTAGG performance goals are partitioned into three separate milestones. JTAGG I goals included a 20 percent reduction in specific fuel consumption (sfc) and a 40 percent increase in shaft horsepower-to-weight ratio (shp/wt). This goal was exceeded in fiscal year 1995. JTAG II goals are a 30 percent reduction in sfc, an 80 percent increase in shp/wt and a 20 percent reduction in production and maintenance costs to be demonstrated in calendar year 2000. The JTAGG III performance goals include a 40 percent reduction in sfc, a 120 percent increase in shp/wt, and a 35 percent reduction in production and maintenance costs to be demonstrated in fiscal year 2003 [Carmo1999a].

In addition to the new engine, the UH-60X is expected to incorporate the following enhancements:

- Longer wide chord main rotor blade to provide additional lift capability (same as the Sikorsky S-92 rotor blade).

- A new flight control system and transmission gearbox.
- A 20-inch larger cabin (to balance the center of gravity).
- A 16-inch longer tail cone (to provide clearance between the longer main rotor blade and the tail rotor).

Because the development of the new engine will force the availability of the UH-60X into the year 2008 timeframe, the UH-60L+ has emerged as the near term focus for the U.S. Army.

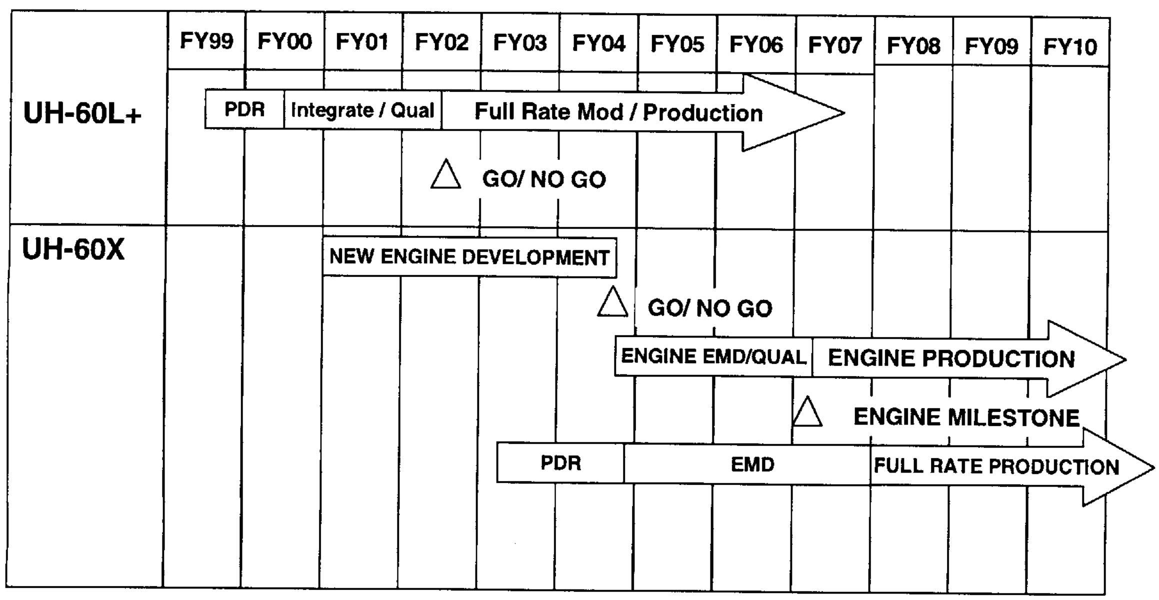

Figure 53: BLACK HAWK Modernization Schedule

Acronyms

Acronym	Definition
A/C	Aircraft
AATD	Army Advanced Technologies Division
AFB	Air Force Base
APL	Advanced Launch System
ASE	Aircraft Survivability Equipment
AVCRAD	Aviation Classification Repair Activity Depot
DOD	Department of Defense
ECP	Engineering Change Proposal
EMD	Engineering and Manufacturing Development
EME	Electromagnetic Emissions
EMU	Electronic Mockup
ESSS	External Stores Support Structure
F	Fahrenheit
Fpm	Feet per Minute
FS	Fuselage Station
FT	Fort
GE	General Electric
HMMWV	High Mobility Multipurpose Wheeled Vehicle
hp	Horsepower
HSM	High Speed Machining
ICH	Improved Cargo Helicopter
IPT	Integrated Product Team
JTAGG	Joint Turbine Advanced Gas Generator
JTR	Joint Technology Rotorcraft
K	Thousands
kts	Knots
lb	Pound
MAVEN	Material Value Engineering
ME	Manufacturing Engineering
MIT	Massachusetts Institute of Technology
NBC	Nuclear, Biological, Chemical
NM	Nautical Miles
NPV	Net Present Value
O & S	Operations and Support
OGE	Out of Ground Effect
ORD	Operation Requirements Document
OT	Overtime

PEM	Program Engineering Manager
QFD	Quality Function Deployment
R & D	Research and Development
R & M	Reliability and Maintainability
RAST	Recovery Assist Secure and Traversing
SDLM	Structural Depot Level Maintenance
SFC	Specific Fuel Consumption
shp	Shaft Horsepower
SLEP	Service Life Evaluation Program
SOA	Special Operations Aircraft
SPS	Sikorsky Process Specification
TRDS	Tail Rotor Drive Shaft
UTTAS	Utility Tactical Transport Aircraft System
VNE	Velocity Not to Exceed
WIP	Work in Progress
WL	Water Line
Wt	Weight
YR	Year

Bibliography

Baker1992a R. Bakerjian, et al (Eds.). *Tool and Manufacturing Engineers Handbook: Volume #6,* Design for Manufacturing, SME, 1992.

Boein1999a Boeing web site, http://boeing.com/rotorcraft/military/ch47d. 1999.

Boppe1998a C. Boppe, System Engineering Course Material, Section 20: Structured Creative Synthesis I, MIT, June 1998.

Carmo1999a W. Carmona, Advanced Common Engine Demonstrator, *Army Aviation*, July 31, 1999.

Cross1994a N. Cross, Engineering Design Methods. John Wiley & Sons, 1994.

Gantc1998a C. Gant, Ft. Rucker. UH-60 BLACK HAWK Modernization Program web site, http://155.147.98.10/dcd/dcd/proj/proj62. 1998.

Griff1993a A. Griffin, J. R. Hauser. The Voice of the Customer, *Marketing Science* 12(1), pp. 1-25, 1993.

Hause1988a J.R. Hauser, D. Clausing. The House of Quality. *Harvard Business Review*, May-June 1988.

Higgi1998a R. Higgins. Analysis for Financial Management. Irwin/ McGraw-Hill, 1998.

Highp1999a Quantifying qualification: the building-block approach to designing composite structures. *High Performance Composites*, July/August 1999.

Holme1998a C.E. Holmes. Effective Platform Designs for Medium Lift Helicopters. Master's Thesis, Massachusetts Institute of Technology. Cambridge, Massachusetts, 1998. Pg. 17 through 47.

Kande1999a S. Dandebo. Chinook Improvements Target Performance, Capability. *Aviation Week & Space Technology*, May 17, 1999 (pg. 65-67).

Matzl1998a K. Matzler, H. Hinterhuber. How to Make Product Development Projects More Successful by Intergrating Kano's Model of Customer Satisfaction into Quality Function Deployment. *Technovation*, Vol. 18 #1, Pergamon, January 1998.

MIT1999a MIT website for discount planning. http://curricula.mit.edu/~dsplan/Docs/Sessions/S7/s7.pdf , 1999.

Moghi1987a A. Moghissi. Risk Analysis: The Process and its Application. *Engineering Applications of Risk Analysis*, ASME, United Engineering Center, Dec. 13, 1987.

Nealg1999a G. Neal, U.S. Army. U.S. Army Programs- BLACK HAWK website, http://www.dcmc.hq.mil/CASSITES/sikorsky/Uh60info, 1999.

Oster1994a S.M. Oster. Modern Competitive Analysis. Oxford University Press, 1994.

Ottok1998a K. Otto, K. Wood. Product-Evolution: A Reverse Engineering and Redesign Methodology. *Research in Engineering Design*, 1998.

Pembe1998a H. Pember, Sikorsky Aircraft, 75 Years of Aviation Firsts. Sikorsky Historical Archives, Inc. 1998.

Phili1998a Defense Daily archive web site. Army EMD Contract for CH-47D Upgrade Work Expecte*d*. http://www.archive.phillips.com. 1998.

Porta1990a P.L. Portanova, et al. Quality Function Deployment in Launch Operations, Aerospace Corp. Report, TOR-009(6561-04)-1, Nov. 1990.

Power1998a C.B. Powers. And That Which is Old Shall be New Again. Georgia Tech Research Horizons website, http://www.gtri.gatech.edu/rh-sf98/rnotSF98, 1998.

Pugh1991a S. Pugh. Total Design. Addision-Wesley Publishing Co., 1991.

Smithr1999a CW4 R. Smith, Improved Cargo Helicopter. Ch-47 web site. http://155.147.98.10/dcd/ich4/ICHprog. 1999.

Tseng1997a M. Tseng, J. Jiao, A Varient Approach to Product Definition by Recognizing Functional Requirement Patterns. Carfax Publishing Ltd, 1997.

Ulric1995a K.T. Ulrich, S.D. Eppinger. Product Design and Developmen*t*. McGraw-Hill, 1995.

Veloc1999a A.L. Velocci, Jr. Merger Impasse Spurs Trend Toward More Global Alliances. *Aviation Week & Space Technology*, Feb. 22,1999, pp. 50-51.

Vetif1999a VERTIFLITE Magazine, Industry Briefs. Spring 1999, Volume 45, No. 2, pp. 6-7.

Wasse1993a G. Wasserman, On How to Prioritize Design Requirements during the QFD Planning Process. *IEE Transactions*, Volume 25, Number 3. May, 1993.

Wrigh1998a I.C. Wright. Design Methods in Engineering Product Design. The McGraw-Hill Publishing Co., 1998.