A FUZZY SET PARADIGM FOR CONCEPTUAL SYSTEM DESIGN EVALUATION

by

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(ABSTRACT)

A structured and disciplined system engineering process is essential for the efficient and effective development of products and systems which are both responsive to customer needs and globally competitive. Rigor and discipline during the later life-cycle phases of design and development (preliminary and detailed) cannot compensate for an ill-conceived system concept and for premature commitments made during the conceptual design phase. This significance notwithstanding, the nascent stage of system design has been largely ignored by the research and development community.

This research is unique. It focuses on conceptual system design and formalizes analysis and evaluation activities during this important life-cycle phase. The primary goal of developing a conceptual design analysis and evaluation methodology has been achieved, including complete integration with the system engineering process. Rather than being a constraint, this integration led to a better definition of conceptual design activity and the coordinated progression of synthesis, analysis, and evaluation.

Concepts from fuzzy set theory and the calculus of fuzzy arithmetic were adapted to address and manipulate imprecision and subjectivity. A number of design decision aids were developed to reduce the gap between commitment and project specific knowledge, to facilitate design convergence, and to help realize a preferred system design concept.

ACKNOWLEDGMENTS

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Beyond those directly involved, I would like to thank two special individuals, Benjamin S. Blanchard and Jezdimir Knezevic. It has been my good fortune to have Dean Blanchard as a mentor, friend, and supporter for many years. He made certain that this endeavor remained true to the system engineering process! Mirce Knezevic has been a valued collaborator and good friend. I used him as a sounding board during conferences, in hotel rooms, and airport lobbies throughout the course of this research and look forward to joint research endeavors with him in the future.

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DEDICATED TO:

CHIRANJEEV AND SATYA VATI NANDA
(My Grandparents)

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CHAPTER 1

INTRODUCTION

The purpose of this chapter is to set the stage and to develop a frame of reference for this research. After summarizing the problem setting, the research motivation is discussed in the form of a problem statement. This discussion is followed by a presentation of the research goal and objectives. The uniqueness of this research (along with its basic premise) is then highlighted. Finally, the organization of this dissertation is summarized.

1.1. THE PROBLEM SETTING

The domain of engineering design has been characterized by increasing interest in the past two decades. This is evident from references at the end of this dissertation. The design phase of the system life cycle is finally being recognized for its potential impact on the development of truly efficient and effective products, systems, and structures that more closely track customer requirements and needs [Shapour, et. al., 1987; Winner, et. al., 1988]. Increased global competition, along with the scarcity of resources, has hastened this recognition. In the past, designs evolved slowly with each revision incorporating small changes. Today, the pace of scientific and technological discovery is accelerating. With the aid of modern communication capability and computing resources, a new body of knowledge develops rapidly and its use, more often than not, may signal a complete break from past practice. Demands are for bolder and more rapid improvements. The technical risks faced by the designer are now greater, as are the stakes.

1.1.1. Concurrency in the System Design Process

In the face of increasing scrutiny, the system design process is undergoing a metamorphosis. Its largely sequential nature is giving way to greater concurrency and to earlier consideration of downstream issues pertaining to production, deployment, operation and support, and phase-out or retirement [Parsaei and Sullivan, 1993].

Blanchard and Fabrycky [1990] proposed consideration of three concurrent life-cycles as part of the overall system engineering process. As illustrated in Figure 1.1, these life cycles track (a) design and development of the primary product, (b) design, development, and installation of the manufacturing facility, and (c) design, development, and deployment of a maintenance capability to support both the deployed product and the manufacturing facility. Accordingly, the concept of concurrent engineering (the simultaneous consideration of product manufacturability and product support during product design) is inherent within the system engineering process.

This concurrency or "totality" during system design makes design more rigorous, comprehensive, and complex. A greater number of competing

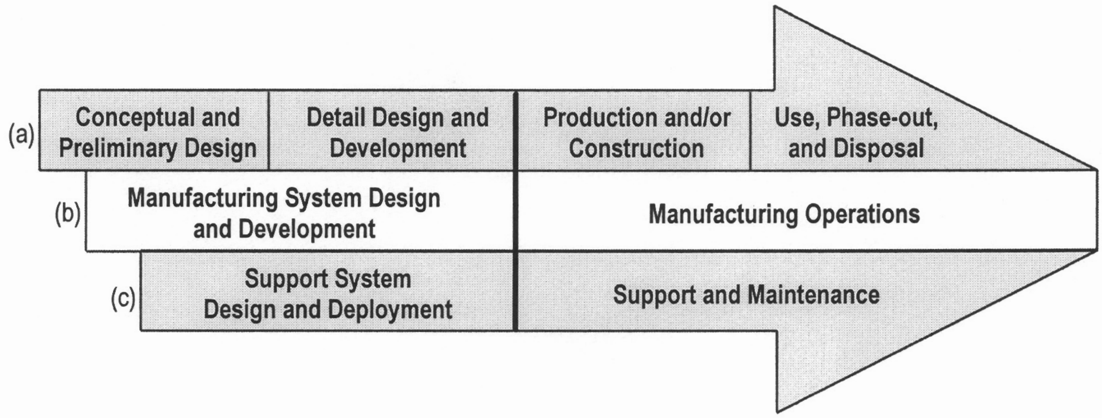


Figure 1.1. Concurrency in system design and development.

requirements play an active role. Further, requirements relating to data and information handling, communication, and data storage within a concurrent engineering design environment pose significant challenges. A structured, disciplined, and properly managed, systems engineering process is essential for the successful development of effective systems (products and/or processes).

A structured and disciplined system engineering process, presented by Blanchard and Fabrycky [1990], is depicted in Figure 1.2. Here systems engineering is defined as the application of efforts to:

1. *transform an operational need into description of system performance parameters and a preferred system configuration through the use of an iterative process of functional analysis, synthesis, optimization, definition, design, test, and evaluation;*
2. *incorporate related technical parameters and assure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and*
3. *integrate performance, producibility, reliability, maintainability, manability, supportability, and other specialties into the overall engineering effort.*

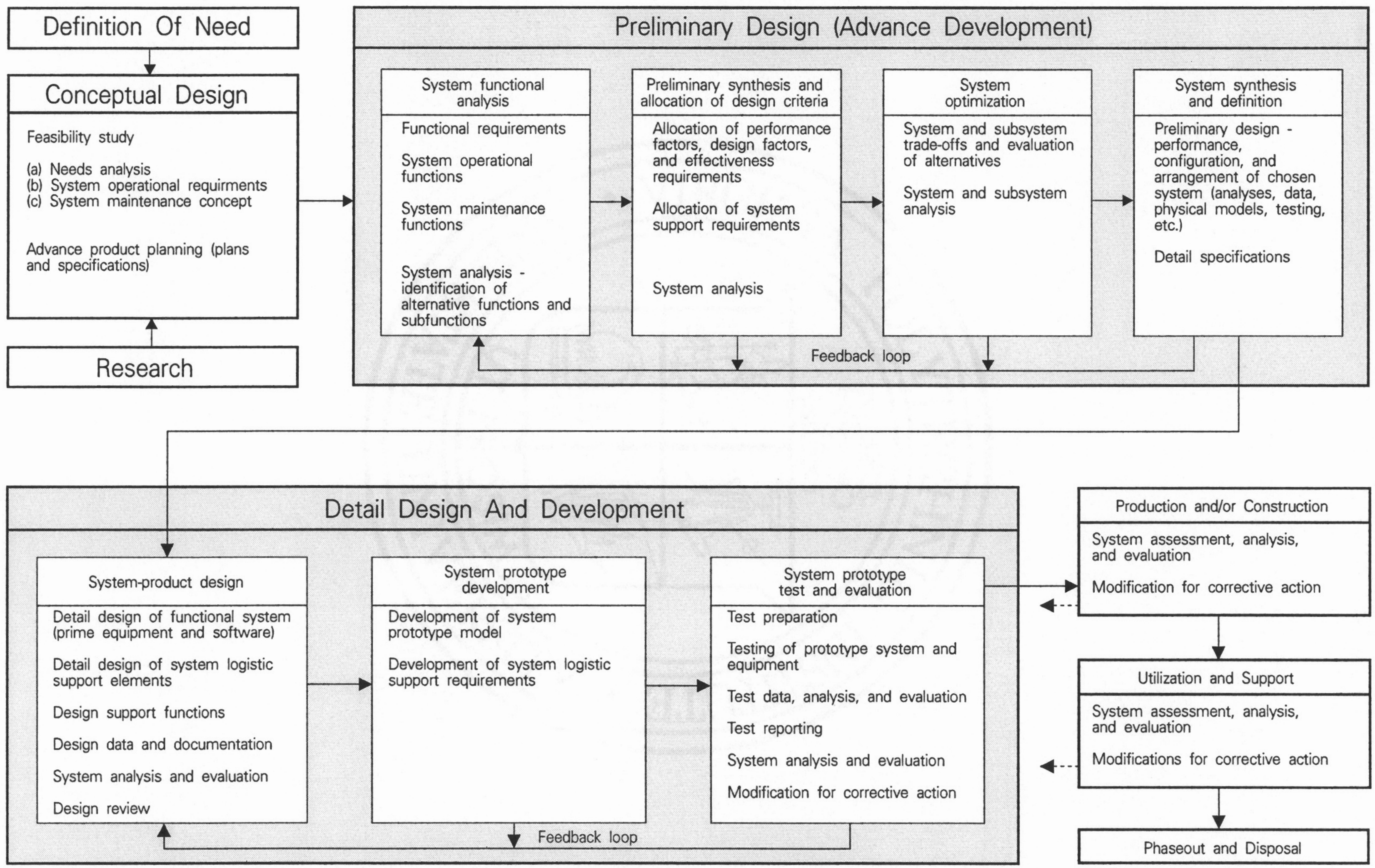


Figure 1.2. The system engineering process [Blanchard and Fabrycky, 1990].

The system life cycle begins with the identification of a functional need or deficiency. This need is translated into system level requirements through the utilization of tools such as Quality Function Deployment and Input-Output matrices. The requirements definition process is then followed by the conceptual design phase (involving the synthesis and selection of system-level conceptual solutions) and the preliminary design phase (involving the modeling of expected system behavior, the allocation of system level requirements to conceptual sub-systems, and their subsequent translation into detailed design specifications). Preliminary design is followed by detailed design and development which, in turn, leads to the actual production and/or construction of the product or structure. The product or structure is then deployed, installed, operated, and maintained. At the end of its operational (design) or economic life, the entity is either re-engineered to satisfy an evolving need or requirement, or properly retired and recycled.

From a broad perspective, any system design and development activity involves the three general tasks of synthesis, analysis, and evaluation. Figure 1.3, which depicts these system design activities, is an extension to the computer-aided concurrent engineering design morphology proposed by Blanchard and Fabrycky [1990].

Design synthesis can be defined as the process of assembling a set of conceptual solutions (which have the potential of satisfying the identified need or deficiency) or a set of candidate designs that seem to satisfy the most significant specifications. Analysis is a process of ascertaining whether the identified conceptual solutions and/or designs satisfy some of the other less obvious specifications and constraints.

The outcome from the analysis phase is a reduced, but feasible, set of candidate designs which merit further consideration. Evaluation involves the anticipation of system behavior. It involves the derivation, estimation, and prediction of values for all relevant design parameters (dependent and independent, to be discussed in Section 1.1.3) and design variables in order to

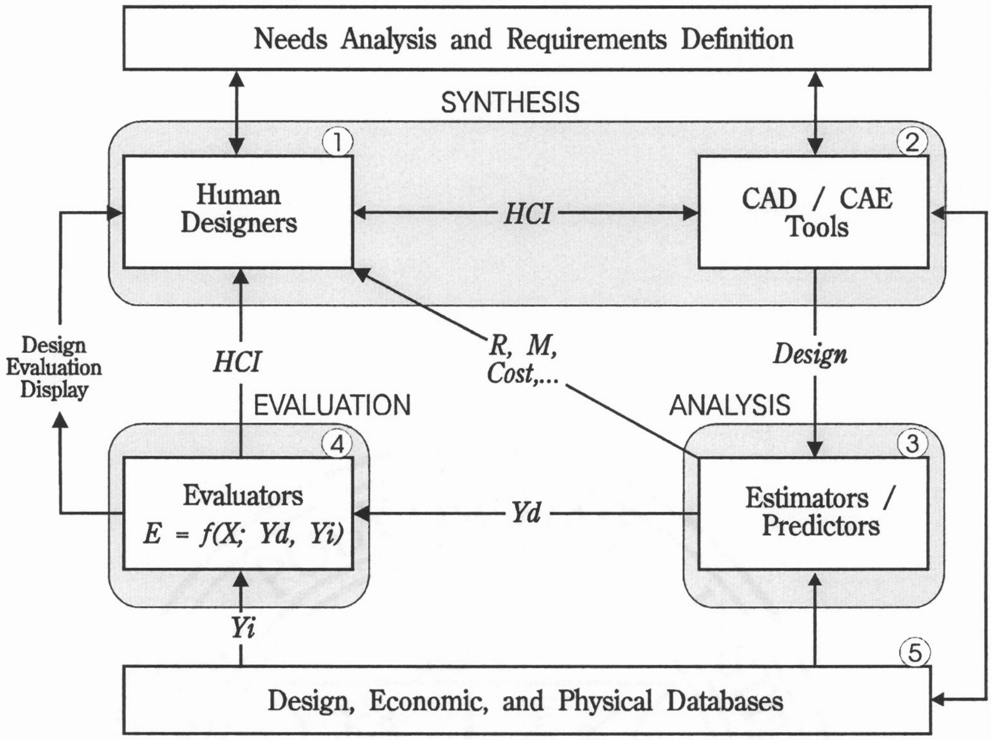


Figure 1.3. Computer-aided concurrent engineering design morphology.

determine acceptability in terms of the initially stated needs, objectives, and specifications. Finally, evaluation includes the task of selecting the "best" or preferred approach.

1.1.2. Uncertainty During System Design Analysis and Evaluation

Design synthesis, analysis, and evaluation activities are not only iterative but also continuously changing in scope with the progression and evolution of the system engineering process. The constant denominator throughout this shifting scenario is the uncertainty that designers and analysts must contend with. This design uncertainty is most pronounced during the nascent (conceptual and preliminary) stages of the design process, and is reflected through the resolution of analyses conducted during this phase.

During early system design uncertainty arises as a result of the "gap" between commitment and design / project specific knowledge. This is depicted in Figure 1.4 as adapted from Fabrycky [1991]. A significant portion of uncertainty during conceptual design is a result of imprecise need definition, system requirements and performance levels, and so on.

Uncertainty inherent in the design process can be broadly classified into two basic types (a) uncertainty due to imprecision, and (b) uncertainty due to randomness. In the context of this discussion, imprecision is uncertainty which manifests itself as a result of human judgment and/or perception and is represented as graded membership in a fuzzy set. Graded membership may be defined as absence of sharp transition from membership to non-membership in a set or class of objects. Uncertainty due to randomness, however, is represented as a membership or non-membership of an element (object, event, etc.) in a "crisp" or non-fuzzy set. In this case, an element is clearly a member or

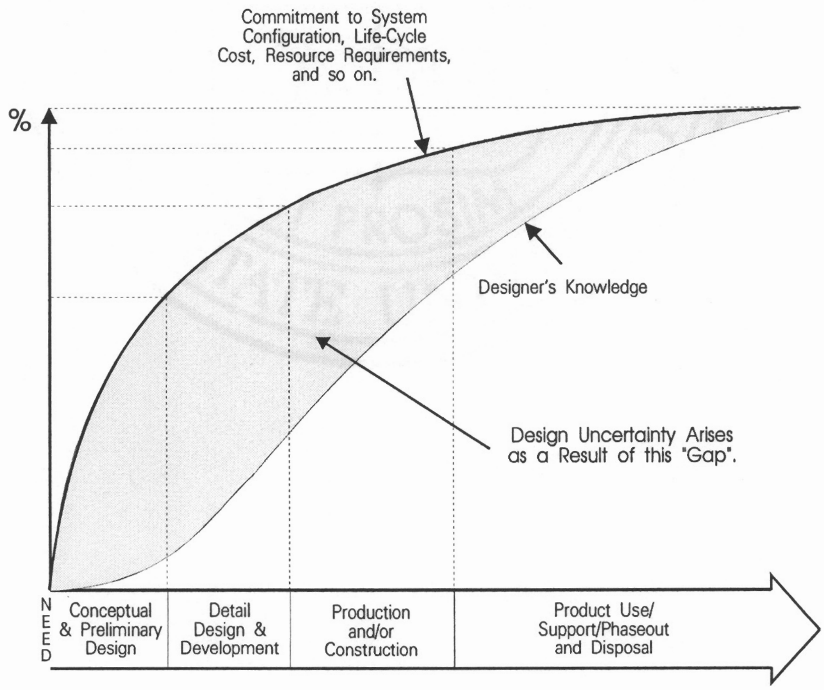


Figure 1.4. The "gap" between knowledge and commitment.

definitely not a member of a particular set or class of objects. To ensure effectiveness, a design evaluation methodology (within the framework of an overall evaluation approach) must address (and adapt to) not only the extent of uncertainty, but also its nature.

Subsequent to identifying the initial need, significant commitments are made by designers during the conceptual design phase. These commitments pertain to system concept, configuration, technology applications, life-cycle cost, and so on. Focus of this research, therefore, is on the conceptual design phase within the overall system engineering process.

1.1.3. Mathematical Framework for System Design Evaluation

The design dependent parameter approach, proposed by Fabrycky, facilitates the life-cycle complete evaluation of alternative system designs [Fabrycky 1994, 1992]. This approach involves separation of the system design space (represented by design dependent parameters) from the search space (represented by design variables). The terms are defined as follows:

1. *Design Dependent Parameters* (Y_d): These are factors with values under the control of designer(s) and which are impacted by the specialty disciplines brought to bear in the development process. Moreover, every instance of the design dependent parameter set represents a distinct and potential candidate system or design alternative, since these parameters represent the design space. Examples of design dependent parameters include reliability, maintainability, time to altitude, and throughput.
2. *Design Independent Parameters* (Y_i): These are factors beyond control of the designer(s), but which impact the overall effectiveness of all candidate systems or design alternatives, and can significantly alter their relative "goodness" or desirability. Examples of design

independent parameters include labor rates, inflation and interest factors, and demand.

3. *Design Variables* (X): These are factors which define the design optimization space. Once a feasible set has been synthesized, each candidate system is optimized over the set of design variables before being compared with the other alternatives.

The design dependent parameter approach offers a framework for the robust and comprehensive evaluation of system designs [Altenhof, et. al., 1990; Duan, 1992, Midkiff and Fabrycky, 1991]. This approach evolved from a concept introduced by Churchman, Ackoff, and Arnoff in 1957 [Churchman, et. al., 1957]. These authors proposed a model structure for operations which expresses system effectiveness as a function of two sets of variables. The general form of the model was given as:

$$E = f(x_i, y_j) \tag{1.1}$$

where, E is a measure of system effectiveness, x_i are the variables under control, and y_j are the variables not subject to direct control.

Equation 1.1 was the genesis of the design dependent parameter approach. Fabrycky [Fabrycky, et. al., 1984] extended it to Operations Research models generally. He proposed an effectiveness function linking effectiveness with variables under the control of the decision maker and variables not under direct control, in the face of constraints. Constraints were expressed as functions of the controllable and uncontrollable variables and a set of constraint constants. This formulation was further extended and applied to the modeling of inventory operations by Banks and Fabrycky [1987] and to the evaluation of engineering designs, as a design evaluation function, by Fabrycky [1991].

The form of the design evaluation function (DEF) was expressed as:

$$E = f(X, Y_d, Y_i); \quad subject \;\; to \;\; g(X, Y_d) > / = / < C \tag{1.2}$$

where E is the evaluation measure, X the set of design variables, Y_d the set of design dependent parameters, and Y_i the set of design independent parameters.

The formulation expressed in Equation 1.2 provides a framework for the evaluation of alternative designs in a concurrent life-cycle engineering mode. The design evaluation function (DEF) is embedded within the computer-aided concurrent engineering morphology (as illustrated in Figure 1.3), which in turn is embedded within a comprehensive system engineering process (as illustrated in Figure 1.2).

Essential in the engineering morphology are the linkages between blocks. The process is initiated by the human designer (or design team) with the aid of applicable computer-based methods and tools, and in response to a user need. Blocks 1 and 2 (with a two-way interface) represent the synthesis aspect of system design and development. Design alternatives which satisfy most of the significant and obvious requirements and specifications are passed (via the interface between Blocks 2 and 3) from the synthesis phase and subject to further analysis.

The analysis activity is comprised of numerous prediction and estimation processes [Verma and Sols, 1992; Blanchard, Verma, and Peterson, 1995]. The objective is to ascertain whether candidate systems or design alternatives satisfy the less obvious requirements/specifications and constraints. Feedback is provided to the design team via an interface between Blocks 3 and 1. Another interface (between Blocks 3 and 4) conveys feasible alternatives or candidate systems, via values for design dependent parameters, to be considered and investigated during the evaluation phase.

While the above interfaces represent the iterative and mainstream system design process, there exist interfaces that represent the supporting information and data flows. Interfaces between Block 5 (database; both static and dynamic) and Blocks 2, 3, and 4, respectively, are such interfaces.

1.2. PROBLEM STATEMENT

A robust system design morphology, enhanced by a sound evaluation methodology, can enable the realization of systems that meet user needs more effectively and efficiently. Development of such systems, in turn, leads to enhanced profitability and “presence” in a competitive market place. However, the applicability of many traditional methodologies and optimization procedures to design evaluation is largely limited due to the qualitative nature of certain design goals, requirements, and criteria. This limitation is particularly evident during the early design phases. Vastly different evaluation methodologies have been proposed [Dixon, et. al. 1989; Fabrycky, 1994; Knosala and Pedrycz, 1987; O'Grady, et. al. 1991; Ostrofsky, 1977; Thurston, et. al. 1993]. These have been developed to primarily address the preliminary and detailed design phases of the system engineering process. There is little evidence in the literature of research to aid the formal and rigorous evaluation of conceptual system designs.

The ultimate goal of design evaluation is to isolate the "best" or "most desirable" alternative. However, this evaluation activity must be compatible with the corresponding engineering design process for maximum effectiveness. The significance and impact (on the overall system life cycle) of design decisions during the nascent stages of the system design and development process has been fairly well conceptualized and documented [Fabrycky and Blanchard, 1991; Osborn, 1991; Nickelson and Belson, 1991]. In keeping with this imperative, evaluation of conceptual system designs is the focus of this investigation.

Fundamental research has been conducted to develop a methodology for addressing the evaluation of designs during the conceptual design phase of the system engineering process. Design decisions at this stage of the development process are generally made in the face of inadequate project specific knowledge. However, these decisions result in substantial (and early) commitment to the ultimate system configuration, design concept, technology application, life-cycle cost, resource requirements, and so on, as was illustrated in Figure 1.4 [Fabrycky and Blanchard, 1990; Nickelson and Belson, 1991; Osborn, 1991].

A formalized system design evaluation methodology, complete in its consideration of the system life cycle, and focused on the evaluation of conceptual designs, should facilitate the design and development of products more responsive to user/consumer needs and requirements. Further, the development of this methodology should contribute to the evolving theory of system design.

1.3. RESEARCH OBJECTIVES

The overarching goal of this research is to make a contribution to the on-going evolution of the field of design theory and methodology. This goal is achieved through the development of a conceptual design evaluation methodology. Specific objectives of this research include:

1. Definition and formalization of the conceptual system design phase.
2. Understanding the nature and source of uncertainty during the nascent stages of system design and development.
3. Development of mechanisms to aid and facilitate definition of system design requirements, while keeping the ultimate customer(s) integral to this process.
4. Delineation of a structured and disciplined approach for making decisions during the conceptual system design phase.
5. Inclusion of subjective criteria and relative weights into the evaluation process in a formal and explicit manner.
6. Development of mechanisms to guide the accomplishment of system redesign or design improvement efforts.
7. And finally, establishment of a baseline for the future development of this field of study.

1.4. UNIQUENESS OF THIS RESEARCH

Evaluating engineering designs continues to be the focus of many research groups. However, these efforts have been targeted to the evaluation of designs during the later stages of system development. There is extensive reference in the literature to the evaluation of detailed designs with regard to manufacturing and assembly.

Boothroyd and Dewhurst investigated the linkage between detail design configuration and the likely time and cost for subsequent assembly [Boothroyd, 1988]. Ulrich, et. al., attempted to correlate the assembly time saved through parts consolidation with the consequent impact on the time and cost to manufacture [Ulrich, et. al., 1991]. O'Grady and Young have conducted research to evaluate preliminary designs from the perspective of manufacturing unacceptability [O'Grady, et. al. 1991; Young, et. al. 1991]. They have proposed an artificial intelligence based approach as a means of tracking production constraint violations during the design and development process.

Neville conducted research to evaluate mechanical structures from the perspective of stiffness and weight [Nevill, 1990]. Lee and Gilmore considered uncertainties in the design of stochastic Kinematic chains (including tolerances on link length, radial clearance, and random pit center location) through the formulation of a probabilistic model [Lee and Gilmore, 1989]. Dhingra and Rao used concepts from fuzzy set theory to analyze the kinematic and dynamic characteristics of high speed planar mechanisms [Dhingra and Rao, 1989].

Thurston, et. al., proposed utilization of multi-attribute utility theory to compare the overall value of alternative design configurations as a function of the levels of multiple performance characteristics of a manufactured item. They apply sensitivity analysis as a mechanism for modifying designs and to enhance overall utility to decision makers [Thurston 1991; Thurston, et. al. 1991; Thurston, et. al. 1992; Thurston, et. al. 1993].

Mistree, et. al., propose extension of concepts from the field of goal programming and traditional mathematical programming in order to formulate a hybrid model called the "Compromise Decision Support Problem" [Mistree, et. al. 1992]. These authors utilize the adaptive linear programming approach to solve compromise decision support problems. This approach has been applied to evaluate detailed system designs and to some extent preliminary system designs. Extension of the basic approach is made possible through the application of fuzzy set theory in order to bypass the requirement for "*precisely defined information and relationships between subsystems*" [Allen, et. al. 1990]. The extended approach has been applied to the detailed design evaluation of a portal frame and a planar four-bar linkage [Zhou, et. al. 1992]. Further the approach has been applied to explicitly link issues pertaining to design and manufacture in the detailed design phase [Karandikar, et. al. 1991].

Otto, Antonsson, and Wood suggest application of concepts from fuzzy logic to evaluate preliminary mechanical designs [Otto and Antonsson, 1991; Wood and Antonsson, 1990]. They have analyzed the vagueness of parameters in the design of a mechanical frame structure [Wood, et. al., 1989].

There have been few efforts to formalize and quantify design evaluation during the conceptual design phase. The conceptual design process in general, and generation of conceptual solutions in particular, has been addressed by Pugh [1990]. However, evaluation of conceptual designs in Pugh's approach has been limited to the simplistic numerical rating of alternative conceptual solutions in terms of the set of applicable attributes and relative weights. Thereafter, these ratings are summed to obtain a relative ranking or "goodness" of the alternatives, and to facilitate selection of the preferred approach.

In comparing the application of utility theory and fuzzy logic to the multiple-attribute evaluation of preliminary designs, Thurston and Carnahan [1992] speak to the likely benefit of applying concepts from fuzzy logic to the earlier phases of the engineering design and development process. They state

"...fuzzy analysis may be most useful in the early stages of the preliminary design, even prior to the development of an initial design concept, while utility analysis may be more useful in later stages of the iterative design process...".

In the context of the above discussion, this research derives its uniqueness from a variety of perspectives, to include:

1. A focus on the conceptual design phase of the system engineering process.
2. Development of design decision aids such as the *IPN* (Improvement Potential and Necessity) and *TOF* (Tolerance of Fuzziness) *Indices* to facilitate the requirements definition activity.
3. Development of a *Feasibility Index* to guide the feasibility assessment of potential design concepts with regard to the relevant design dependent parameters.
4. Development of a framework to guide focused redesign or design improvement efforts in the face of scarce resources.
5. Development of an evaluation methodology within the robust framework of the design dependent parameter approach.
6. Close integration of the evaluation methodology with the system engineering process.
7. Utilization of concepts from fuzzy set theory and the calculus of fuzzy arithmetic to handle the uncertainty borne of imprecision and human judgment during the conceptual design phase.

1.5. THE THESIS OF THIS RESEARCH

System design and development generally involves extensive indirect experimentation through mathematical modeling and simulation. Analysts often trade-off fidelity and resolution (through the use of simplifying assumptions) to formulate a model which facilitates application of a particular modeling technique or reduces overall model complexity. However, most traditional modeling techniques require precise definition and formulation of the scenario and are limited in their application to design evaluation. While many classical modeling techniques can be "force fitted" to analyze and evaluate early system designs, undesirable separation between the model and reality may result.

The fundamental thesis of this research is that addressing uncertainty due to imprecision and randomness, simultaneously, through the complementary utilization of concepts from fuzzy logic and probability theory, can facilitate realistic and robust evaluation of candidate conceptual system designs.

Numerous references suggest and make a case for the utilization of fuzzy set theory to enrich the multi-attribute decision making process through a more realistic modeling of imprecise uncertainty [Belman and Zadeh, 1970; Baas and Kwakernaak, 1977; Kwakernaak, 1979; Knosala and Pedrycz, 1987; Wood and Antonsson, 1989]. Moreover, given that a significant component of uncertainty during conceptual design is imprecise rather than stochastic in nature, it is better addressed through the utilizing of concepts from fuzzy set theory and the calculus of fuzzy arithmetic.

1.6. ORGANIZATION OF THIS DISSERTATION

This dissertation document has been organized into seven chapters and a supporting appendix as shown in Figure 1.5. The overall research setting and problem domain was introduced in this chapter (Chapter 1). This setting was then discussed from the viewpoint of focusing attention on the problem statement and research objectives, followed by a brief synopsis of the uniqueness of this research. Thereafter, the thesis underlying this research endeavor was outlined.

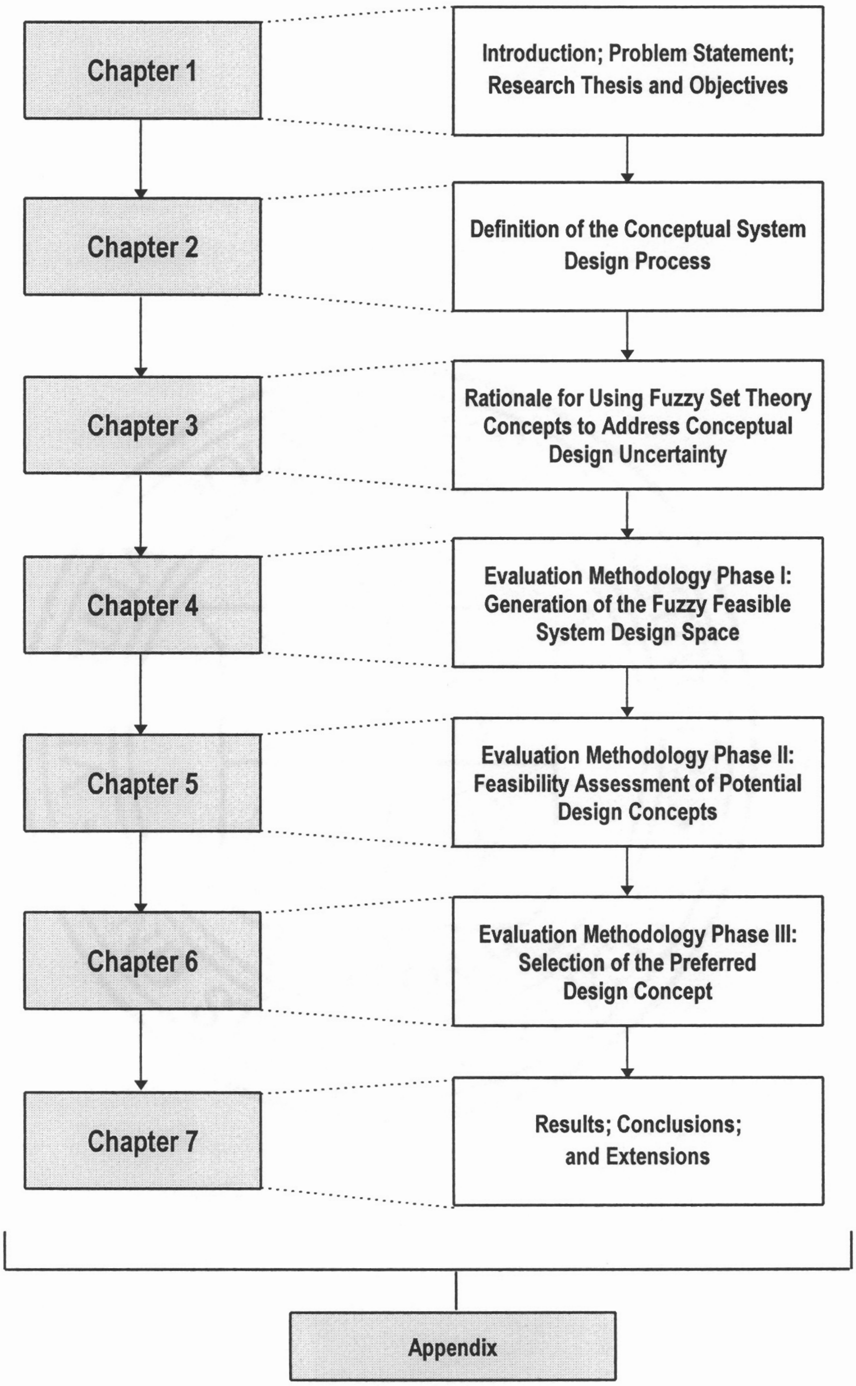


Figure 1.5. The organization of this dissertation.

Given the research emphasis, Chapter 2 is devoted to defining and formalizing the conceptual system design process. Constituent activities are initially delineated, classified by type (i.e., synthesis, analysis, and/or evaluation), and then discussed in terms of necessary inputs, expected outputs, and applicable "best practices". The evaluation aspect of conceptual system design is presented in terms of the current state of the art, and significant opportunities for extension are then identified.

Rationale for the use of concepts from fuzzy set theory in general, and fuzzy arithmetic in particular, to address uncertainty during the conceptual system design phase is developed in Chapter 3. Uncertainty is classified into two types, stochastic uncertainty and imprecision. Further, the complementary utilization of pertinent concepts from probability theory and fuzzy set theory is proposed to address these two types of uncertainty.

The conceptual design analysis and evaluation methodology is developed in three phases with each phase treated in a separate chapter. The concept of a fuzzy feasible design space is developed in Chapter 4, the feasibility assessment of potential conceptual solutions is addressed in Chapter 5, and the analysis of feasible concepts and selection of the "best" or preferred approach is outlined in Chapter 6.

Finally, the results of this research, pertinent conclusions, and recommendations for future research are summarized in Chapter 7. The overall document is supported by an Appendix which presents pertinent concepts and operations relating to fuzzy arithmetic.

CHAPTER 2

CONCEPTUAL SYSTEM DESIGN

Although the emphasis of this research is on evaluating design concepts, it is important to simultaneously address the underlying process. This is necessary to better integrate evaluation with the process. Therefore, the purpose of this chapter is to formally define the conceptual system design process along with its constituent activities and tasks. This discussion leads to the identification of selected design methods and practices which may be utilized to "operationalize" and implement the process.

2.1. THE CONCEPTUAL SYSTEM DESIGN PROCESS

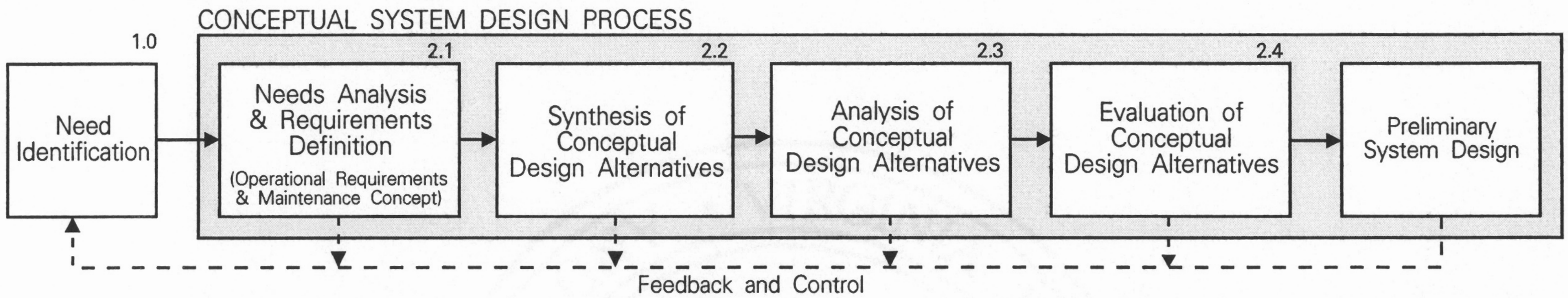
Identification of a current need or deficiency marks the beginning of the system engineering process. This was depicted in Figure 1.2. Tools and techniques such as benchmarking, customer surveys, and competitive product analyses facilitate the delineation of a valid need statement. It is important to express this need in functional terms and not commit prematurely to a particular configuration or conceptual solution [Pugh, 1990; Blanchard and Fabrycky, 1990]. Organizations which can effectively "capture", expose, and then exploit a not-so-obvious need, may very often gain a head start over the competition.

The expression of a need or deficiency in functional terms becomes an input to the conceptual design phase. Activities which constitute this design phase are depicted in Figure 2.1, and discussed in the following sections.

2.1.1. Needs Analysis and Requirements Definition

The first step in conceptual system design is to analyze and translate the functional need into a specific set of qualitative and quantitative customer and design requirements. This translation must be carefully orchestrated to completely track and truthfully represent the initially delineated customer need. Need analysis involves the coordinated accomplishment of a number of activities to include data collection, data analysis, parametric analysis, investigation of applicable patents, standards, and regulations, competition analysis, customer surveys, and so on. These activities are shown in Figure 2.2. Competent use of design methods and tools such as Quality Function Deployment (QFD) and Input / Output matrix analysis facilitates translation of the functional need into a relevant set of system-level requirements.

QFD was initially developed as a design tool in 1972 at the Kobe Shipyard of Mitsubishi Heavy Industries, Ltd., and has evolved considerably since. It involves an attempt to identify an applicable and prioritized set of subjectively stated customer desired attributes. These subjective attributes drive the subsequent identification of a more objective (and correlated) set of quantitative and qualitative engineering characteristics.



Activity Number	Activity Description	Required Inputs	Expected Outputs	Tools and Techniques or "Best Practices"
1.0	Need Identification	Customer surveys; marketing inputs; shipping and servicing department logs; market niche studies; competitive product research	A specific qualitative and quantitative needs statement responding to a current deficiency. Care must be taken to state this need in functional terms.	Benchmarking; statistical analyses of data (i.e., data collected as a result of surveys and consolidated from shipping and servicing logs, etc.)
2.1	Needs Analysis and Requirements Definition	A specific qualitative and quantitative needs statement expressed in functional terms.	Qualitative and quantitative factors pertaining to system performance levels, geographical distribution, expected utilization profiles, user/consumer environment; operational life-cycle, effectiveness requirements, the levels of maintenance and support, consideration of the applicable elements of logistic support, the support environment, and so on.	Quality Function Deployment (QFD); input/output matrix; checklists; value engineering; statistical data analysis; trend analysis; matrix analysis; parametric analysis; various categories of analytical models and tools for simulation studies, trade-offs, etc.
2.2	Synthesis of Conceptual System Design Alternatives	Results from needs analysis and requirements definition process; technology research studies; supplier information	Identification and description of candidate conceptual system design alternatives and technology applications.	Pugh's concept generation approach; brain storming; analogy; checklists.
2.3	Analysis of Conceptual System Design Alternatives	Candidate conceptual solutions and technologies; results from the needs analysis and requirements definition process	Approximation of "goodness" of feasible conceptual solutionS relative to pertinent parameters, both direct and indirect. This goodness may be expressed as a numeric rating, probabilistic or fuzzy measure.	Indirect system experimentation (e.g., mathematical modeling and simulation); parametric analyses; risk analyses.
2.4	Evaluation of Conceptual System Design Alternatives	Results from the analysis task in the form of a set of feasible conceptual system design alternatives.	A single or short listed set of preferred conceptual system designs. Further, a "feel" for how much better the preferred approach(es) is relative to all other feasible alternatives.	Design dependent parameter approach; generation of hybrid numbers to represent candidate solution "goodness"; conceptual system design evaluation display.

Figure 2.1. Conceptual system design activities.

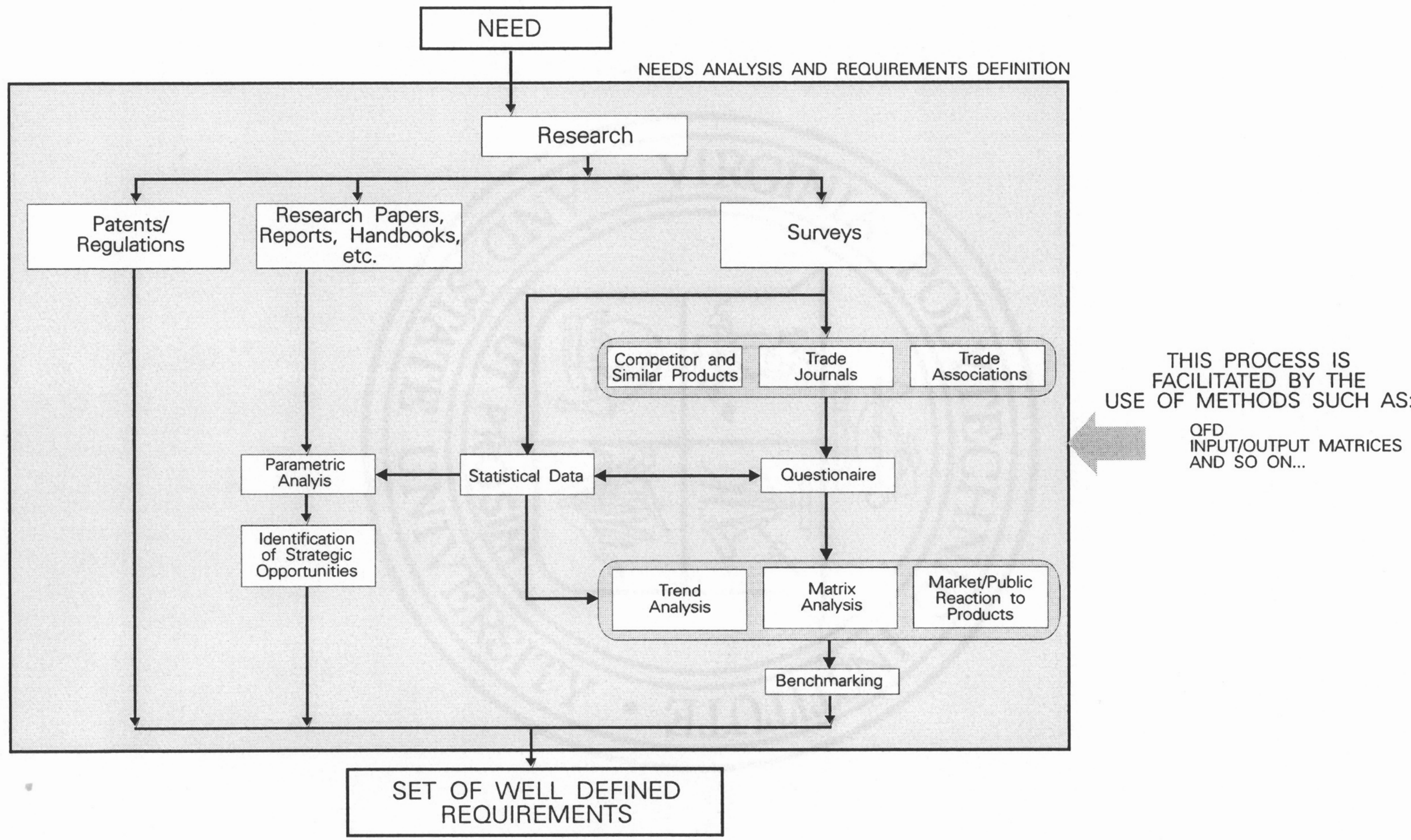


Figure 2.2. Needs analysis and requirements definition.

Benchmarking of competitors' products and consumer / customer perceptions is folded into the methodology to aid delineation of desired performance levels for various engineering characteristics. A "house of quality", such as the one illustrated in Figure 2.3, serves as an excellent framework for the synthesis and representation of information involved in the implementation of the QFD technique. For a more detailed discussion of QFD refer to [Hauser and Clausing, 1988; Sullivan, 1986; Akao, 1990; Kagure and Akao, 1983].

When defining a comprehensive set of system-level requirements, it is essential that due attention be given to the complete system life cycle. According to Blanchard and Fabrycky [1990], "*the tendency is to cover primarily those elements of the system that relate to performance; that is, prime mission-oriented equipment, operational software and associated data, operating personnel, and so on. At the same time, there is usually very little attention given to system support, particularly at the early stages of design and development.*" Proper implementation of the input-output matrix proposed by Ostrofsky can facilitate this completeness [1977].

The objective in developing an Input / Output matrix is to explicitly consider every phase of the system life cycle and then attempt to identify not only the desired functional / operational outputs from the system, but also the undesired outputs. In addition, all intended and environmental inputs likely to impact system desirability are also addressed, as shown in Figure 2.4.

2.1.2. Synthesis of Conceptual Design Alternatives

Subsequent to the requirements definition activity, the system engineering process involves synthesis of potential conceptual design solutions. In the context of this research, a design concept is defined as a basic technical approach to potentially satisfy system-level requirements. Further, each candidate conceptual design must be sufficiently defined to a consistent level of detail to facilitate subsequent analysis and evaluation activities. In the case of

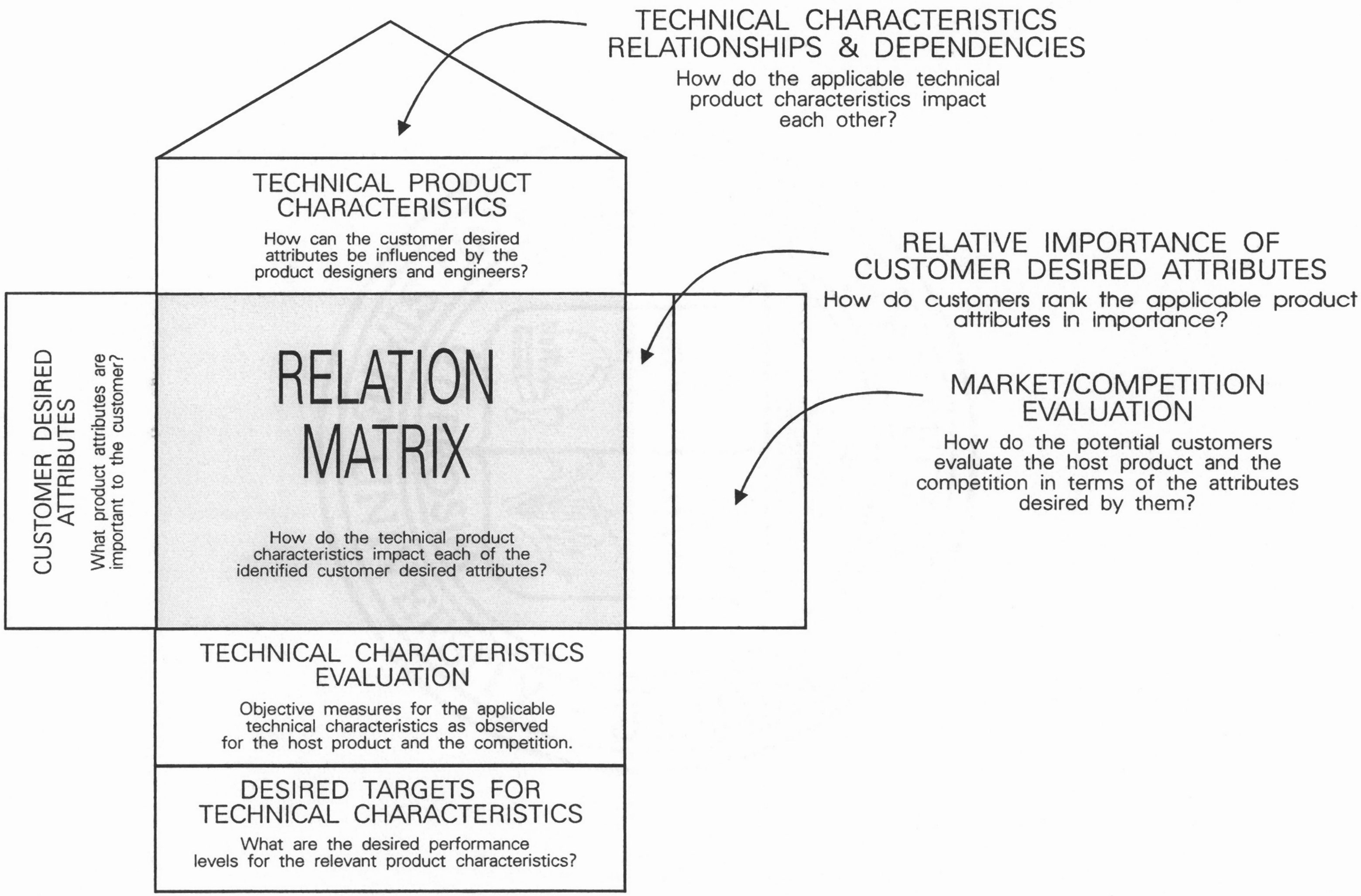


Figure 2.3. The "house of quality" schema.

	INPUTS		OUTPUTS	
	Intended	**Environmental**	**Desired**	**Undesired**
Production				
Distribution				
Consumption and/or Operation				
Retirement				

Figure 2.4. Input-output matrix to facilitate requirements definition [Ostrofsky, 1977].

large complex systems, it may be necessary to identify sub-concepts for selected sub-systems, along with concepts at the system level, as depicted in Figure 2.5.

The generation of conceptual solutions is a highly subjective process. Past experience, and familiarity with similar problems, impacts this phase of the system design process significantly. Significant research has been conducted to provide further insight into this abstract process which involves creative thought and innovation. According to McGrath [1984], while generating or synthesizing conceptual system design solutions "*individuals working separately generate many more, and more creative ideas than do groups, even when the redundancies among member ideas are deleted, and, of course, without the stimulation of hearing and piggy-backing on the ideas of others*". His extensive research concluded that conceptual system design solutions are best generated by design team members working individually. On the other hand, a group effort is best suited to the process of concept evaluation and ultimate selection.

Extensive use is made of techniques such as brainstorming, analogy, checklists, and so on, to aid the process of creative thinking and conceptual solution synthesis as is evident in the literature. Brainstorming, the technique most commonly used, was developed by Alex Osborn and involves a process

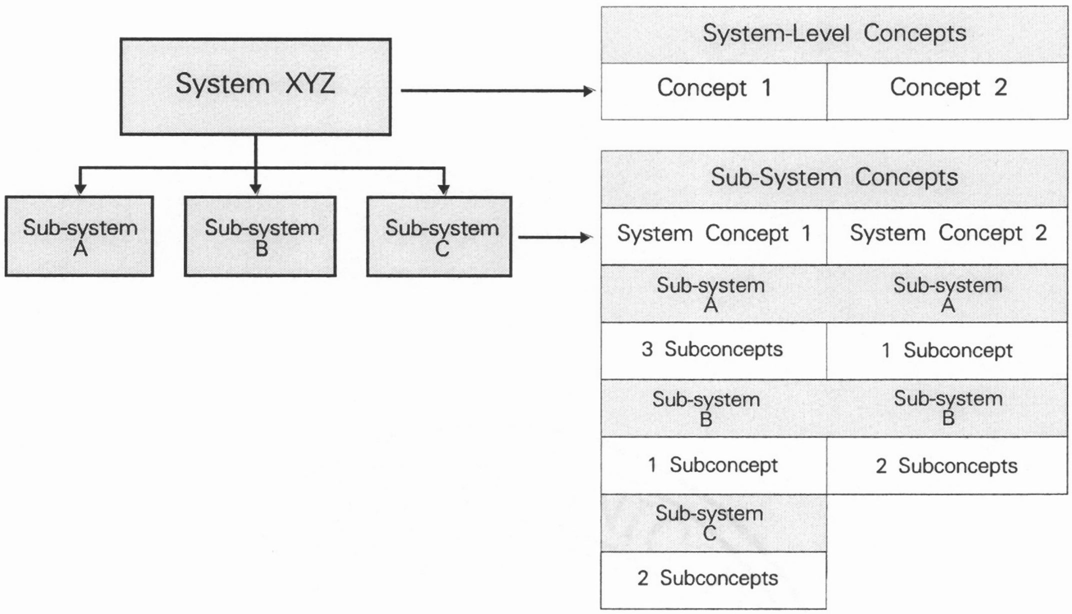


Figure 2.5. System and sub-system level conceptual solution generation.

whereby "*a group attempts to find a solution for a specific problem by amassing all the ideas spontaneously contributed by its members*" [Osborn, 1957]. Analogy involves the translation of a conceptual solution across disciplines and its adaptation to solve similar problems. Checklists, on the other hand, involve a set of thought provoking questions with the objective of enhancing innovation and creative thought.

Nevill and Crowe describe the process of concept generation as a search through a problem space. They describe this problem space as being a function of the designer's interpretation of the real world, all information and knowledge available to the designer, the goals and constraints of the problem, and the nature of the designer and design team. Further, the initial location of the designer within this problem space is determined by his or her perception of the design problem. A computer-based prototype, IDEAS, has been developed to help the design team navigate through the conceptual system design space towards a reasonable set of conceptual solutions. Holt discusses other such computer-based creativity aids [Holt, 1987]. Another aid for the synthesis of conceptual solutions was developed by Virkkala called IDEGEN and can be used by individuals or groups, while the Center for Commercial Innovation in Sweden developed a similar tool called the Idea Generator. Dickey developed a computer-based environment to facilitate the generation of creative ideas and solutions called CyberQuest - The Innovation Support System [Dickey, 1993].

Its abstract nature notwithstanding, the ability to generate, evaluate, and then select a suitable conceptual solution impacts the overall system design and development process very significantly. While an excellent conceptual system design does not "guarantee" a successful design and development effort, no amount of rigor and discipline during the later phases of system design can make up for or salvage an ill conceived conceptual solution.

2.1.3. Analysis of Conceptual Design Alternatives

Once a set of conceptual solutions has been synthesized, each is analyzed for feasibility in terms of physical realizability, functional compatibility, economic worthiness, and financial / budgetary constraints. The objective of the analysis phase is to screen out unfeasible concepts so that only feasible ones enter the more rigorous evaluation and selection phase. The process involved in screening out the unfeasible conceptual solutions may be such as the one depicted in Figure 2.6.

It is important to discard only those conceptual solutions which are very definitely infeasible or impossible to implement. This is in keeping with the "*principle of least commitment*" in system design and development as promulgated by Asimow [1964]. Premature commitment to a particular conceptual solution may be detrimental to the overall objectives of the system design and development process.

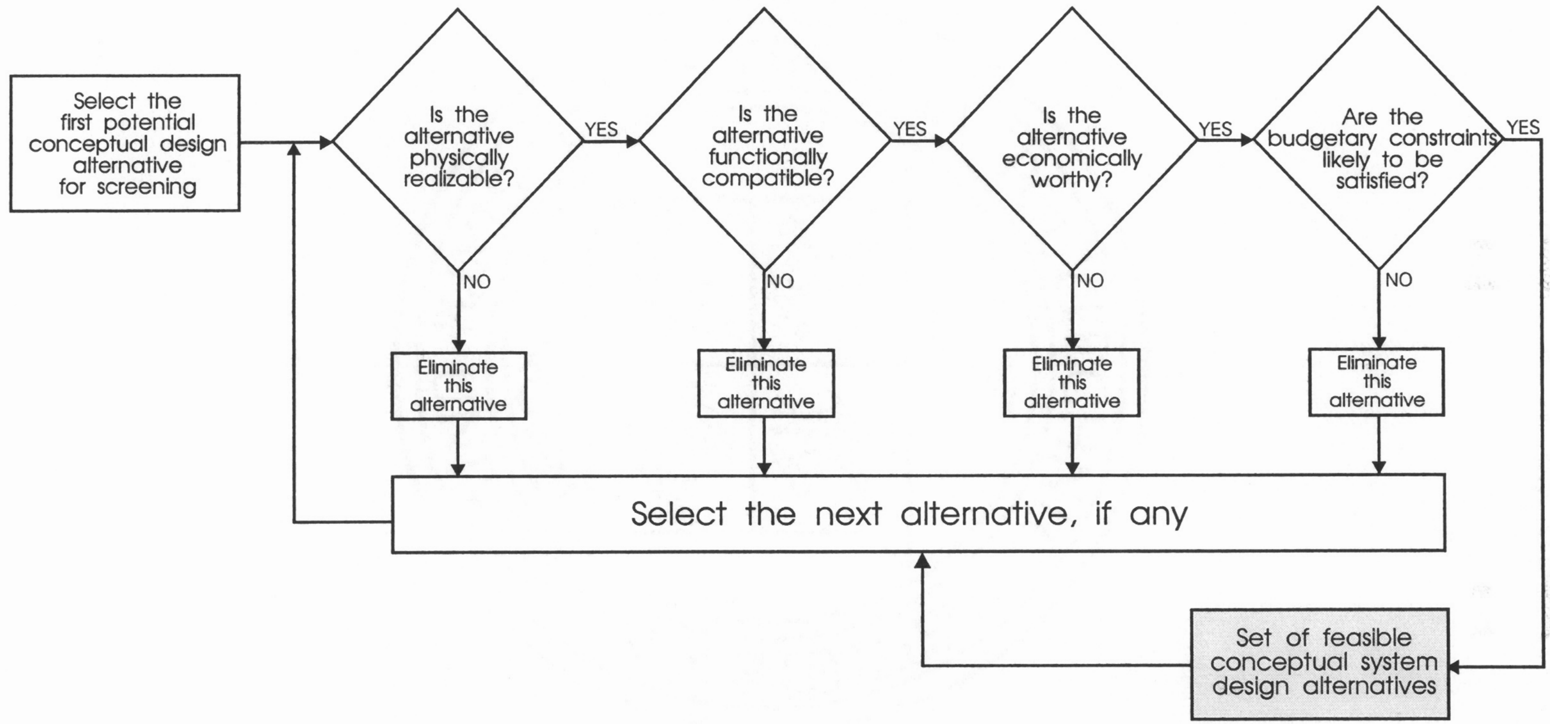


Figure 2.6. Analysis and screening of conceptual system design solutions.

2.1.4. Evaluation of Conceptual Design Alternatives

Feasible conceptual solutions are subjected to a more rigorous process of evaluation in order to select the most desirable concept(s) for further development. While this discussion of the conceptual design process addressed the constituent activities (synthesis, analysis, and evaluation) in a sequential manner, continuous feedback and iteration are an integral part of the overall process. Hopefully this iteration will converge to the most desired concept through a process of increasing resolution.

As discussed in Chapter 1, most research efforts in design evaluation have concentrated on the later stages of system development. Pugh first introduced formality to evaluation during the conceptual system design phase by proposing a concept generation and evaluation methodology [Pugh, 1990]. However, evaluation methods during this phase rely almost entirely on the development of matrices containing numeric criteria relative weights and criteria ratings. An example conceptual design evaluation matrix is illustrated in Figure 2.7. A simplistic weighted sum is often utilized to represent the desirability of various conceptual design solutions.

Stauffer, et. al., have been conducting research in the domain of design evaluation matrix development [Stauffer and Diteman, 1991; Diteman and Stauffer, 1993]. Their current research is directed at comparing the absolute rating method (ARM) and the relative comparison method (RCM) in terms of reliability, sensitivity, and validity.

ARM involves the consideration of every conceptual design alternative in an individual manner, independent of all the other alternatives. Every criterion is rated on a scale of 1 through 7 reflecting the extent to which the alternative is able to satisfy applicable requirements. With the RCM, the designer/analyst considers all conceptual design alternatives simultaneously and ranks them relative to each member of the criteria set. Research to date indicates that the ARM is a more consistent and reliable decision aid, while RCM was more

	Conceptual System Design Alternatives							
Criteria ⇓	✌ 1	👌 2	👍 3	👎 4	☜ 5	☞ 6	☝ 7	☟ 8
A	+	-	+	-	+	-	D	-
B	+	S	+	S	-	-		+
C	-	+	-	-	S	S	A	+
D	-	+	+	-	S	+		S
E	+	-	+	-	S	+	T	S
F	-	-	S	+	+	-		+
$\sum +$	3	2	4	1	2	2	U	3
$\sum -$	3	3	1	4	1	3		1
$\sum S$	0	1	1	1	3	1	M	

Figure 2.7. Conceptual design evaluation matrix (Adapted from [Pugh, 1990]).

sensitive. However, both the RCM and ARM techniques, failed to identify the "best" conceptual system design alternative development [Stauffer and Diteman, 1991; Diteman and Stauffer, 1993].

Representation of knowledge and uncertainty in the form of "crisp" numeric relative weights and performance levels is often too simplistic, forces a certain degree of precision on the part of analysts and decision makers, and may or may not represent reality in a sufficient manner. This is because system design evaluation is characterized by parameters and variables which are often very subjective and qualitative in nature. The argument is even more valid for the nascent stages of system design, when high levels of uncertain and imprecise knowledge is the norm. Accordingly, the reduction of parameter performance and relative weights to deterministic numeric values may reflect an oversimplification of the problem scenario.

The above discussion notwithstanding, in order for the evaluation process to proceed effectively, a set of relevant, applicable, and consistent criteria must be identified initially. Further, to ensure consistency with the functional need, this set of criteria must be based upon results obtained from properly utilized design practices such as QFD and Input-Output matrices.

Given their relevance to this research effort, the following sections briefly discuss two methodologies pertinent to the development of a robust conceptual design evaluation methodology.

2.1.5. Pugh's Concept Generation and Evaluation Methodology

Pugh proposed a methodology for the synthesis and selection of conceptual system designs in the early 1980s [Pugh, 1983, 1983a, 1983b, 1990; Hollins and Pugh, 1990]. The approach involves the development of a design evaluation matrix like the one illustrated in Figure 2.7. After the initial set of conceptual solutions has been identified, they are subjected to a process of "*controlled convergence*". According to Pugh "*a major advantage of controlled convergence over other matrix selection methods is that it allows alternative convergent (analysis and evaluation) and divergent (synthesis) thinking to occur, since as the reasoning proceeds and a reduction in the number of concepts comes about for rational reasons, new concepts are generated* " [Pugh, 1990]. Once again, the overall process involves the three activities pertaining to synthesis, analysis, and evaluation conducted in an iterative manner, evolving with increasing resolution. This is depicted in Figure 2.8.

After defining the evaluation criteria set, based on the need analysis and requirements definition phase, each potential conceptual solution is defined and reduced to a consistent level of detail. Consistency (in the extent of detail) in defining alternatives is important to avoid any biased and/or premature decisions. Thereafter, the evaluation matrix is populated with data reflecting the performance of each concept/criterion (with reference to applicable requirements) as was illustrated in Figure 2.7. Pugh proposed the use of three levels, "+" to denote performance which is better than required, "-" to denote

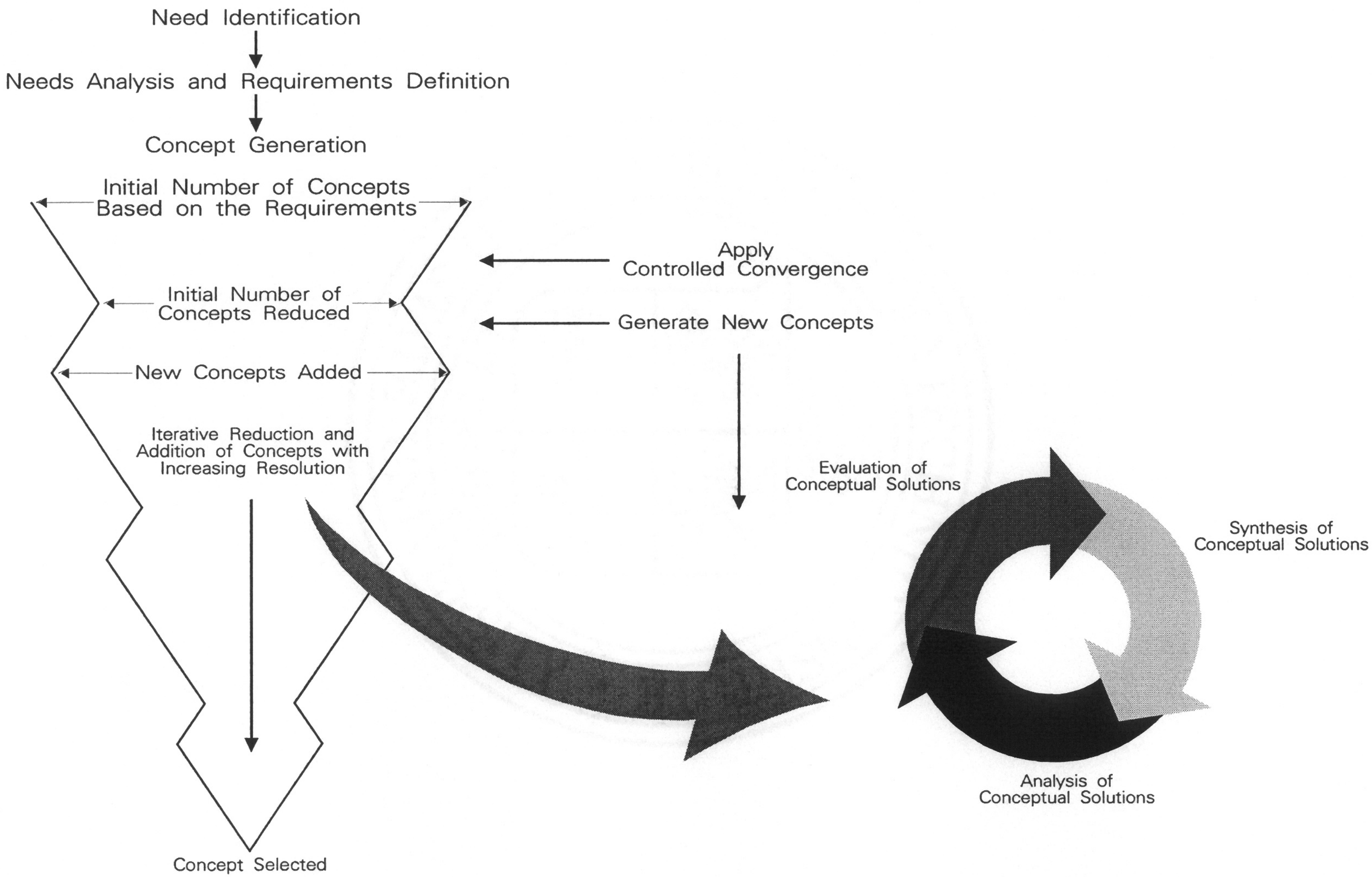


Figure 2.8. Pugh's concept generation and evaluation methodology [Pugh, 1990].

performance which is lower than required, and "S" to denote performance on par with the requirement.

This simple and subjective evaluation leads to the identification of the strongest likely conceptual solutions. At this stage it is recommended that weak points of every good conceptual solution be further studied with the possible objective of compensating for, or removing, the weaknesses and undesirable features. In addition, the very weak concepts are studied for modifications and changes which can strengthen them. This process is likely to result in the generation of additional, yet modified, concepts.

The above process of controlled convergence, constituting concept evaluation, concept generation, subsequent evaluation, and so on, is repeated until the strongest concept becomes obvious. This concept is then further refined and developed. A team approach to the analysis and evaluation of concepts is often utilized to ensure completeness and effectiveness of the methodology.

2.1.6. Fabrycky's Design Dependent Parameter Approach

The design dependent parameter approach proposed by Fabrycky was discussed in Chapter 1. It may be embedded within a computer-based concurrent engineering design morphology as was shown in Figure 1.3. The iterative activities pertaining to synthesis, analysis, and evaluation are explicit in this morphology.

The primary characteristic of the design dependent parameter approach is the specific delineation of design dependent parameters. These obvious parameters directly impact system design desirability and are under the control of the design team. Others, the often ignored design externalities, are represented by design independent parameters. They are not under control of the designer.

According to Fabrycky, the delineation of design dependent and design independent parameters "*provides the basis for a clarification of the true difference between alternatives (a design-based choice) and optimization (a search-based choice)*" [Fabrycky, 1994, 1992]. Further, incorporation of design dependent and design independent parameters into the evaluation process facilitates enhanced concurrency during the system design and development process. This occurs by mathematically linking the acquisition and utilization phases of the system life cycle in the design evaluation function of Equation 1.2.

2.2. EVALUATION AND OPTIMIZATION IN CONCEPTUAL SYSTEM DESIGN

Evaluation and optimization are two terms commonly used in the process of system design. Unfortunately, the two terms are often used either interchangeably or to articulate seemingly inseparable activities.

As discussed in Chapter 1, evaluation, along with synthesis and analysis, constitute the three categories or "types" of activities during system design and development. Evaluation, in particular, can be described as an act of identifying the "best" or "preferred" approach. Webster's New Collegiate Dictionary defines evaluation as an activity to "*determine the significance by careful appraisal and study* " [Webster's, 1988]. This act of "significant appraisal" and of selecting the best (very often the "relative best") alternative may or may not involve utilization of classical optimization techniques. In the context of this discussion, optimization may be defined as "*an act, process, or methodology of making something as fully perfect, functional, or effective as possible*" [Webster's, 1988].

Although the field of classical optimization is very well developed, most techniques require (as a prerequisite) the ability to model the system or scenario with a certain degree of precision. Assumptions are often made to "force" such precision, and to facilitate the application of a selected technique. While modeling (by definition) is an attempt to describe and work with an abstraction of reality, this "forced precision" (through numerous simplifying assumptions) often results in greater separation between reality and its mathematical representation.

Many mathematical optimization techniques have been developed and effectively applied to the operational stage of the development process, but their applicability to system design in general, and to design evaluation in particular, is limited. This is due in part to the qualitative nature of many design goals, requirements, and criteria. Moreover, tradeoff studies and sensitivity analyses are often more important to selection of the "best" alternative in system design evaluation than the optimal solution itself.

The inability to describe the scenario in precise terms is most pronounced during the conceptual system design phase. According to Pugh, optimization "*represents tangling with a set of visible tangibles, decisions can be made on the basis of mathematical techniques which give the user a feeling of confidence, safety and rightness which is comforting*" [Pugh, 1983]. However, the conceptual system design phase "*is an area of almost complete intangibles which, by definition, since the situation is intangible and not fully understood, cannot be meaningfully or usefully addressed (yet) by the application of mathematical optimization techniques*" [Pugh, 1983].

Ostrofsky, differentiating between evaluation and optimization, has coined the terms *optimum* and *optimal* [Ostrofsky, 1977]. An optimum alternative is the theoretical best, while the optimal alternative is the "relative best" with respect to the alternatives identified or synthesized, the criteria delineated, and the extent of information available. Very often in system design, the concept selected reflects the best possible combination of compromises, subjectively determined.

2.3. DOMAIN INDEPENDENCE DURING CONCEPTUAL SYSTEM DESIGN

During the conceptual stage of system design, focus is on the need, and the resulting requirements, functions, and functionality. Issues relative to manifestations of functions as hardware, software, firmware, or humanware are addressed later, generally during preliminary system design.

Activities which constitute the conceptual design phase along with applicable methods and techniques (as illustrated in Figure 2.1) are discipline independent and not focused on any particular application. While prior experience and association does have a bearing on definition of requirements, and the synthesis and analysis of conceptual solutions, the process and methods remain the same. The example developed in later chapters of this dissertation serves only to illustrate potential application of the conceptual system design methodology developed herein. It does not suggest (nor imply) application of the evaluation methodology in any one particular domain.

2.4. STRATEGIC IMPORTANCE OF CONCEPTUAL SYSTEM DESIGN

The significance of design decisions during conceptual and preliminary phases of the system engineering process has been emphasized and documented in the literature [Fabrycky and Blanchard, 1991; Osborn, 1991; Nickelson and Belson, 1991]. Definition of system-level requirements and commitment to a design concept is of strategic importance and impacts not only the preliminary and detail design phases but also the downstream activities pertaining to manufacturing, distribution, deployment, installation, operations, sustaining system maintenance and support, and ultimately system phase-out and retirement.

Analysis and evaluation activities during conceptual design focus on a finite (and generally small) number of potential design concepts, as opposed to the detail design phase where designers generate numerous design iterations requiring quick feedback. Careful consideration (during conceptual design) must be given to customer requirements, design requirements, and associated predictions and estimations before commitment is made to a design concept.

This is particularly true for design activities resulting in the development of large, complex, and distributed systems with dynamic concepts [Hollins and Pugh, 1990].

Given the scarcity and nature (vague and imprecise) of information during conceptual design, the methodology developed herein is very elaborate. As discussed earlier, the strategic importance of committing to a system design concept justifies such an elaborate methodology. An objective of the conceptual design evaluation methodology is to handle and manipulate this information while preserving its characteristics and content. Further, mechanisms are developed to provide insight and facilitate informed design related decisions.

CHAPTER 3

CONCEPTUAL SYSTEM DESIGN EVALUATION: CONSIDERING THE UNCERTAINTY

Development of a design evaluation methodology (independent of the system design phase) is, and must be, influenced by issues pertaining to (a) the extent of uncertainty to be addressed, (b) the source and nature of this uncertainty, and (c) the explicit involvement of uncertainty in the design decision making process. Accordingly, the focus of this chapter is on the uncertainty (its extent and nature) that designers and analysts must contend with during the conceptual system design phase.

Fuzzy set theory concepts, best suited to address design uncertainty, are introduced. These concepts will be extended (in later chapters) and synthesized into a coherent design evaluation methodology. This chapter concludes with a brief discussion on the relative merits of applying concepts from probability and fuzzy set theories to system design analysis and evaluation.

3.1. UNCERTAINTY DURING THE CONCEPTUAL SYSTEM DESIGN PHASE

Design uncertainty is constantly changing in character. It needs to be considered and addressed using different analytical techniques, depending upon the state of design evolution.

Morgan and Henrion have identified various sources of uncertainty in an attempt to differentiate between different types [1990]. These are defined as: (a) *statistical variation*, which reflects the random error in the measurement of quantities, (b) *systematic error and subjective judgment*, which is attributable to factors such as inaccurate assumptions, bias and prejudices, and imprecise calibrations, (c) *linguistic imprecision*, which is a result of imprecision in human articulation, (d) *variability*, which is as a result of an element or quantity changing over time, (e) *inherent variability*, (f) *disagreement*, and (g) *approximation.* These authors further state that "*probability is an appropriate way to express some of these kinds of uncertainty but not others*".

Over and above the classification of general sources of uncertainty, the more specific sources of uncertainty during the conceptual system design phase include: (a) imprecise "capture" of the consumer/customer need, (b) imprecise translation of this need into qualitative and quantitative system-level requirements, (c) imprecise and vague prioritization of system-level requirements and the associated engineering characteristics, (d) uncertain user profile, and (e) uncertain market and technology trends.

Uncertainty during system design and development, in general, and conceptual system design, in particular, has two distinct components, stochastic uncertainty and design imprecision. For instance, consider system reliability. Design imprecision reflects itself through uncertainty relative to the system reliability requirement (*is it precisely 500 hours MTBF? At what level below 500 hours would the design be unacceptable? and so on*) [Verma and Knezevic, 1994]. While this requirement is usually (or should be) translated from market /

user need analysis, benchmarking, and so on, a "crisp" and precise assignment of reliability requirement may not be realistic.

Alternatively, the random or stochastic component of design uncertainty is reflected through the very nature of reliability and its dependence on a host of factors (inherent, environmental, and operational) that are stochastic in nature, such as raw material composition, dimensions and tolerances, assembly, temperature, dust, vibration, stresses, and so on. Wood, Antonsson, and Beck conceptualized the extent and composition of system design uncertainty as shown in Figure 3.1 [Wood, Antonsson, and Beck, 1990].

3.2. EXISTING METHODS FOR DEALING WITH DESIGN UNCERTAINTY

Consideration of design uncertainty is not a new or novel. However, there are different schools of thought on how to best approach and resolve the problem of uncertainty in design. More often than not, classical and deterministic optimization techniques have been applied to solve a wide range of engineering design problems. The rigid formulation requirements imposed by these techniques often force an excessive simplification or modification of actual conditions through assumptions [Pugh, 1983; Azarm, et. al., 1987]. This tends to place the entire analysis and evaluation activity in a highly quantitative vein. Further, while these approaches have a definite purpose and obvious utility during the detailed design, manufacturing / construction, and deployment phases of the system life cycle, their use is largely limited during conceptual and preliminary design phases (given the subjective, imprecise, and stochastic nature of most design parameters and variables).

A review of the relevant literature suggests that most research groups have concentrated their efforts on analysis and evaluation activities during the latter stages of system design and development (refer Section 1.4). Research is ongoing to adapt selected optimization techniques to better address design

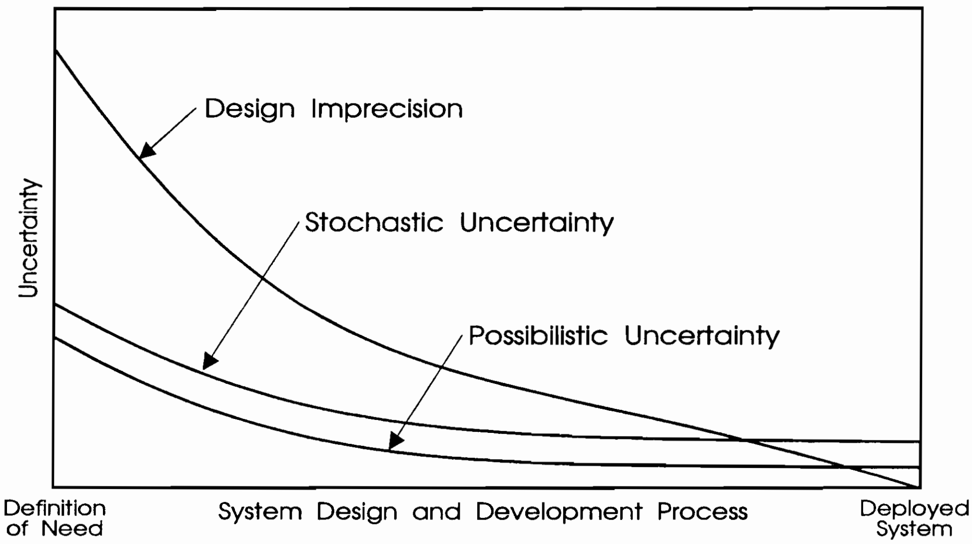


Figure 3.1. Conceptualization of the extent and composition of design uncertainty [Wood, Antonsson, and Beck, 1990].

analysis and evaluation activities [Balachandran and Gero, 1987; Diaz, 1988; Fabrycky, 1991; Papalambros, 1987]. Diaz, in particular, has explored the development of optimization techniques with fuzzy constraints.

Thurston, Carnahan, and Liu have applied multi-attribute utility analysis to the analysis and evaluation of engineering designs during the preliminary system design phase [1991; Thurston, 1991; Thurston, et. al., 1993; Thurston, et. al., 1992]. Assuming preference independence, the multiplicative form of the utility function applied by [Thurston, et. al., 1993] is expressed as:

$$(X) = \frac{1}{K}[[\prod_{i=1}^{n}(Kk_iU_i(x_i)+1)-1]-1] \qquad (3.1)$$

where:

$U(X)$ = Overall alternative utility

x_i = Performance level of attribute i

X = Set of attributes at levels $(x_1, x_2, ..., x_n)$

k_i = Assessed single attribute scaling constant

$U_i(x_i)$ = Assessed single attribute utility function

K = Scaling constant

These authors adopted this approach to measure the overall utility of alternative system design configurations as a function of the performance levels of multiple engineering characteristics. However, after comparing the relative merits of approaches based upon utility theory and fuzzy set theory, Thurston and Carnahan concluded that fuzzy set theory may be better suited to address conceptual design evaluation [Thurston and Carnahan, 1992].

Interval analysis has also been utilized to address the imprecision in design parameters and variables which are represented by a range of potential values. The output is similarly represented by a range of values. The correlation of input values with outputs, except at the extremes of their applicable ranges, is not easily possible. This absence of an explicit and obvious correlation between inputs and outputs is also true of probabilistic approaches. This correlation is significant if an improvement to the overall "goodness" of a design alternative is to be accomplished by modifying pertinent parameters and variables through system redesign or design improvement.

Numerous references illustrate the use of probability theory by "force fitting" probabilistic concepts to address design imprecision and subjectivity [Ostrofsky, 1977; Arora, 1989]. At the same time, references exist which make a case for the use of fuzzy concepts alone to address design uncertainty. Both approaches result in a certain amount of information "loss." It can be argued that information available to the designers and analysts during the conceptual system design phase is a scarce and valuable resource and best used "as is" through the complementary use of probabilistic and fuzzy approaches, and minimally adapted or modified for maximum effectiveness [Knosala and Pedrycz, 1987; Verma and Knezevic, 1994; Wood, et. al., 1989].

3.3. PERTINENT CONCEPTS FROM FUZZY SET THEORY

Zadeh published the seminal paper on fuzzy sets in 1965 [Zadeh, 1965]. It evolved out of his work on the analysis of complex humanistic systems and problems where uncertainty derives from a lack of criteria for non-ambiguous class membership, rather than the presence of stochastic variables.[1] This theory is attractive since it is based on the intuitive idea of a graded membership and linguistic imprecision. Fuzziness is not an obvious concept. It requires further explanation and discussion.

Webster's dictionary defines fuzzy as something "*that lacks clarity or definition*" [Webster's, 1988]. "*Fuzziness*" is what Black calls "*vagueness*" and he distinguishes it from "*generality*" and "*ambiguity*" [Black, 1937]. In the context of this discussion, generalizing refers to the application of a symbol to a multiplicity of objects in the field of reference, while ambiguity reflects the association of a finite number of alternative meanings having the same phonetic form. On the other hand, fuzziness of a symbol is defined as the lack of well defined boundaries to the set of objects to which this symbol applies.

Let X be the field of reference encompassing a definite range of objects (i.e., the relevant universe). Consider a subset $\tilde{A}$ where the transition between membership and non-membership of an element is gradual rather than abrupt. In other words, this fuzzy subset of the relevant universal set has no well defined boundaries. For example, assume $\tilde{A}$ to be the set of tall children in a classroom X. There will obviously exist children in the classroom who are definite members of this set, and those who are definitely not. But then there also exist children who are the so-called "*borderline*" cases.

---

[1] Humanistic systems and/or problems can be defined as those whose nature and behavior is strongly influenced by human judgment, perception or emotions. The problem of analyzing and evaluating conceptual system engineering design alternatives solutions fits this description.

Traditionally, the grade of membership *1* is assigned to elements that completely belong to $\tilde{A}$ (in the example above, that would be the children who are definitely tall); conversely, elements that absolutely do not belong to $\tilde{A}$ are assigned a membership value *0*. Quite naturally, the grades of membership for the "*borderline*" cases fall in the range between *0* and *1*. Further, the more an element or object x belongs to $\tilde{A}$, the closer to *1* is its grade of membership, $\mu_{\tilde{A}}(x)$. Use of a numerical scale, such as the interval [*0, 1*], allows a convenient representation of gradation in membership. Precise membership values do not exist by themselves, they are tendency indices that are subjectively assigned by an individual or a group. The grades of membership reflect an "*ordering*" of the objects in the universe, induced by the predicate associated with $\tilde{A}$; this ordering when it exists, is often more important than the membership values themselves.

Zadeh proposed the concept of linguistic variables in 1973 and the concept of an extension principle in 1975 [Zadeh, 1973, 1975]. These concepts are invoked and extended in developing a methodology for the evaluation of conceptual system designs herein. Accordingly, each of these concepts is reviewed separately in the following sections. An introduction to some of the more common operations on fuzzy subsets is outlined in the Appendix.

3.3.1. The Concept of a Linguistic Variable

Linguistic variables have words or sentences in natural language as their values, rather than numbers. The totality of values that a linguistic variable can assume constitutes its *term-set*. A *term-set* could conceptually have an infinite number of elements. For example, the term set of the linguistic variable *Reliability* might read as follows:

T(*Reliability*) = *reliable* + *not reliable* + *very reliable* + *not very reliable* + *very very reliable* + ... + *unreliable* + *not unreliable* + *very unreliable* + *not very unreliable* + ..., In the case of the linguistic variable *Reliability*, the numerical variable *reliability* whose values could be real numbers in the range between 0.0 and 1.0 constitutes the base variable for *Reliability*. In terms of this variable, a linguistic value such as *reliable* or *unreliable* may be interpreted as a label for a fuzzy restriction on values of the base variable. This fuzzy restriction constitutes the meaning of *reliable* or *unreliable*.

A fuzzy restriction on values of the base variable is characterized by a *compatibility function* (similar to a membership or characteristic function) which associates a number in the interval [0,1] with each value of the base variable. This in turn represents compatibility with the fuzzy restriction. For example, the compatibility of numerical reliabilities 0.98, 0.87, and 0.62 with the fuzzy restriction labeled *reliable* might be 1.0, 0.75, 0.15, respectively. The meaning of *reliable* could then be represented by a graph as shown in Figure 3.2. This graph is a plot of the compatibility function of *reliable* with respect to the base variable *reliability*.

It is important to understand the distinction between the notions of compatibility and probability. As an illustration, the statement that the compatibility of 0.87 with *reliable* is 0.75, has no relation to the probability of the reliability value being equal to 0.87. The correct interpretation of the compatibility value of 0.75 is that it is merely a subjective indication of the extent to which the reliability value 0.87 fits one's conception of the label *reliable*.

Zadeh also introduced the concept of *linguistic hedges* and connectives [Zadeh, 1973]. Hedges and connectives are linguistic operators which modify the meaning of the operand in a specified fashion. Thus, if the meaning of *reliable* is defined by the compatibility function in Figure 3.2, then the meaning of *very reliable* could be obtained by squaring the compatibility function of *reliable*, while that of *not reliable* would be given by subtracting the compatibility function of *reliable* from unity. These modifications are shown in Figure 3.3.

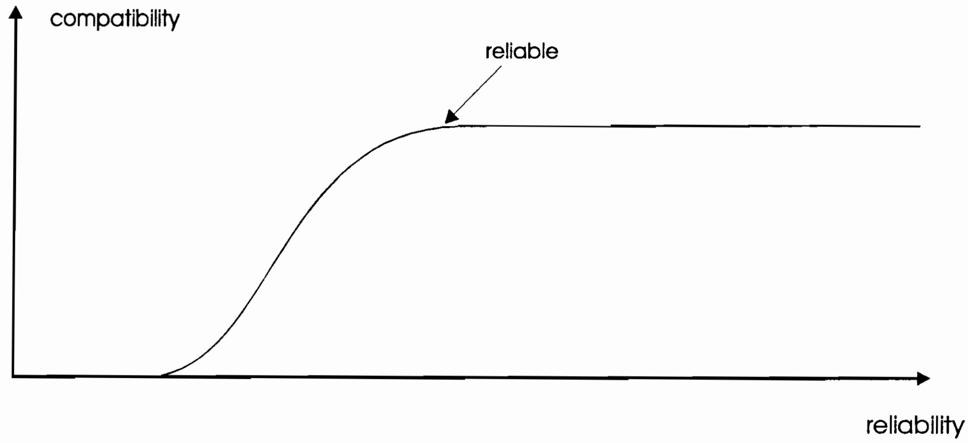


Figure 3.2 The compatibility function of reliable.

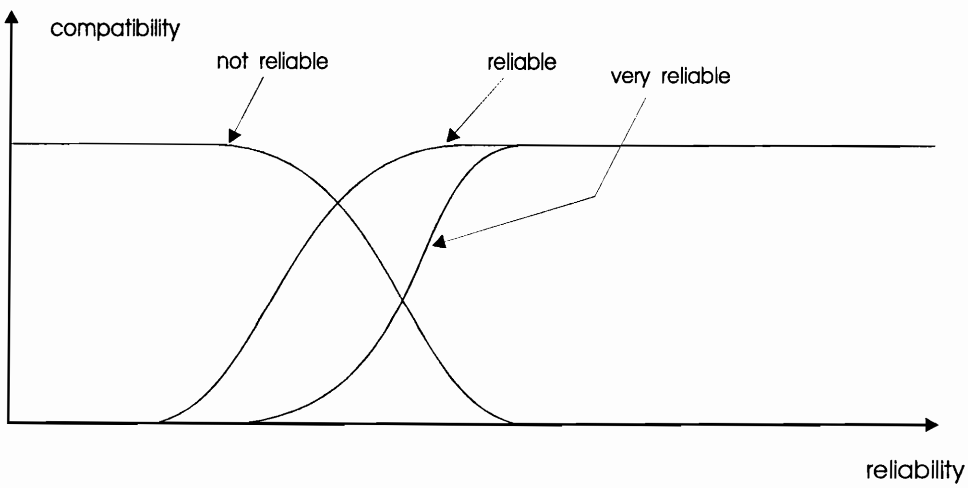


Figure 3.3 The compatibility functions of reliable, very reliable, and not reliable.

The concept of a linguistic variable includes within itself the concept of a fuzzy variable. That is, the values of a linguistic variable (elements of its *term-set*) are themselves fuzzy variables. Therefore, the linguistic variable *Reliability* can take on values such as *reliable*, *unreliable*, etc., which are all fuzzy variables. In this context a fuzzy variable, such as reliable, can be completely defined by a triplet given as

$$[\tilde{A},X,R(\tilde{A};x_i)] \tag{3.2}$$

where $\tilde{A}$ is the fuzzy variable name such as *reliable*, X is the universe of discourse such as 0.0 through 1.0, and $R(\tilde{A};x_i)$ is a fuzzy subset of X representing the fuzzy restriction on values of x_i imposed by fuzzy variable $\tilde{A}$.

The objective of this section was to provide an introduction to the concept of fuzzy and linguistic variables. This baseline will be further extended in later chapters and included as an integral component of the conceptual system design evaluation methodology. It will be invoked to allow flexibility in the assignment of imprecise requirements, in the estimation of imprecise and subjective performance levels, and in the assignment of relative priorities.

3.3.2. The Extension Principle

The extension principle allows generalization of crisp mathematical concepts to the fuzzy framework. It provides a means for any function f which maps points $x_1, x_2, \ldots, x_n$ in the crisp set X to the crisp set Y to be generalized such that it maps fuzzy subsets of X to Y. Formally, given a function f mapping points in set X to points in set Y and any fuzzy set $\tilde{A} \in \tilde{P}(X)$, where:

$$\tilde{A} = \mu_1 / x_1 + \mu_2 / x_2 + \cdots + \mu_n / x_n \tag{3.3}$$

and $\tilde{P}(X)$ is the power set of the universe of discourse, or the set of all possible fuzzy subsets of X. The extension principle states that:

$$\begin{aligned} f(\tilde{A}) &= f[(\mu_1 / x_1) + (\mu_2 / x_2) + \cdots + (\mu_3 / x_3)] \\ &= [\mu_1 / f(x_1)] + [\mu_2 / f(x_2)] + \cdots + [\mu_n / f(x_n)] \end{aligned} \tag{3.4}$$

To illustrate the principle, consider X (*universe*) to be the set of integers. Then a fuzzy subset, *small*, of X may be given as:

small = 1/1 + 0.9/2 + 0.8/3 + 0.7/4 + 0.6/5 + 0.5/6 + 0.4/7 + 0.3/8 + 0.2/9 + 0.1/10

Further, let the function f be a cubing operation or $f(small) = (small)^3$, then according to the extension principle:

$$small^3 = 1/1 + 0.9/8 + 0.8/27 + 0.7/64 + 0.6/125 + 0.5/216 + 0.4/343 + 0.3/512 + 0.2/729 + 0.1/1000$$

If the fuzzy set, $\tilde{A}$, is not discrete but continuous, and of the form

$$\tilde{A} = \int_X \mu_{\tilde{A}}(x_i) / x_i \tag{3.5}$$

then the extension principle may be applied as

$$f(\tilde{A}) = f\left(\int_X \mu_{\tilde{A}}(x_i) / x_i\right) = \int_Y \mu_{\tilde{A}}(x_i) / f(x_i) \tag{3.6}$$

As an extension, when dealing with fuzzy relations consider a fuzzy relation $\tilde{A}$ in ($X_1 \times X_2 \times \cdots X_n$) and a function f which maps this n-ary relation to a space Y. The fuzzy relation $\tilde{A}$ will take the form

$$\tilde{A} = \left(\int_{X_1 x X_2 \cdots X_n} \mu_{\tilde{A}}(x_1, x_2, \cdots, x_n) / (x_1, x_2, \cdots, x_n)\right) \tag{3.7}$$

Therefore, the extension principle may be applied as

$$\begin{aligned} f(\tilde{A}) &= f\left(\int_{X_1 x X_2 \cdots X_n} \mu_{\tilde{A}}(x_1, x_2, \cdots, x_n) / (x_1, x_2, \cdots, x_n)\right) \\ &= \int_Y \mu_{\tilde{A}}(x_1, x_2, \cdots, x_n) / f(x_1, x_2, \cdots, x_n) \end{aligned} \tag{3.8}$$

To illustrate the above concept consider

$$X_1 = X_2 = 1 + 2 + 3 + \cdots$$

and two fuzzy subsets $\tilde{A}_1$ and $\tilde{A}_2$, given as:

$$\tilde{A}_1 \text{ (almost 4)} = 0.3/3 + 1/4 + 0.4/5$$
$$\tilde{A}_2 \text{ (almost 7)} = 0.4/6 + 1/7 + 0.55/8$$

For a function f such that:

$$f(x_1, x_2) = (x_1)(x_2)$$

Application of the extension principle yields:

$$\begin{aligned} f(\tilde{A}_1, \tilde{A}_2) &= (\tilde{A}_1)(\tilde{A}_2) \\ &= (0.3/3 + 1/4 + 0.4/5)(0.4/6 + 1/7 + 0.55/8) \\ &= (0.3/18 + 0.3/21 + 0.3/24 + 0.4/24 + 1/28 + 0.4/32 + 0.4/30 + \\ &\qquad 0.4/35 + 0.4/40) \\ &= (0.3/18 + 0.3/21 + 0.4/24 + 1/28 + 0.4/30 + 0.4/32 + 0.4/35 \\ &\qquad + 0.4/40) \end{aligned}$$

Therefore, the arithmetic product of the two fuzzy subsets, or fuzzy numbers, yields a fuzzy number given by (0.3/18 + 0.3/21 + 0.4/24 + 1/28 + 0.4/30 + 0.4/32 + 0.4/35 + 0.4/40).

It is important to note that if more than one element of X is mapped by f to the same element $y \in Y$, then the maximum of the membership grades of these elements in the fuzzy set $\tilde{A}$ is chosen as the membership grade for y in $f(\tilde{A})$. If no element $x \in X$ is mapped to y, then the membership grade of y in $f(\tilde{A})$ is zero. Often a function f maps ordered tuples of elements of several different set X_1, X_2, ..., X_n such that $f(x_1, x_2, ..., x_n) = y$, $y \in Y$. In this case, for any arbitrary group of fuzzy sets $\tilde{A}_1$, $\tilde{A}_2$, ..., $\tilde{A}_n$ defined on X_1, X_2, ..., X_n, respectively, the membership grade of element y in $f(\tilde{A}_1, \tilde{A}_2, ..., \tilde{A}_n)$ is equal to the minimum of the membership grades of x_1, x_2, ..., x_n in $\tilde{A}_1$, $\tilde{A}_2$, ..., $\tilde{A}_n$, respectively.

The extension principle provides a means for the rigorous manipulation of fuzzy subsets in general, and fuzzy numbers in particular. It will be extended and applied in later chapters.

3.3.3. The Concept of a Fuzzy Number

The concept of a fuzzy number can be derived from the notion of a fuzzy variable. Fuzzy numbers are fuzzy subsets which can be defined on any universe of discourse which is completely or totally ordered such as the set of real numbers, the set of natural numbers, or the set of integers. Further, the fuzzy subset representing a fuzzy number must be convex and normal.

To further clarify, a fuzzy subset is termed convex if, and only if:

$$A_\alpha = \{ x | \mu_{\tilde{A}}(x) \geq \alpha \}, \quad \textit{and} \ \alpha \in [0,1] \tag{3.9}$$

where, A is an ordinary subset, A_α is an ordinary subset of level α , and $\tilde{A}$ is a fuzzy subset of R (the universal set of real numbers). This is also explained in Figure 3.4a which depicts a convex and non-normal fuzzy subset of the set of real numbers. Extending this discussion, a convex fuzzy subset is normal if, and only if, there is at least one element, x, for which the characteristic function has a value equal to *1*. This is shown in Figure 3.4b and can be formally expressed as:

$$\vee \mu_{\tilde{A}}(x) = 1, \ \forall x \in R \ (\textit{set of real numbers}) \tag{3.10}$$

where, $\mu_{\tilde{A}}(x) = [0,1]$.

The delineation of fuzzy numbers from fuzzy variables is significant and will be extended later. Basic properties of fuzzy numbers and associated common operations are outlined in the Appendix. For a more detailed presentation of fuzzy numbers refer to [Gupta and Kaufmann, 1991].

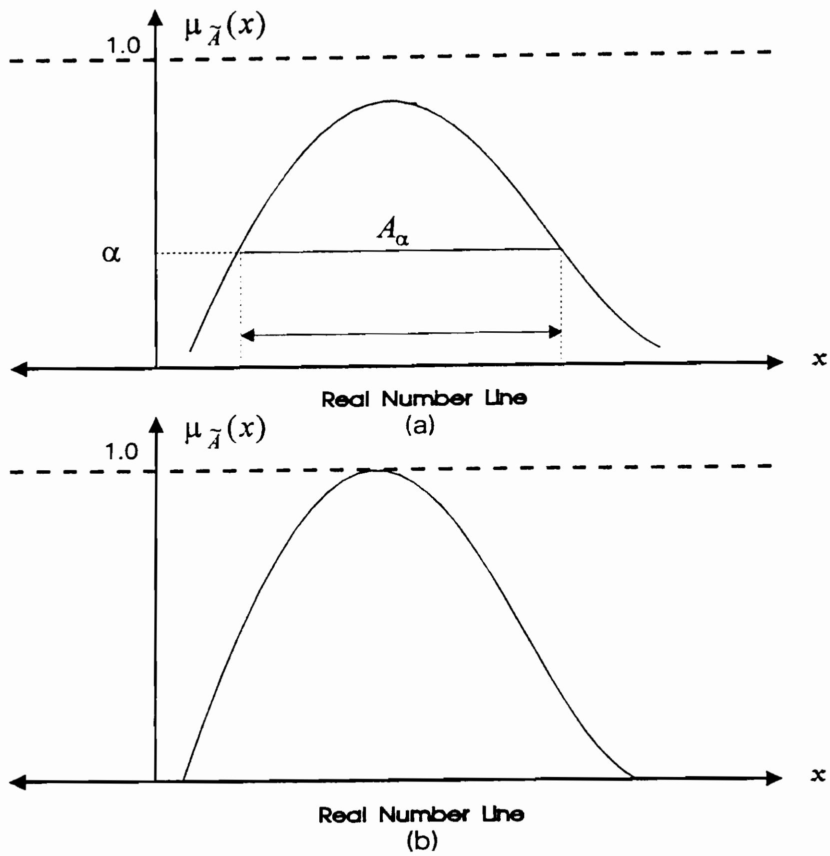


Figure 3.4. Convex, normal and non-normal fuzzy subsets.

3.4. APPLICATION OF PROBABILITY AND FUZZY SET THEORIES

Numerous researchers have compared the application of probability and fuzzy logic to multi-attribute decision problems in general, and various aspects of system design analysis and evaluation in particular [Baas and Kwakernaak, 1977; Whalen and Bronn, 1982; Wood, Antonsson, and Beck, 1990]. Baas and Kwakernaak [1977] carefully constructed a multi-attribute decision problem in order to gauge the relative merits of the two approaches. In their study, a fuzzy logic based evaluation procedure was compared to a probabilistic approach promulgated by Kahne [1975]. Kahne addressed the problem by assuming all input parameters and relative weights to be random variables, and assigning applicable probability distributions to each. Thereafter, a Monte Carlo approach was adopted and the alternative which ranked first most frequently was picked as the preferred alternative. On the other hand, Baas and Kwakernaak assumed input parameters and relative weights to be fuzzy variables with experimentally derived membership functions [1977].

At the conclusion of this study, they observed a certain degree of bias in Kahne's approach which, while not very substantial, was eliminated in the fuzzy logic based approach through the generation of membership profiles. Further, the difference in the "goodness" of alternatives was a lot more pronounced when using Kahne's approach. This did not seem to very well represent the fact that difference between input parameter values from one alternative to the next was not significant. The biggest difference, however, was in the extent of computational resources required. The Monte Carlo approach required significantly more computation time, and further, this increased dramatically with an increase in the number of input variables. This is also observed by Wood, Antonsson, and Beck in their comparison of the probabilistic and fuzzy logic based approaches to design analysis and evaluation [1990].

The above references also speak to the ease of backward traceability of the analyses in the use of fuzzy logic. This is understandable since the "peak" of the membership profile representing the output parameter in the fuzzy logic based approach corresponds to the "best" values of the input variables, per the extension principle. Further, the range of the output profile subsumes the range of all the input variables and relative weights and as such the tails of the membership profiles are fairly wide. Given this explicit correlation between input and output profiles, it becomes possible to investigate any point on the output profile and "trace back" to the corresponding combination of input values. This backward tracing is not possible in the probabilistic approach. It can be very useful in navigating and iterating through the design space.

Given the basic premise of this research, the two components of design uncertainty (randomness and imprecision) will be addressed distinctly using probability theory and fuzzy logic in a complementary manner. Further, studies such as those referenced earlier in this section, at best, reflect the theoretical soundness of the two approaches. Force-fitting any particular approach is unnecessary when both can be used jointly to address different aspects of the overall uncertainty [Knosala and Pedrycz, 1987; Wood and Antonsson, 1990].

CHAPTER 4

CONCEPTUAL DESIGN EVALUATION METHODOLOGY - PHASE I: GENERATING THE FEASIBLE DESIGN SPACE

The first phase in the conceptual system design evaluation methodology is developed in this chapter. Activities and steps which constitute this phase are shown in Figure 4.1. Whenever possible, examples are utilized to illustrate and clarify constituent steps. Need analysis and requirements definition activities are addressed through the development of an adapted Quality Function Deployment technique called "Fuzzy QFD". This technique serves as a useful mechanism for linking the hierarchy of system-level customer requirements (i.e., the WHATS) with a relevant set of design dependent parameters (i.e., the "HOWS"). The set of design dependent parameters establishes a fuzzy design space. This space, in turn, impacts the feasibility of system-level conceptual solutions.

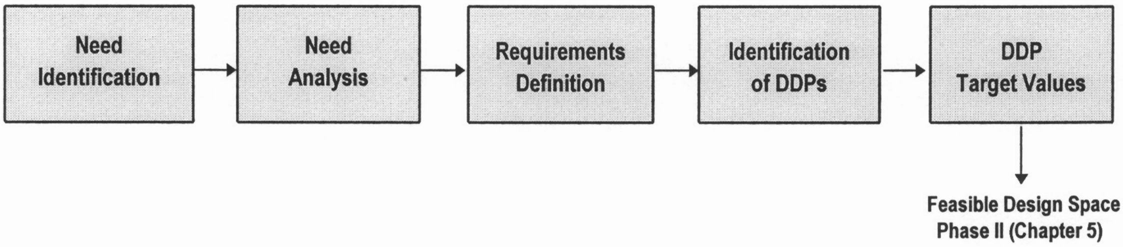


Figure 4.1. Activities comprising Phase I of the evaluation methodology.

Concepts from fuzzy set theory are used to define importance metrics for the requirements as perceived by the ultimate customers/consumers. Also, two indices called the *Improvement Potential and Necessity (IPN) Index* and the *Tolerance of Fuzziness (TOF) Index* have been developed herein to aid and facilitate the delineation of design dependent parameter target values.

4.1. NEED IDENTIFICATION IN FUNCTIONAL TERMS

The conceptual design phase within the overall system engineering process is triggered through the identification of a need or deficiency. Identification of a not-so-obvious need can be of strategic importance to an organization. This need, through prudent and systematic exploitation, can often lead to a more competitive position in the marketplace.

A critical aspect of this step is to define the need in functional terms and resist premature commitment to a configuration or concept.[2] Accordingly, it would be incorrect to identify a need as *"A car is needed for the transportation of four people..."*. This statement not only refers to the WHAT ("*transportation of four people*") but also mentions (prematurely) the HOW ("*car*").

To further illustrate, an example need could be stated as: *An organization needs a system to facilitate an interactive session/meeting between multiple*

2 This is also consistent with Asimow's "*Principle of Least Commitment*" in Engineering Design [1964].

remote parties.[3] While this statement only conveys the basic deficiency in functional terms and not much else, its functional nature is analyzed in greater detail as part of the subsequent need analysis and requirements definition activities.

4.2. NEED ANALYSIS AND REQUIREMENTS DEFINITION

During the need analysis step of the process, the initially identified need or deficiency is examined in an attempt to further specify its nature. It is important to address this specification from a life-cycle perspective. In order to maintain the necessary customer focus, a technique such as Quality Function Deployment is invaluable [Hauser and Clausing, 1988]. However, this technique has been adapted here to incorporate the imprecision and vagueness inherent during the requirements definition phase of the system design process. This adaptation is referred to as "Fuzzy QFD" and involves linking imprecise customer requirements with a relevant set of Design Dependent Parameters, themselves defined as fuzzy variables.

Design Dependent Parameters (DDPs) reflect design requirements. Their consolidation through the use of "Fuzzy QFD" ensures a strong correlation with customer wants and desires. Further, the DDPs identified at this stage also serve as the evaluation criteria for conceptual designs. In this manner, the selected conceptual design should correspond closely to the requirements identified as being important to the ultimate users.

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3 This example will evolve in this chapter and in Chapters 5 and 6, and will be used to illustrate application of the evaluation methodology being developed. The example was constructed over several meetings and brain-storming sessions with Dr. Scott F. Midkiff in the Bradley Department of Electrical Engineering at Virginia Polytechnic Institute and State University. Attempts were made to convey a sense of realism and complexity which may be encountered on an actual project. However, this example is hypothetical and its construction did not involve rigorous interaction with "real" customers having actual requirements and preferences.

4.2.1. Definition of Customer Requirements and Design Dependent Parameters

Consistent with the arguments presented in Chapters 1, 2, and 3, customer requirements are identified in subjective and imprecise terms and then linked with an associated set of fuzzy design dependent parameters. Figure 4.2 gives a generic taxonomy of design dependent parameters which should be addressed to ensure completeness. However, every design and development effort is likely to involve a unique set of design dependent parameters. Design dependent parameters can be classified as in Figure 4.3. Some design dependent parameters have an associated numeric base variable (e.g., speed, weight, space, and so on). Others do not (e.g., user friendliness, aesthetics, and so on) and must be mapped onto a [0,1] interval.

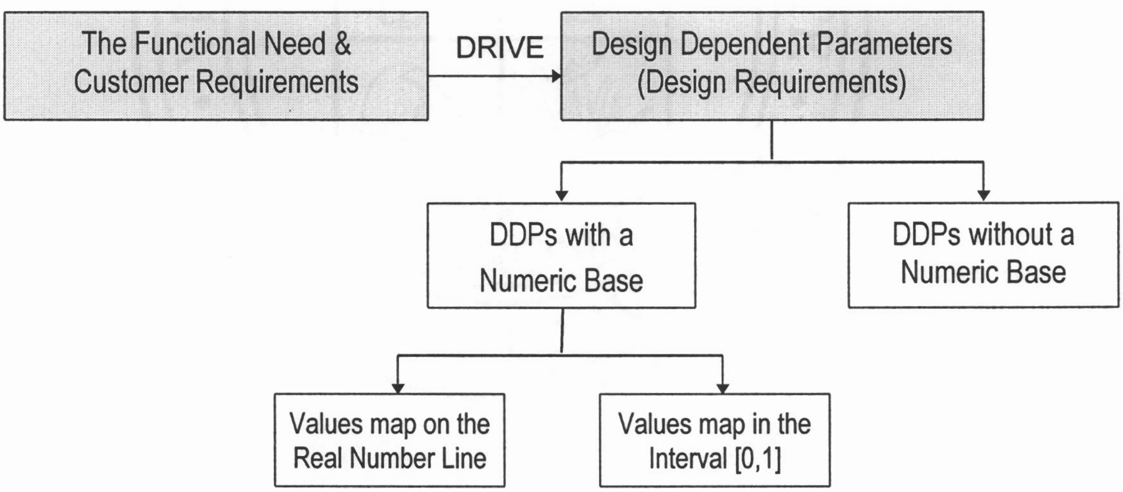


Figure 4.3. Classification of design dependent parameters (design requirements).

Numeric design dependent parameters may be further classified into two groups. The first group of numeric DDPs assume values on the real number line (e.g., weight, size, and so on), while the second group takes its values in

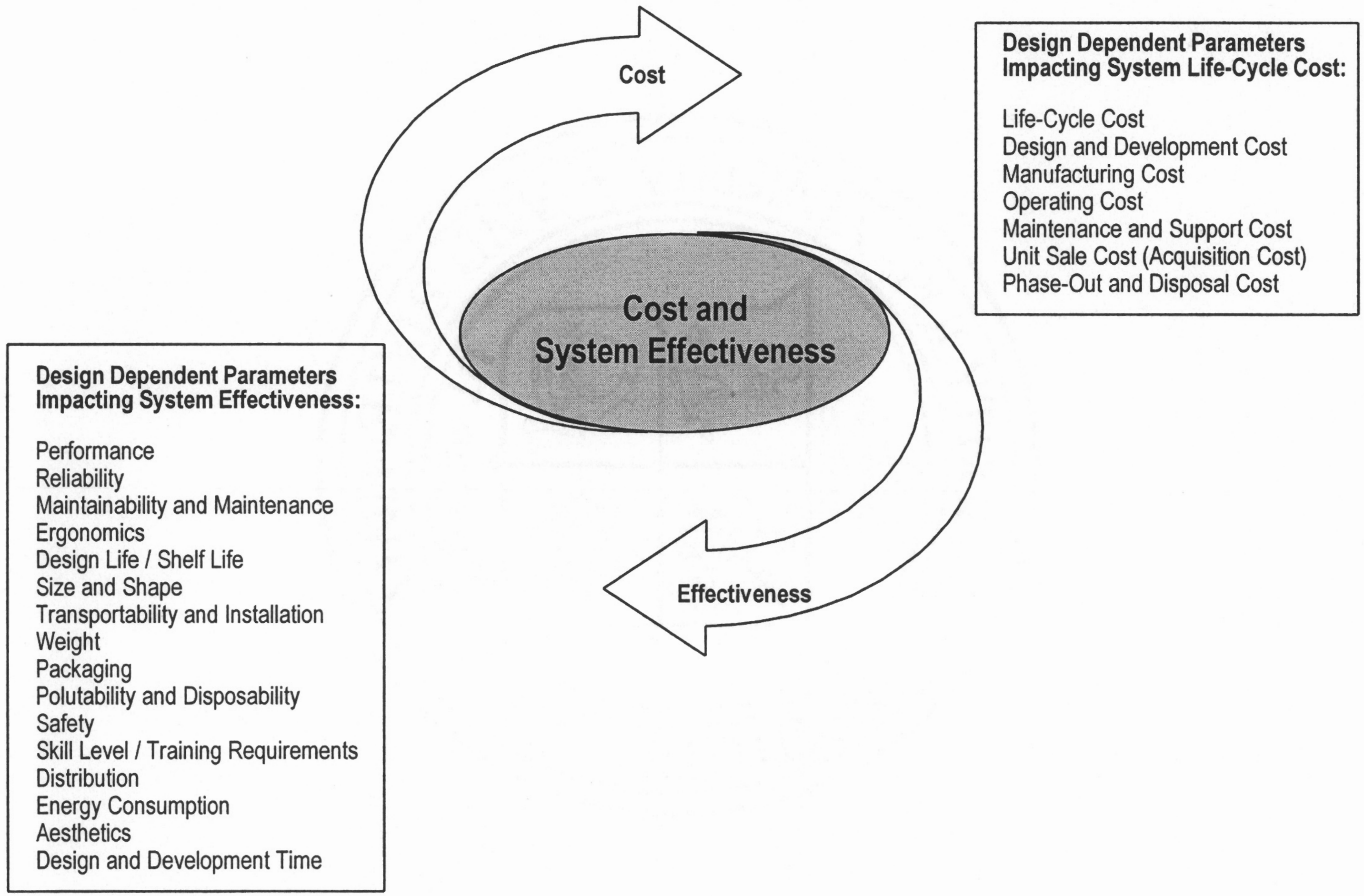


Figure 4.2. A taxonomy of design dependent parameters.

the [0,1] interval (e.g., reliability, and so on). The mechanism for assigning target values to the DDPs, and thereby defining the feasible design space, depends upon their inherent nature (e.g., numeric versus non-numeric and continuous versus discrete). A triangular or trapezoidal shape is assumed for all DDPs. Application of the evaluation methodology is independent of the shape of the DDP profiles (provided that they are all normal and convex). However, this assumption facilitates simplicity in the computations and allows better conveyance of the concepts.

Defining numeric design dependent parameters. DDPs with a numeric base variable are defined through the combined use of a linguistic variable along with one or two numeric constants, as:

Target DDP Value = (linguistic variable) (numeric constants) (4.1)

The designer has the option of using any one of four linguistic variables when assigning target values to the design dependent parameters. These options are:

1. *None* (this is a special case where the DDP is deterministic and crisp in nature)
2. *Approximately*
3. *Greater Than Or Less Than*, and
4. *Between*

Each linguistic option refers to a particular preference profile. The above linguistic options along with the associated graphic profiles are illustrated in Figure 4.4. Note, that each profile in Figure 4.4 represents a family of similar shaped profiles with different slopes for the triangular or trapezoidal shape. Further, some of the linguistic options may represent special cases as presented in Figure 4.5.

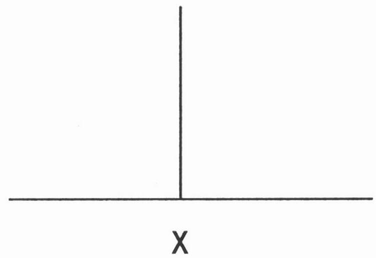
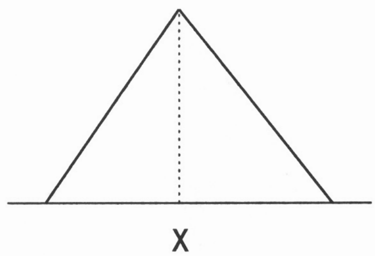
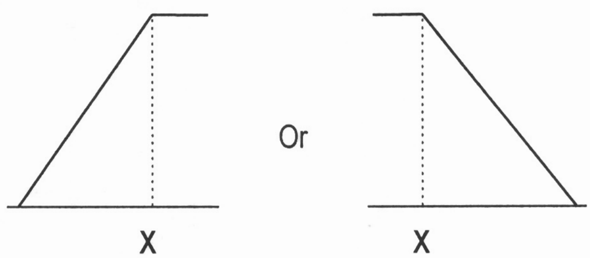
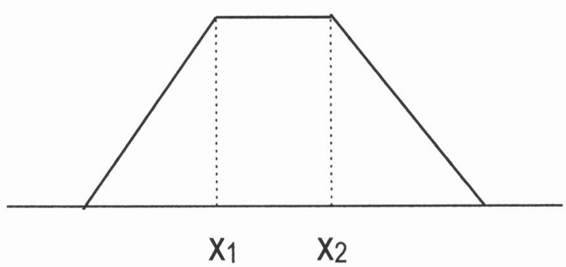
Linguistic Option	Associated Preference Profile
X (Special case of a deterministic and crisp DDP)	
Approximately X	
Greater Than X Or Less Than X	
Between X_1 and X_2	

Figure 4.4. Linguistic options for numeric DDPs along with the associated preference profiles.

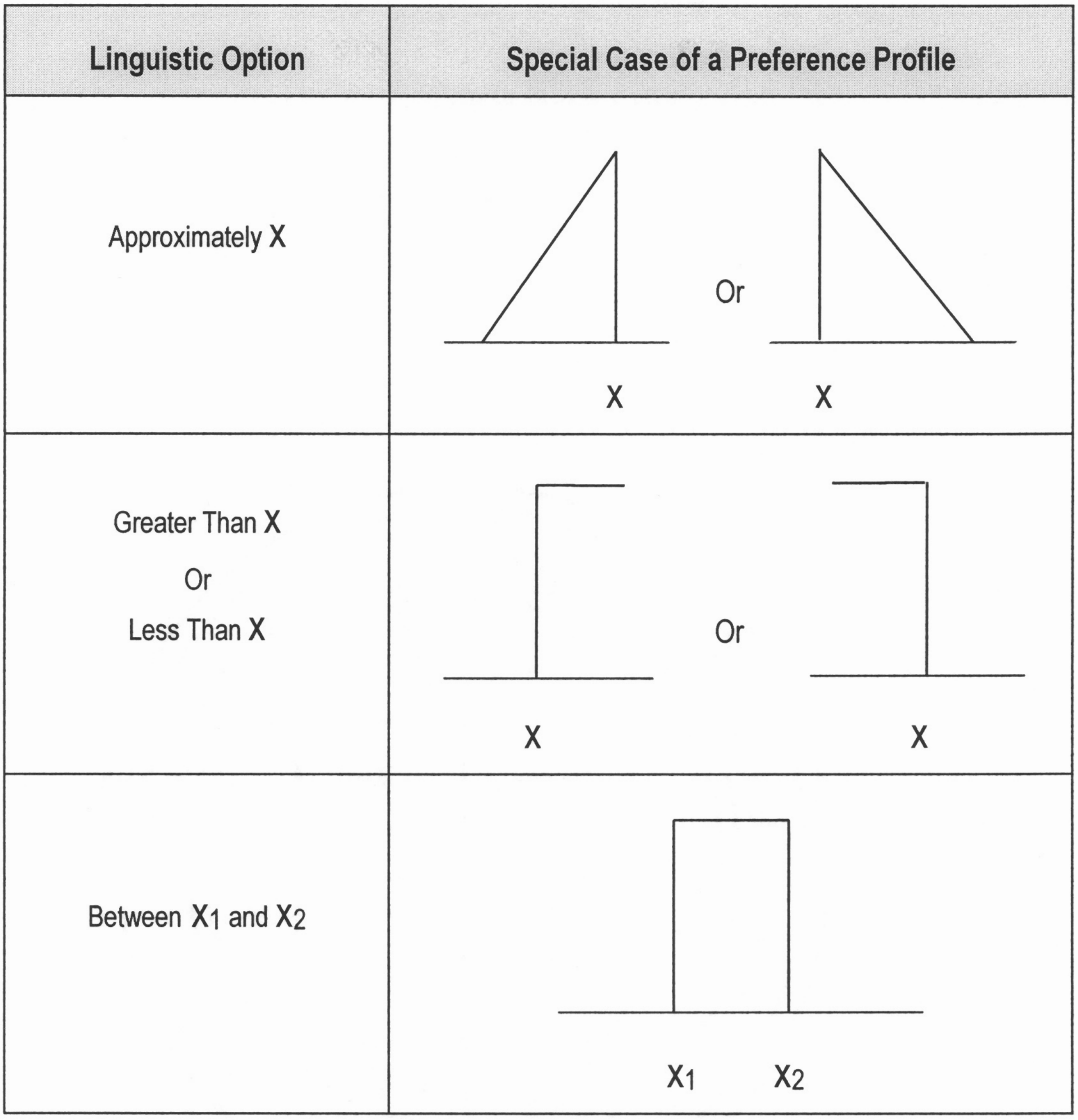


Figure 4.5. Special case preference profiles for the linguistic options.

Using any linguistic option along with a numeric constant(s), the design team is capable of defining target requirements for numeric DDPs.[4] This

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4 While design requirements may be defined as in Equation 4.1, the *Tolerance of Fuzziness Index* gives the designer a "sense" for the amount of fuzziness acceptable. This then guides the magnitude of the Support (discussed in the Appendix: Basic Operations in Fuzzy Arithmetic) associated with each fuzzy requirement, and the designer will have to identify the requirement level where the preference level with regard to a particular design dependent parameter definitely reaches zero and unity.

provides a design team with necessary flexibility during the system-level requirements definition stage through providing a formal means for handling imprecision and human/expert judgment. For example, a requirement for weight may be defined as *Less Than 2 pounds.*

Table 4.6 represents instances of DDP target values for a conferencing capability to be utilized by multiple remote parties. Algebraic representations are delineated to facilitate manipulation of the associated graphic profiles. These target values were developed through the application of a Fuzzy QFD and have a strong correlation with the subjectively stated customer requirements. As mentioned earlier, these fuzzy DDP target values represent portions of the feasible and fuzzy design space. The Fuzzy QFD technique is discussed and then applied to this example in Section 4.2.1.

Defining non-numeric DDPs and numeric DDPs that map onto the [0,1] interval. These DDPs may be defined through the use of a linguistic scale which maps associated linguistic labels onto a [0,1] interval. This mechanism "allows" design characteristics such as polutability, disposability, which do not (as yet) have a formal index of measurement or metric to be more aggressively "involved" in the up-front design analysis and evaluation process. Further, design requirements such as reliability, often expressed as a probability, can also be defined through the use of a similar linguistic scale.

The design team can make use of five linguistic variables, along with the associated preference profiles, as depicted in Figure 4.6.[5] These linguistic variables are (a) *Very Low,* (b) *Low,* (c) *Medium,* (d) *High, and* (e) *Very High.*

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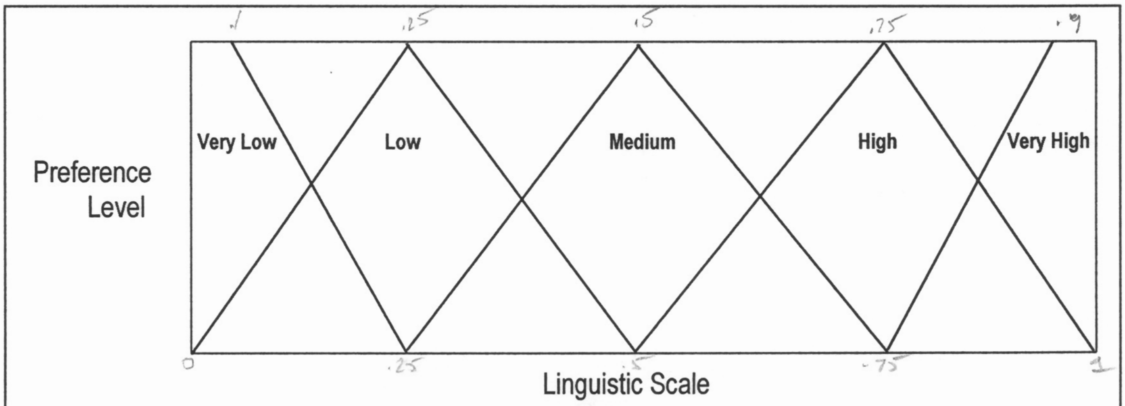
[5] It is not necessary for the fuzzy profiles representing the linguistic variables/labels in Figure 4.6 to be either linear or symmetrical. This particular set of linear and symmetrical profiles have been delineated only to simplify the underlying calculations and to convey the concepts. Further, the number of levels selected (in this case, five) is also flexible. Application of the methodology developed here is independent of the number of levels and the shapes of profiles representing these levels.



Linguistic Scales	Algebraic Representation
	$R = [0,1], and\ \forall \rho \in R$
Very Low	$\mu_{Very\ Low}(\rho) = 0 \qquad \rho \le 0.0$
	$= 1 \qquad 0 \le \rho \le 0.1$
	$= \frac{-20}{3}\rho + \frac{5}{3} \qquad 0.1 \le \rho \le 0.25$
	$= 0 \qquad \rho \ge 0.25$
Low	$\mu_{Low}(\rho) = 0 \qquad \rho \le 0.0$
	$= 4\rho \qquad 0 \le \rho \le 0.25$
	$= -4\rho + 2 \qquad 0.25 \le \rho \le 0.5$
	$= 0 \qquad \rho \ge 0.5$
Medium	$\mu_{Medium}(\rho) = 0 \qquad \rho \le 0.25$
	$= 4\rho - 1 \qquad 0.25 \le \rho \le 0.5$
	$= -4\rho + 3 \qquad 0.5 \le \rho \le 0.75$
	$= 0 \qquad \rho \ge 0.75$
High	$\mu_{High}(\rho) = 0 \qquad \rho \le 0.5$
	$= 4\rho - 2 \qquad 0.5 \le \rho \le 0.75$
	$= -4\rho + 4 \qquad 0.75 \le \rho \le 1.0$
	$= 0 \qquad \rho \ge 1.0$
Very High	$\mu_{Very\ High}(\rho) = 0 \qquad \rho \le 0.75$
	$= \frac{20}{3}\rho - \frac{15}{3} \qquad 0.75 \le \rho \le 0.90$
	$= 1 \qquad 0.90 \le \rho \le 1.0$
	$= 0 \qquad \rho \ge 1.0$

Figure 4.6. Definition of non-numeric and numeric DDP target values ([0,1] interval).

As an illustration, Table 4.6 depicts target values for selected non-numeric and numeric DDPs for the remote conferencing facility example. Once again, these values have been synthesized through the application of the Fuzzy QFD technique.

Classification of DDPs as depicted in Figure 4.3 and the manipulation of non numeric DDPs (along with the DDPs that take their values In the unit interval) through the mechanism discussed in this section allows explicit inclusion of qualitative design requirements into the conceptual design analysis and evaluation activity. These qualitative requirements can then "influence" the feasible design space and impact the ultimate desirability of conceptual design alternatives.

Discrete DDP definition. The preceding sub-sections focused on the definition of continuous DDPs. Very often DDPs are discrete in nature and must be addressed differently. For example, when defining the capacity (a numeric DDP) of a transportation system (for people), the requirement can take on only integer values. Such DDPs may be represented with a stepped-profile which also satisfies the normality and convexity requirements such as the profile in Figure 4.7. This profile represents the capacity requirement for a transportation system expressed as *Approximately 8*.[6]

The profile in Figure 4.7 is generated in two steps. The profile to the left of the most preferred capacity requirement 8, is generated from the left boundary inwards by making a horizontal movement from left to right (i.e., from one capacity requirement to the next higher requirement) and then a vertical movement to the preference level (in the interval [0,1]) of this next higher capacity value. The process continues until the capacity requirement with the

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6 As discussed in Chapter 3, the normality of a fuzzy subset is expressed as $\vee\,\mu_{\tilde{A}}(x) = 1,\ \forall x \in R$ (In other words, a normal fuzzy subset must have at least one element for which the preference level is 1). Further, a fuzzy subset is convex if and only if, $A_\alpha = \left\{x | \mu_{\tilde{A}}(x) \geq \alpha\right\},\ \textit{and}\ \ \alpha \in [0,1]$, where A_α is an ordinary subset of level α , and $\tilde{A}$ is a fuzzy subset of R.

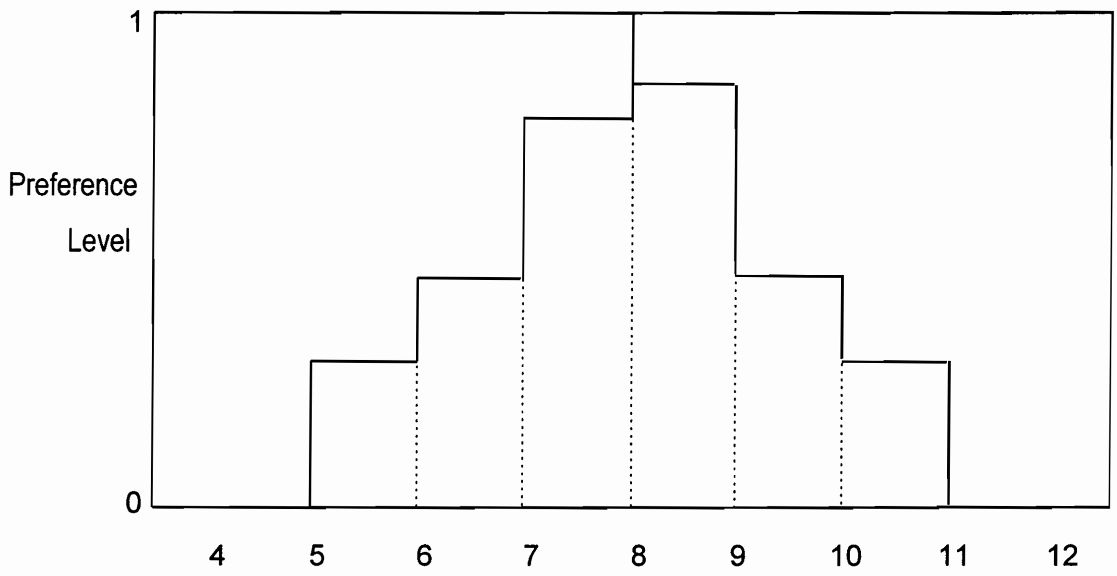


Figure 4.7. Capacity requirement for transportation system defined as *Approximately 8.*

highest preference value (which is 1 in the case of normal fuzzy numbers) is reached. Next, the profile to the right of the most preferred capacity requirement of 8 is generated from the right boundary inwards, in a similar manner.

To generalize the above approach, continuous preference profiles depicted in Figure 4.4 can be discretized for use with both discrete and numeric design dependent parameters. These discretized preference profiles are shown in Figure 4.8.

This section addressed the classification of design dependent parameters. Based upon their nature (numeric vs. non-numeric and continuous vs. discrete), mechanisms were developed to facilitate definition of DDP requirement levels. Meaningful definition of system design requirements requires utilization of a design practice such as Quality Function Deployment (QFD). Accordingly, development of the Fuzzy QFD design method and tool is discussed in the following section.

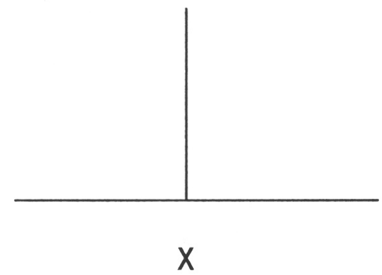
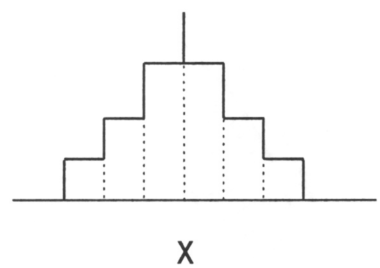
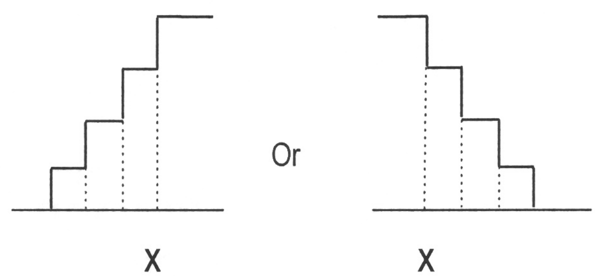
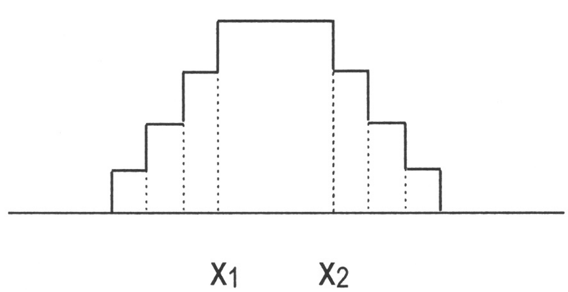
Linguistic Option	Associated Preference Profile for Discrete DDPs
X (Special case of a deterministic and crisp DDP)	
Approximately X	
Greater Than X Or Less Than X	
Between X_1 and X_2	

Figure 4.8. Discrete preference profiles for discrete and numeric DDPs.

4.2.2. Fuzzy Quality Function Deployment Method (Fuzzy QFD)[7]

The Quality Function Deployment (QFD) method has been used extensively as a design method to facilitate customer-focus during the system design and development (product, process, and/or structure) activities. While the underlying intent remains the same here, given the nature of available information, the procedure for QFD practice has been adapted herein to better address and manipulate the imprecision and vagueness during the conceptual design phase.

The QFD matrix provides a framework for conducting activities such as customer surveys, requirements identification, DDP identification, benchmarking, and so on, in a coherent and integrated manner. The overall objective is the identification of relevant DDPs, their relative importance, and associated target values as an input to the subsequent design activity. A QFD matrix schema, along with its constituent elements, is shown in Figure 4.9.

This matrix is developed by completing the following activities in sequence:

1. *Identification of customer requirements.* The first step in the implementation of this design method is the identification of customer requirements or "WHATS". These requirements, often subjectively stated, are grouped together in an effort to form a logical hierarchy

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7 The Quality Function Deployment (QFD) method while being very general in its applicability and potential use, did not gain early broad-based acceptance due to confusion resulting from its name. When used as part of the early system design process to elicit customer requirements, QFD facilitates inclusion of the *"Voice of the Customer"* in the design and development process. However, as a general quality tool (in the TQM context) the QFD matrix is also called "*The House of Quality*" by some authors. In this research, this method is used as a means for generating the feasible design space (represented by the relevant design dependent parameters) such that this space very closely correlates with potential customer requirements. In doing so, the tool goes a long way to help make the customer an integral part of the design synthesis process.

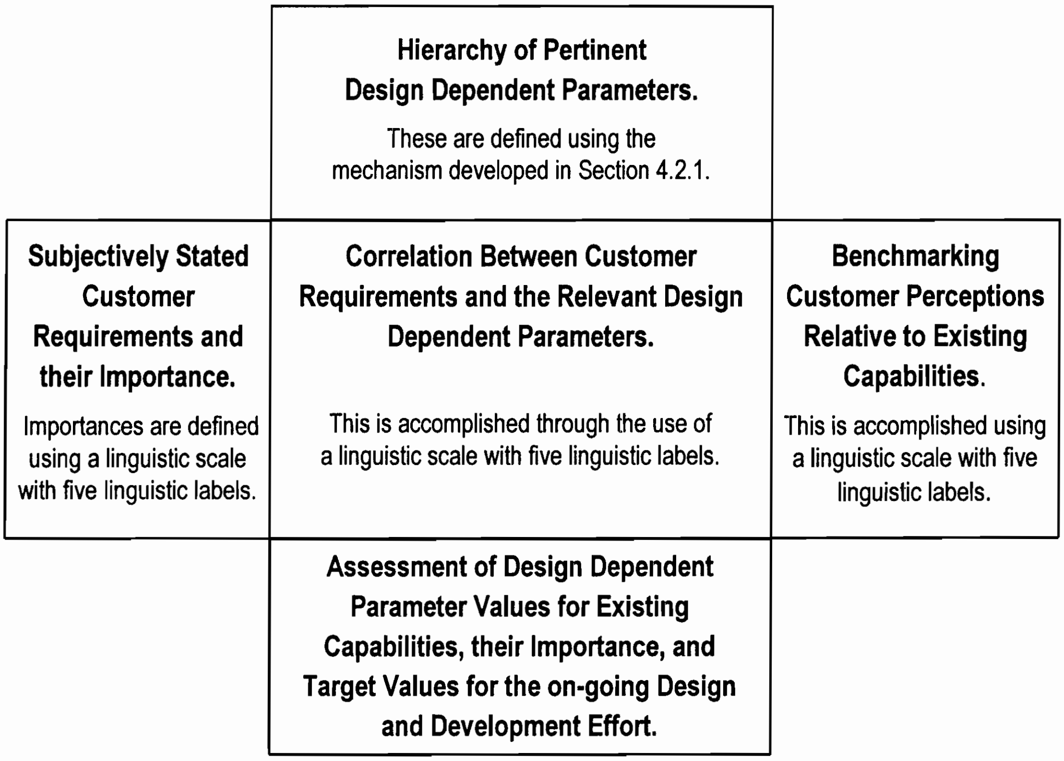

Figure 4.9. Fuzzy QFD matrix schema utilized to define the feasible design space (refer to Figure 2.3).

of related customer requirements, going from the most abstract to the most specific. This breakout of the top level need is continued to a requisite level of resolution. Thereafter, the importance of these requirements (from the customer's perspective) are delineated. The linguistic scale (with five linguistic labels) used to accomplish this is shown in Figure 4.10.[8] A partially completed QFD matrix for the conferencing system example is depicted in Figure 4.11. Linguistic labels are represented in this matrix through the use of numbers (i.e., 1 represents the label *Not Important* and 5 represents *Very Important*).

8 Refer to the text of footnote 5 on page 62. The entire note applies to this linguistic scale as well, as it does to all subsequent scales.

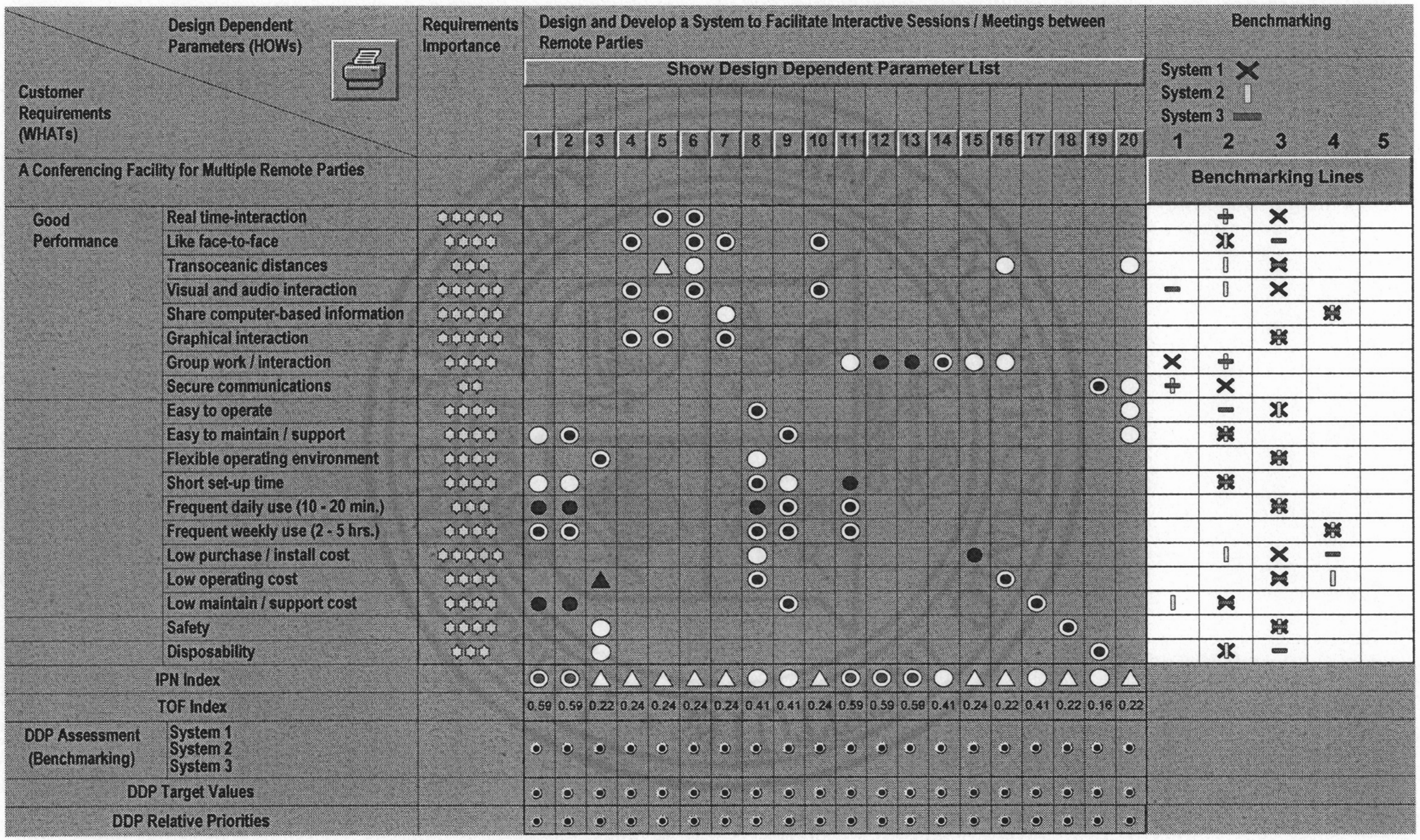

Figure 4.11. A partially completed QFD matrix (refer to Table 4.2).

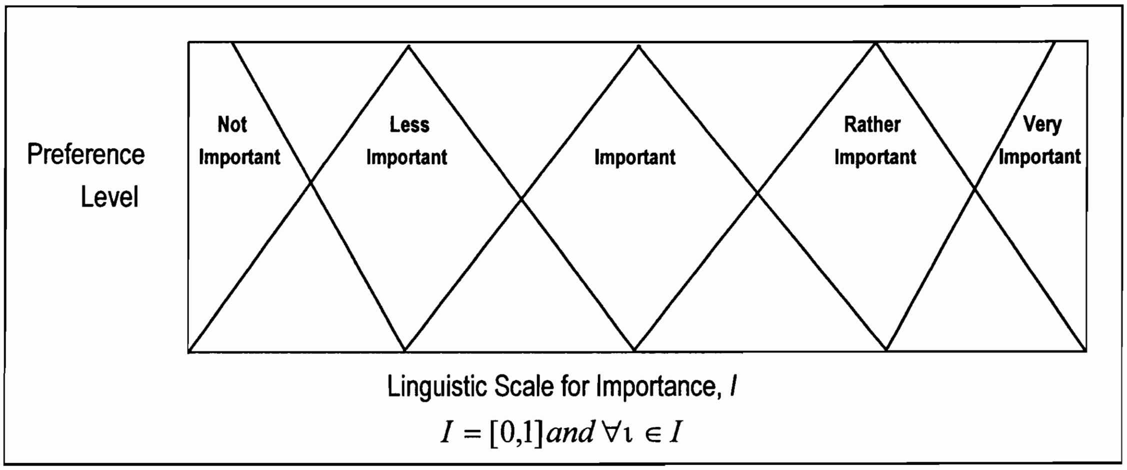

Figure 4.10. Linguistic scale for defining requirements importance.

2. *Identification of design dependent parameters.* Once customer requirements have been identified and classified into logical groups, a relevant set of design dependent parameters (also called engineering characteristics, technical performance measures, or design requirements) is identified. By controlling and manipulating "appropriate" DDPs, a design team may indirectly respond to the functional need and associated customer requirements. Further, the QFD approach facilitates and strengthens traceability and correlation between customer requirements and design requirements (represented by the DDPs). The relevant set of DDPs for the conferencing facility are delineated in Figure 4.11.
3. *Correlation of customer requirements and design dependent parameters.* This is a significant step which ensures that DDPs have been identified which address (and impact) each and every customer requirement. Further, DDPs which cannot be traced back to a customer requirement can be eliminated. Also, the correlation between customer requirements and DDPs is subjectively assessed

through use of the linguistic scale depicted in Figure 4.12. These labels are represented in the matrix shown in Figure 4.11 through the use of icons given in Table 4.1. Finally, upon completing the correlation exercise, it is important to investigate the grid for any empty rows or columns. An empty row signifies a customer requirement that has not yet been addressed, while an empty column may identify an unnecessary design requirement.

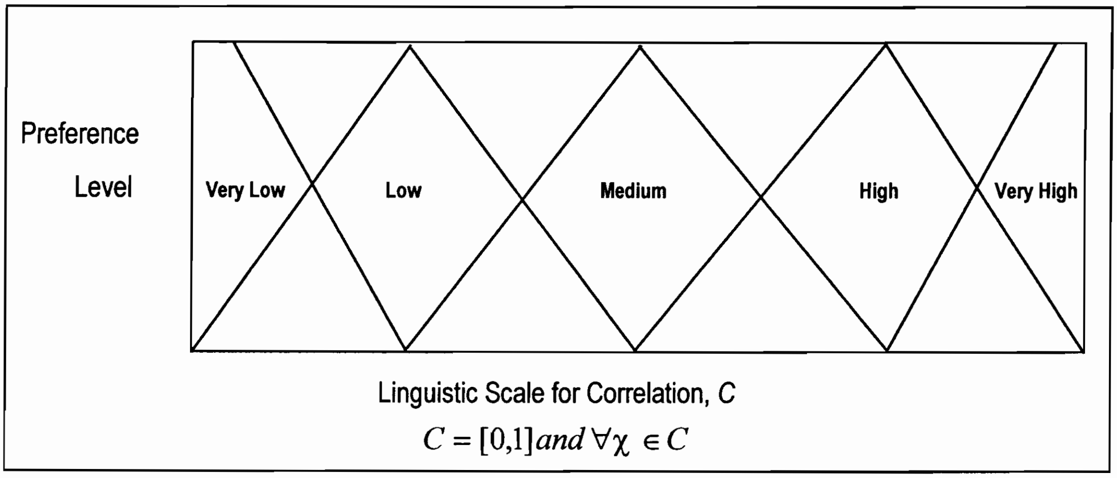

Figure 4.12. Linguistic scale for defining correlation between customer requirements and DDPs.

4. *Benchmarking existing capabilities from the customer perspective.* A key activity when implementing QFD is to identify currently available systems/products capable of responding to the functional need (to whatever extent) and to then benchmark customer perceptions on how well each of these capabilities satisfy the various customer requirements. This step is important in order to determine the extent of improvement necessary in the capability being designed and developed. Further, this activity affords the designer invaluable insight into avenues where competitive gains can be made most effectively.

Table 4.1. Icons representing correlation.

Correlation Label	Corresponding Icon
Very Low	▲
Low	△
Medium	○
High	⊙
Very High	●

Customer perceptions delineated during this activity are expressed in subjective terms and can be formally "captured" through the use of the linguistic scale depicted in Figure 4.13. Satisfaction levels are represented in the QFD matrix as numbers (i.e., 1 represents *Dissatisfied* and 5 represents *Very Satisfied*). This benchmarking effort as it pertains to the remote conferencing system is depicted in Figure 4.11. In this case-study three existing capabilities were analyzed and compared.

5. *Assessment of design dependent parameter values.* After benchmarking customer perceptions, the next step involves assessing values for the design dependent parameters as they pertain to existing capabilities. Mechanisms developed in Section 4.2.1 are utilized to express these assessments. As an illustration, assessed DDP values for the conferencing facility case-study are consolidated in Table 4.2.

Table 4.2. Assessed design dependent parameter values.*

Design Dependent Parameters	System 1	System 2	System 3	Type of DDP	Units/Notes
Reliability	Approximately 30,000 Hrs.	Approximately 25,000	Approximately 35,000	Numeric, continuous	Mean Time Between Failures (MTBF)
Maintainability	Less Than 1.5 Hrs.	Less Than 1.5	Less Than 2.0	Numeric, continuous	Mean Time To Repair (MTTR)
Environmental Compliance	Very High	Very High	Very High	Non-numeric	Degree Of Compliance
Visual quality	Very High	High	Very Low	Non-numeric	FOM
Data (graphic) transfer rate	Approximately 64	Approximately 1000	Approximately 16	Numeric, discrete	Kilo Bits Per Second (Kbps)
Audio/visual synchronization	Approximately 400	Approximately 2000	Approximately 800	Numeric, discrete	A/V Jitter (milliseconds)
Color capability	256	256	16	Numeric, discrete	Levels Of Color/Gray Scale
Skill level (operation)	Low	Low	Low	Non-numeric	Minimum Skill Level
Skill level (maintenance)	Medium	High	Medium	Non-numeric	Minimum Skill Level
Audio quality	Medium	Medium	Medium	Non-numeric	Perception of Audio Quality
Communication initiation time	Less Than 3	Less Than 3	Less Than 3	Numeric, continuous	Time (minutes)
Maximum group size	2	8	2	Numeric, discrete	Number Of People
Simultaneous groups active	Approximately 100	Approximately 20	Approximately 100	Numeric, discrete	Number Of Groups
Maximum membership size	Greater Than 1000	Greater Than 1000	Greater Than 1000	Numeric, discrete	Number Of People
Design/production cost	Approximately 2,200	Approximately 2,500	Approximately 800	Numeric, continuous	Dollars/Unit
Operating cost	Approximately 720	Approximately 450	Approximately 720	Numeric, continuous	Dollars/Unit/Month
Support/maintenance cost	Approximately 10	Approximately 11	Approximately 4	Numeric, continuous	Dollars/Unit/Month
Safety	High	High	High	Non-numeric	User Safety
Disposability	Medium	Medium	High	Non-numeric	Ease Of Component Disposal/Reuse
Communication security	Medium	Low	Medium	Non-numeric	Security Level

* Refer to the QFD Matrix depicted in Figure 4.11.

6. *Delineating target values for the design dependent parameters.* Definition of design requirements is a critical step in the system design and development process. It represents a commitment by the design team to the ultimate system effectiveness and cost. Further, this step significantly impacts subsequent syntheses, analyses, and evaluation activities.

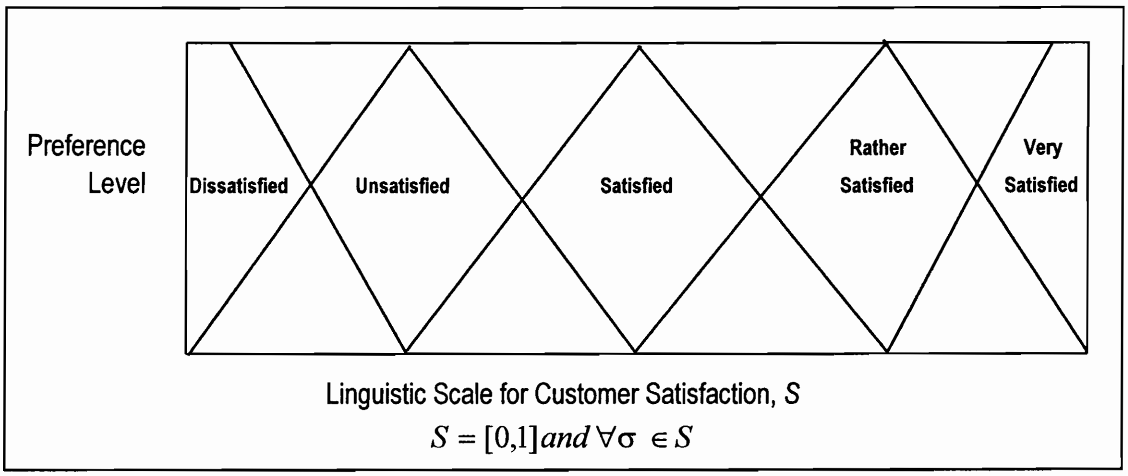

Figure 4.13. Linguistic scale to define customer satisfaction as part of the benchmarking effort.

Its significance notwithstanding, the need analysis and requirements definition activity involves human judgment and intuition, and prior experience with similar efforts is invaluable. Decisions have to be made in the presence of little information. Conducting steps 1 through 6 serves to rigorously enhance project-specific knowledge of designers and reduces the “gap” between commitment and knowledge as was shown in Figure 1.4.

Two mechanisms are developed here as aids to this subjective, yet critical, process. The first mechanism provides insight into the extent of improvement desirable and necessary for each of the design dependent parameters.[9] Thereafter, the second mechanism provides the design team with insight into the amount of fuzziness which could be tolerated for each of the design dependent parameters.[10]

Design dependent parameter tolerance is a function of its *Improvement Potential and Necessity (IPN)*, along with the importance attached by the customer(s) to requirements that are impacted by the DDP. Utilization of the second mechanism is facilitated through the development of an index called the *Tolerance Of Fuzziness (TOF)*. Each of these mechanisms are developed and discussed next.

4.2.3. Design Dependent Parameter Improvement Potential and Necessity (IPN)

To give designers an indication of the improvement potential of a design dependent parameter (in terms of customer satisfaction levels), along with the necessity for this improvement, a matrix is developed linking customer satisfaction levels and the correlation between customer requirements and design dependent parameters.[11] This matrix in populated with linguistic variables which represent the extent of Improvement Potential and Necessity associated with each instance of a particular design dependent parameter. The most demanding instance is the *IPN Index* for this DDP.

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9 This is reflected through enhanced requirement levels for the relevant design dependent parameters.

10 This concept is very similar to the idea of dimensional tolerances during the manufacturing phase (which are also based upon functional and form-based requirements). In the case of system-level requirements, tolerances are based upon the importance and impact of these requirements upon the overall customer satisfaction levels.

11 In this case, improvement potential is a function of the correlation between customer requirements and design dependent parameters, while improvement necessity is impacted by current customer satisfaction (or dissatisfaction) levels. It is important to remember that a design team's objective is to enhance overall customer satisfaction levels, and this is accomplished indirectly by manipulating relevant design dependent parameters.

The resulting matrix is illustrated in Figure 4.14, and the associated linguistic scale is shown in Figure 4.15. For example, if a customer is very satisfied with regard to a requirement, then the Improvement Potential and Necessity for this instance of a design dependent parameter with *Very Strong* correlation is *Very Low.* It is non-existent for DDPs with weaker correlation. All possible combinations are given in Figure 4.14. This correlation is used to impact decisions relative to the extent of improvement necessary when specifying design dependent parameter target values. This rationale allows exploitation of the most prominent opportunities in order to gain a strategic advantage in the marketplace. Further, this focuses the design effort towards avenues where improvements can be accomplished in the most effective and efficient manner (in terms of overall customer satisfaction levels).[12]

The Improvement Potential and Necessity for all instances of the *Reliability* parameter are enumerated in Table 4.3, Column 2. Further, the *IPN Index* for *Reliability* is *High* (since this is the most demanding instance in the improvement potential and improvement necessity for this design dependent parameter). Using a similar rationale, design dependent parameter target values for the remote conferencing example are delineated in Table 4.6.

4.2.4. Design Dependent Parameter Tolerance of Fuzziness (TOF)

To define design requirements in a meaningful way, it is necessary to specify not only the required levels for relevant design dependent parameters, but also the associated tolerance levels. This information may be conveyed through an index called the *Tolerance Of Fuzziness (TOF)* which is to be developed next.

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[12] This concept is very similar to the Pareto Analysis used to delineate critical factors requiring most attention [Verma and Blanchard, 1994].

Level of Customer Satisfaction \ Level of Correlation	●	⊙	○	△	▲
Dissatisfied	Very High	High	Medium	Low	Very Low
Unsatisfied	High	Medium	Low	Very Low	
Satisfied	Medium	Low	Very Low		
Rather Satisfied	Low	Very Low			
Very Satisfied	Very Low				

Figure 4.14. Matrix to derive DDP Improvement Potential and Necessity level.

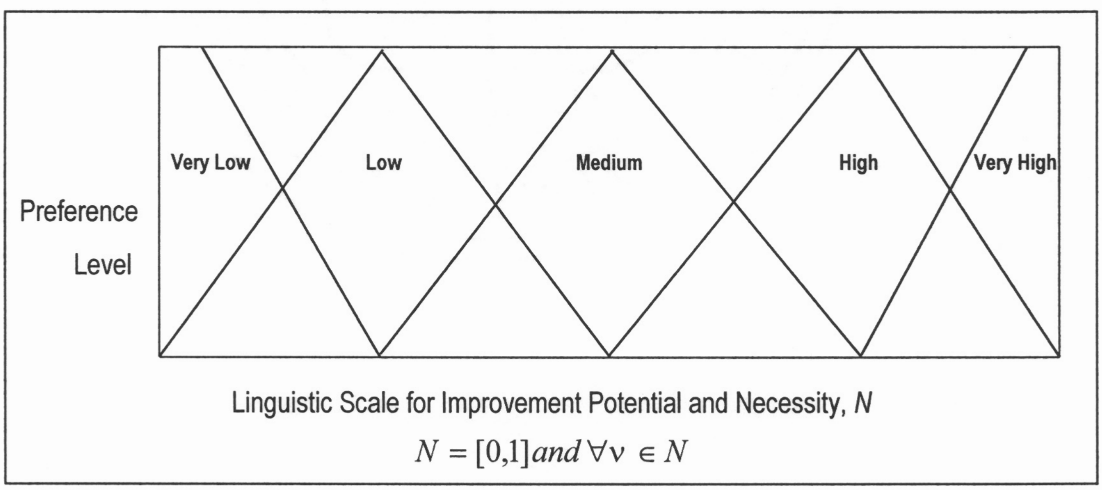

Figure 4.15. Scale for defining Improvement Potential and Necessity.

The *TOF* index for every design dependent parameter is a function of its Improvement Potential and Necessity, *N* (according to the matrix developed in Figure 4.14), relative to each of the correlating customer requirements along with the importance of these requirements, *I*. For instance, in Figure 4.11 (which depicts the partially completed QFD), *Reliability* impacts five customer requirements (a) Easy to maintain/support, (b) Short set-up time, (c) Frequent daily use, (d) Frequent weekly use, and (e) Low maintain/support cost. By correlating data in Figures 4.11 and 4.14, information may be synthesized to derive the *TOF* for *Reliability*. This is given in Table 4.3.

Table 4.3. Development of the *Tolerance Of Fuzziness* index.

Customer Requirements Impacted by Reliability	The Improvement Potential and Necessity for Reliability (*N*)	Importance of Customer Requirements (*I*)
Easy to maintain/support	Low	Rather Important
Short set-up time	Low	Rather Important
Frequent daily use	Medium	Important
Frequent weekly use	Very Low	Rather Important
Low maintain/support cost	High	Rather Important
	IPN Index (Reliability): High	

Calculation of the Tolerance Of Fuzziness (*TOF*). The *TOF* is unique and calculated separately for each design dependent parameter. A table such as Table 4.3 is developed for each DDP depicting details regarding its every instance on the QFD matrix relative to the customer requirements. Thereafter, the index is calculated by completing the following steps:

Step 1. Every instance of a fuzzy label, representing the Improvement Potential and Necessity of a DDP on the QFD matrix, is multiplied by the fuzzy label representing the importance of the associated customer requirement. In each case, the result in a non - linear fuzzy number.[13] This operation for the Reliability parameter is presented below. The relevant linguistic labels represented in Table 4.4 can now be manipulated to yield the *TOF* for Reliability.[14]

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[13] The multiplication of two linear (triangular or trapezoidal) fuzzy numbers yields a non-linear fuzzy number. However, the normality and convexity conditions are maintained in the resulting fuzzy number. This is shown in more detail in the Appendix (Basic Operations in Fuzzy Arithmetic).

[14] In accordance with Zadeh's Extension Principle (discussed in Section 3.3.2), a fuzzy output, ψ, which is induced from multiple fuzzy input variables, *a ...z*, through the function *f*, may be represented generically as:

$$\mu_{\psi=f(a,\cdots,z)}(\psi) = \bigvee_{\psi=f(a,\cdots,z)} \min(\mu_{\tilde{A}}(a),\cdots,\mu_{\tilde{Z}}(z))$$

This approach, applied to the multiplication operation, may be represented as:

$$\mu_{Low.Rather\ Important}(\psi) = \bigvee_{\psi=\nu.\iota}(\mu_{Low}(\nu) \wedge \mu_{Rather\ Important}(\iota))$$

Although this approach may be used to facilitate the calculations leading to synthesis of the *TOF* index, an equivalent approach proposed and proved by Gupta and Kaufmann (1991) is applied here. This approach involves working with the input fuzzy variables in terms of their α-cuts, leading to the generation of the fuzzy output profile. In terms of this approach, the multiplication operation may be represented as:

$$Low^{\alpha}(.)Rather\ Important^{\alpha} = (\nu_1,\nu_2).(\iota_1,\iota_2) = [(\nu_1.\iota_1),(\nu_2.\iota_2)]$$

where Low^{α} and $Rather\ Important^{\alpha}$ are α-cutsets of the two fuzzy subsets Low and $Rather\ Important$. The concept of α-cuts and the conductance of basic operations with fuzzy numbers is discussed in the Appendix (Basic Operations in Fuzzy Arithmetic).

Table 4.4. Algebraic representations of the relevant linguistic labels.

DDP Improvement Potential and Necessity	Importance of Customer Requirements
$N = [0,1], and\ \forall \nu \in N$	$I = [0,1], and\ \forall \iota \in I$
$\mu_{V.L}(\nu) = 0 \quad \nu \le 0$ $= 1 \quad 0 \le \nu \le 0.1$ $= \frac{-20}{3}\nu + \frac{5}{3} \quad 0.1 \le \nu \le 0.25$ $= 0 \quad \nu \ge 0.25$	$\mu_I(\iota) = 0 \quad \iota \le 0.25$ $= 4\iota - 1 \quad 0.25 \le \iota \le 0.5$ $= -4\iota + 3 \quad 0.5 \le \iota \le 0.75$ $= 0 \quad \iota \ge 0.75$
$\mu_L(\nu) = 0 \quad \nu \le 0$ $= 4\nu \quad 0 \le \nu \le 0.25$ $= -4\nu + 2 \quad 0.25 \le \nu \le 0.5$ $= 0 \quad \nu \ge 0.5$	$\mu_{R.I}(\iota) = 0 \quad \iota \le 0.5$ $= 4\iota - 2 \quad 0.5 \le \iota \le 0.75$ $= -4\iota + 4 \quad 0.75 \le \iota \le 1.0$ $= 0 \quad \iota \ge 1.0$
$\mu_M(\nu) = 0 \quad \nu \le 0.25$ $= 4\nu - 1 \quad 0.25 \le \nu \le 0.5$ $= -4\nu + 3 \quad 0.5 \le \nu \le 0.75$ $= 0 \quad \nu \ge 0.75$	
$\mu_H(\nu) = 0 \quad \nu \le 0.5$ $= 4\nu - 2 \quad 0.5 \le \nu \le 0.75$ $= -4\nu + 4 \quad 0.75 \le \nu \le 1.0$ $= 0 \quad \nu \ge 1.0$	

It can be shown that:[15]

1.
$$\begin{aligned}
\mu_{Low(.)RatherImportant}(\psi) &= 0 && \psi \le 0\\
&= -1+\sqrt{16\psi+1} && 0 \le \psi \le 0.19\\
&= 3-\sqrt{16\psi+1} && 0.19 \le \psi \le 0.50\\
&= 0 && \psi \ge 0.50
\end{aligned}$$

2.
$$\begin{aligned}
\mu_{High(.)Rather\ Important}(\psi) &= 0 && \psi \le 0.25\\
&= -2+2\sqrt{4\psi} && 0.25 \le \psi \le 0.56\\
&= 4-4\sqrt{\psi} && 0.56 \le \psi \le 1.0\\
&= 0 && \psi \ge 1.0
\end{aligned}$$

3.
$$\begin{aligned}
\mu_{Very\ Low(.)Rather\ Important}(\psi) &= 0 && \psi \le 0.08\\
&= 1 && 0.0 \le x \le 0.08\\
&= \frac{17-\sqrt{49+960\psi}}{6} && 0.08 \le \psi \le 0.25\\
&= 0 && \psi \ge 0.25
\end{aligned}$$

and,

4.
$$\begin{aligned}
\mu_{Medium(.)Important}(\psi) &= 0 && \psi \le 0.06\\
&= -1+\sqrt{16\psi} && 0.06 \le \psi \le 0.25\\
&= 3-\sqrt{16\psi} && 0.25 \le \psi \le 0.56\\
&= 0 && \psi \ge 1.0
\end{aligned}$$

The multiplication operations above and the results are depicted graphically in Figure 4.16.

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[15] Details regarding the multiplication operator are given in the Appendix.

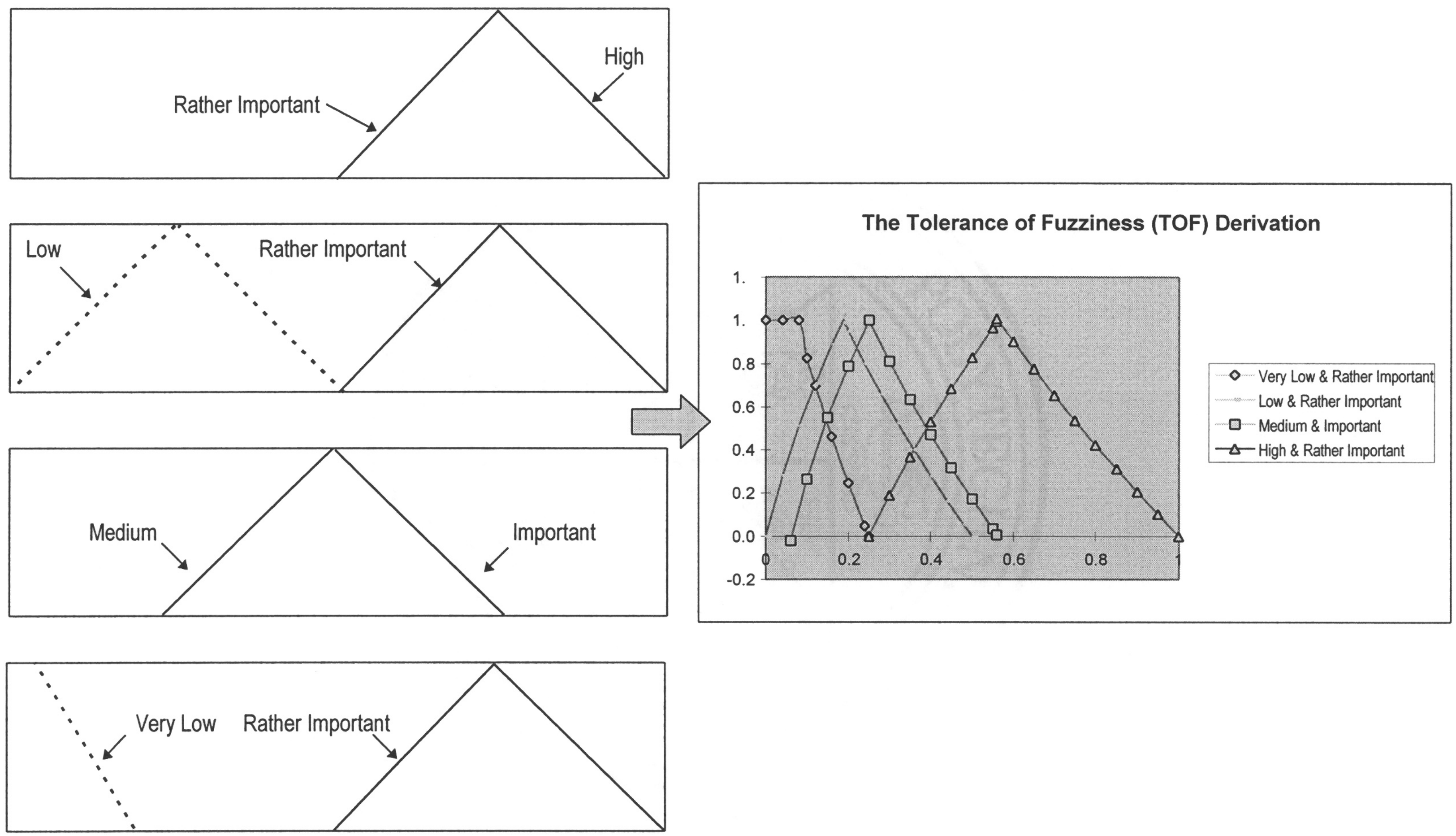

Figure 4.16. Illustration of the fuzzy multiplication operation along with output profiles.

Step 2. Once the output profiles resulting from Step 1 have been consolidated (Figure 4.16), the maximum fuzzy number is extracted from this combination. When comparing two fuzzy numbers, the maximum fuzzy number is given by:[16]

$$\mu_{(Low)\vee(Rather\ Important)}\psi = \underset{\psi = \nu \vee \iota}{\vee} (\mu_{Low}(\nu) \vee \mu_{Rather\ Important}(\iota)) \tag{4.2}$$

Applying Equation 4.2 to the Reliability parameter for the conferencing example gives the maximum fuzzy number as shown in Figure 4.17. It is represented as:

$$\mu_{[(Low).(Rather Important)\vee(Very\ Low).(Rather\ Important)\vee(High).(Rather\ Important)\vee(Medium).(Important)]}(\psi)$$

$$\begin{aligned} &= 0 && x \leq 0.25 \\ &= -2 + 2\sqrt{4\psi} && 0.25 \leq \psi \leq 0.56 \\ &= 4 - 4\sqrt{\psi} && 0.56 \leq \psi \leq 1.00 \\ &= 0 && \psi \geq 1.00 \end{aligned}$$

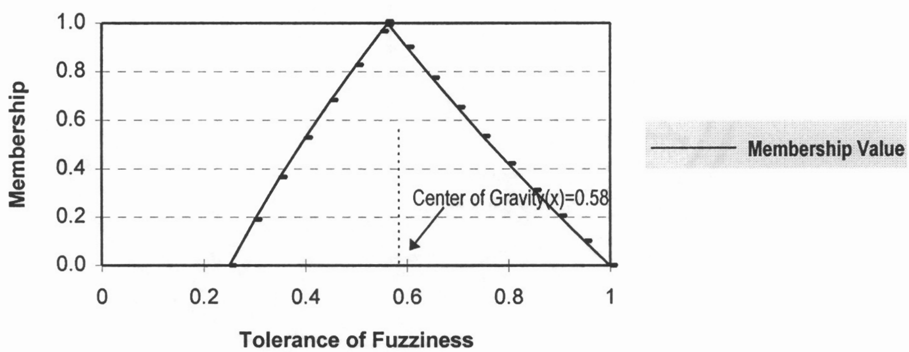

Figure 4.17. The maximum fuzzy number and *TOF* Index derivation.

Step 3. To derive a crisp value of the *TOF* index, the maximum fuzzy number is defuzzified to generate a crisp output with a value in the interval [0,1].

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[16] This is not an obvious concept, since fuzzy numbers are not characterized by total order; they display only partial order. The concept of maximum and minimum fuzzy numbers and their calculation is discussed in more detail in the Appendix (Basic Operations in Fuzzy Arithmetic).

The *Center of Gravity* approach is used in this defuzzification process.[17] The crisp output from this defuzzification procedure is found by deriving the abscissa of the center of gravity for the maximum fuzzy number delineated in Step 2 as:

$$ToF = CoG_{\mu(\psi)} = \frac{\int_0^1 \mu(\psi).\psi \, d\psi}{\int_0^1 \mu(\psi) \, d\psi} \tag{4.3}$$

Equation 4.3 may be applied to the maximum fuzzy number for the *Reliability* parameter in the remote conferencing case-study as:

$$ToF_{Reliability} = CoG_{\mu(\psi)} = \frac{\int_{0.25}^{0.56} (-2 + 2\sqrt{4\psi})\,\psi d\psi + \int_{0.56}^{1.0} (4 - 4\sqrt{\psi})\,\psi d\psi}{\int_{0.25}^{0.56} (-2 + 2\sqrt{4\psi})\, d\psi + \int_{0.56}^{1.0} (4 - 4\sqrt{\psi})\, d\psi}$$

$$= CoG_{\mu(\psi)} = \frac{\int_{0.25}^{0.56} (-2\psi + 4\psi^{3/2})\, d\psi + \int_{0.56}^{1.0} (4\psi - 4\psi^{3/2})\, d\psi}{\int_{0.25}^{0.56} (-2 + 4\psi^{1/2})\, d\psi + \int_{0.56}^{1.0} (4 - 4\psi^{1/2})\, d\psi}$$

$$= \frac{0.074 + 0.148}{0.164 + 0.211} = 0.58$$

---

[17] The *Center of Gravity* (CoG) approach is one of the more popular defuzzification procedures as is evident from the relevant literature [Runkler and Glesner, 1993; Pelaez and Bowles, 1993]. In computing the *TOF* index, the fuzzy maximum operator was used prior to the defuzzification process. This is consistent with a conservative approach to setting tolerances on system-level design requirements. Defuzzification (in some form) is often necessary when rating and ranking fuzzy sets. This is discussed more in Chapter 5. A consolidation of requirements for a good defuzzification procedure, along with a discussion and critique of various defuzzification procedures currently in use, is also presented in [Runkler and Glesner, 1993].

The *TOF* index for the Reliability parameter of 0.58 is used, along with *IPN* index, to provide guidance to the design team when defining design requirements. Using a similar approach, the *IPN* and *TOF* indices for all design dependent parameters, as they pertain to the remote conferencing example, are given in Table 4.5.

4.2.5. Delineating Design Dependent Parameter Target Values

Information in the QFD matrix (e.g., Figure 4.11 and Table 4.2), along with the two indices developed in Sections 4.2.3 and 4.2.4, become significant inputs to the process of defining design requirements (i.e., target values for the design dependent parameters). As discussed earlier, the *IPN* index of every Design Dependent Parameter is a function of its correlation with customer requirements and related customer satisfaction levels. As such, the *IPN* index provides insight into the extent of improvement potential of any design dependent parameter (in terms the overall customer satisfaction level) along with the necessity for improvement. The *TOF* index indicates the extent of fuzziness which may be tolerated in each case.

The highest assessed value of every DDP (delineated as part of the competitive benchmarking activity) is studied along with the value of the indices before delineating target values for the ongoing design and development effort. For example, as part of the conferencing case-study, the highest assessed value of the *Reliability* parameter is *Approximately* 35,000 hours. The associated value of the *IPN* index is *High* and the *TOF* index is 0.58. This information may be presented as:

> *With the value of the Reliability parameter estimated at Approximately 35,000 hours, the improvement potential and necessity is High with a tolerance tending towards crispness.*

This information provides an indicator to the design team that the *Reliability* requirement needs to be raised substantially during the on-going design and development effort, and that this requirement should have a tolerance profile that tends towards crispness. A similar rationale may be adopted for the other design dependent parameters. Table 4.5 gives values of the two indices along with the best assessed value for the complete set of design dependent parameters. This exercise becomes a useful input to the design requirements definition activity. The associated design dependent parameter target values for the remote conferencing example are delineated in Table 4.6, along with algebraic representations to facilitate necessary manipulation during the later stages of the evaluation.

It is important to mention that development of the *IPN* and *TOF* indices can significantly "influence" design requirements definition. However, many issues have not been included or explicitly considered in the current effort. Some of these are identified in Chapter 7 as recommendations for potential extensions. Therefore, it is important to utilize the two indices only as aids or indicators (where none exist currently) to supplement and/or validate experience and expert judgment.

Table 4.5. *IPN* and *TOF* values for the remote conferencing example.

Design Dependent Parameter	Best Assessed Value	*IPN* Index	*TOF* Index
Reliability	Approximately 35,000 hours	High	0.580
Maintainability	Less Than 1.5 hours	High	0.594
Environmental compliance	Very High	Low	0.219
Visual quality	Very High	Low	0.243
Data (graphic) transfer rate	Approximately 1000 Kbps	Low	0.243
Audio/video synchronization	Approximately 400 milliseconds	Low	0.243

Table 4.5. *IPN* and *TOF* values for the remote conferencing example (continued).

Design Dependent Parameter	Best Assessed Value	*IPN* Index	*TOF* Index
Color capability	256	Low	0.243
Skill level requirement (operate)	Low	Medium	0.406
Skill level requirement (maintain/support)	Medium	Medium	0.406
Audio quality	Medium	Low	0.243
Communication initiation time	Less Than 3 minutes	High	0.594
Number of members possible within each group	8 members	High	0.594
Number of simultaneous group meetings	Approximately 100	High	0.594
Maximum membership size	Greater Than 1000	Medium	0.406
Design/production cost	Approximately 800 $/unit/user	Low	0.243
Operating cost	Approximately 450 $/unit/user/mo.	Low	0.219
Support/maintenance cost	Approximately 4 $/unit/user/mo.	Medium	0.406
Safety	High	Low	0.219
Disposability	High	Medium	0.156
Communication security	Medium	Low	0.219

4.3. GENERATING THE FUZZY FEASIBLE DESIGN SPACE

The first step in the evaluation of system design alternatives in general, and conceptual system designs in particular, is to establish the feasible design space. The sequence of activities delineated in Sections 4.1 and 4.2 of this chapter are directed toward this objective. Further, it is shown in this chapter

Table 4.6. Design dependent parameter target values for the example.

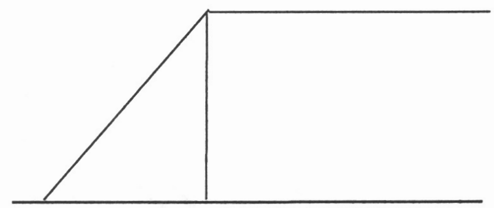
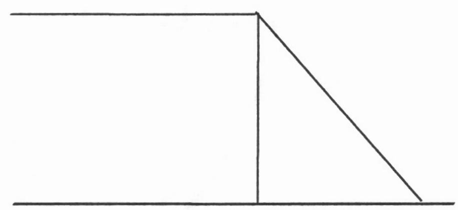
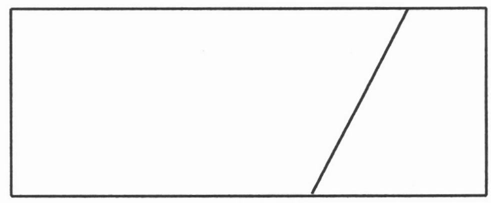
Design Dependent Parameter	Target Value	Algebraic Representation
Reliability	Greater Than 40,000 Hours	$y = 0 \quad x \le 36{,}000$ $y = \frac{x}{4{,}000} - 9 \quad 36{,}000 \le x \le 40{,}000$ $y = 1 \quad x \ge 40{,}000$ 
Maintainability	Less Than 45 Minutes	$y = 0 \quad x \ge 50$ $y = 10 - \frac{x}{5} \quad 50 \ge x \ge 45$ $y = 1 \quad x \le 45$ 
Environmental compliance	Very High	$y = 0 \quad x \le 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \quad 0.75 \le x \le 0.90$ $y = 1 \quad 0.90 \le x \le 1.0$ 

Table 4.6. Design dependent parameter target values for the example (continued).

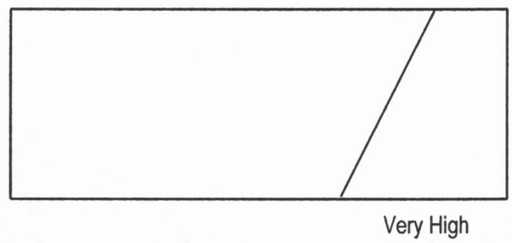
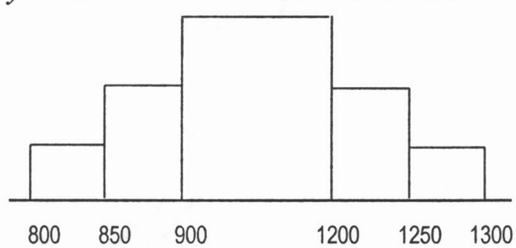
Design Dependent Parameter	Target Value	Algebraic Representation
Visual quality	Very High	$y = 0 \qquad x \le 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \qquad 0.75 \le x \le 0.90$ $y = 1 \qquad 0.90 \le x \le 1.0$ 
Data (graphic) transfer rate	Approximately 1000 Kbps	$y = 0.00 \qquad x \le 800 \text{ and } \ge 1300$ $y = 0.20 \qquad 800 \le x \le 850 \text{ and } 1250 \le x \le 1300$ $y = 0.60 \qquad 850 \le x \le 900 \text{ and } 1200 \le x \le 1250$ $y = 1.00 \qquad 900 \le x \le 1200$ 
Audio/video synchronization	Less Than 400 Milliseconds	$y = 0 \qquad x \ge 400$ $y = 1 \qquad x \le 400$ 

Table 4.6. Design dependent parameter target values for the example (continued).

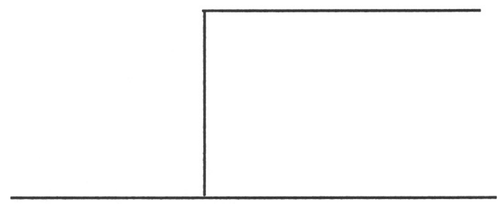
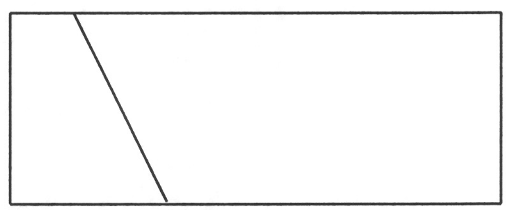
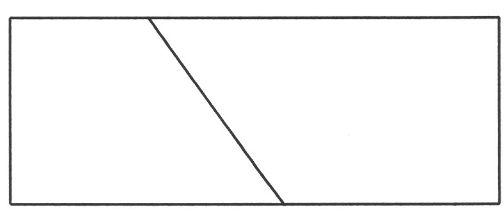
Design Dependent Parameter	Target Value	Algebraic Representation
Color capability	Greater Than or Equal To 256	$y = 0 \qquad x \le 256$ $y = 1 \qquad x \ge 256$  256
Skill level requirement (operate)	Very Low	$y = 1 \qquad 0 \le x \le 0.10$ $y = \frac{-20x}{3} + \frac{5}{3} \qquad 0.10 \le x \le 0.25$ $y = 0 \qquad x \ge 0.25$  Very Low
Skill level requirement (maintain/support)	Low or Lower	$y = 0 \qquad x \le 0.00$ $y = 1 \qquad 0.00 \le x \le 0.25$ $y = -4x + 2 \qquad 0.25 \le x \le 0.50$ $y = 0 \qquad x \ge 0.50$  Low or Lower

Table 4.6. Design dependent parameter target values for the example (continued).

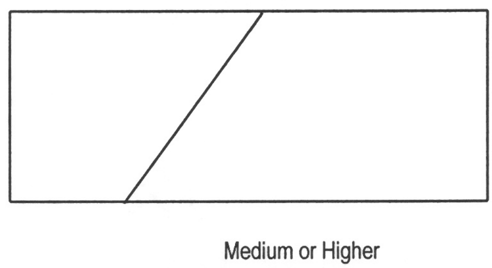
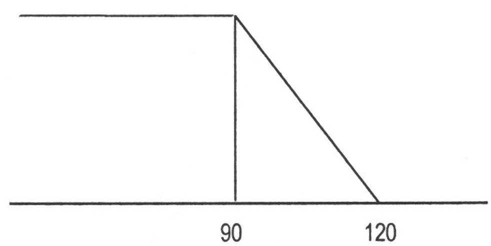
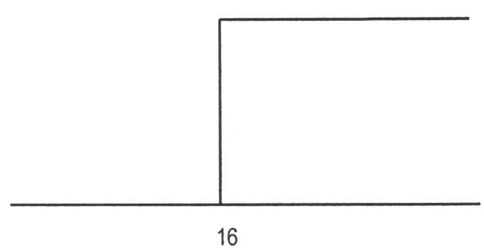
Design Dependent Parameter	Target Value	Algebraic Representation
Audio quality	Medium or Higher	$y = 0 \qquad x \le 0.25$ $y = 4x - 1 \qquad 0.25 \le x \le 0.50$ $y = 1 \qquad 0.50 \le x \le 1.0$ $y = 0 \qquad x \ge 1.0$ 
Communication initiation time	Less Than or Equal To 90 Seconds	$y = 1 \qquad x \le 90$ $y = 4 - \dfrac{x}{30} \qquad 90 \le x \le 120$ $y = 0 \qquad x \ge 120$ 
Number of members possible within group	Greater Than or Equal To 16	$y = 1 \qquad x \ge 16$ $y = 0 \qquad x \le 16$ 

Table 4.6. Design dependent parameter target values for the example (continued).

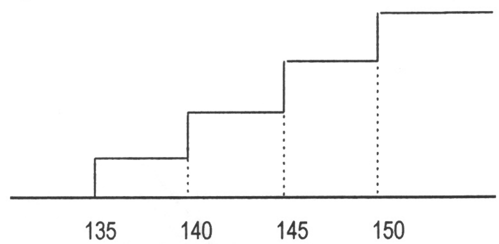
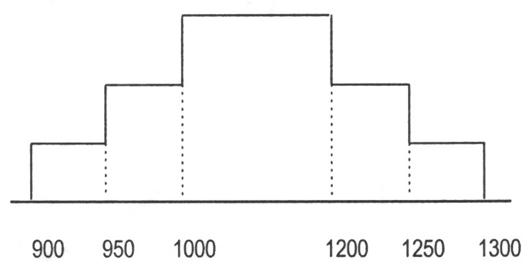
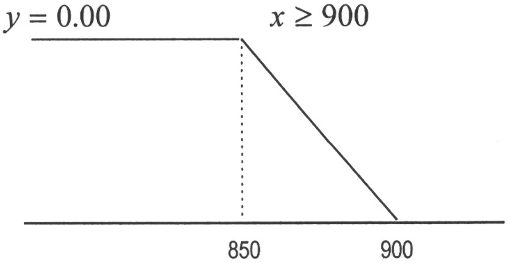
Design Dependent Parameter	Target Value	Algebraic Representation
Number of simultaneous group meetings	Greater Than 150	$y = 0.00 \quad x \le 135$ $y = 0.30 \quad 135 \le x \le 140$ $y = 0.50 \quad 140 \le x \le 145$ $y = 0.80 \quad 145 \le x \le 150$ $y = 1.00 \quad x \ge 150$ 
Maximum membership size	Between 1000 and 1200	$y = 0.00 \quad x \le 900$ *and* ≥ 1300 $y = 0.30 \quad 900 \le x \le 950$ *and* $1250 \le x \le 1300$ $y = 0.70 \quad 950 \le x \le 1000$ *and* $1200 \le x \le 1250$ $y = 1.00 \quad 1000 \le x \le 1200$ 
Design/production cost	Less Than $ 850 /unit/user	$y = 1.00 \quad x \le 850$ $y = 18 - \frac{x}{50} \quad 850 \le x \le 900$ $y = 0.00 \quad x \ge 900$ 

Table 4.6. Design dependent parameter target values for the example (continued).

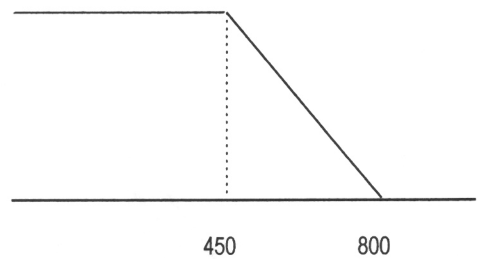
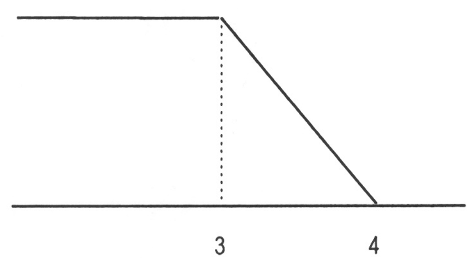
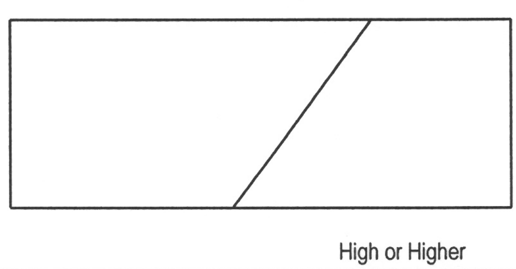
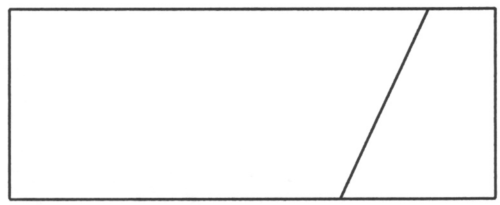
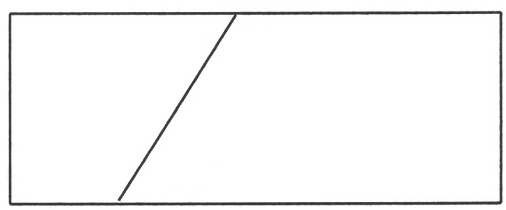
Design Dependent Parameter	Target Value	Algebraic Representation
Operating cost	Less Than \$450 /unit/user/month	$y = 0 \qquad x \geq 450$ $y = \frac{16}{7} - \frac{x}{350} \qquad 400 \leq x \leq 450$ $y = 1 \qquad x \leq 400$ 
Support/maintenance cost	Less Than \$3 /unit/users/month	$y = 0 \qquad x \geq 4$ $y = 4 - x \qquad 3 \leq x \leq 4$ $y = 1 \qquad x \leq 3$ 
Safety	High or Higher	$y = 0 \qquad x \leq 0.50$ $y = 4x - 2 \qquad 0.50 \leq x \leq 0.75$ $y = 1 \qquad 0.75 \leq x \leq 1.00$ $y = 0 \qquad x \geq 1.00$ 

Table 4.6. Design dependent parameter target values for the example (continued).

Design Dependent Parameter	Target Value	Algebraic Representation
Disposability	Very High	$y = 0 \quad x \le 0.75$ $y = \frac{20x}{3} - \frac{15}{3} \quad 0.75 \le x \le 0.90$ $y = 1 \quad 0.90 \le x \le 1.00$ $y = 0 \quad x \ge 1.00$  Very High
Communication security	Medium or Higher	$y = 0 \quad x \le 0.25$ $y = 4x - 1 \quad 0.25 \le x \le 0.50$ $y = 1 \quad 0.50 \le x \le 1.0$ $y = 0 \quad x \ge 1.0$  Medium or Higher

that integration of the analysis and evaluation activities with the underlying system engineering process and use of appropriate design methods and tools "allows" a strong customer/consumer focus throughout.

Design dependent parameters, along with the associated target values and tolerances, represent the feasible design space. This design space may be visualized through the development of a multi-axis radial chart as is illustrated in Figure 4.18. This figure shows eight design dependent parameters with each axis representing a separate design dependent parameter (expressed in appropriate units). The shading between the axes is keyed to the preference/requirement profiles (also shown on the figure) of the design dependent parameters. Further, the darker the shading, stronger is the associated preference. Accordingly, for a crisp requirement, the shading converges to a single point on the applicable axis, as shown in Figure 4.18.

Utilizing a similar approach, Figure 4.19 represents the feasible design space for the remote conferencing case-study. To provide greater visibility to the more critical design dependent parameters in this example, the parameters have been divided into three groups depending upon their criticality (with the six most critical represented in Figure 4.19). It is this feasible design space which dictates the feasibility of potential conceptual design solutions (discussed in Chapter 5), and their ultimate desirability (discussed in Chapter 6).

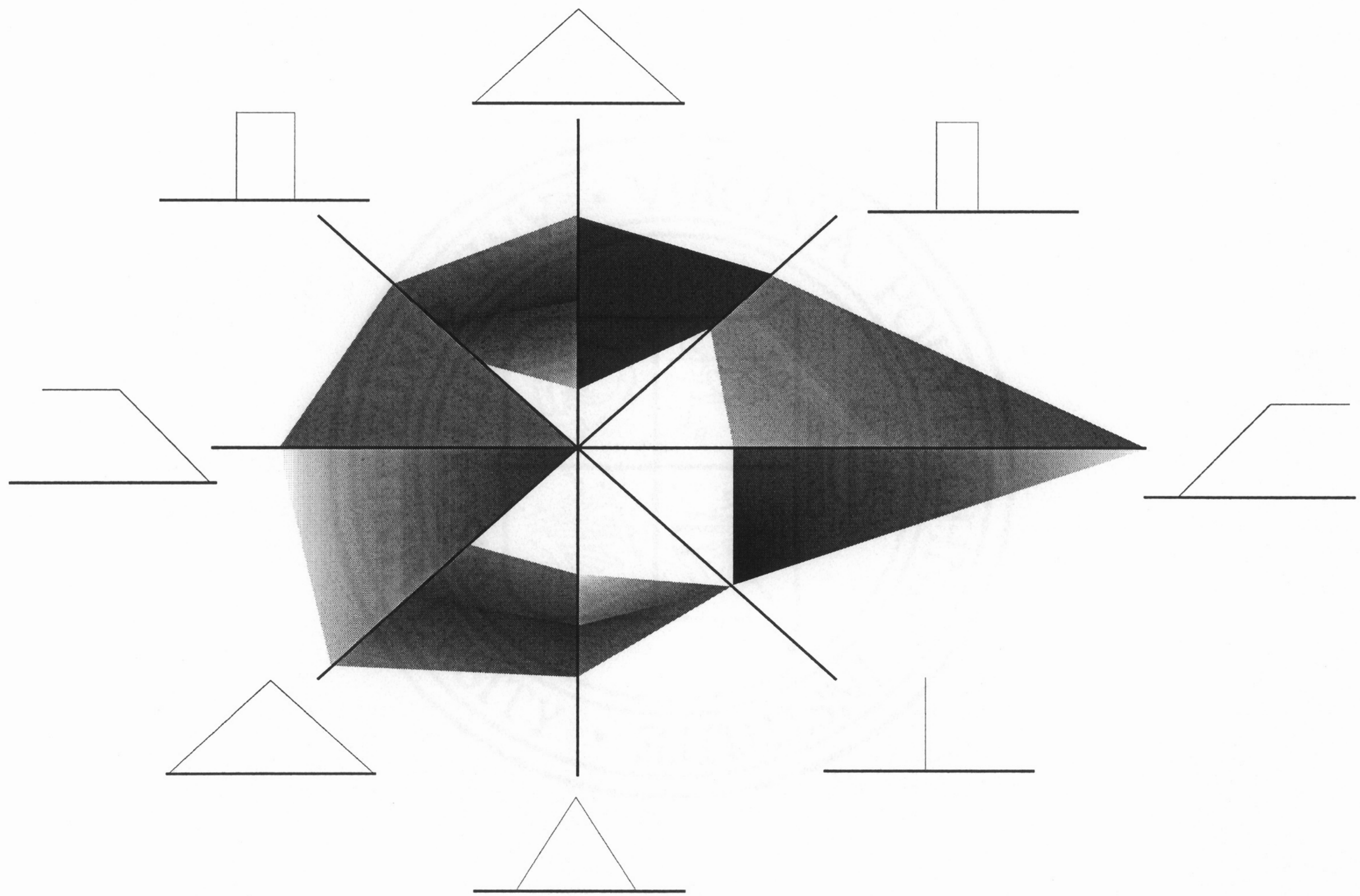


Figure 4.18. The fuzzy feasible design space.

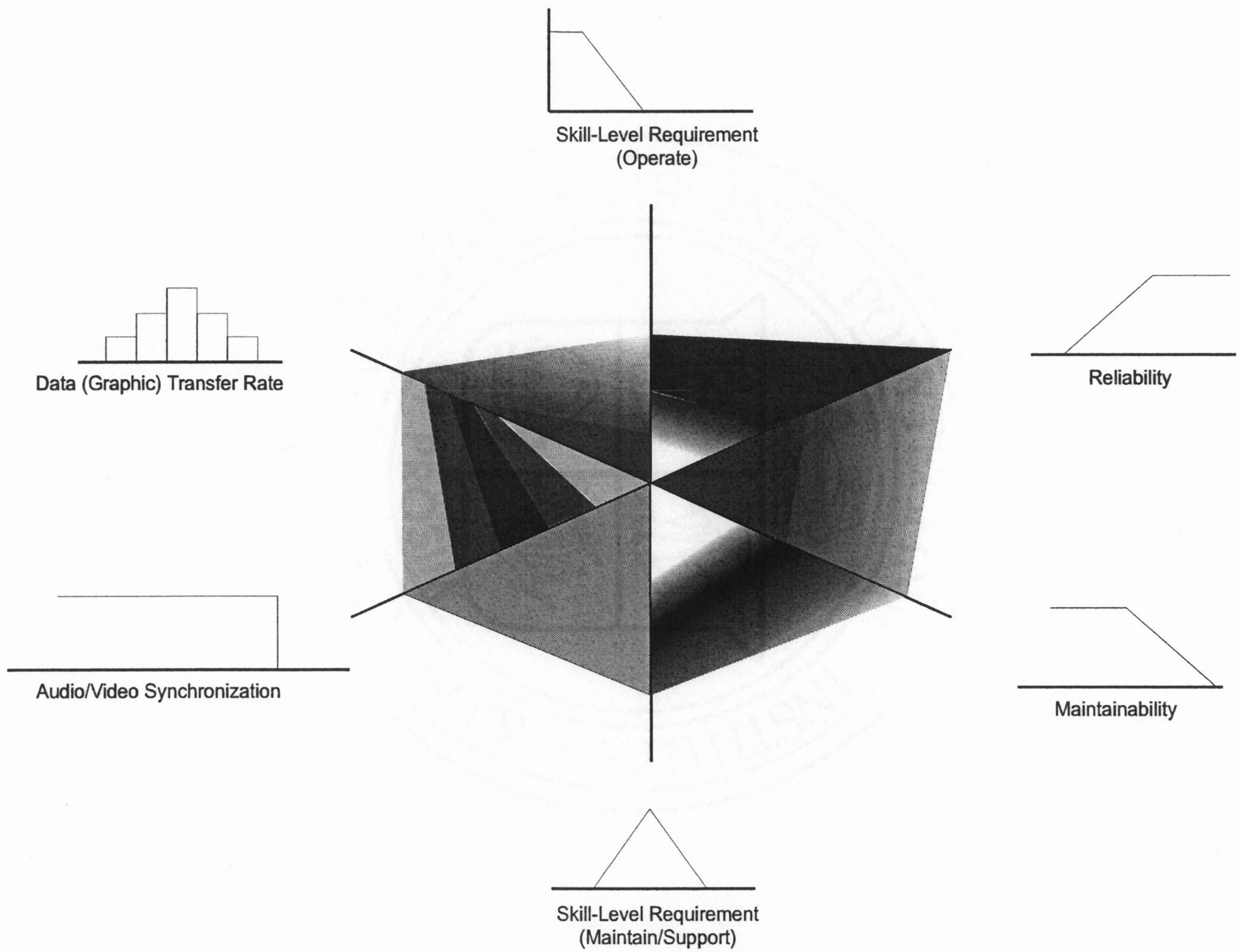


Figure 4.19. Fuzzy feasible design space for the conferencing example.

CHAPTER 5

CONCEPTUAL DESIGN EVALUATION METHODOLOGY - PHASE II: SELECTING FEASIBLE CONCEPTUAL SOLUTIONS

The second phase of the conceptual system design evaluation methodology is developed in this chapter. Activities and steps which constitute this phase are depicted in Figure 5.1. The remote conferencing example is developed further to illustrate and clarify the constituent steps. Emphasis in this phase is on the feasibility of candidate conceptual designs. This phase correlates very closely with the controlled convergence stage in Pugh's concept generation and evaluation methodology [Pugh, 1990]. In fact, the iteration of steps in Figure 5.1 is also consistent with Pugh's methodology. It involves the

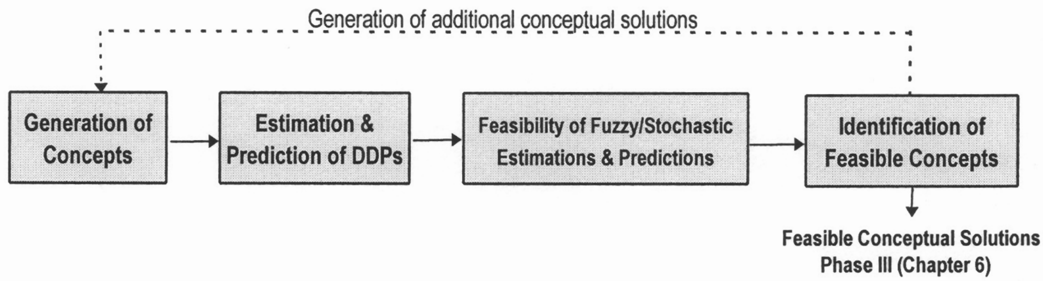


Figure 5.1. Activities comprising Phase II of the evaluation methodology.

iterative and controlled convergent and divergent processes in the generation and selection of the preferred conceptual design solution(s) (refer to Figure 2.8).

Both fuzzy and stochastic predictions and estimations are addressed in the analysis of concept feasibility. Stochastic measures are fuzzified to facilitate this analysis by normalizing the probability density function. A mechanism has been developed to weight areas of overlap and non-overlap between the preference and anticipation profiles. This mechanism is then utilized to provide insight into the feasibility of alternatives in terms of the difference between the required and predicted/estimated values of design dependent parameters. Further, the mechanism "allows" flexibility by setting different feasibility constraints on individual parameters. Accordingly, a strict feasibility requirement may be imposed on critical parameters but be relaxed for others.

An explicit measure of the "degree of feasibility" highlights the specific weaknesses and strengths of design concepts. These indicators can then be used to guide designers in their efforts to improve an existing conceptual design or to seek a new concept.

5.1. GENERATING CONCEPTUAL SYSTEM DESIGNS

Synthesis of conceptual design solutions is considered beyond the scope of this research and will not be addressed. However, numerous research groups within industry and academia (as discussed in Chapter 2, Section 2.1.2., and as is evident from the relevant literature) are making significant progress towards the improvement and formalization of this aspect of conceptual design. These on-going research endeavors may be classified into two categories. The first group is investigating the human thought processes during this stage of design in an effort to "capture", and then automate, the process. The second group is addressing the development of environments to stimulate and even "encourage" the innovative human thought process. Recent developments in high-speed and multi-media (simultaneous audio, video, and olfactory stimuli) capabilities have provided an impetus to this research which is often characterized by its highly subjective and "soft" nature.

In order to ensure completeness and to illustrate the application of the overall methodology, three conceptual solutions have been assumed for the remote conferencing example.[17] Tables 5.1, 5.2, and 5.3 give brief descriptions of the candidate solutions. These conceptual designs will be analyzed and evaluated in greater detail in subsequent sections as the methodology is developed.

5.2. PREDICTING AND ESTIMATING DESIGN DEPENDENT PARAMETERS

Prediction and estimation of design dependent parameters is a significant step when analyzing candidate conceptual design feasibility. However, a treatise on the specific processes and methods used to predict and estimate design dependent parameter values during the nascent stages of system design is not included. It is considered beyond the scope of this research. However, a survey of the relevant literature suggests that the techniques most often used to predict and estimate design dependent parameter values (during early design phases)

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[17] These conceptual solutions were developed through discussions with Dr. Scott F. Midkiff in the Bradley Department of Electrical Engineering at Virginia Polytechnic Institute and State University.

include parametric approaches, standards and nomographs, analogy and complexity factors, and expert judgment.

Depending upon the technique and methods utilized, design dependent parameter predictions and estimations for candidate conceptual designs may be expressed as fuzzy or as stochastic measures. The subsequent feasibility analysis is generally similar in both situations. A few additional steps are required in the case of stochastic measures in order to fuzzify them. Both are discussed and illustrated in detail in the following sub-sections.

It is pertinent to note that relative priorities of design dependent parameters impact the desirability of alternatives and influence the ultimate selection process. However, since Phase II of the evaluation methodology is focused on the delineation of feasible alternatives only (so that the rigor of the evaluation activity is not wasted on infeasible alternatives), handling of relative priorities has been deferred to Phase III of the process (addressed in Chapter 6).

This stage of the evaluation methodology is focused on Blocks 3 and 1 (and more significantly on the link between these two blocks) of the morphology depicted in Figure 1.3. Design dependent parameter predictions, as they pertain to the three candidate conceptual solutions, are enumerated in Tables 5.1, 5.2, and 5.3. For the purposes of illustrating the methodology, predicted values are assumed to be either deterministic or fuzzy.

5.3. FEASIBILITY ANALYSIS FOR FUZZY PREDICTIONS AND ESTIMATIONS

This section addresses predictions and estimations of applicable design dependent parameters expressed as fuzzy measures, and represented as "anticipation" profiles. In order to facilitate a comparative analysis, related anticipation and preference profiles are mapped together. As an illustration, Figure 5.2 depicts the requirement profile for system *Reliability*, stated as

Greater Than 40,000 hours. Predictions of this design dependent parameter for the three conceptual solutions expressed as fuzzy measures (anticipation profiles) are also shown in Figure 5.2.

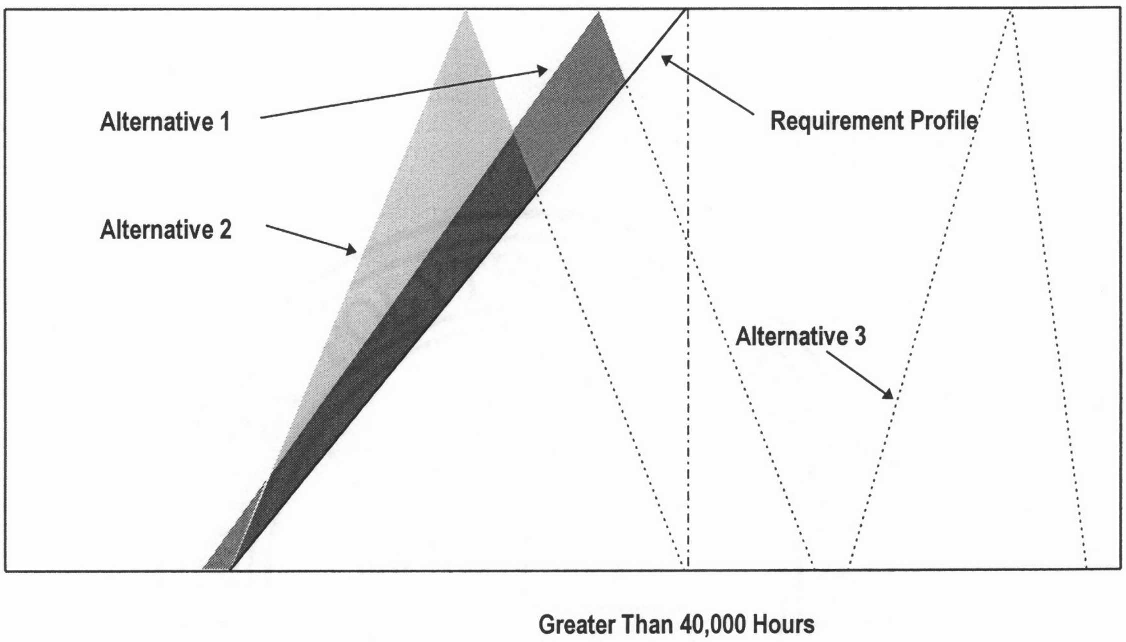


Figure 5.2. Feasibility assessment of fuzzy predictions and estimations.

In any realistic design activity designers have to contend with multiple design dependent parameters. Attention is focused (for the moment) on a singular design dependent parameter (*Reliability*), the associated requirement, and its predicted values with regard to the three conceptual solutions being analyzed. Mapping the predicted or anticipated profiles, along with the required or preferred profile, facilitates a visual comparison. The next step is to decide whether the three conceptual designs fall in the feasible design space with regard to *Reliability*.

Alternative 3 satisfies the design requirement to *Reliability,* and falls completely within the feasible system design space. This is shown in Figure 5.2.

Table 5.1. First design concept and associated predictions and estimations.

Conceptual Design 1:

The first concept pertains to implementation of the system as a PC-based, desktop, video conferencing capability which utilizes the public switch telephone network for communications.

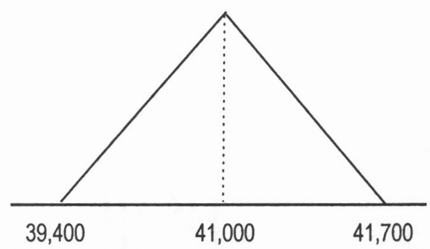
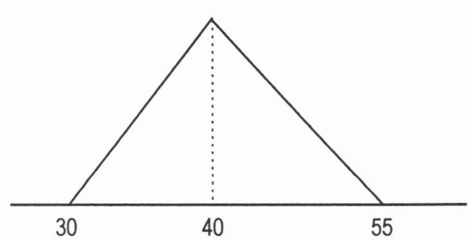
Design Dependent Parameter	Predicted Value	Algebraic Representation
Reliability	Approximately 41,000 hours	$y = 0 \quad x \le 39{,}400$ $y = \frac{x}{1600} - \frac{197}{8} \quad 39{,}400 \le x \le 41{,}000$ $y = \frac{417}{7} - \frac{x}{700} \quad 41{,}000 \le x \le 41{,}700$ $y = 0 \quad x \ge 41{,}700$ 
Maintainability	Approximately 40 minutes	$y = 0 \quad x \le 30$ $y = \frac{x}{10} - 3 \quad 30 \le x \le 40$ $y = \frac{11}{3} - \frac{x}{15} \quad 40 \le x \le 55$ $y = 0 \quad x \ge 55$ 

Table 5.1. First design concept and associated predictions and estimations (continued).

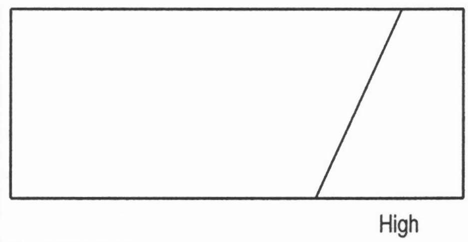
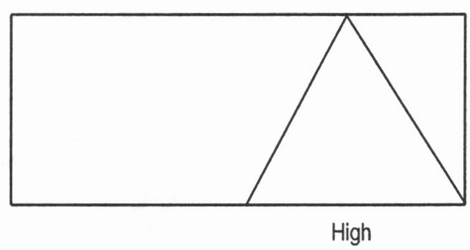
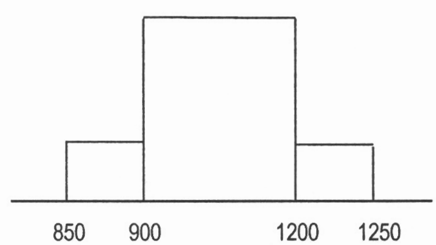
Design Dependent Parameter	Predicted Value	Algebraic Representation
Environmental compliance	Very High	$y = 0 \qquad x \le 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \qquad 0.75 \le x \le 0.90$ $y = 1 \qquad 0.90 \le x \le 1.0$ 
Visual quality	High	$y = 0 \qquad x \le 0.50$ $y = \frac{5}{2}x - \frac{5}{4} \qquad 0.50 \le x \le 0.90$ $y = 10 - 10x \qquad 0.90 \le x \le 1.00$ $y = 0 \qquad x \ge 1.00$ 
Data (graphic) transfer rate	Approximately 1000	$y = 0.00 \qquad x \le 850$ *and* ≥ 1250 $y = 0.20 \qquad 850 \le x \le 900$ *and* $1200 \le x \le 1250$ $y = 1.00 \qquad 900 \le x \le 1200$ 

Table 5.1. First design concept and associated predictions and estimations (continued).

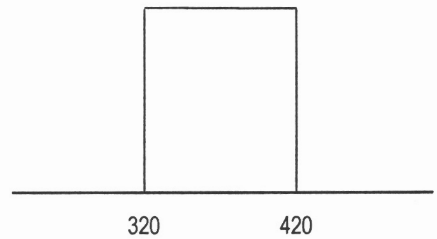
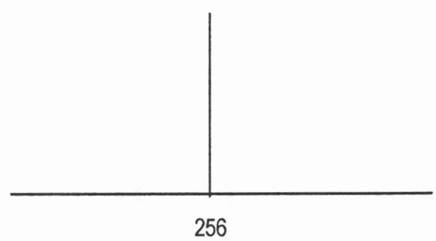
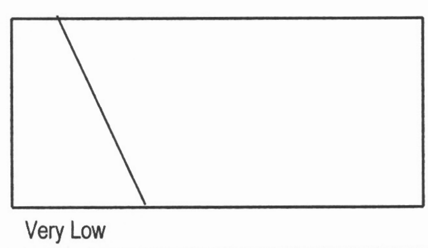
Design Dependent Parameter	Predicted Value	Algebraic Representation
Audio / video synchronization	Between 320 and 420	$y = 0.00 \quad x \le 320 \; and \; \ge 420$ $y = 1.00 \quad 320 \le x \le 420$ 
Color capability	256	$y = 0.00 \quad x < 256 \; and \; > 256$ $y = 1.00 \quad x = 256$ 
Skill level requirement (operate)	Very Low	$y = 0 \quad x \le 0.00$ $y = 1 \quad 0.00 \le x \le 0.15$ $y = \frac{5}{2} - 10x \quad 0.15 \le x \le 0.25$ $y = 0 \quad x \ge 0.25$ 

Table 5.1. First design concept and associated predictions and estimations (continued).

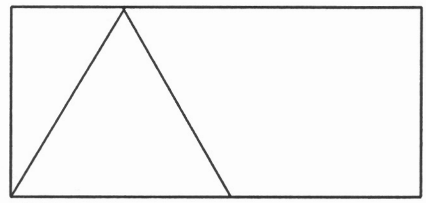
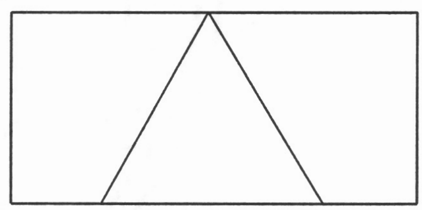
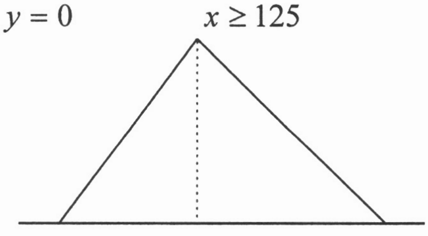
Design Dependent Parameter	Predicted Value	Algebraic Representation
Skill level requirement (maintain / support)	Low	$y=0 \quad x \le 0.00$ $y=4x \quad 0.00 \le x \le 0.25$ $y=-4x+2 \quad 0.25 \le x \le 0.50$ $y=0 \quad x \ge 0.50$  Low
Audio quality	Medium	$y=0 \quad x \le 0.25$ $y=\frac{20}{3}x-\frac{5}{3} \quad 0.25 \le x \le 0.40$ $y=\frac{15}{7}-\frac{20}{7}x \quad 0.40 \le x \le 0.75$ $y=0 \quad x \ge 0.75$  Medium
Communication initiation time	Approximately 90	$y=0 \quad x \le 60$ $y=\frac{1}{30}x-2 \quad 60 \le x \le 90$ $y=\frac{25}{7}-\frac{x}{35} \quad 90 \le x \le 125$ $y=0 \quad x \ge 125$ 

Table 5.1. First design concept and associated predictions and estimations (continued).

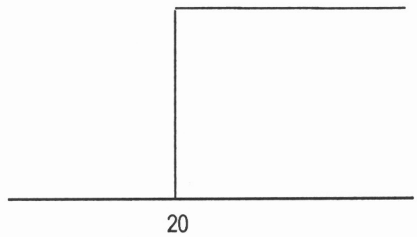
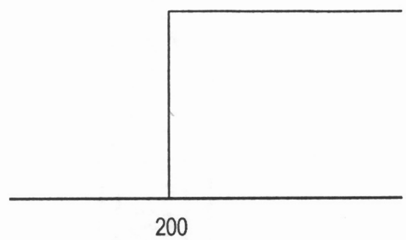
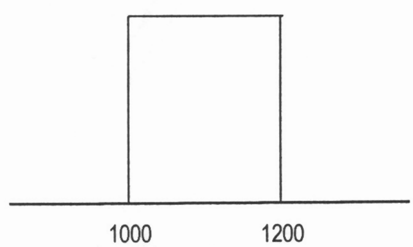
Design Dependent Parameter	Predicted Value	Algebraic Representation
Numbers of members possible within group	Greater Than 20	$y = 0.00 \quad x \leq 20$ $y = 1.00 \quad x \geq 20$ 
Number of simultaneous group meetings	Greater than 200	$y = 0.00 \quad x \leq 200$ $y = 1.00 \quad x \geq 200$ 
Maximum membership size	Between 1000 and 1200	$y = 0.00 \quad x \leq 1000 \text{ and } x \geq 1200$ $y = 1.00 \quad 1000 \leq x \leq 1200$ 

Table 5.1. First design concept and associated predictions and estimations (continued).

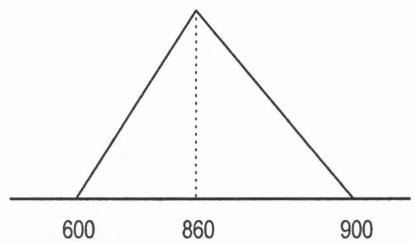
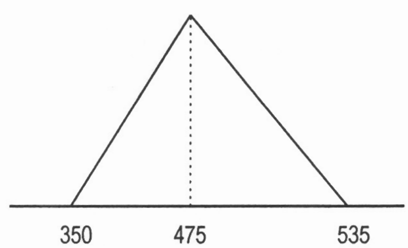
Design Dependent Parameter	Predicted Value	Algebraic Representation
Design / production cost	Approximately 860	$y = 0 \qquad x \leq 600$ $y = \frac{x}{260} - \frac{30}{13} \qquad 600 \leq x \leq 860$ $y = \frac{45}{2} - \frac{x}{40} \qquad 860 \leq x \leq 900$ $y = 0 \qquad x \geq 900$ 
Operating cost	Approximately 475	$y = 0 \qquad x \leq 350$ $y = \frac{x}{125} - \frac{14}{5} \qquad 350 \leq x \leq 475$ $y = \frac{107}{12} - \frac{x}{60} \qquad 475 \leq x \leq 535$ $y = 0 \qquad x \geq 535$ 

Table 5.1. First design concept and associated predictions and estimations (continued).

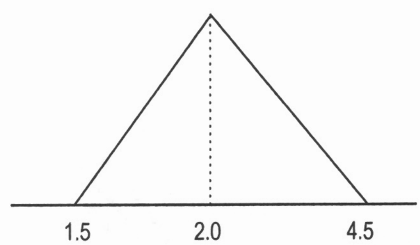
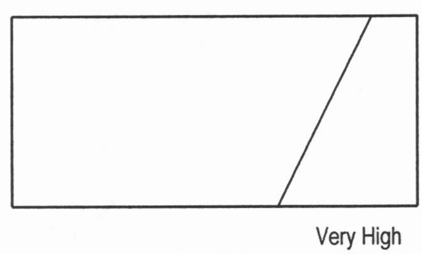
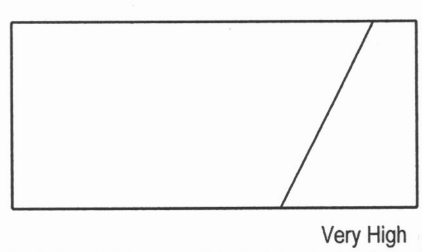
Design Dependent Parameter	Predicted Value	Algebraic Representation
Support / maintenance cost		$y = 0 \quad x \le 1.5$ $y = 2x - 3 \quad 1.5 \le x \le 2.0$ $y = \frac{9}{5} - \frac{2x}{5} \quad 2.0 \le x \le 4.5$ $y = 0 \quad x \ge 4.5$ 
Safety	Very High	$y = 0 \quad x \le 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \quad 0.75 \le x \le 0.90$ $y = 1 \quad 0.90 \le x \le 1.0$ $y = 0 \quad x \ge 1.0$ 
Disposability	Very High	$y = 0 \quad x \le 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \quad 0.75 \le x \le 0.90$ $y = 1 \quad 0.90 \le x \le 1.0$ $y = 0 \quad x \ge 1.0$ 

Table 5.1. First design concept and associated predictions and estimations (continued).

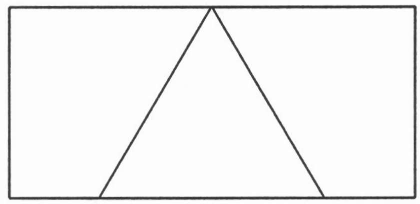
<table>
<tr><th>Design Dependent Parameter</th><th>Predicted Value</th><th>Algebraic Representation</th></tr>
<tr><td>Communication security</td><td>Medium</td><td>$y = 0 \qquad x \le 0.25$
$y = 4x - 1 \qquad 0.25 \le x \le 0.50$
$y = -4x + 3 \qquad 0.50 \le x \le 0.75$
$y = 0 \qquad x \ge 0.75$

Medium</td></tr>
</table>

Table 5.2. Second design concept and associated predictions and estimations.

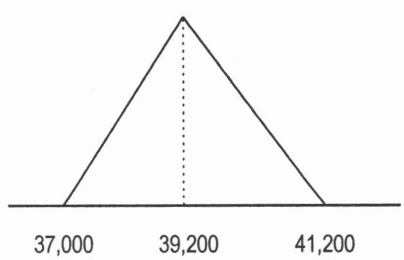
<table>
<tr><td colspan="3">Conceptual Design 2:
A shared video-audio conferencing capability per site (40 people at the same geographical site). Computer-based and utilizing the public switch telephone network for communications.</td></tr>
<tr><th>Design Dependent Parameter</th><th>Predicted Value</th><th>Algebraic Representation</th></tr>
<tr><td>Reliability</td><td>Approximately
39,200 hours</td><td>$y=0 \qquad x \le 37{,}000$
$y=\frac{x}{2{,}200}-\frac{185}{11} \qquad 37{,}000 \le x \le 39{,}200$
$y=\frac{103}{5}-\frac{x}{2{,}000} \qquad 39{,}200 \le x \le 41{,}200$
$y=0 \qquad x \ge 41{,}200$
</td></tr>
</table>

Table 5.2. Second design concept and associated predictions and estimations (continued).

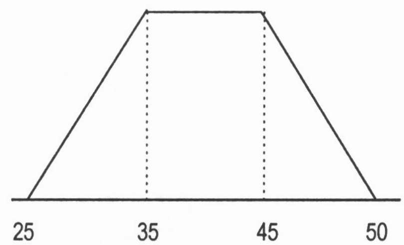
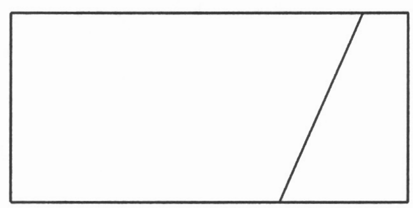
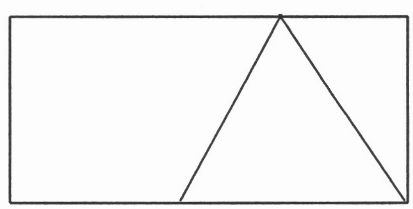
Design Dependent Parameter	Predicted Value	Algebraic Representation
Maintainability	Between 35 and 45 minutes	$y=0 \quad x\le 25$ $y=\frac{x}{10}-\frac{5}{2} \quad 25\le x\le 35$ $y=1 \quad 35\le x\le 45$ $y=10-\frac{x}{5} \quad 45\le x\le 50$ $y=0 \quad x\ge 50$ 
Environmental compliance	Very High	$y=0 \quad x\le 0.75$ $y=\frac{20x}{5}-\frac{15}{3} \quad 0.75\le x\le 0.90$ $y=1 \quad 0.90\le x\le 1.0$  Very High
Visual quality	High	$y=0 \quad x\le 0.50$ $y=\frac{5}{2}x-\frac{5}{4} \quad 0.50\le x\le 0.90$ $y=10-10x \quad 0.90\le x\le 1.00$  High

Table 5.2. Second design concept and associated predictions and estimations (continued).

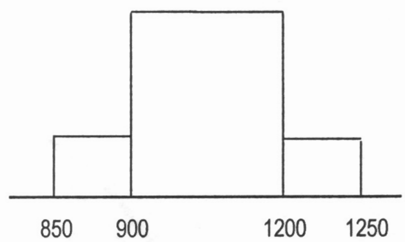
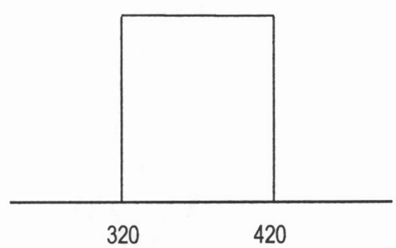
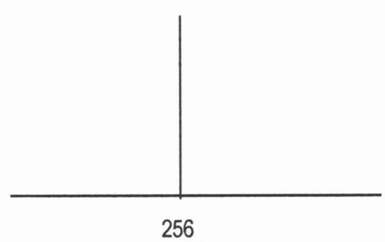
Design Dependent Parameter	Predicted Value	Algebraic Representation
Data (graphic) transfer rate	Approximately 1000	$y = 0.00 \quad x \leq 850 \ \textit{and} \ \geq 1250$ $y = 0.20 \quad 850 \leq x \leq 900 \ \textit{and}$ $1200 \leq x \leq 1250$ $y = 1.00 \quad 900 \leq x \leq 1200$ 
Audio / video synchronization	Between 320 and 420	$y = 0.00 \quad x \leq 320 \ \textit{and} \ \geq 420$ $y = 1.00 \quad 320 \leq x \leq 420$ 
Color capability	256	$y = 0.00 \quad x < 256 \ \textit{and} \ > 256$ $y = 1.00 \quad x = 256$ 

Table 5.2. Second design concept and associated predictions and estimations (continued).

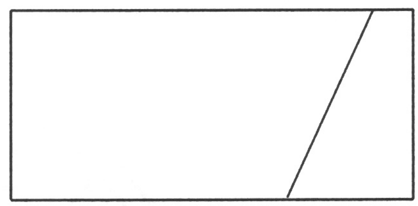
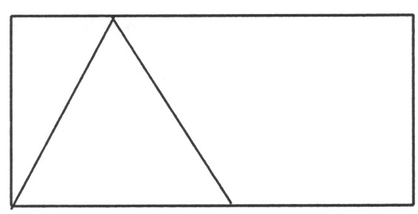
Design Dependent Parameter	Predicted Value	Algebraic Representation
Skill level requirement (operate)	Very Low	$y = 0 \quad x \le 0.00$ $y = 1 \quad 0.00 \le x \le 0.13$ $y = \frac{25}{12} - \frac{25}{3}x \quad 0.13 \le x \le 0.25$ $y = 0 \quad x \ge 0.25$  Very Low
Skill level requirement (maintain / support)	Low	$y = 0 \quad x \le 0.00$ $y = \frac{10}{3}x \quad 0.00 \le x \le 0.30$ $y = \frac{5}{2} - 5x \quad 0.30 \le x \le 0.50$ $y = 0 \quad x \ge 0.50$  Low

Table 5.2. Second design concept and associated predictions and estimations (continued).

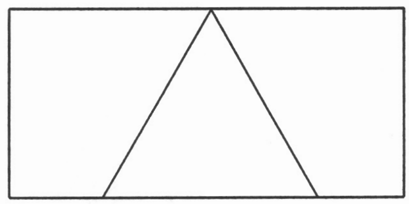
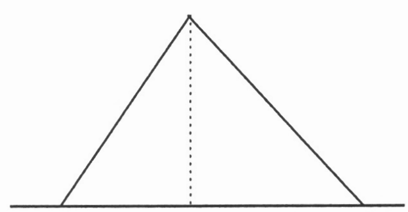
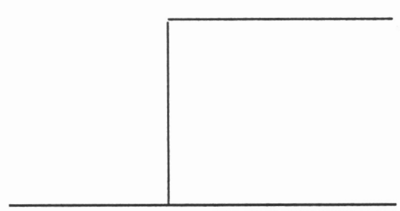
Design Dependent Parameter	Predicted Value	Algebraic Representation
Audio quality	Medium	$y = 0 \quad x \le 0.25$ $y = 5x - \frac{5}{4} \quad 0.25 \le x \le 0.45$ $y = \frac{5}{2} - \frac{10}{3}x \quad 0.45 \le x \le 0.75$ $y = 1 \quad x \ge 0.75$  Medium
Communication initiation time	Approximately 90	$y = 0 \quad x \le 60$ $y = \frac{1}{30}x - 2 \quad 60 \le x \le 90$ $y = 3 - \frac{x}{45} \quad 90 \le x \le 135$ $y = 0 \quad x \ge 135$  60 90 135
Number of members possible within group	Greater Than 20	$y = 0.00 \quad x \le 20$ $y = 1.00 \quad x \ge 20$  20

Table 5.2. Second design concept and associated predictions and estimations (continued).

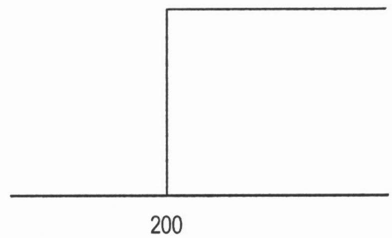
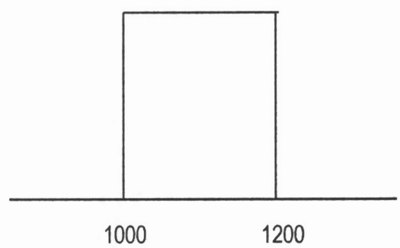
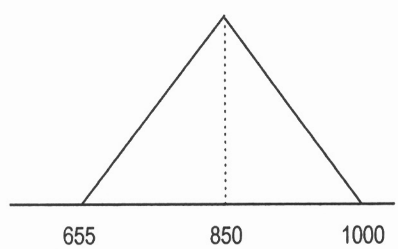
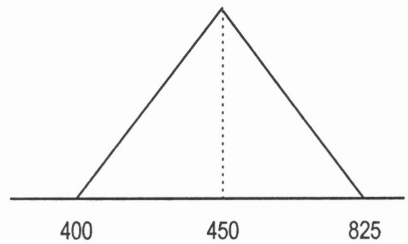
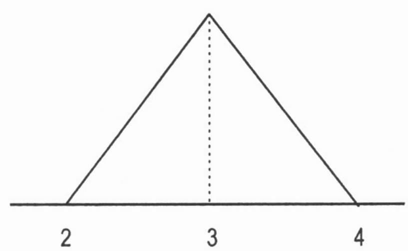
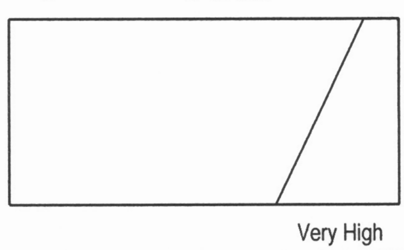
Design Dependent Parameter	Predicted Value	Algebraic Representation
Number of simultaneous group meetings	Greater Than 200	$y = 0.00 \quad x \le 200$ $y = 1.00 \quad x \ge 200$ 
Maximum membership size	Between 1000 and 1200	$y = 0.00 \quad x \le 1000 \text{ and } x \ge 1200$ $y = 1.00 \quad 1000 \le x \le 1200$ 
Design / production cost	Approximately 850	$y = 0 \quad x \le 655$ $y = \frac{x}{195} - \frac{131}{39} \quad 655 \le x \le 850$ $y = \frac{20}{3} - \frac{x}{150} \quad 850 \le x \le 1000$ $y = 0 \quad x \ge 1000$ 

Table 5.2. Second design concept and associated predictions and estimations (continued).

<table>
<tr><th>Design Dependent Parameter</th><th>Predicted Value</th><th>Algebraic Representation</th></tr>
<tr><td>Operating cost</td><td>Approximately 450</td><td>
$$
\begin{array}{ll}
y = 0 & x \le 400 \\
y = \dfrac{x}{50} - 8 & 400 \le x \le 450 \\
y = \dfrac{11}{5} - \dfrac{x}{375} & 450 \le x \le 825 \\
y = 0 & x \ge 825
\end{array}
$$


</td></tr>
<tr><td>Support / maintenance cost</td><td>Approximately 2</td><td>
$$
\begin{array}{ll}
y = 0 & x \le 2.0 \\
y = x - 2 & 2.0 \le x \le 3.0 \\
y = 4 - x & 3.0 \le x \le 4.0 \\
y = 0 & x \ge 4.0
\end{array}
$$


</td></tr>
<tr><td>Safety</td><td>Very High</td><td>
$$
\begin{array}{ll}
y = 0 & x \le 0.75 \\
y = \dfrac{20x}{5} - \dfrac{15}{3} & 0.75 \le x \le 0.90 \\
y = 1 & 0.90 \le x \le 1.0 \\
y = 0 & x \ge 1.0
\end{array}
$$


</td></tr>
</table>

Table 5.2. Second design concept and associated predictions and estimations (continued).

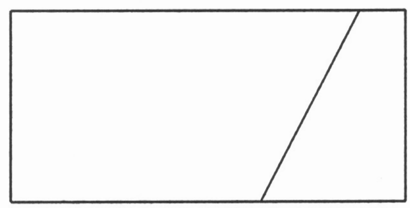
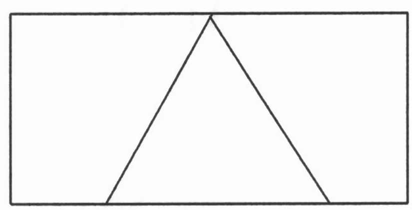
Design Dependent Parameter	Predicted Value	Algebraic Representation
Disposability	Very High	$y = 0 \quad x \leq 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \quad 0.75 \leq x \leq 0.90$ $y = 1 \quad 0.90 \leq x \leq 1.0$ $y = 0 \quad x \geq 1.0$  Very High
Communication security	Medium	$y = 0 \quad x \leq 0.25$ $y = 4x - 1 \quad 0.25 \leq x \leq 0.50$ $y = -4x + 3 \quad 0.50 \leq x \leq 0.75$ $y = 0 \quad x \geq 0.75$  Medium

Table 5.3. Third design concept and associated predictions and estimations.

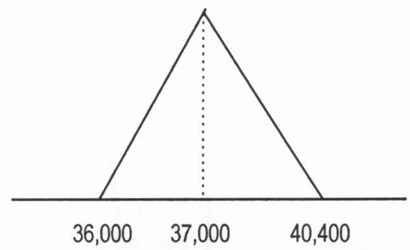
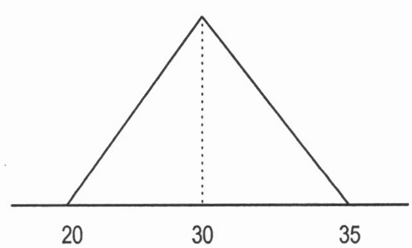
Conceptual Design 3: Communication using telephone, facsimile, and electronic mail linked in the existing manner to remotely located persons.		
Design Dependent Parameter	**Predicted Value**	**Algebraic Representation**
Reliability	Approximately 37,000 hours	$y=0 \quad x\leq 36{,}000$ $y=\dfrac{x}{1{,}000}-3{,}600 \quad 36{,}000\leq x\leq 37{,}000$ $y=\dfrac{202}{17}-\dfrac{x}{3{,}400} \quad 37{,}000\leq x\leq 40{,}400$ $y=0 \quad x\geq 40{,}400$ 
Maintainability	Approximately 30 minutes	$y=0 \quad x\leq 20$ $y=\dfrac{x}{10}-2 \quad 20\leq x\leq 30$ $y=7-\dfrac{x}{5} \quad 30\leq x\leq 35$ $y=0 \quad x\geq 35$ 

Table 5.3. Third design concept and associated predictions and estimations (continued).

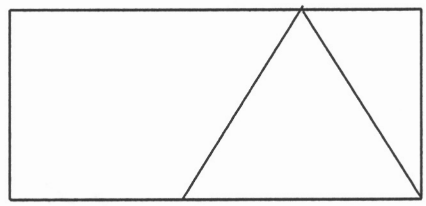
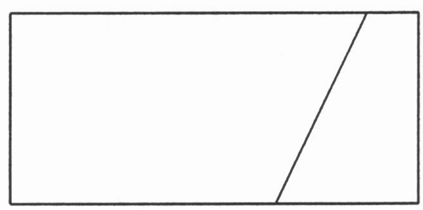
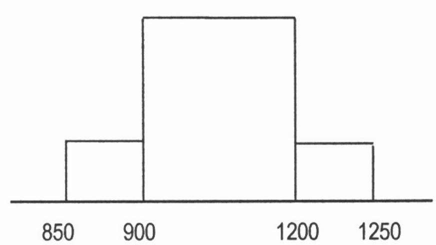
Design Dependent Parameter	Predicted Value	Algebraic Representation
Environmental compliance	High	$y = 0 \quad x \le 0.50$ $y = 4x - 2 \quad 0.50 \le x \le 0.75$ $y = -4x + 4 \quad 0.75 \le x \le 1.00$ $y = 0 \quad x \ge 1.00$  High
Visual quality	Very High	$y = 0 \quad x \le 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \quad 0.75 \le x \le 0.90$ $y = 1 \quad 0.90 \le x \le 1.0$  Very High
Data (graphic) transfer rate	Approximately 1100	$y = 0.00 \quad x \le 850 \; and \; \ge 1250$ $y = 0.20 \quad 850 \le x \le 900 \; and$ $1200 \le x \le 1250$ $y = 1.00 \quad 900 \le x \le 1200$ 

Table 5.3. Third design concept and associated predictions and estimations (continued).

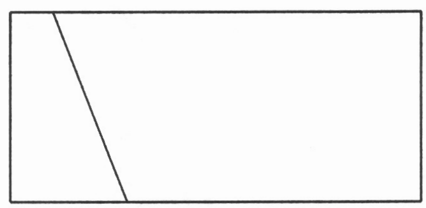
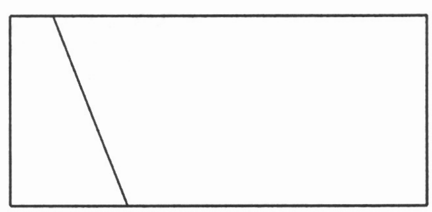
Design Dependent Parameter	Predicted Value	Algebraic Representation
Audio / video synchronization	Optimum	ZERO milliseconds
Color capability	Optimum	Human Capacity>>256
Skill level requirement (operate)	Very Low	$y = 1 \quad 0 \le x \le 0.10$ $y = \frac{-20x}{3} + \frac{5}{3} \quad 0.10 \le x \le 0.25$ $y = 0 \quad x \ge 0.25$  Very Low
Skill level requirement (maintain / support)	Very Low	$y = 1 \quad 0 \le x \le 0.10$ $y = \frac{-20x}{3} + \frac{5}{3} \quad 0.10 \le x \le 0.25$ $y = 0 \quad x \ge 0.25$  Very Low

Table 5.3. Third design concept and associated predictions and estimations (continued).

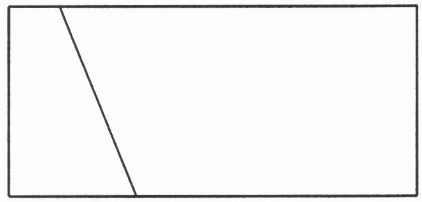
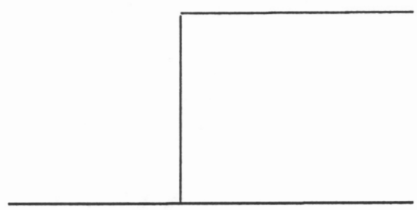
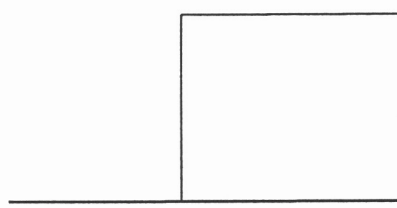
Design Dependent Parameter	Predicted Value	Algebraic Representation
Audio quality	Very High	$y = 0 \quad x \leq 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \quad 0.75 \leq x \leq 0.90$ $y = 1 \quad 0.90 \leq x \leq 1.0$  Very High
Communication initiation time	Very High	OUT OF BOUNDS
Number of members possible within group	Greater Than 20	$y = 0.00 \quad x \leq 20$ $y = 1.00 \quad x \geq 20$  20
Number of simultaneous group meetings	Greater Than 200	$y = 0.00 \quad x \leq 200$ $y = 1.00 \quad x \geq 200$  200

Table 5.3. Third design concept and associated predictions and estimations (continued).

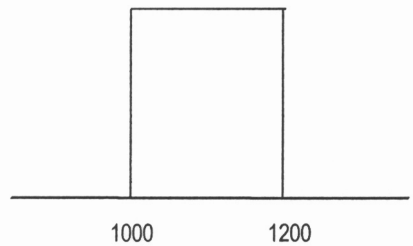
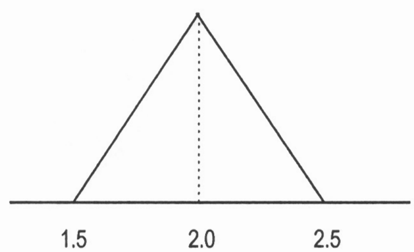
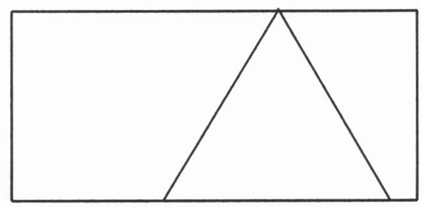
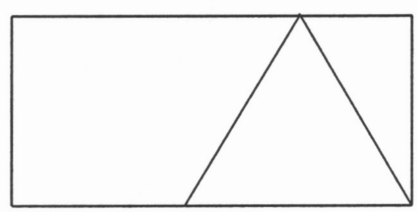
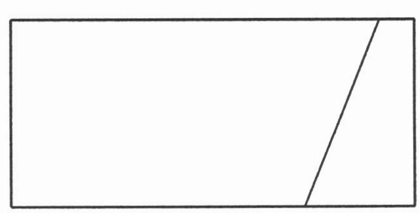
Design Dependent Parameter	Predicted Value	Algebraic Representation
Maximum membership size	Between 1000 and 1200	$y = 0.00 \quad x \leq 1000 \textit{ and } x \geq 1200$ $y = 1.00 \quad 1000 \leq x \leq 1200$ 
Design / production cost	Non Existent	EXISTING INFRASTRUCTURE
Operating cost	Very High	OUT OF BOUNDS
Support / maintenance cost	Approximately 2	$y = 0 \quad x \leq 1.5$ $y = 2x - 3 \quad 1.5 \leq x \leq 2.0$ $y = 5 - 2x \quad 2.0 \leq x \leq 2.5$ $y = 0 \quad x \geq 2.5$ 

Table 5.3. Third design concept and associated predictions and estimations (continued).

Design Dependent Parameter	Predicted Value	Algebraic Representation
Safety	High	$y = 0 \quad x \le 0.5$ $y = 10x - 5 \quad 0.5 \le x \le 0.6$ $y = \frac{5}{2} - \frac{5}{2}x \quad 0.6 \le x \le 1.0$ $y = 0 \quad x \ge 1.0$ 
Disposability	High	$y = 0 \quad x \le 0.50$ $y = 4x - 2 \quad 0.50 \le x \le 0.75$ $y = -4x + 4 \quad 0.75 \le x \le 1.00$ $y = 0 \quad x \ge 1.00$ 
Communication security	Very High	$y = 0 \quad x \le 0.75$ $y = \frac{20x}{5} - \frac{15}{3} \quad 0.75 \le x \le 0.90$ $y = 1 \quad .90 \le x \le 1.0$ $y = 0 \quad x \ge 1.0$ 

Compliance with the reliability design requirement (and its associated feasibility) is not obvious from Figure 5.2, nor trivial in the case of Alternatives 1 and 2. Further investigation is necessary. A study could be conducted of the overlap and non-overlap areas to gauge separation between anticipated and preferred profiles and between two different anticipated profiles. However, such a study would not only be too simplistic, but could lead to flawed decisions since it would be unable to offer enough resolution to properly distinguish between anticipation profiles in certain situations.

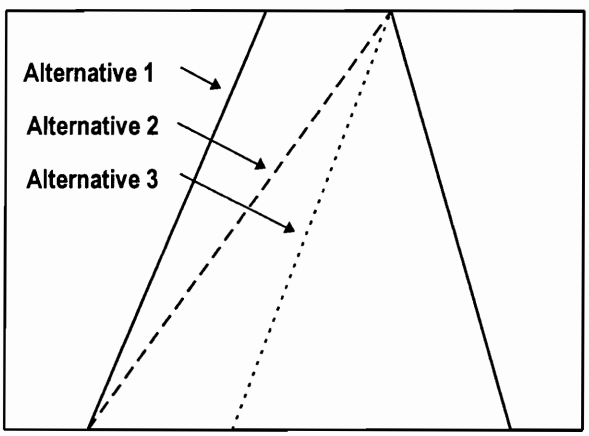
This is confirmed through a study of the *Reliability* anticipation profiles for Alternatives 1 and 2 shown in Figure 5.2. Assume that the area of non-overlap relative to the *Reliability* parameter for Alternative 1, , is equal to the corresponding area of non-overlap for Alternative 2, . A simple study of the areas of non-overlap cannot distinguish the relative desirability of the two alternatives with regard to *Reliability*. In fact, an infinite number of profiles may be generated where the total area of non-overlap remains the same as that of Alternatives 1 and 2. However, from a design sense, each of these profiles is unique and possesses a different degree of acceptability. Accordingly, this becomes a critical requirement for the development of any feasibility assessment mechanism.

Separation between fuzzy sub-sets in general, and fuzzy numbers in particular (since they do not possess total order), is of great interest. It has been analyzed in different ways by numerous researchers. A comparison of the different approaches confirms that there is no one “best” approach [Bortolan and Degani, 1985]. To further emphasize this, consider the three fuzzy subsets shown in Figure 5.3, along with their relative rankings using five different ranking approaches.

In spite of their obvious differences, fuzzy set ranking methods fall into two broad based categories. The first group utilizes the notion of mapping each fuzzy subset to the real number line, where a natural and total order exists.

Within this group the approaches differ in the nature of the mapping function used. For instance, Yager [1981] proposes a mapping based on the center of gravity calculation of each fuzzy subset given as:

$$F[\mu_{\tilde{A}}(x)] = \frac{\int_0^1 \mu(x).x\,dx}{\int_0^1 \mu(x)\,dx} \tag{5.1}$$



Ranking of t three fuzzy numbers according to:

Baas and Kwakernaak [1977]:	**A1 = A2 = A3**
Jain [1977]:	**A1 = A2 = A3**
Baldwin and Guild [1979]:	**A1 > A2 = A3**
Chang [1981]:	**A1 < A2 = A3**
Yager [1981]:	**A1 > A2 > A3**

Figure 5.3. Comparison of fuzzy subset ranking methods [Adapted from Bortolan and Degani, 1985].

Yager [1981] proposed an alternative approach involving the calculation of the area between the membership axis and the line representing the average for each α-cut. This may be represented as:

$$F[\mu_{\tilde{A}}(x)] = \int_0^{\alpha_{\max}} M(A^{\alpha})d\alpha, \qquad where\ \alpha_{\max} = height(\tilde{A}) \tag{5.2}$$

In the above formulation, A^{α} represents the α-level set for the fuzzy subset $\widetilde{A}$, and $M(A^{\alpha})$ represents the mean of the elements of the α-level set.[18] Adamo [1980] suggests the calculation of an α-preference index as a means for ranking fuzzy subsets.

The second group of approaches involves the development of a fuzzy set containing all the alternatives as elements with their corresponding membership function values. These values indicate the degree to which each alternative may be considered best. The approaches differ in their manipulation of these membership values. For instance, according to Bass and Kwakernaak [1977] the fuzzy subset with the greatest peak value is the preferred one. Dubois and Prade [1978] have proposed utilization of the fuzzy maximum operator to resolve the ranking problem. However, this approach suffers from the fact that the maximum fuzzy set may often be a combination of alternatives.

In view of the preceding discussion, it is necessary to define the requirements which dictate the feasibility analysis activity. These requirements would then influence the selection of one of the above approaches, or the development of a new approach tailored specifically to the problem at hand.

Feasibility assessment of potential concepts involves a comparative analysis of anticipation and preference profiles for every design dependent parameter and for each concept. This assessment differs in essence and by objective from a separation analysis between fuzzy numbers or fuzzy profiles (i.e., in a hamming distance sense). Feasibility analysis involves an investigation of the extent of "overlap" between the anticipation and preference profiles. Further, the greater this overlap the better.[19] In the extreme, an anticipation profile which falls completely within a preference profile signifies a concept which

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18 The concept of α-level sets and the support of fuzzy subsets is explained in the Appendix (Basic Operations in Fuzzy Arithmetic).

19 This is analogous to the concept of confidence intervals in the probabilistic domain. The extent of overlap represents the degree (confidence level) to which the anticipation or prediction of a particular design dependent parameter satisfies the corresponding requirement.

is completely in the feasible design space with regard to the design dependent parameter in question (e.g., Alternative 3 in Figure 5.1). However, from a hamming distance, or separation perspective, there is still some separation between these two profiles. The requirement for overlap or compliance analysis versus separation analysis makes most of the rating and ranking approaches discussed earlier unsuitable for the feasibility assessment of concepts.

The analysis of overlap and non-overlap of anticipation and preference profiles needs to be extended by weighting the areas of overlap/non-overlap. This becomes necessary in order to provide the requisite amount of resolution necessary to distinguish the relative desirability of anticipation profiles (this requirement was discussed in more detail earlier in this section). A formal and graceful weighting mechanism will also allow the rating and ranking of design dependent parameter criticality for all potential concepts, and subsequently, when combined with relative priorities, the rating and ranking of the concepts themselves.

5.3.1. Weighting the Areas of Overlap and Non-Overlap

Inherent in the feasibility analysis of concepts and associated design dependent parameters, is the assessment of requirement compliance of predicted or anticipated values. This compliance is not only a function of the extent of overlap between anticipation and preference profiles, but also the nature (location on the two co-ordinate Cartesian plane) of this overlap. This is further explained and illustrated in Figure 5.4.

From the designers' perspective, a unit area of non-overlap at higher membership levels is less desirable than a unit area of non-overlap at lower membership levels. As an example, in Figure 5.4 the area of non-overlap 1 is more critical than the area of non-overlap 2. A large amount of non-overlap at higher membership levels signals greater separation between preference and anticipation values, where it matters most. Therefore, even if two anticipation

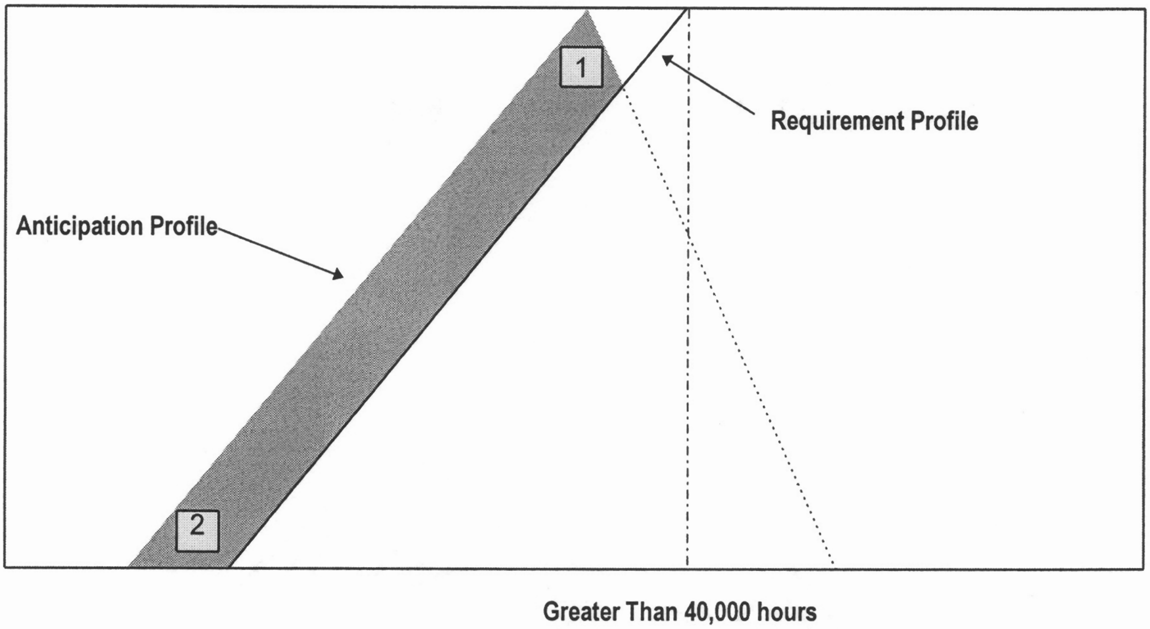

Figure 5.4. Nature of overlap between preference and anticipation profiles.

profiles have the same amount of non-overlap (in terms of area, as is the case with Alternatives 1 and 2 in Figure 5.2), they are distinguishable and unique in terms of their relative desirability to the designer because of the location of this non-overlap.

Difference in importance of area of overlap or non-overlap, as a function of its location, is "captured" by means of a weighting scheme. The primary idea behind this mechanism is to conduct a volumetric analysis rather than limit the analysis to the areas of overlap or non-overlap. Utilization of this weighting mechanism results in the association of greater volume (or weight) with a unit area of non-overlap at higher preference levels as compared to the same area at lower preference levels. Further, subsequent to analyzing the feasibility of concepts, the mechanism is utilized to assess the relative "goodness" of concepts as well. This then becomes a significant input to rating and ranking, and the ultimate selection of the preferred conceptual solution.

To explain the weighting concept, consider Figure 5.5. This illustration represents the diagonal half of a rectangular cube with a height (preference axis) and width (weighting axis) of unit length.

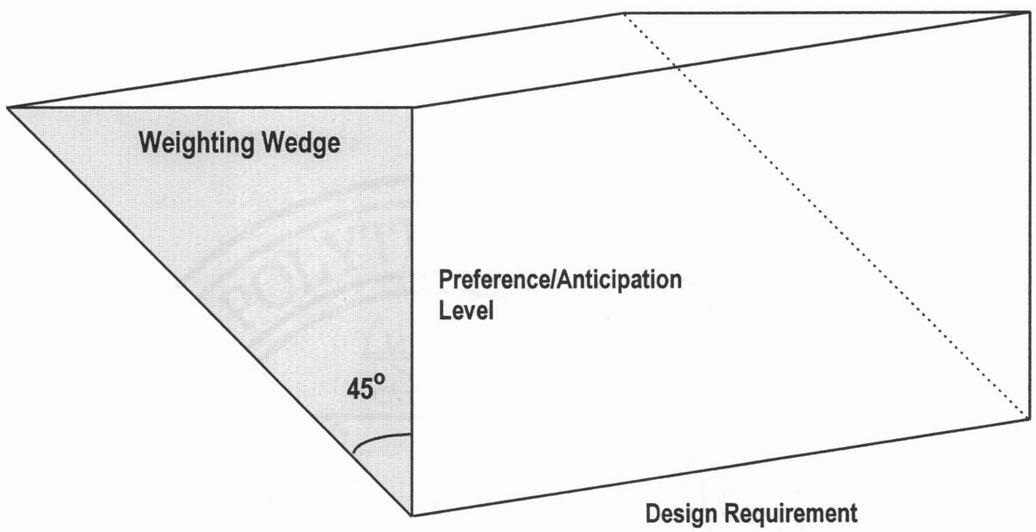

Figure 5.5. Weighing mechanism for the feasibility assessment of design dependent parameters.

Discussion to this point has been limited to the two-dimensional Cartesian plane, with the design dependent parameter requirements represented along the x-axis and the preference or anticipation of their values represented along the y-axis. To properly weight the areas of overlap or non-overlap, a third dimension is added. This dimension provides the necessary weighting mechanism and facilitates a volumetric analysis of the overlap or non-overlap between preference and anticipation profiles. As a result of adding this third dimension, the feasibility analysis involves a "wedge" shaped volume. This wedge is bounded by the original two-dimensional Cartesian plane forming one face. Thereafter, a plane is created at a 45 degree angle to this vertical Cartesian space, as shown in Figure 5.5. A face, with a width of unity (the same as the height of the Cartesian space), forms the third face which is perpendicular to the original Cartesian plane. Accordingly, there is a varying amount of depth associated with every point on the two-dimensional Cartesian plane, and further, this depth is a function of the height of the point.

There is a different amount of volume associated with a unit area as a function of the location of this area. This is depicted in Figure 5.6. Even though Areas 1 and 2 in the figure are equal, the volume associated with each is a function of their shape and location in terms of the preference axis. In this example, the volume associated with Area 1 is greater than that associated with Area 2.

The approach above provides a formal weighting scheme for analyzing the overlap or non-overlap of preference and anticipation profiles. It can be extended for the subsequent analysis of relative desirabilities of a number of feasible anticipation profiles. The use of this mechanism is explained in terms of assessing the feasibility of conceptual designs.

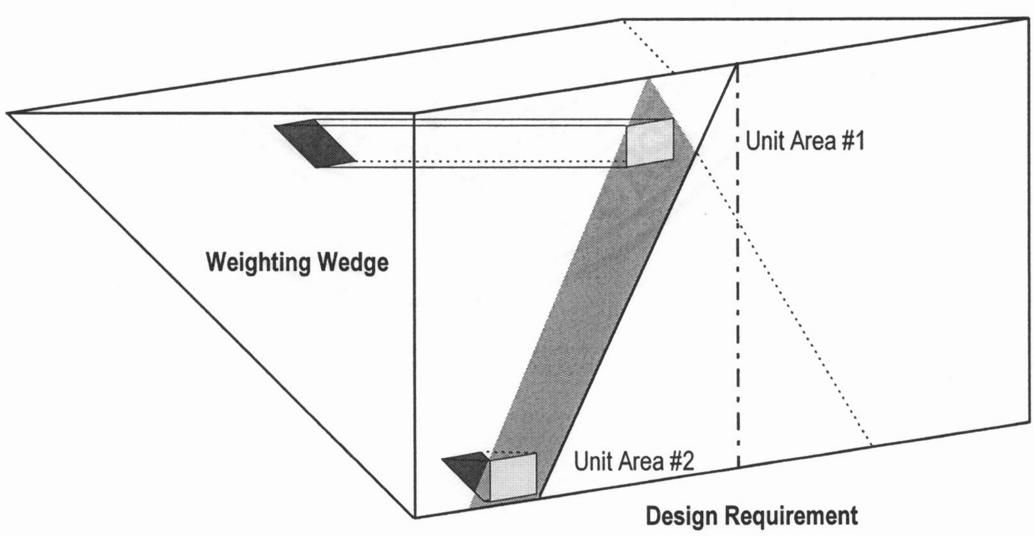

Figure 5.6. Volumetric analysis of overlap/non-overlap between preference and anticipation profiles.

5.3.2. Developing a Feasibility Index

The mechanism described in Section 5.3.1 facilitates development of a feasibility index. A feasibility index, FI_{ni}, for the *ith* design dependent parameter of the *nth* conceptual design alternative may be expressed as:

$$FI_{ni} = \frac{\textit{Projected overlap volume for the ith DDP of nth concept}}{\textit{Total projected volume of anticipated profile for the ith DDP of nth concept}} \tag{5.3}$$

Examining only the projected volume of non-overlap (or non-compliance) does not convey the associated (and essential) sense of compliance. Both are necessary to assess the "degree of compliance" or the "degree of feasibility." This makes it necessary to compute a ratio of the projected overlap and total volumes of an anticipated profile to obtain a comprehensive assessment of its feasibility. As an illustration of this, consider the two anticipation profiles along with the requirement profile in Figure 5.7.

If the feasibility assessment was limited to the projected volume of non-overlap only, *Anticipation Profile 2* shown in Figure 5.6 would "score" higher than *Anticipation Profile 1*. However, this analysis is incomplete since it does not truly consider the "degree of compliance." A comprehensive assessment of compliance involves assessment of the projected volume of overlap as well, along with its contribution to the total volume. This intent is represented in Equation 5.3 giving the *Feasibility Index*. From this perspective *Anticipation Profile 1* may be more compliant with regard to the corresponding requirement as compared to *Anticipation Profile 2* if:

$$FI_{1i} > FI_{2i}$$

$$\textit{if and only if} \tag{5.4}$$

$$\frac{\textit{Projected overlap volume for Profile 1}}{\textit{Total projected volume of Profile 1}} > \frac{\textit{Projected overlap volume for Profile 2}}{\textit{Total projected volume of Profile 2}}$$

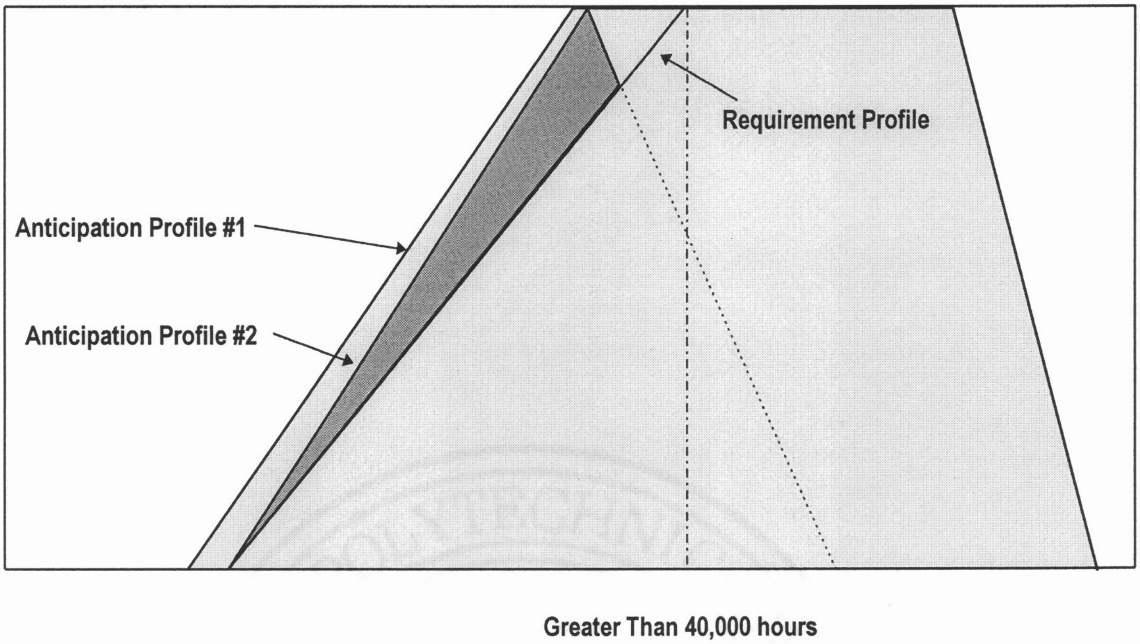

Figure 5.7. Assessment of the degree of feasibility (or the degree of compliance).

The *Feasibility Index* FI_{ni} can take on values in the interval [0,1]. A higher FI_{ni} value indicates greater compliance. In the extreme, a value of 1 signifies complete and absolute feasibility of the *nth* concept with regard to the *ith* design dependent parameter, or design requirement.

5.3.3. Calculating Projected Volumes

The approach utilized for the calculation of projected volumes (overlap, non-overlap, or total) needs to be generic and independent of the shape of the associated area. In this sub-section a generic approach is presented.

Consider the illustration in Figure 5.8 and the square-shaped area on the two-dimensional Cartesian plane. The lowest point of this area is at a height, *a*, while the difference between the lowest and highest points of this area is *b*. Further, because of the uniformity in the shape of this area, the difference is constant for the entire cross-section in question. When the area of interest in

Figure 5.8 is projected onto the 45 degree-angled plane, the volume generated can be computed as described below.

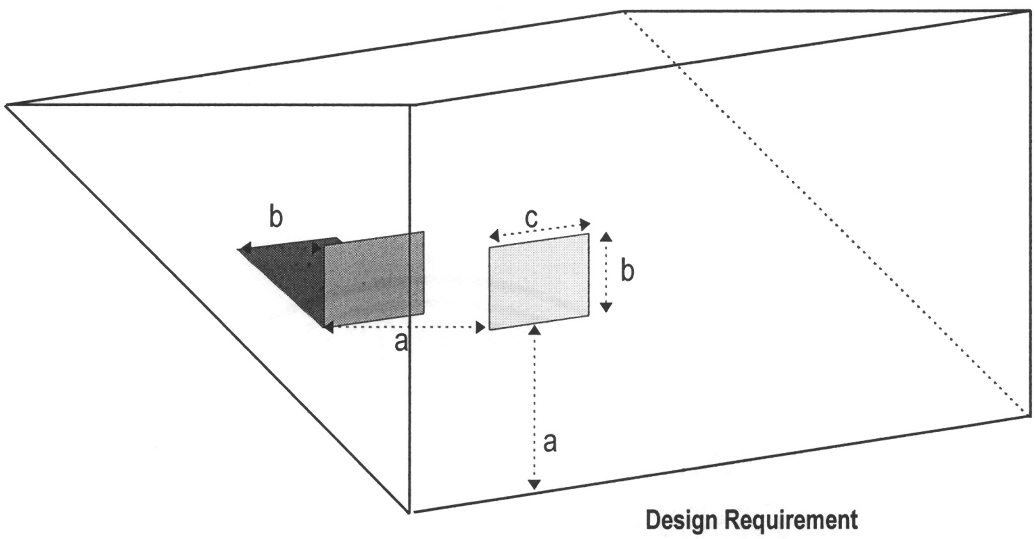

Figure 5.8. Calculation of projected volumes for anticipation profiles.

The first step involves calculation of that portion of the volume where the cross-sectional area remains uniform. Given the nature of the weighting wedge, in every case the length of this constant cross-sectional volume is equal to the height of its lowest point. This is also conveyed in Figure 5.9 which represents another perspective on Figure 5.8. This is expressed in a generic manner as:

(Primary area on Cartesian plane) x (Height of the lowest point in this area of concern)

Further, in the case of the area in Figure 5.8, this volume is given as:

$$(b.c)\ (a) = abc \qquad (5.5)$$

It is only after an area on the two-dimensional Cartesian plane has "traveled" a distance equal to "*a*" (the height of its lowest point on the Cartesian plane) into the weighting wedge that it begins to get projected onto the projection plane as depicted in Figures 5.8 and 5.9. This is because the projection plane is at a 45 degree angle to the primary plane. In the limit, the volume of this remaining piece is equal to half the volume of the space bounded by the primary area on two ends and with a length equal to b (distance between the highest and lowest points of the area on the Cartesian plane). The calculation of this section of the overall projected volume may be expressed in a generic manner as:

(Primary area on Cartesian plane) x (Distance between highest and lowest points in area of concern)

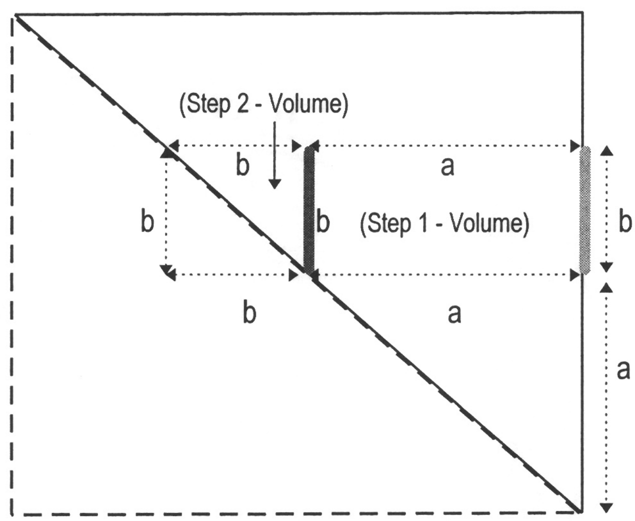

Figure 5.9. The two step process in the calculation of projected volumes.

Further, in the case of the area in Figure 5.8, this volume is given as:

$$[(b.c)\ (b)]\ /\ 2 \qquad (5.6)$$

Therefore, the volume of concern may be expressed:

$$\begin{aligned} Projected\ \ volume\ \ of\ \ concern &= (a)(b.c) + \frac{(b.c)(b)}{2} \\ &= abc + \frac{b^2c}{2} \qquad (5.7) \\ &= \frac{bc(2a+b)}{2} \end{aligned}$$

Equation 5.7 can be applied directly and with reasonable ease to address the feasibility assessment of discrete design dependent parameters by analyzing the associated requirement and anticipation profiles. This generic approach can be adapted to assess the feasibility of DDPs with triangular, trapezoidal, and other non-linear requirement and prediction profiles.

Consider the triangular profile and associated nomenclature in Figure 5.10. Computation of the projected volume in this case is accomplished through application of Equation 5.7. The following hold for this example:

$$
\begin{aligned}
&a = 0\\
&c = \delta_1 = \frac{x_2 - x_1}{n_1},\ x_1 \le x \le x_2 \ \textit{and}\\
&c = \delta_2 = \frac{x_3 - x_2}{n_2},\ x_2 \le x \le x_3\\
&b_i = y_i = \alpha_1[x_1 + (i - 0.5)\delta_1] + \beta_1,\ 1 \le i \le n_1 \ \textit{and}\\
&b_k = y_k = \alpha_2[x_2 + (k - 0.5)\delta_2] + \beta_2,\ 1 \le k \le n_2
\end{aligned}
\tag{5.8}
$$

Application of Equation 5.7 yields:

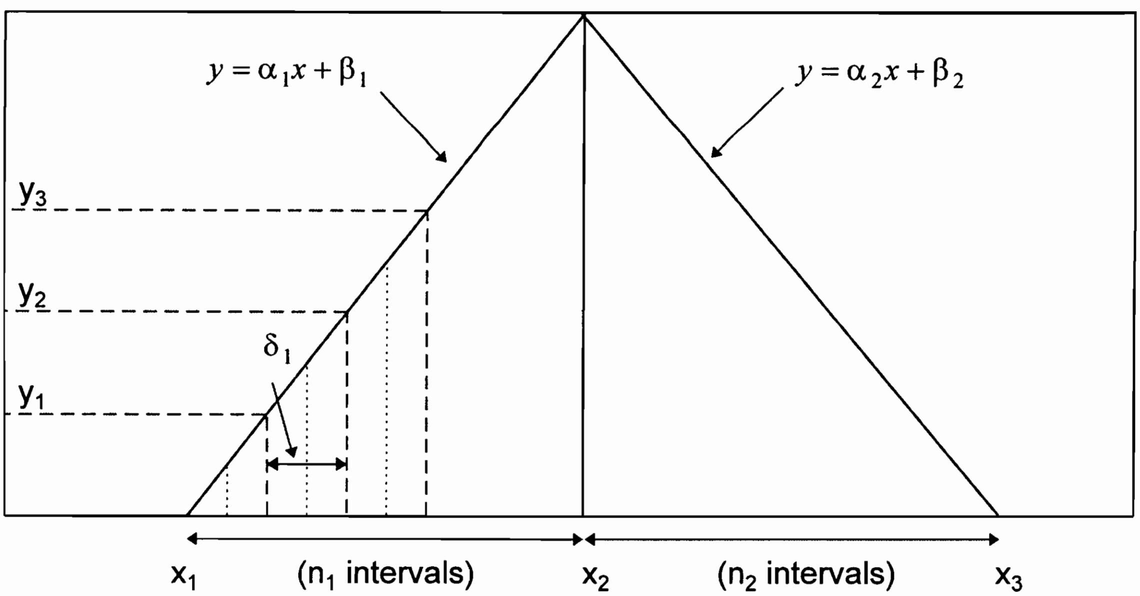

Figure 5.10. Feasibility assessment of triangular requirement and anticipation profiles.

$$Projected\ \ volume = abc + \frac{b^2 c}{2}$$

$$= 0 + \frac{\sum_{i=1}^{i=n_1} b_i^2 \delta_1}{2} + \frac{\sum_{k=1}^{k=n_2} b_k^2 \delta_2}{2}$$

$$= \frac{\sum_{i=1}^{i=n_1} \{\alpha_1 [x_1 + (i - 0.5)\,\delta_1] + \beta_1\}^2 \left\{\frac{x_2 - x_1}{n_1}\right\}}{2} + \tag{5.9}$$

$$\frac{\sum_{k=1}^{k=n_2} \{\alpha_2 [x_1 + (k - 0.5)\,\delta_2] + \beta_2\}^2 \left\{\frac{x_3 - x_2}{n_2}\right\}}{2}$$

The above approach is focused on computing the projected volume of the entire triangular profile. A similar approach can be applied to address the projected volumes of overlap or non-overlap of any linear or non-linear profile. To illustrate the application of this generic approach, consider the design requirement for the *Reliability* parameter depicted in Figure 5.11.

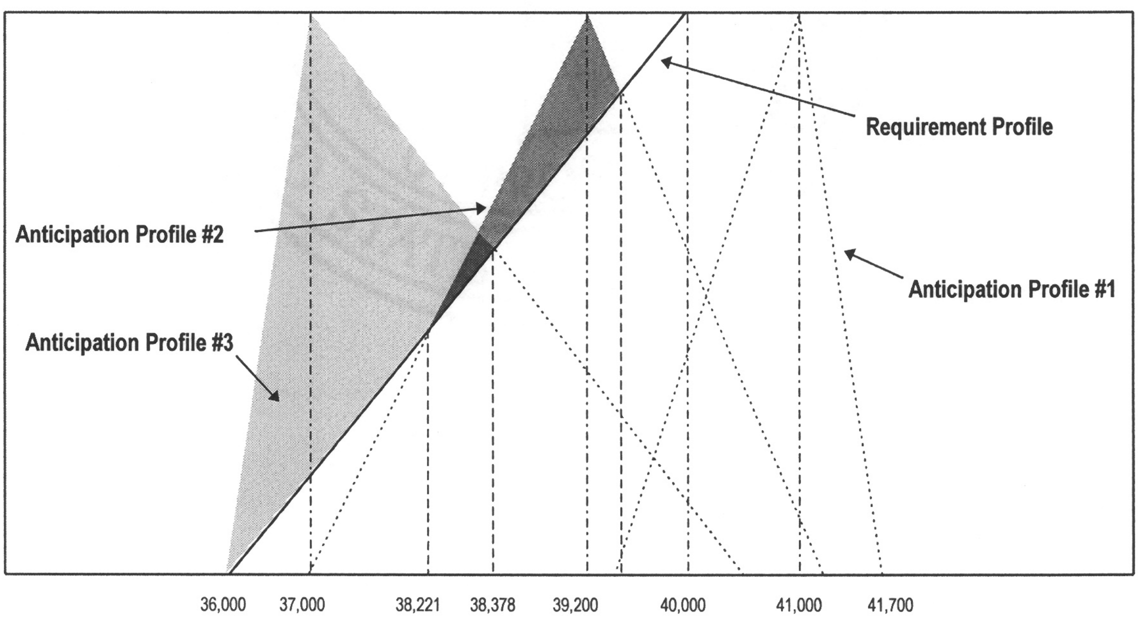

Figure 5.11. Feasibility assessment (degree of compliance) for the Reliability parameter.

Reliability predictions for the three potential conceptual solutions are also mapped in Figure 5.11. Further, Table 5.4 shows the algebraic representations for the applicable requirement and prediction profiles. With this information as input, the feasibility analysis may be conducted as follows:

1. *Feasibility analysis for Concept 1 (Reliability).* The feasibility index may be expressed as:

$$FI_{Reliability_1} = \frac{Projected\ overlap\ volume\ for\ anticipation\ profile}{Total\ projected\ volume\ for\ anticipation\ profile} = 1.00$$

2. *Feasibility analysis for Concept 2 (Reliability).* Given the non-overlap between required and anticipation profiles in this instance, Equations 5.8 and 5.9 are applied in the following manner:

Table 5.4. Reliability requirement and predictions.

Description	**Algebraic Representation** (From Figure 5.8)
Requirement: Greater Than 40,000 hours	$y = 0 \quad x \le 36{,}000$ $y = \frac{x}{4{,}000} - 9 \quad 36{,}000 \le x \le 40{,}000$ $y = 1 \quad x \ge 40{,}000$
Prediction (Concept 1)	$y = 0 \quad x \le 39{,}400\ or \ge 41{,}700$ $y = \frac{x}{1600} - \frac{197}{8} \quad 39{,}400 \le x \le 41{,}000$ $y = \frac{417}{7} - \frac{x}{700} \quad 41{,}000 \le x \le 41{,}700$
Prediction (Concept 2)	$y = 0 \quad x \le 37{,}000\ or \ge 41{,}200$ $y = \frac{x}{2{,}200} - \frac{185}{11} \quad 37{,}000 \le x \le 39{,}200$ $y = \frac{103}{5} - \frac{x}{2{,}000} \quad 39{,}200 \le x \le 41{,}200$

Table 5.4. Reliability requirement and predictions (continued).

Description	**Algebraic Representation** (From Figure 5.8)
Prediction (Concept 3)	$y = 0 \qquad x \le 36{,}000 \text{ or } \ge 40{,}400$ $y = \dfrac{x}{1{,}000} - 3{,}600 \qquad 36{,}000 \le x \le 37{,}000$ $y = \dfrac{202}{17} - \dfrac{x}{3{,}400} \qquad 37{,}000 \le x \le 40{,}400$

$$Overlap\ \ volume = \frac{\sum_{i=0}^{i=9}\left\{\frac{1}{2{,}200}[37{,}000+(i+0.5)\ 122.1]-\frac{185}{11}\right\}^2(122.1)}{2} + \frac{\sum_{i=0}^{i=9}\left\{\frac{1}{4{,}000}[38{,}221.5+(i+0.5)\ 124.6]-9\right\}^2(124.6)}{2} + \frac{\sum_{i=0}^{i=19}\left\{\frac{103}{5}-\frac{1}{2{,}000}[39{,}466.67+(i+0.5)\ 86.65]\right\}^2(86.65)}{2}$$

$$= \frac{125.10+640.10+433.70}{2} = 599.45$$

$$Total\ \ volume = \frac{\sum_{i=0}^{i=21}\left\{\frac{1}{2{,}200}[37{,}000+(i+0.5)\ 100]-\frac{185}{11}\right\}^2(100)}{2} + \frac{\sum_{i=0}^{i=19}\left\{\frac{103}{5}-\frac{1}{2{,}000}[39{,}200+(i+0.5)\ 100]\right\}^2(100)}{2}$$

$$= \frac{732.955+666.25}{2} = 699.603$$

Feasibility index for the second conceptual solution is expressed as:

$$FI_{Reliability_2} = \frac{Projected\ volume\ of\ overlap}{Total\ projected\ volume\ of\ profile} = \frac{599.450}{699.603} = 0.8568$$

3. *Feasibility analysis for Concept 3 (Reliability).* The approach adopted in analyzing Concept 2 can be applied to this concept as well. The relevant expressions are:

$$Overlap\ \ volume = \frac{\sum_{i=0}^{i=24}\left\{\frac{1}{4{,}000}[36{,}000+(i+0.5)\ 95.12]-9\right\}^2(95.12)}{2} + \frac{\sum_{i=0}^{i=19}\left\{\frac{202}{17}-\frac{1}{3{,}400}[38{,}378.4+(i+0.5)\ 101.1]\right\}^2(101.1)}{2}$$

$$= \frac{280.04+238.08}{2} = 259.06$$

$$Total\ \ volume = \frac{\sum_{i=0}^{i=9}\left\{\frac{1}{1{,}000}[36{,}000+(i+0.5)\ 100]-36\right\}^2(100)}{2} + \frac{\sum_{i=0}^{i=33}\left\{\frac{202}{17}-\frac{1}{3{,}400}[37{,}000+(i+0.5)\ 100]\right\}^2(100)}{2}$$

$$= \frac{332.50+1133.088}{2} = 732.794$$

Feasibility index for the third conceptual solution is expressed as:

$$FI_{Reliability_{32}} = \frac{Projected\ volume\ of\ overlap}{Total\ projected\ volume\ of\ profile} = \frac{259.06}{732.794} = 0.3535$$

A summary of the feasibility analysis is presented in Table 5.5.

Table 5.5. Feasibility analysis for the *Reliability* parameter.

Conceptual Solution	Feasibility Index
Concept 1	1.00
Concept 2	0.86
Concept 3	0.35

Assuming a feasibility threshold of 85% for *Reliability*, Concepts 1 and 2 are feasible, whereas Concept 3 is infeasible. In this context, the design team decides on the minimum acceptable "degree of compliance" between required and anticipated values of a Design Dependent Parameter. This minimum acceptable level of compliance is expressed as a percentage and called the feasibility threshold. This exercise is completed for the other design dependent parameters to identify the feasible conceptual solutions (i.e., feasible with regard to all relevant and applicable design dependent parameters). Table 5.6 presents feasibility analysis results for the candidate conceptual solutions.

Table 5.6. Feasibility analysis results (infeasible cells shaded).

Design Dependent Parameter	Concept 1	Concept 2	Concept 3	Feasibility Threshold
Reliability	1.00	0.87	0.35	0.85
Maintainability	0.95	1.00	1.00	0.90
Environmental compliance	1.00	1.00	0.20	0.90
Visual quality	0.50	0.54	1.00	0.50
Data (graphic) transfer rate	1.00	1.00	1.00	0.80
Audio/video synchronization	0.80	0.80	1.00	0.80
Color capability	1.00	1.00	1.00	0.80
Skill level requirement (operate)	0.89	0.85	1.00	0.85
Skill level requirement (maintain/support)	0.99	0.76	1.00	0.75
Audio quality	0.70	0.78	1.00	0.60
Communication initiation time	0.92	0.80	0.00	0.80
Number of members possible within group	1.00	1.00	1.00	0.90
Number of simultaneous group meetings	1.00	1.00	1.00	0.90

Table 5.6. Feasibility analysis results (infeasible cells shaded) (continued).

Design Dependent Parameter	Concept 1	Concept 2	Concept 3	Feasibility Threshold
Maximum membership size	1.00	1.00	1.00	0.90
Design/production cost	0.99	0.71	1.00	0.70
Operating cost	0.99	0.93	0.00	0.90
Support/maintenance cost	0.98	1.00	1.00	0.90
Safety	1.00	1.00	0.80	0.80
Disposability	1.00	1.00	0.20	0.70
Communication security	0.99	0.99	1.00	0.75

5.4. FEASIBILITY ANALYSIS FOR STOCHASTIC PREDICTIONS AND ESTIMATIONS

In the unlikely event that predictions and/or estimations for selected design dependent parameters are expressed in probabilistic terms, the associated probability density function is normalized. This is to facilitate the transformation of a probabilistic measure into a fuzzy measure.

The operation of normalizing a probability density function is discussed in the Appendix entitled, Basic Operations in Fuzzy Arithmetic. Once transformed into a non-linear or linear fuzzy profile, the mechanisms and operations developed and discussed in Section 5.3 can be applied to assess the associated feasibility of the parameters in question.

5.5. SELECTING FEASIBLE CONCEPTUAL DESIGNS

Once the feasibility analysis has been completed for all potential solutions, those concepts which satisfy the feasibility threshold for relevant and applicable design dependent parameters are declared feasible. From Table 5.6 as an illustration, all concepts that do not have a shaded block in the column representing them are feasible (i.e., Concepts 1 and 2).

In reality, selected infeasible concepts may be further studied, revisited, improved, and then reconsidered. This process is in concert with Pugh's methodology of controlled convergence and divergence in the selection of a preferred concept [Pugh, 1990]. The feasibility analysis may also provide insight into specific technologies that need to be developed in order to finally implement a particular concept. Accordingly, the feasibility assessment of potential conceptual solutions is an iterative process. The mechanisms developed in this part of the methodology facilitate the rapid convergence of this process to a short-listed set of feasible conceptual solutions. These feasible conceptual solutions are analyzed further (and in more detail) during the evaluation process, with the objective of ultimately selecting the preferred concept.

5.6. CONDUCTING FOCUSED RE-DESIGN OR DESIGN IMPROVEMENT

Feasibility assessment of conceptual design solutions, through the mechanism of feasibility indices, affords significant flexibility to a design team conducting subsequent re-design or design improvement activities. The computation of feasibility indices for all applicable design dependent parameters provides designers with insight relative to the strength and weakness of each design concept. Further, in conjunction with the relative importance of design dependent parameters, the extent of separation between feasibility threshold and corresponding feasibility index values conveys the nature and criticality of a design concept's weakness. By utilizing this approach, the more critical weaknesses may be identified and then addressed through either re-design or design improvement strategies.

CHAPTER 6

CONCEPTUAL DESIGN EVALUATION METHODOLOGY - PHASE III: RATING AND RANKING FEASIBLE CONCEPTUAL SOLUTIONS

The third and final phase of the conceptual system design evaluation methodology is developed in this chapter. Activities and steps which comprise this phase are depicted in Figure 6.1. As in the previous phases, the remote conferencing example is developed and evolved to illustrate and clarify the process leading to selection of the preferred system design concept. Initially, this methodology addresses the computation of design dependent parameter relative importances. Here the relative importance of applicable design dependent parameters is a function of their correlation with subjectively stated customer requirements, and the absolute importance of these requirements (as subjectively perceived by potential customers).

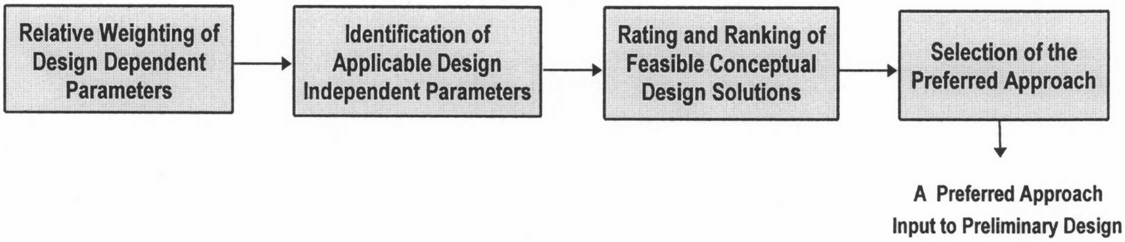

Figure 6.1. Activities comprising Phase III of the evaluation methodology.

Design dependent parameter relative importance values are consolidated with the corresponding feasibility index values for each feasible conceptual solution. This consolidation provides insight into the relative and overall desirability (or "goodness") of each potential candidate.

The preferred design concept, along with the corresponding predicted and estimated values (and feasibility indices) of design dependent parameters, becomes an input to preliminary system design. During this phase, a functional analysis of the preferred concept is conducted leading to the top-down allocation of system level requirements to the various functional sub-systems. Allocated requirements become design specifications for the lower-level elements in the system functional hierarchy [Blanchard, Fabrycky, and Verma, 1994]. Further, these sub-systems and other lower-level entities may be implemented as hardware, software, or human elements. The allocation of system functions to hardware, software, or firmware manifestations has been explored and investigated by Midkiff and Fabrycky [1991].

6.1. A FRAMEWORK FOR ROBUST SYSTEM DESIGN EVALUATION

A robust system design evaluation framework "allows" and facilitates the comprehensive evaluation of system designs. Further, a comprehensive system design evaluation methodology "views" the prime-mission product or equipment (along with its performance characteristics) as a component within the overall system being designed and developed. Due consideration must be given to downstream life-cycle phases involving the manufacture or construction of this product or equipment, its distribution, setup, and operation, its sustaining support and maintenance in the field, and its ultimate phase-out, disposal, and/or (in some cases) re-engineering to address an evolving requirement. Therefore, in the context of this discussion, the overall desirability of system design is impacted by a host of factors, to include both features inherent within the system design and issues pertaining to the economic, political, and social environments external to the system design.

6.1.1. Features Inherent Within the Design

Features or characteristics within the design are represented by design dependent parameters (DDPs) which, in turn, strongly correlate (or should correlate) with requirements as specified by the potential customers/consumers. Further, these features together with their target values (design requirements) represent the feasible design space, and each feasible alternative or design concept represents an instance within this space. Since the term optimization does not apply to conceptual system design in a strict sense, the preferred design concept often represents the most efficient compromise between anticipated values of the relevant design dependent parameters.

A disciplined system design and development process enforces a life-cycle perspective (i.e., consideration of "downstream" life-cycle activities as they pertain to product or equipment manufacture, assembly, distribution, operation, sustaining maintenance/support, and ultimate product phase-out and/or disposal) in the delineation and definition of the design dependent parameters. The conceptual design evaluation methodology developed herein is life-cycle complete. This is a result of its strong integration with the underlying system engineering process and its traceability (back) to the desires and concerns of the ultimate customer/consumer.

6.1.2. Factors External to the Design

Generic design independent parameters address labor rates (these impact system operating, maintenance, and support costs), interest rates, inflation rates, available labor-force skill levels (these impact training requirements and costs, which in turn impact product manufacturing/ construction costs, and the cost to operate, maintain, and support the system), raw material costs (this impact product manufacturing or construction cost), government subsidies and incentives (selected geographical regions or technologies may be subsidized by the state and/or federal government which may in turn impact design, manufacturing and assembly costs), applicable regulations, shortage-penalty costs, energy costs (which impact manufacturing and operating costs), and so on. Identification of design independent parameters is inherent in a robust system design analysis and evaluation activity.

Issues pertaining to manufacturing, operations, and support are also represented by design independent parameters. In spite of their obvious (and often significant) impact on overall design desirability, a designer or design team has little control over these parameters or the "noise" associated with them, individually or in combination.

Together, these issues represent design "externalities" with regard to manufacturing, operation, and support factors, and as impacted by social, political, and economic environments. These externalities should be forecast and their impact explicitly considered during system design evaluation. Impact is accomplished through targeted sensitivity studies undertaken to anticipate likely shifts in the overall system desirability as a result of perturbations in the design independent parameters. Often, such considerations may result in preference reversal of system concepts and designs.

The impact of design independent parameters is implicitly considered in this research and reflected through predictions and estimations of relevant design dependent parameters. However, in concert with the philosophies of "robust design", the impact of these design independent parameters and the "noise" associated with them should be investigated and considered in greater detail. That extension, however, is considered beyond the scope of this research. Duan has addressed this aspect of system design during the preliminary design phase in considerable detail [Duan, 1993].

6.1.3. Design Space and Search Space Implications in System Design

Along with the consideration of design dependent and design independent parameters, the applicable system design variables should be included in the system design analysis and evaluation process. These design variables were defined in Chapter 1. Their definition leads to the concept of system design space versus system search space implications, and its significant role in design analysis and evaluation. Note that in the context of this discussion, the search space for any system design is established by the set of applicable design variables (while design dependent parameters define the system design space).

The system design and development activity commences with the identification of the initial need, deficiency, or a strategic market/economic opportunity. At this stage, while the design and development stimulus (need) is still in functional form, the potential design space is unlimited since commitments to requirements, technology, or architecture have not yet been made. However, greater and greater constraints are imposed on this unbounded design space through the progressive evolution of the system design and development process. This is as a result of increasing commitment on the part of the design team, as depicted in Figure 6.2. For instance, upon the identification of the pertinent customer requirements, the design team delineates a corresponding

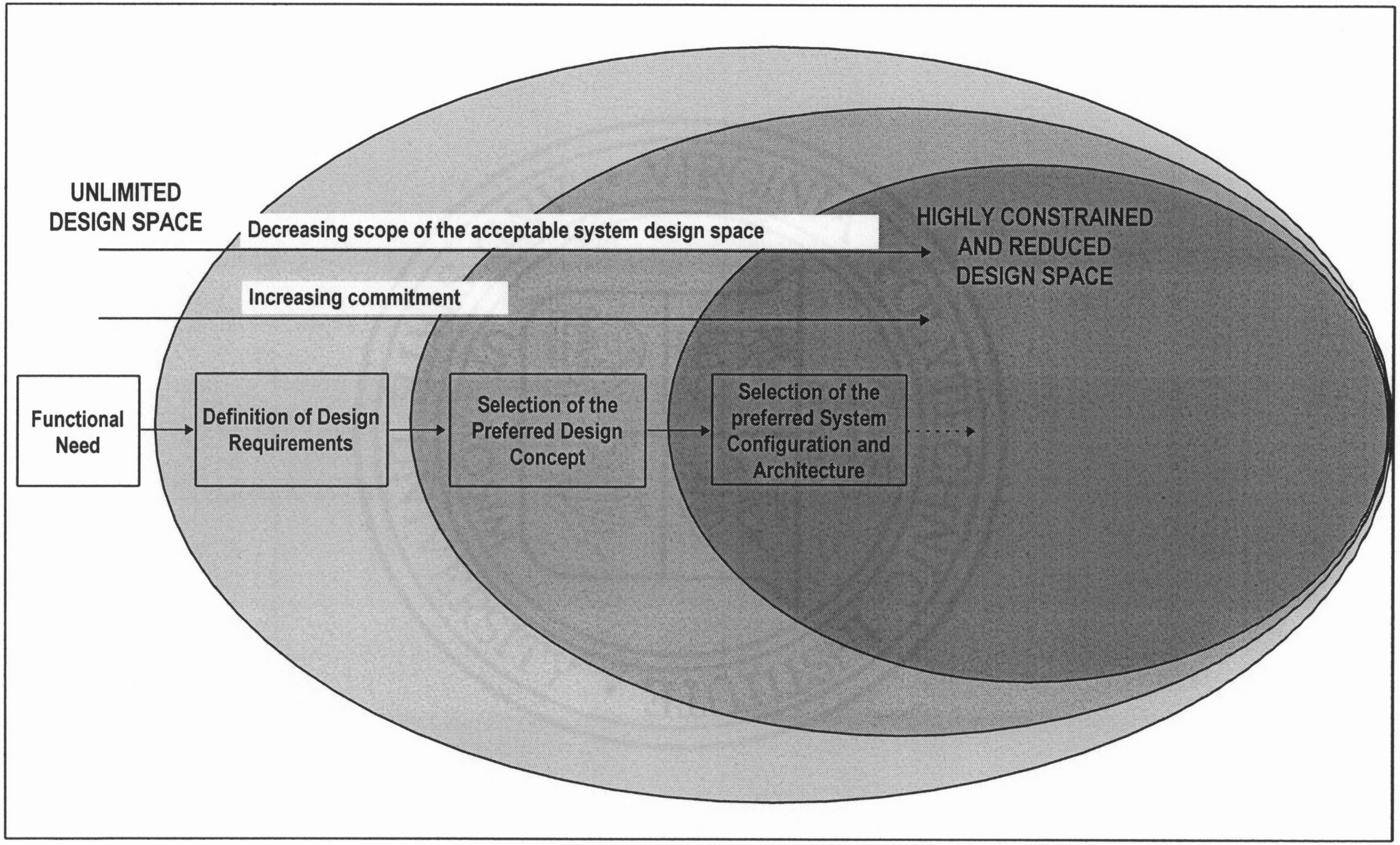

Figure 6.2. The progressive reduction in the scope of the acceptable design space with increasing design commitments.

set of design dependent parameters. Thereafter, proceeding through the steps discussed in Chapter 4, target values are identified for this set of design dependent parameters. This exercise identifies a “feasible design space”. Upon analyzing all potential alternatives to assess their feasibility (as discussed in Chapter 5), the preferred design concept is selected. This concept is an instance within the feasible design space and represents a further restriction.

The feasible concept is analyzed further and translated into an effective and efficient design configuration and/or architecture during the preliminary design phase. This is accomplished through the iterative functional analysis and requirements allocation activities. Even greater commitment and a further restriction on the applicable design space occurs. This process continues through the detail design space, and so on. In other words, the system design and development activity is characterized by the progressive “collapse” (or resolution) of the acceptable design space. However, this acceptable design space is not amenable to a structured and planned search in order to identify the “best” design implementation.

As the system design space contracts, an associated system search space becomes more and more defined. Applicable design variables can be identified early during the preliminary design phase. Their “coupling” with design dependent parameters becomes more and more refined. They become more identifiable with the progression of the design process and with an increase in the project/design specific knowledge gained by the design team. This process is depicted in Figure 6.3. Knowledge pertaining to the coupling is significant if the system design is to be optimized over the relevant design variables. Finally, during the preliminary and detailed design phases, alternative designs are compared in terms of their relative goodness only after each has been optimized over the identified set of design variables.

The search space represents aspects of the overall system design which are amenable to a structured search routine to locate the optimal design

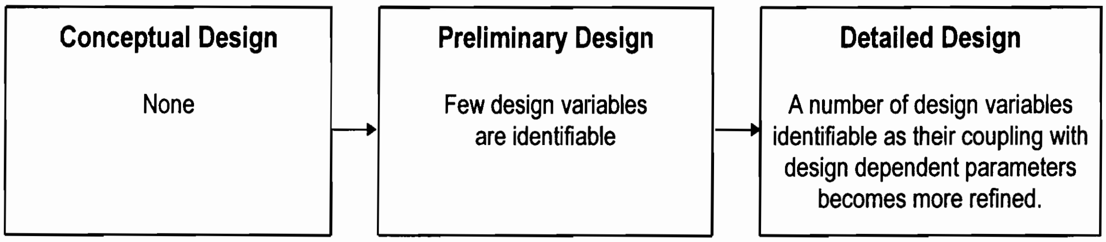

Figure 6.3. The number of identified design variables is a function of the design phase.

configuration or implementation, given a particular set of design dependent parameters. Very often these design variables pertain to the system support environment and address issues pertaining to the optimal number of repair channels, the optimal allocation and location of spare and repair parts, the number of equipment items necessary for deployment given a particular demand, the optimal number of maintenance crews, and so on. Other design variables consider economic elements and address issues such as the economic design life of the system.

6.2. RELATIVE IMPORTANCE OF DESIGN DEPENDENT PARAMETERS

Once feasible design concepts are identified, the next step involves identification and selection of the "best" or preferred approach. This invokes a requirement for rating and ranking all candidates, making it necessary to compute design dependent parameter relative importances or priorities. These relative importances are consolidated with corresponding feasibility index values to yield the overall merit for every feasible design concept.

The computation of design dependent parameter relative importances must remain true to the intent of the system engineering process. Traceability back to the initially identified customer requirements and the importance associated with these requirements must be maintained.[20] This requirement is in concert with the philosophy of keeping the "Voice of the Customer" loud and clear throughout the design and development process.

6.2.1. Traceability From Importance of Customer Requirements

The relative importance of any design dependent parameter is defined as a function of the importance of all customer requirements that it impacts, along with the extent or correlation of this impact. For example, consider the Reliability parameter in the remote conferencing example as shown in Table 6.1. Importance of the Reliability parameter is a function of the information outlined in Columns 2 and 3. Such a table may be constructed for every design dependent parameter in order to calculate the corresponding absolute priorities. These priorities can then be normalize to yield the associated relative priorities.

---

[20] The Analytic Hierarchy Process (AHP) [Saaty, 1980, 1982] was also explored as a methodology for the development of design dependent parameter relative importance. The AHP approach initially involves the delineation of a criteria hierarchy and the identification of alternatives. Next, relative importance of the decision criteria or decision elements is computed by first conducting a pairwise comparison of evaluation criteria. This comparison data is used to construct a comparison matrix. The eigenvector of this comparison matrix is then computed and normalized. This vector conveys the relative importance of the decision/evaluation criteria. The extent of consistency within the comparison matrix is calculated in a subsequent step. In the event that inconsistency within the matrix exceeds acceptable levels, the problem is re-visited and the comparisons confirmed/revised, and the analysis repeated [Canada, Sullivan, and White, 1996].

The basic and numerical Analytical Hierarchy Process has been extended through the utilization of concepts from fuzzy arithmetic (triangular and trapezoidal fuzzy scales) by some researchers [Mon, Chen, and Lin, 1994]. However, this approach was ultimately not used since the intent of this research (and a necessary requirement during the implementation of system engineering) is to maintain traceability in the system design process. Instead, the DDP relative importances were derived from customer importance regarding requirements and the correlation of these requirements with DDP's. Recently some researchers have reported application of the AHP technique to generate relative importances of customer requirements [Armacost, et. al., 1994]. This approach would require greater involvement on the part of the customers as compared to the approach utilized herein.

Table 6.1. Correlation of Reliability with selected customer requirements.

Customer Requirements Impacted by Reliability	Correlation of the Reliability with Customer Requirements	Importance of the Relevant Customer Requirements
Easy to maintain/support	Medium	Rather Important
Short set-up time	Medium	Rather Important
Frequent daily use	Very High	Important
Frequent weekly use	High	Rather Important
Low maintain/support cost	Very High	Rather Important

6.2.2. Calculating Design Dependent Parameter Absolute Importance

Absolute importance of design dependent parameters is computed through accomplishment of the activities outlined in Figure 6.4. Accordingly, absolute priority of the *i* th DDP, I_i , may be expressed as:

$$I_i = \sum_{k=1}^{k=n} (Customer\ \ Requirement\ \ Importance)_k \ . (Correlation)_{ki} \qquad (6.1)$$

This formulation assumes that parameter *i* impacts *n* customer requirements.

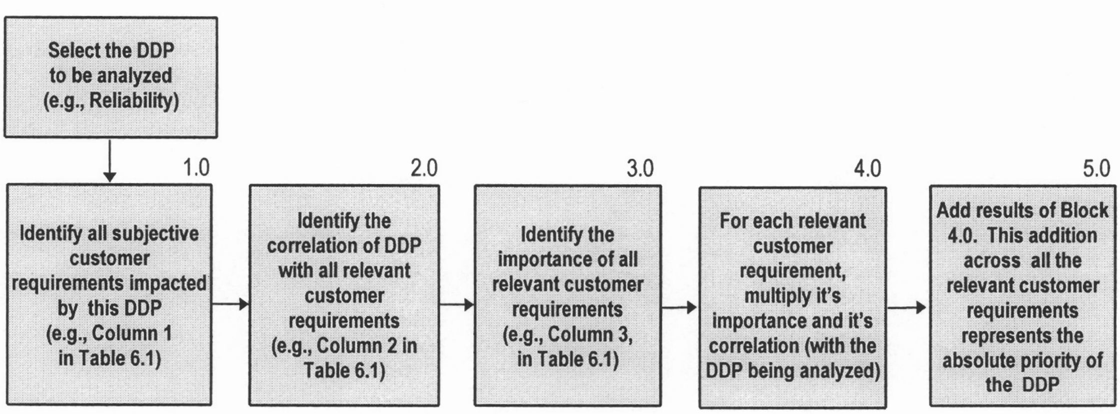

Figure 6.4. Sequence of steps necessary to compute DDP absolute priorities.

Equation 6.1 may be applied to compute the absolute importance of *Reliability* in the video conferencing example (utilizing the information presented in Table 6.1) as:

$$I_{Reliability} = [(Rather\ Important).(Medium)] + [(Rather\ Important).(Medium)] + [(Important).(Very\ High)] + [(Rather\ Important).(High)] + [(Rather\ Important).(Very\ High)] \qquad (6.2)$$

Fuzzy numbers, representing customer requirement importance and correlation, can now be consolidated. This is accomplished through fuzzy multiplication and addition operations as discussed in the Appendix. Therefore, Equation 6.2 may be represented as:

$$I_R = \left| \begin{array}{ll} 0 & x \le 0.125 \\ \dfrac{-3+\sqrt{64x+1}}{2} & 0.125 \le x \le 0.375 \\ \dfrac{7-\sqrt{49-16(3-4x)}}{2} & 0.375 \le x \le 0.750 \\ 0 & x \ge 0.750 \end{array} \right| + \left| \begin{array}{ll} 0 & x \le 0.125 \\ \dfrac{-3+\sqrt{64x+1}}{2} & 0.125 \le x \le 0.375 \\ \dfrac{7-\sqrt{49-16(3-4x)}}{2} & 0.375 \le x \le 0.750 \\ 0 & x \ge 0.750 \end{array} \right|$$

$$+ \left| \begin{array}{ll} 0 & x \le 0.1875 \\ \dfrac{-9+\sqrt{81-3(15-80x)}}{3} & 0.1875 \le x \le 0.45 \\ 1 & 0.45 \le x \le 0.500 \\ -4x+3 & 0.50 \le x \le 0.750 \end{array} \right| + \left| \begin{array}{ll} 0 & x \le 0.25 \\ -2+2\sqrt{4x} & 0.25 \le x \le 0.56 \\ 4-\dfrac{4}{\sqrt{x}} & 0.56 \le x \le 1.00 \\ 0 & x \ge 1.00 \end{array} \right|$$

$$+ \left| \begin{array}{ll} 0 & x \le 0.375 \\ \dfrac{-21+\sqrt{441-120(3-8x)}}{6} & 0.375 \le x \le 0.675 \\ 1 & 0.675 \le x \le 0.750 \\ -4x+4 & 0.75 \le x \le 1.0 \end{array} \right| \qquad (6.3)$$

Equation 6.3 represents the result of five multiplication operations (on triangular or trapezoidal fuzzy numbers) resulting in five normal and convex, but non-linear profiles. These fuzzy numbers, depicted graphically in Figure 6.5, now need to be added. Accordingly, Equation 6.3 reduces to:

$$
\begin{aligned}
I_{Reliability} &= 0 && x \leq 1.0625 \\
&= \frac{-89 + \sqrt{781 + 6720x}}{42} && 1.0625 \leq x \leq 2.435 \\
&= 1 && 2.435 \leq x \leq 2.56 \qquad (6.4) \\
&= \frac{15 - \sqrt{21 + 48x}}{3} && 2.56 \leq x \leq 4.25 \\
&= 0 && x \geq 4.25
\end{aligned}
$$

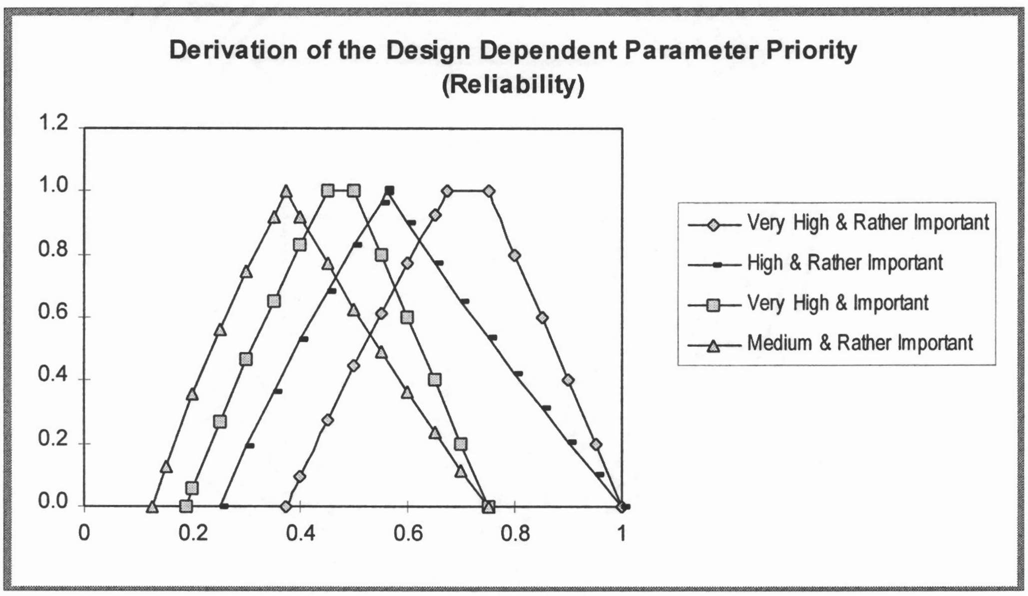

Figure 6.5. Computation of absolute priority for the *Reliability* parameter (example).

Equation 6.4 is a fuzzy representation of the absolute priority for the *Reliability* parameter in the video conferencing example. As discussed earlier, it is a function of the importance of customer requirements impacted by it along with the extent of this impact (i.e., correlation). Figure 6.6 depicts this priority graphically. The absolute importances for all other design depende parameters resulting from a similar approach are shown in Figure 6.7.

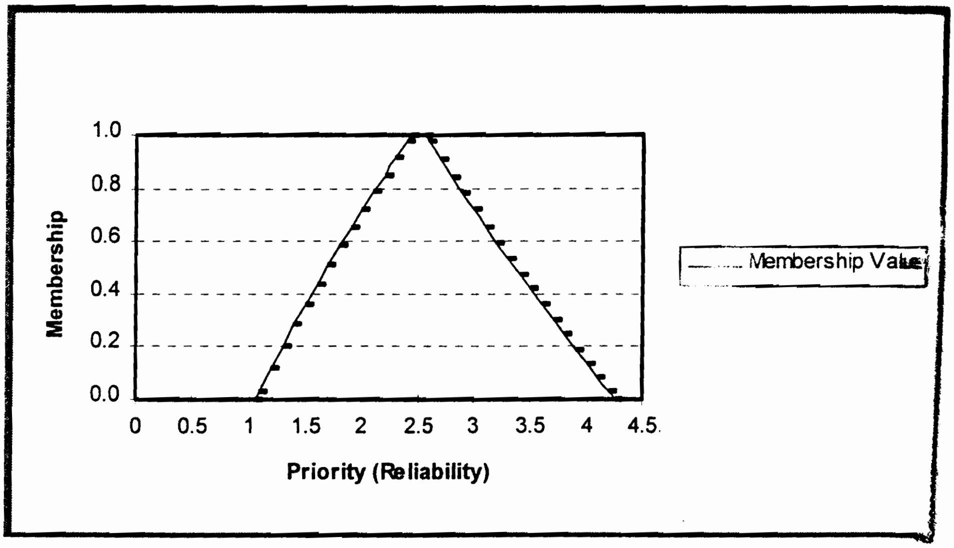

Figure 6.6. Absolute priority for the *Reliability* parameter (example).

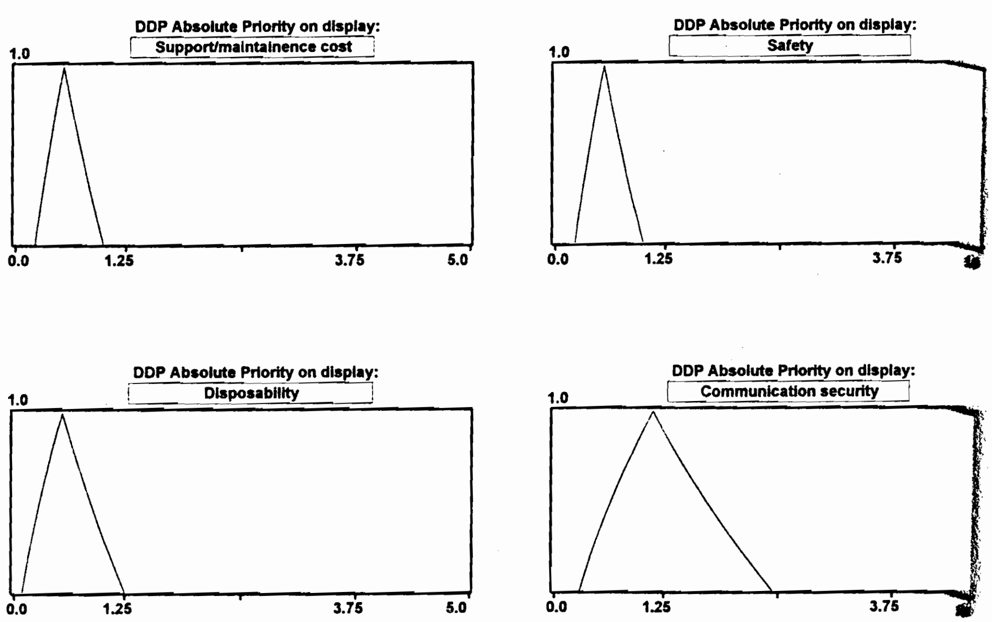

Figure 6.7. DDP absolute priorities for the conferencing example.

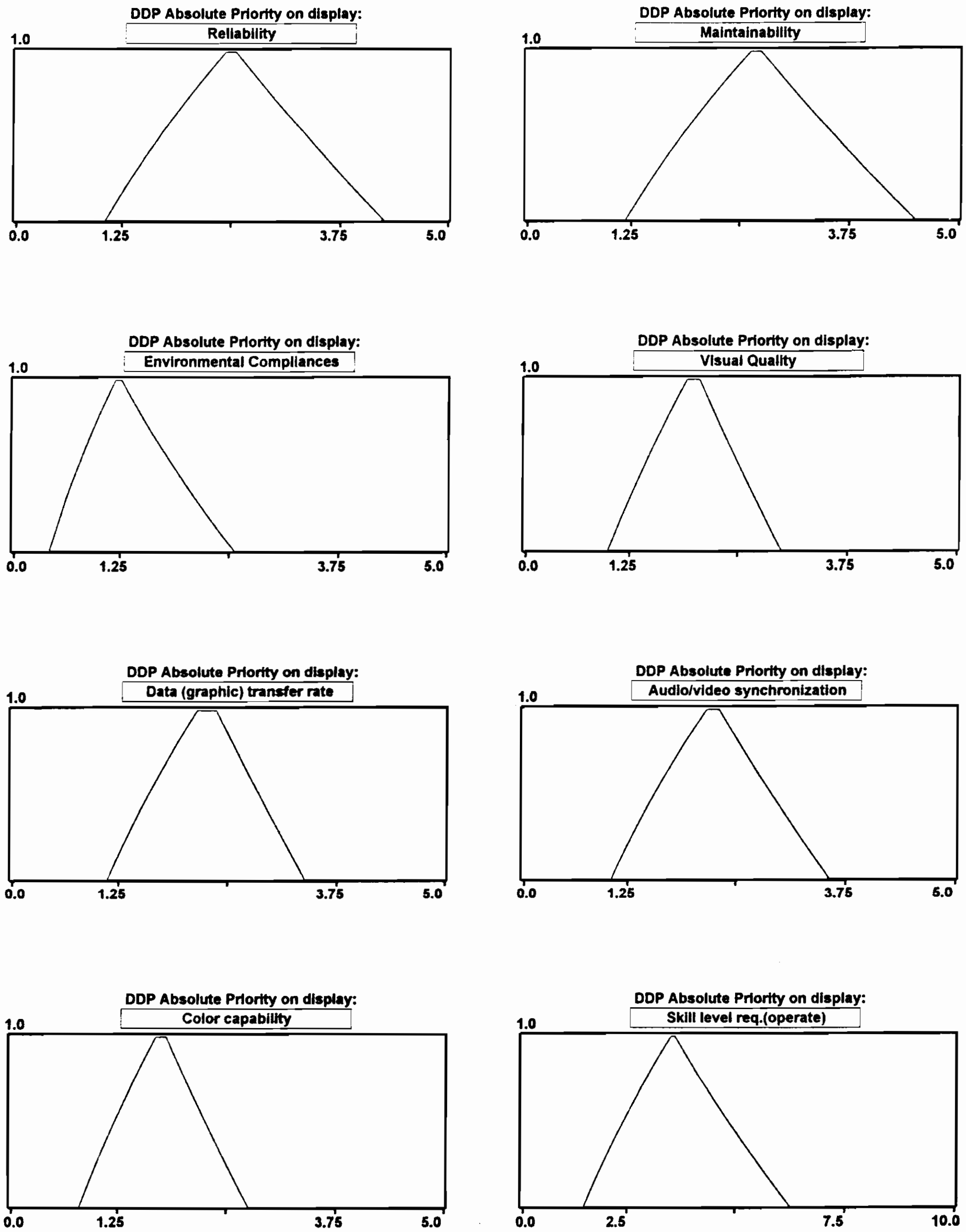

Figure 6.7. DDP absolute priorities for the conferencing example (continued).

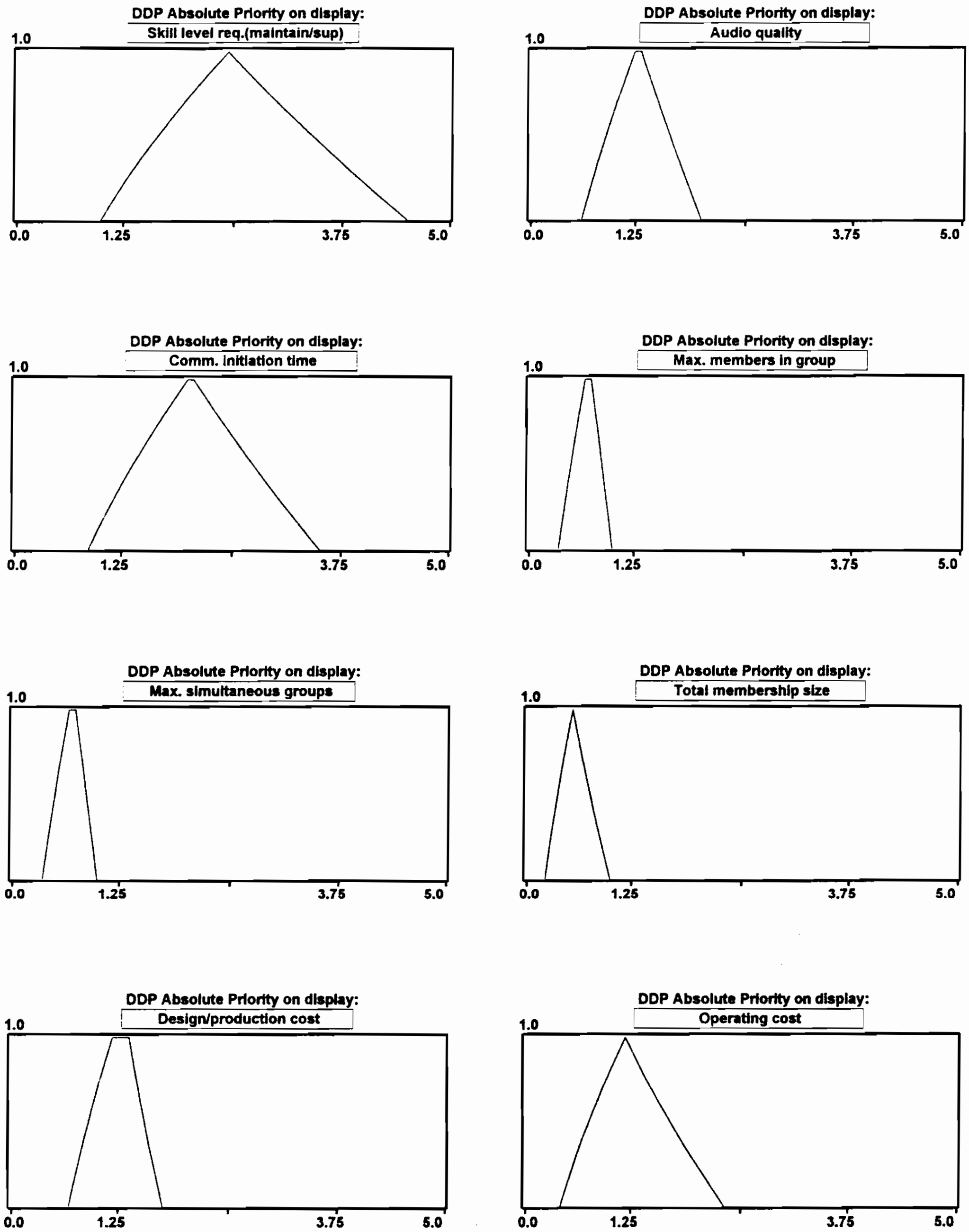

Figure 6.7. DDP absolute priorities for the conferencing example (continued).

6.2.3 Calculating Design Dependent Parameter Relative Importance

The relative importance of design dependent parameters is derived through normalizing their absolute importance values. With reference to Equation 6.1, which represents design dependent parameter importance, the relative importance of applicable parameters is computed as:

$$RI_i = \frac{I_i}{\sum_{i=1}^{i=m} I_i} = \frac{\sum_{k=1}^{k=n} (Customer\ Requirement\ Importance)_k . (Correlation)_{ki}}{\sum_{i=1}^{i=m} \sum_{k=1}^{k=n} (Customer\ Requirement\ Importance)_k . (Correlation)_{ki}} \qquad (6.5)$$

where RI_i represents the relative importance of the i th design dependent parameter. Further, this formulation assumes that there are a total of m design dependent parameters, and that the i th design dependent parameter impacts n customer requirements.

The aggregate profile resulting from the addition of absolute importances for all design dependent parameters in the remote conferencing example is shown in Figure 6.8. In accordance with Equation 6.5, absolute importance of each design dependent parameter is divided by the aggregate of all to yield the corresponding relative importance. Relative importances for design dependent parameters in the remote conferencing example are shown in Figure 6.9.

6.3. RATING AND RANKING FEASIBLE CONCEPTUAL SOLUTIONS

Final phase of the evaluation methodology involves rating and ranking feasible design concepts. This is accomplished by consolidating design dependent parameter relative importances (which remain the same for all design

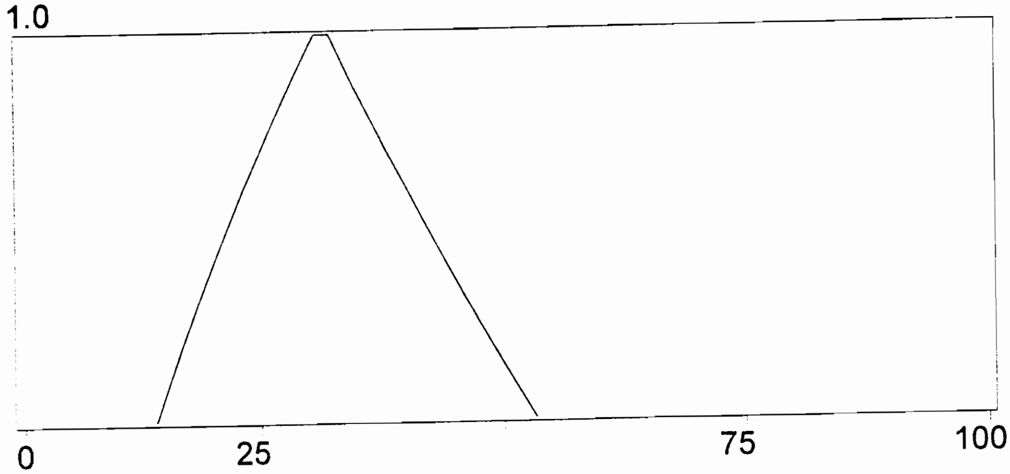

Figure 6.8. Aggregate of DDP absolute importances in the conferencing example.

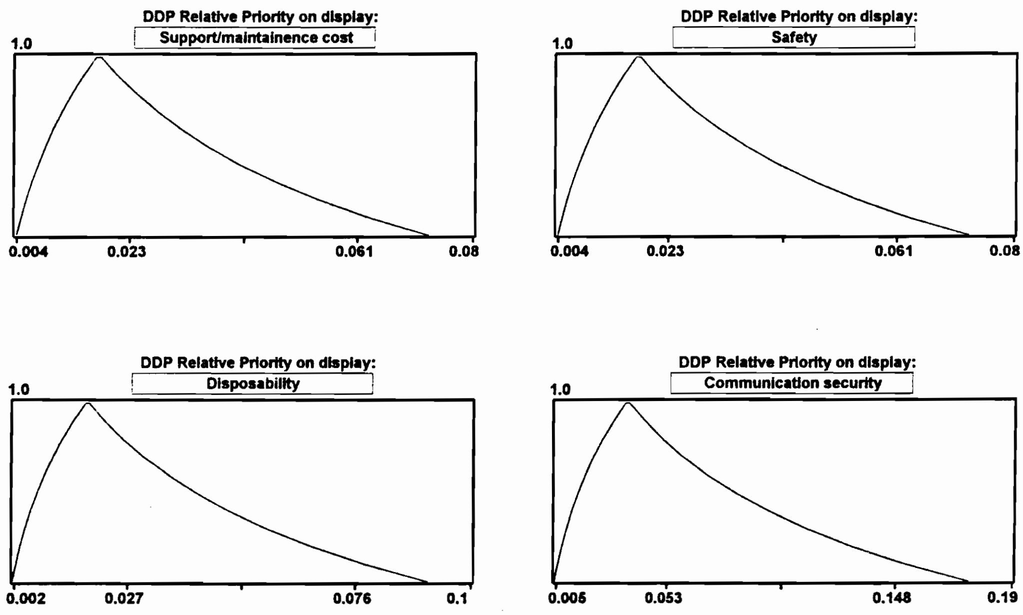

Figure 6.9. DDP relative importances for the remote conferencing example.

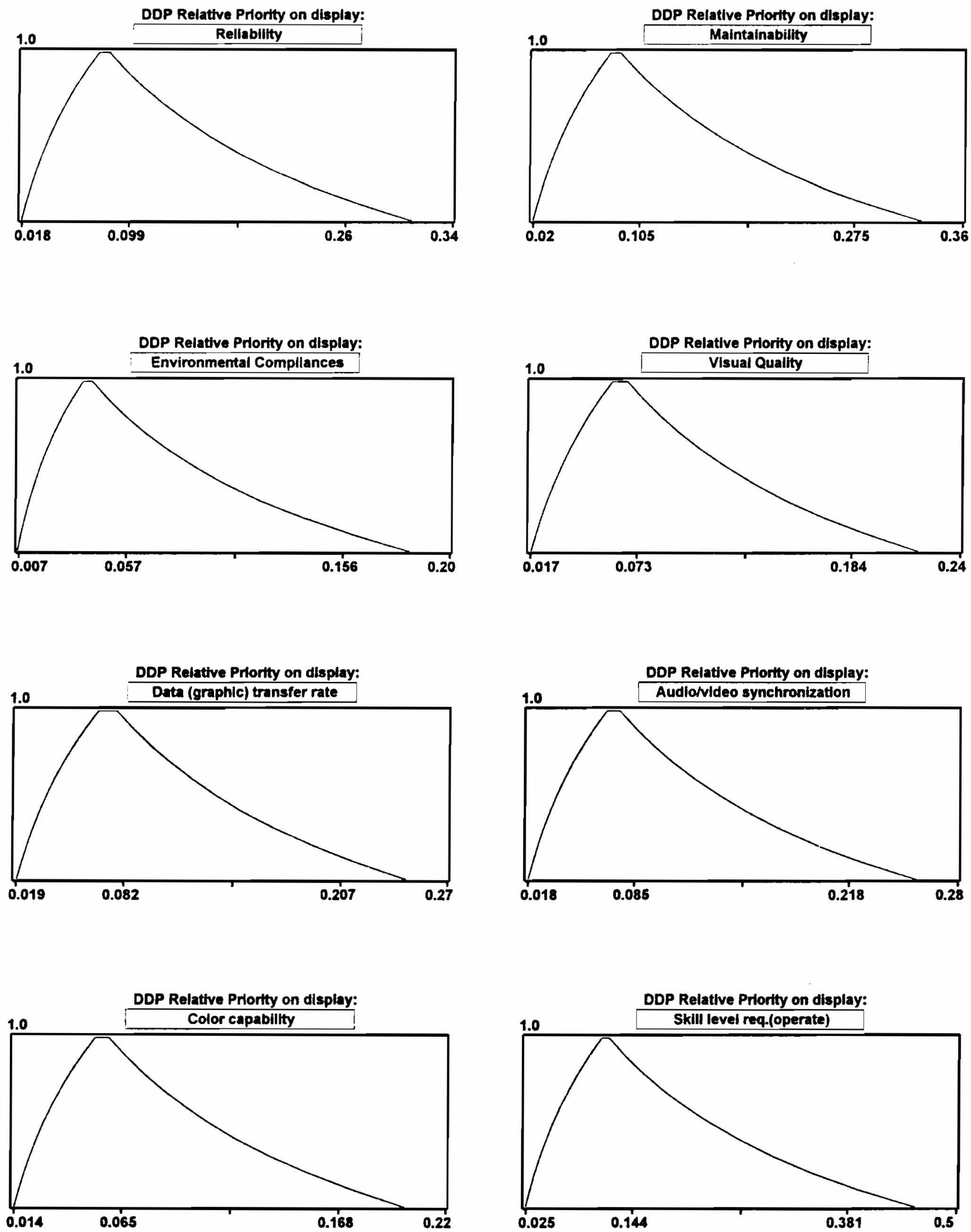

Figure 6.9. DDP relative importances for the remote conferencing example (continued).

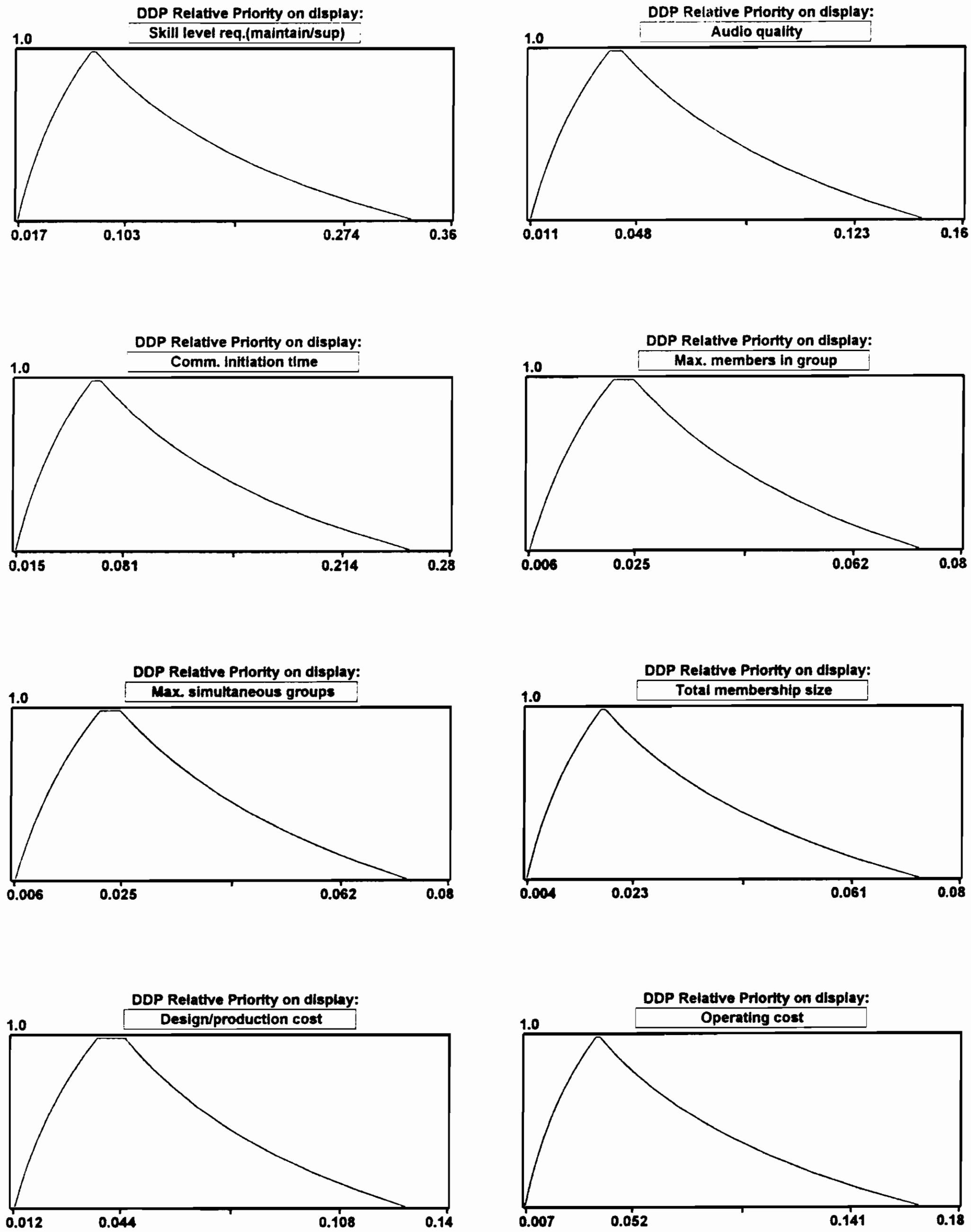

Figure 6.9. DDP relative importances for the remote conferencing example (continued).

concepts) and corresponding feasibility index values. Design dependent parameter relative importances for the remote conferencing example are shown in Figure 6.9. Table 5.6 lists feasibility index values for each design concept.

The overall merit rating for each feasible design concept is given as:

$$MR_{C_1} = \left(\sum_{i=1}^{i=m} (RI_i)\,(FI_{C_1 i}) \right) \tag{6.6}$$

where MR_{C_1} represents the merit rating of design concept 1. RI_i is the relative importance of the i th design dependent parameter and $FI_{C_1 i}$ is the feasibility index of the i th design dependent parameter as it applies to Concept 1.

Profiles depicting the overall "goodness" of the two feasible system design concepts in the remote conferencing example are shown in Figure 6.10. Uncertainty (imprecision) inherent within these profiles is a function of the uncertainty associated with the inputs. These profiles represent relative goodness and facilitate commitment to the preferred concept(s).

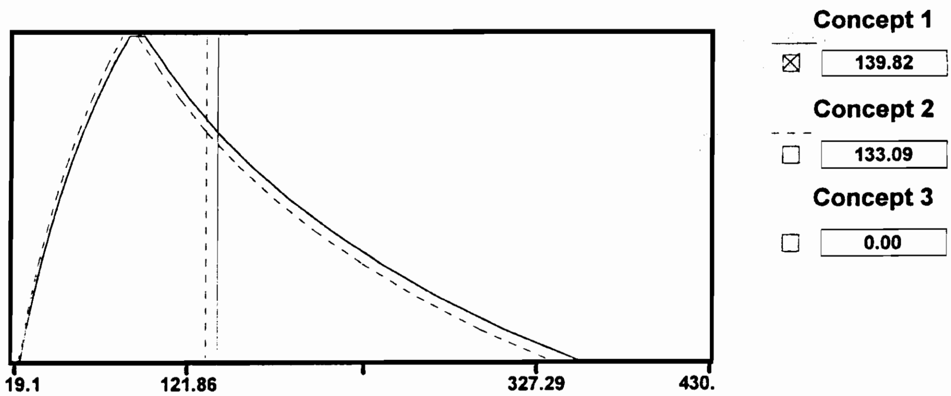

Figure 6.10. Merit ratings for feasible design concepts in the remote conferencing example.

After reviewing the analysis and evaluation results, the design team may decide to utilize the knowledge gained thus far and revisit the system design problem. In the case of the illustrative remote conferencing example, the ordering between the “goodness” profiles is obvious. Concept 1 is the preferred approach.

As discussed in Chapter 4, fuzzy numbers lack total order, and the ranking of fuzzy numbers/profiles is not always obvious or trivial. There is no “best” approach to rank fuzzy numbers. Numerous rating and ranking mechanisms were referenced and discussed in Chapter 5. The center of gravity defuzzification approach is applied here to translate fuzzy profiles into crisp merit ratings. The two vertical lines in Figure 6.10 represent crisp ratings for the two feasible design concepts in the remote conferencing example. Translation of fuzzy profiles into crisp numbers (defuzzification) involves significant information “loss”. Accordingly, it is important that crisp merit ratings be reviewed in the context of the corresponding fuzzy profiles.

6.4. DISCUSSION OF THE RESULTS

Validation of the evaluation methodology developed herein has not been accomplished. Validation was considered beyond the scope of this research. Nonetheless, such validation is essential and identified as a significant extension opportunity. It is pertinent at this time to briefly summarize and subjectively critique the results of this evaluation methodology with comparative approaches.

Analysis and evaluation activities, and their coordination with design synthesis during conceptual design, have been largely ignored by the research community (as discussed in Chapter 1). Pugh first introduced formality to the analysis and evaluation of system design concepts [1990]. He proposed a concept generation and evaluation methodology for the integrated accomplishment of synthesis, analysis, and evaluation activities during conceptual design. This methodology is depicted in Figure 2.8 and discussed in Section 2.1.5. A concept selection matrix, shown in Figure 2.7, drives this methodology. The traditional QFD method is used for the definition of system-level design requirements. These requirements then define a design "envelope" within which all feasible design concepts must lie. A schematic of this approach is shown in Figure 6.11, and contrasted with the approach developed herein.

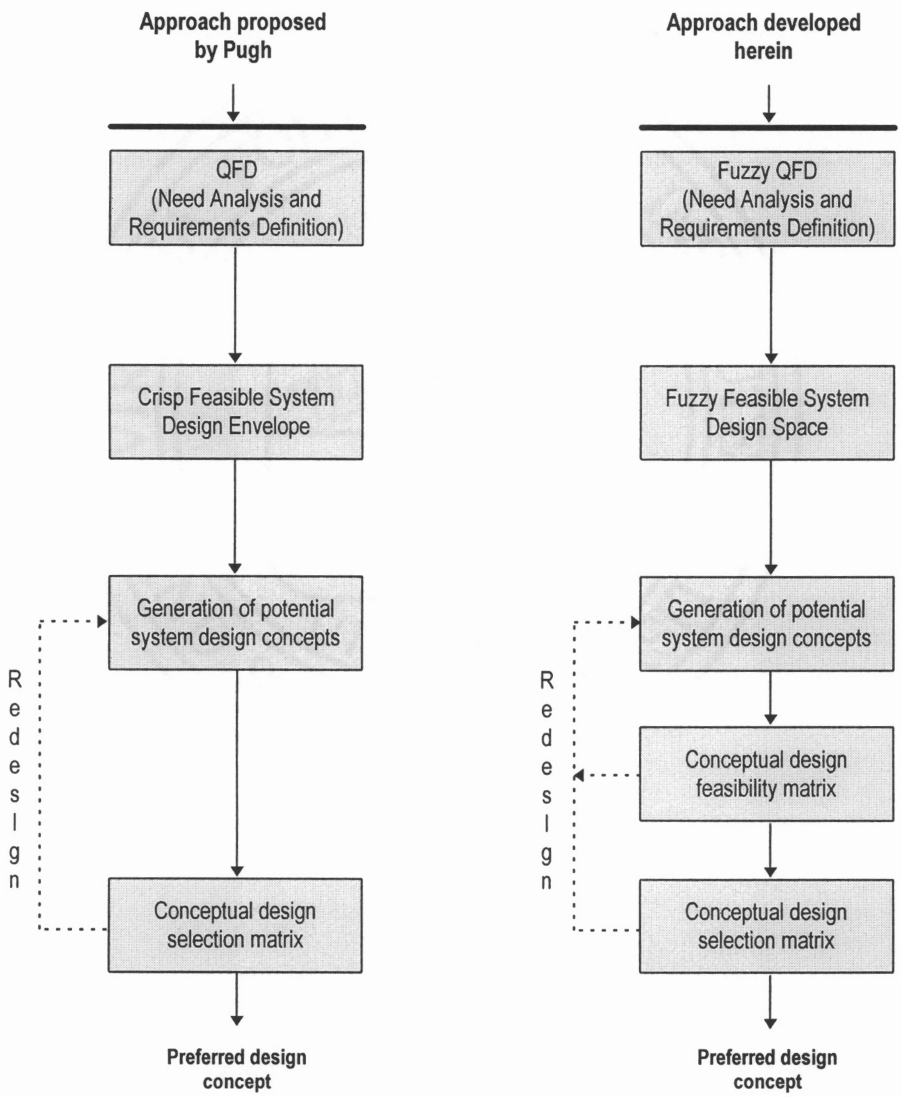

Figure 6.11. Comparison of conceptual design evaluation methodologies.

The following observations highlight differences between Pugh's concept generation and evaluation methodology and the methodology developed from this research:

1. *Need analysis and requirements definition.* Pugh proposed utilization of the traditional QFD method to define system-level design requirements. On the other hand, a fuzzy QFD method has been developed herein to model imprecise (a) correlation between customer requirements and design requirements, (b) importance of customer requirements, and (c) customer satisfaction levels as part of the benchmarking activity. This imprecise input is utilized in the development of two indices, *IPN* and *TOF*, to facilitate definition of fuzzy system-level design requirements. While the *IPN* index conveys a sense for the extent of improvement necessary (relative to a baseline), the *TOF* index provides insight into the tolerance of design requirements. While subjective, such indicators convey valuable information to a design team during the requirements definition activity.
2. *A crisp design envelop versus a fuzzy feasible design space.* Utilization of the traditional QFD method leads to the definition of crisp system-level requirements. These requirements define a non-fuzzy feasible design envelop. On the other hand, the fuzzy QFD method results in the delineation of a fuzzy feasible design space with varying degrees of preference within relevant tolerance bands. The concept of a fuzzy feasible design space is consistent with the nature (imprecise and vague) of information available during this design phase. While this approach seems more intuitive it has not yet been validated.
3. *Analysis and evaluation of potential system design concepts.* Subsequent to the definition of system-level requirements, potential design concepts are synthesized. These concepts are next analyzed

and evaluated. Synthesis, analysis, and evaluation activities are continuously iterative and progressively more resolved, ultimately leading to the selection of the preferred design concept(s). Pugh has proposed a concept selection matrix to facilitate this process as shown in Figure 2.7. This matrix is populated with data reflecting the performance of each design concept relative to corresponding design requirements. Three levels or scales are utilized to capture this performance as: (a) better than required, (b) same as required, and (c) not as much as required.

In the approach developed as part of this research, a concept feasibility matrix precedes the concept selection matrix. The feasibility matrix includes computation of a design dependent parameter feasibility index. This index "captures" the extent (or lack) of compliance between required and predicted values of the various design parameters. Further, design dependent parameter feasibility thresholds may be defined by a design team as a function of their criticality. A feasible design concept must satisfy the feasibility thresholds of all design dependent parameters. Such a formal feasibility mechanism highlights the weak and strong aspects of all design concepts. Further, it provides direction to any subsequent redesign or design improvement activity.

Although the merit of this approach still needs validation, the evaluation methodology developed herein is rich and elaborate as compared to Pugh's approach. This is due to the explicit consideration of design imprecision, development of *IPN* and *TOF* indices, and computation of the feasibility index. Accordingly, the design specific information "captured" and conveyed to the designer is more comprehensive.

CHAPTER 7

RESEARCH SUMMARY AND CONCLUSIONS: CONTRIBUTIONS, ASSUMPTIONS, AND POSSIBLE EXTENSIONS

The uniqueness of this research is revisited and discussed in the first section of this chapter. This is followed by an enumeration of the specific research contributions, a presentation of assumptions made, and a discussion of possible research extensions. Finally, some observations are made regarding possible applications of the methods developed.

7.1. UNIQUENESS OF THIS RESEARCH

A disciplined and structured system engineering process is essential for the effective and efficient development of products and systems which are both responsive to customer needs and requirements and competitive in the global economy. Rigor and discipline during later stages of the design (preliminary and detail) and development process cannot salvage or "make-up-for" an ill-conceived design concept and premature design commitments (i.e., technology applications) made during the conceptual system design phase.

Development of concepts in the field of fuzzy set theory in general, and fuzzy arithmetic in particular, offer a means to first consider and then manipulate the imprecise and subjective information which characterizes the conceptual system design phase. Tailored and innovative manipulation of this subjective, imprecise, and scarce information can provide increased insight for the design team when making early design decisions and associated commitments.

Its significance notwithstanding, the nascent stage of system design (in terms of the process and the associated analysis and evaluation activities) has been largely ignored by the research community [Pugh, 1990; Verma and Knezevic, 1994]. This research undertaking is unique, not only in its focus on the conceptual design phase, but also in its attempt to formalize the analysis and evaluation activities during this phase.

Although the primary goal of this research involved the development of a conceptual design analysis and evaluation methodology, an overarching imperative required this methodology to be completely integrated with the underlying system engineering process. Rather than being a constraint, this requirement resulted in a better definition and formalization of the conceptual system design process itself, along with an enhanced understanding of the integrated and coordinated accomplishment of synthesis, analysis, and evaluation activities during this phase of system development.

Given the imprecise and subjective nature of information available to the designer(s) during this nascent stage of system development, relevant concepts from the field of fuzzy set theory and fuzzy arithmetic were identified, adapted, and then applied in the development of the evaluation methodology. The rationale for the use of fuzzy set concepts versus probabilistic approaches was developed based upon the classification of uncertainty into two broad-based groups, imprecision and randomness. Rather than debate the superiority of one approach over the other, complementary use of concepts from both fields is proposed.

The methodology developed accounts for selected predictions and estimations to be expressed as probabilistic measures. On the other hand, fuzzy concepts were invoked to address the imprecision relative to customer requirements, their importance, their correlation with applicable design dependent parameters, including customer perceptions as to the "goodness" of similar existing systems or products. Further, these concepts facilitated the explicit inclusion of "soft" and subjective design requirements, such as those pertaining to aesthetics or user friendliness, into the overall design analysis and evaluation activity. Similar approaches were used to address the involvement of design requirements such as disposability and polutability, which do not (as yet) have useful metrics.

Finally, the methodology was developed within the design dependent parameter framework for the robust evaluation of designs. This framework was further defined and explained, in terms of a contracting feasible system design space, along with the concurrent refinement of the system search space.

7.2. SUMMARY OF RESEARCH CONTRIBUTIONS

Given its unique emphasis (on the conceptual system design phase) and imperative (integration with the system engineering process), this research adds to the body of systematic knowledge (methods, best practices, methodologies, design decision aids, techniques, and processes) as it pertains to system engineering and analysis. This research concluded with the development of a formal evaluation methodology (along with a number of conceptual design decision aids in the form of indices). Further, it should provide an impetus to the continued formalization and evolution of the theory of system design and development.

In the context of the discussion above, specific and unique contributions of this research are enumerated as follows:

1. *Definition and formalization of the conceptual system design process.* The conceptual design process was first defined and then

reduced to its constituent activities. Each of these activities was analyzed in terms of necessary inputs and expected outputs. This analysis provided insight into the nature of design methods and best practices needed to "operationalize" this phase of system design. The activities within this phase were also classified based upon their inherent nature (i.e., synthesis, analysis, and evaluation). This lead to a better integration of evaluation methodology with the underlying process. Further, the difference between evaluation and optimization, as it pertains to system design, was clarified and extended. (Chapter 2)

2. *Application of relevant concepts from fuzzy set theory and fuzzy arithmetic.* Relevant concepts within the broad field of fuzzy logic and fuzzy arithmetic were identified and summarized with regard to their potential application in the analysis and evaluation of engineering designs in general, and conceptual system designs in particular. (Chapter 3)

3. *Development of the conceptual design evaluation process.* The conceptual system design evaluation process was developed. Constituent activities, which need to be completed in sequence, were identified. This process is entwined with, and reflects an enhancement to, the basic system engineering process [Blanchard and Fabrycky, 1990; Blanchard, Fabrycky, and Verma, 1994]. (Chapters 4, 5, and 6)

4. *Classification of design dependent parameters.* Actual development of the evaluation methodology was preceded by a classification of design dependent parameters or design criteria. This classification was based upon the nature of the corresponding design characteristics (discrete versus continuous), and the nature of the

associated metric (numeric or non-numeric base, along with its mapping on the real number line versus being restricted to the [0,1] interval). Based upon the classification of DDPs, procedures were developed for their assessment and definition using linguistic labels (along with numeric constants). These procedures “allowed” the explicit involvement of not only the subjective design dependent parameters (e.g., user friendliness) in the analysis and evaluation process, but also DDPs that do not (as yet) have metrics (e.g., disposability, polutability, etc.) associated with them. The classification of design dependent parameters was further supplemented with the development of a taxonomy for generic design dependent parameters. (Chapter 4)

5. *Development of a Fuzzy Quality Function Deployment (Fuzzy QFD) method.* A Fuzzy QFD method was developed by adapting and extending the basic QFD technique. Pertinent concepts from fuzzy set theory were utilized to address the imprecise and subjective assessment of requirement importance by potential customers, the imprecise correlation between customer requirements and relevant design dependent parameters, and the subjective benchmarking of customer perceptions relative to existing facilities and systems. Linguistic scales, with five linguistic labels, were developed to facilitate this process. The fuzzy concepts utilized in this manner were further manipulated and developed to construct design decision aids, in the form of indices, to facilitate the definition of system-level design requirements, or target values, for the design dependent parameters. (Chapter 4)

6. *Development of an Improvement Potential and Necessity (IPN) index.* The *IPIN* index was developed to provide designers insight

into the extent of improvement required and possible when defining target values for design dependent parameters. The *IPN* index for each design dependent parameter is delineated by developing a matrix linking customer satisfaction levels and the correlation between customer requirements and design dependent parameters. This index allows exploitation of the most prominent opportunities in order to gain a strategic advantage for a given system. Design effort should be focused along avenues where improvements can be accomplished (in terms of overall customer satisfaction levels) in the most effective and efficient manner. (Chapter 4)

7. *Development of a Tolerance Of Fuzziness (TOF) Index*. For the completeness of the design requirement definition process, it is necessary to define not only the required target values for design dependent parameters, but also the associated tolerance levels. This concept of tolerance for system-level requirements was developed and expressed as a *Tolerance Of Fuzziness* (*TOF*) index. This index provides an indication of the acceptable band of values (with varying degrees of preference), about the most desired target value for each design dependent parameter. The *TOF* index for each design dependent parameter was defined as a function of it's *IPN* index and the associated importance of customer requirements. (Chapter 4)

8. *Development of the concept of a fuzzy feasible design space*. The definition of system-level design requirements, with associated tolerance levels, was followed by the development of the concept of a fuzzy feasible design space, and represented as a radial multi-dimensional chart. This concept was later extended, discussed in

more detail, and distinguished from the concept of a design search space. (Chapters 4 and 6)

9. *Development of the Feasibility Index.* A method was developed for assessing the feasibility of conceptual designs. Feasibility of concepts was defined here as a function of compliance between predicted (and estimated) values and corresponding required values for applicable design dependent parameters. The *Feasibility Index* was formulated to facilitate this process. This index allows a design team ease and flexibility while assigning varying feasibility threshold levels for different design dependent parameters. The feasibility threshold of a DDP depends upon its relative priority within the scope of the overall design and development effort. This feasibility index also facilitates a "backwards" perspective for the design team. Critical aspects of a design can be quickly identified, and addressed, as part of a focused redesign or design improvement undertaking. (Chapter 5)

10. *Development of the concept of compliance analysis as contrasted with separation between fuzzy sets.* The feasibility index was developed through the delineation of a concept called compliance analysis as opposed to the separation of or ranking of fuzzy sets. Current methods used to rank and rate fuzzy numbers were surveyed and studied. Discussion was presented regarding the difference between rating and ranking fuzzy numbers or analyzing their separation, versus analyzing the compliance of one fuzzy number with another in the context of assessing system design feasibility. Based upon the above discussion and rationale, a mechanism to facilitate compliance analysis was developed through

the use of a unique scheme to weight the areas of overlap between two relevant fuzzy numbers. (Chapter 5)

11. *Definition of design dependent parameter relative importance.* Relative importance (or relative priorities) of design dependent parameters must be defined in order to facilitate selection of the preferred approach or design concept. These relative priorities were traced from the importance attached to requirements by potential customers, and the correlation of these requirements with design dependent parameters. These relative priorities were ultimately consolidated with the corresponding feasibility indices, and then aggregated to provide an indication of the relative desirability of competing feasible design alternatives. (Chapter 6)

12. *Development of an illustrative example.* In order to better convey the underlying concepts and to illustrate their applicability, a fairly comprehensive example was developed as part of this research. This example concerned the design and development of a system to facilitate an interactive session between multiple remote parties.

7.3. PRIMARY ASSUMPTIONS AND POSSIBLE EXTENSIONS

Extra care has been taken to keep the "Voice of the Customer" integral to all synthesis, analysis, and evaluation activities during early system design. Given that the customer or consumer is the dominant force (or driver) behind this methodology, enough groundwork must be done to truly capture the corresponding intent regarding customer likes and dislikes.

A study of demographics to determine the population of potential customers, and the subsequent assessment of their desires, is (or should be) a significant program activity within most commercial organizations. This activity involves extensive use of tools such as customer surveys, questionnaires, interviews, benchmarking, trade studies, parametric analyses, and so on. As a result of this data collection and analysis activity (and especially in the case of a large customer population), a surrogate and generic customer profile (targeted to a particular market segment) is often constructed to guide the early design decision making.

With the above discussion in mind, this research presumed that enough effort has been expended in the study of the potential customer and that a specific market niche has been targeted in the delineation of customer wants and desires. Given this overriding presumption, more specific assumptions inherent within the methodology, along with its potential extensions are as follows:

1. *Assumption of complete consistency in the Fuzzy QFD correlation matrix.* During development of the Fuzzy QFD method, complete consistency was assumed between the customers' perception of existing products and systems (i.e., customer benchmarking) and the corresponding engineering/technical assessment of applicable design dependent parameters. This assumption played a role in the delineation of target values for the on-going design and development activity. Although highly desired, complete consistency is almost impossible to achieve. It is necessary for designers to assess the extent of inconsistency present within the QFD mechanism. Further, remedial action must be undertaken to address the more critical inconsistencies.

   An investigation of the extent of inconsistency within a QFD correlation matrix would be a significant extension to this evaluation methodology. Such a study has the potent to identify and point to a) an incomplete set of design dependent parameters, b) a revision in the extent of correlation between requirements and design dependent parameters, c) an unnecessary design dependent parameter, d) an important customer requirement which has not been completely addressed, and so on.

Although it may be possible for designers to manually study a QFD matrix in an attempt to delineate these inconsistencies, such a study is likely to be tedious and time consuming when dealing with large matrices. Accordingly, the development of an intelligent decision support system would be valuable. This support system could parse a QFD matrix and identify critical inconsistencies.

2. *Influence of design independent parameters on design desirability.* The influence of design externalities (represented by the design independent parameter set), as they pertain to corresponding social, economic, and political environments, has not been explicitly considered in this research. Shifts in values of pertinent design independent parameters may have a bearing on the overall "goodness" of design alternatives or design concepts. Inclusion of such considerations into the design concept selection process could make the evaluation more robust in nature. The impact of such issues has been explored and illustrated for the preliminary design phase but not the conceptual design phase. This extension would greatly benefit the methodology.

3. *Generation of more realistic linguistic scales.* Linguistic scales used in this methodology to address requirements importance, correlation, and the customer benchmarking activity are linear and symmetrical in nature. Implementation and application of the methodology is independent of the shape of the linguistic profiles. Symmetrical and linear profiles were selected only to simplify the underlying mathematics and to facilitate a more lucid conveyance of concepts.

Research needs to be conducted in order to construct a more representative set of linguistic profiles. This research would enhance the applicability and responsiveness of the methodology.

4. *Minimize system over-design.* To fully explain this research extension, consider the requirement profile for the *Reliability* parameter in the remote conferencing example, along with the three prediction profiles, as shown in Figure 5.11. Note the predicted or anticipated profile with regard to reliability for Concept 1. In accordance with the feasibility index mechanism, this Concept is definitely and absolutely feasible with regard to the reliability design requirement. However, the predicted or anticipated reliability figure of merit for this alternative is much higher than required. This information is invaluable from a designer's perspective and may be used in a variety of ways:

   a) Over-design within a concept relative to a particular design dependent parameter may be used to facilitate a design trade-off decision whereas another parameter, with a negative correlation, may need to be improved in order to enhance the overall "goodness" of the alternative.

   b) Cost savings may be realized by relaxing the design effort relative to this design dependent parameter, while still meeting the system level requirement.

5. *Non-linear weighting.* The concept of a weighting wedge was developed in Chapter 5 to assist the assessment of conceptual system design feasibility. In order to simplify the corresponding calculations, this wedge was assumed to be linear as depicted in Figure 5.5. It may be useful to explore the utilization of a non-linear wedge. Such an approach would result in non-uniform penalty for

lack of compliance with the associated design requirement as a function of the preference level. This would be analogous to Taguchi's quadratic loss function as applied to the detailed system design phase.

6. *Extension into the preliminary system design phase*. The evaluation methodology developed herein concludes with the selection of a preferred system concept. Opportunities should be explored to link it in a seamless manner to preliminary design. This link should enable explicit traceability, with activities pertaining to functional analysis, functional packaging, requirements allocation, and functional allocation to hardware, software, and human subsystems. This would lead to the identification of a preferred design configuration.

7. *Validation of the evaluation methodology*. Validation of the evaluation methodology developed herein was considered beyond the scope of this research. Nonetheless, this is significant and should be conducted. Such a study is likely to identify further extensions and also allow a more objective comparison with comparative approaches.

7.4. CONCLUSIONS

This research was successful, not only in formalizing the analysis and evaluation activities as they pertain to conceptual design, but also in the development of a methodology which integrates these activities with the underlying design and development process. A consolidated system design process depicting the integration of synthesis, analysis, and evaluation activities during the conceptual phase of system design is shown in Figure 7.1.

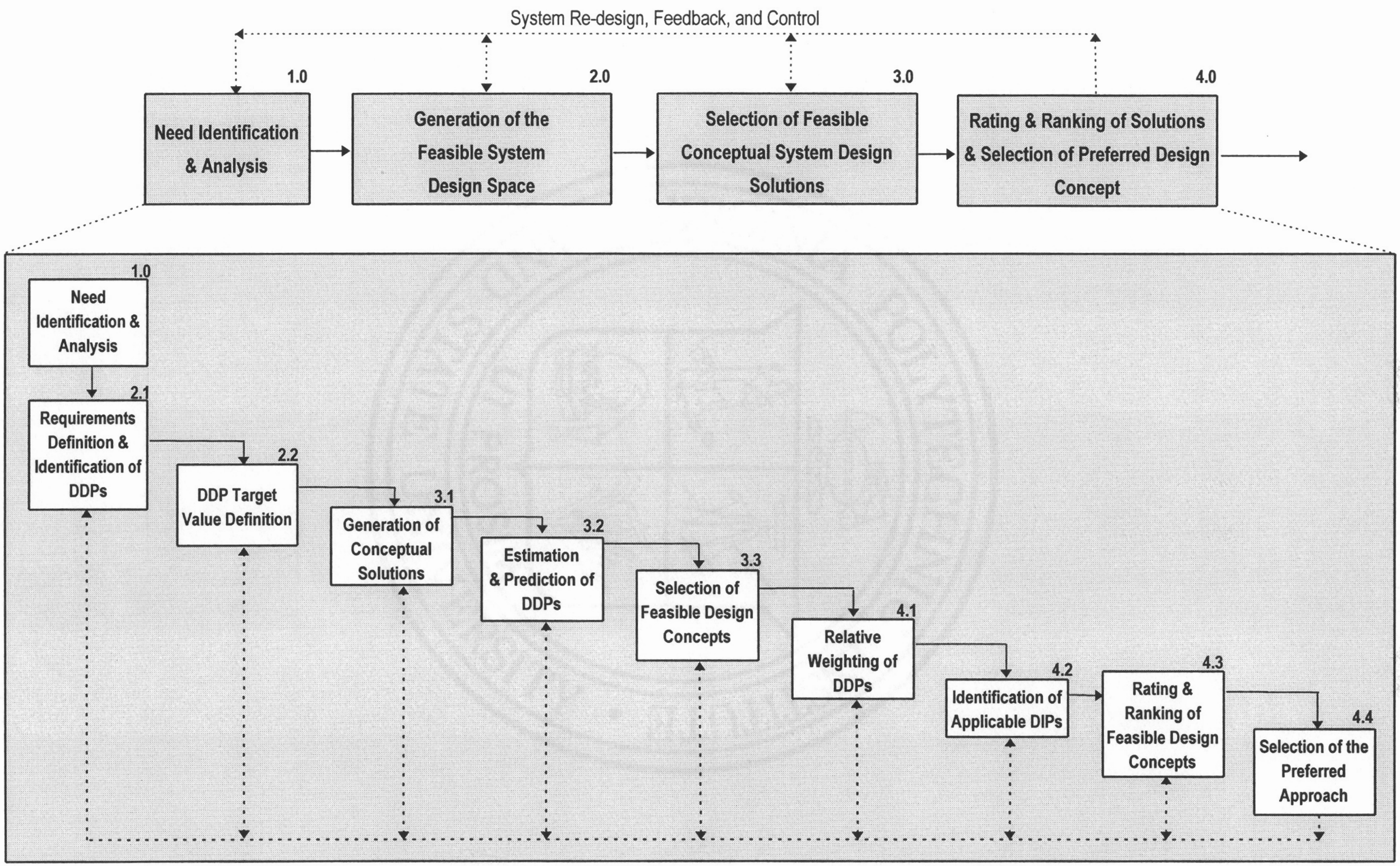

Figure 7.1. Conceptual system design process (synthesis, analysis, and evaluation).

Other concluding observations may help to facilitate the application of the methods developed during the course of this research. Figure 7.1 provides a basis for these observations.

First, development of the conceptual system design evaluation methodology was accomplished in a sequential manner. Adequate reference was not made in the body of this document to activities pertaining to system re-design, feedback, and control as indicated in Figure 7.1. All system design activity is iterative in nature and knowledge gained during the progressive evolution of design can often be used to retrace some steps, or to conduct focused system re-design and implement necessary design improvements.

During conceptual design, subsequent to computing feasibility index values for the various design dependent parameters, the design team gains insight relative to a particular design's strengths and weaknesses. It may then be possible to rethink the design concept and re-design some aspect of it in order to realize improvements. The concept generation, analysis, and evaluation process is iterative and leads to greater refinement of the initially delineated conceptual solutions, and the ultimate selection of a preferred approach. The system engineering process is characterized by the progressive refinement of synthesis, analysis, and evaluation activities. This refinement is a result of system design evolution.

This research focused on and discussed the generation, analysis, and evaluation of design concepts at the system level. However, the process and procedures can be applied at lower levels in the system hierarchy as well. For example, in the case of a large, complex, distributed system, after a system-level design concept is identified, a similar approach may be utilized with focus on the sub-system level.

APPENDIX

BASIC OPERATIONS IN FUZZY ARITHMETIC

Relevant concepts from the field of fuzzy arithmetic are addressed in this appendix. Several simple examples are offered to help convey the concepts. For a more exhaustive converage of fuzzy subset theory in general, and fuzzy arithmetic in particular, refer to [Gupta and Kaufmann, 1991; Dubois and Prade, 1980; and Kaufmann, 1975].

A.1. BASIC CONCEPTS FROM TRADITIONAL SET THEORY

If set *A* is a subset of the universal set *E*, it is denoted as:

$$A \subset E$$

And, if *x* is an element of set *A*, it is denoted as:

$$x \in A$$

A characteristic function $\mu_A(x)$ indicates whether or not *x* is a member of set *A*,

$$\mu_A(x) = 1 \Rightarrow x \in A$$
$$\mu_A(x) = 0 \Rightarrow x \notin A$$

When working with "crisp" sets, the characteristic function can assume only two values {0, 1}. Accordingly, the set *A* can be represented by accompanying elements of the universal set E with their characteristic function values, such as:

$$A = \{(x_1, 0), (x_2, 1), (x_3, 1), (x_4, 0)\}$$

If $\overline{A}$ is the complement of A then,

$$\overline{A} = \{(x_1, 1), (x_2, 0), (x_3, 0), x_4, 1)\}$$

Further, $\overline{A} \cup A = E;\ and\ \overline{A} \cap A = \phi$

Selected operations on crisp sets include intersection and union of sets. These operations may be defined as:

1. *Intersection*. Intersection between two sets, A and B, is denoted by:

   $$A \cap B$$

   where

   $$\mu_{A \cap B}(x) = 1, \text{if } x \in A\, and\, x \in B$$
   $$\mu_{A \cap B}(x) = 0, \text{if } x \notin A\, or\, x \notin B$$

   Further,

   $$\mu_{A \cap B}(x) = \mu_A(x).\mu_B(x)$$

2. *Union*. Union between two sets, A and B, is denoted by:

   $$A \cup B$$

   where

   $$\mu_{A \cup B}(x) = 1, \text{if } x \in A\, or\, x \in B$$
   $$\mu_{A \cup B}(x) = 0, \text{if } x \notin A\, and\, x \notin B$$

   Further,

   $$\mu_{A \cup B}(x) = \mu_A(x) \dot{+} \mu_B(x)$$

   where $\dot{+}$ represents boolean sum, i.e., 1+1=1, 1+0=1, 0+0=0.

A.2. BASIC CONCEPTS FROM FUZZY SET THEORY

Given a universal set E, a fuzzy subset may be denoted as $\widetilde{A}$ and represented as:

$$\widetilde{A} \subset E$$

If x is an element of $\widetilde{A}$, it is denoted as:

$$x \in \widetilde{A}$$

Unlike traditional crisp sets, when dealing with fuzzy subsets the characteristic function $\mu_{\widetilde{A}}(x)$ indicates the "degree" or extent to which an element x "belongs" to, or is a member of, the fuzzy subset $\widetilde{A}$. In other words, rather than taking on one of two values {0, 1}, in fuzzy set theory $\mu_{\widetilde{A}}(x)$ takes on any value in the interval [0, 1].

Given the universal set E and the element x, a fuzzy subset $\widetilde{A}$ can be represented as a set of ordered pairs expressed as:

$$\widetilde{A} = \{(x|\mu_{\widetilde{A}}(x))\}, \forall x \in E$$
$$or, \ \widetilde{A} = (\mu_1|x_1 + \mu_2|x_2 + \mu_3|x_3 + \cdots + \mu_n|x_n), \forall x_{1,\cdots,n} \in E$$

where $\mu_{\widetilde{A}}(x)$ is called the membership, characteristic, anticipation, preference or compatibility function, depending upon the source and usage. It expresses the degree or grade of membership of x in $\widetilde{A}$.

Using the above nomenclature, the fuzzy set *Small* may be expressed as:

$$Small = 1/1 + 0.9/2 + 0.8/3 + 0.7/4 + 0.6/5 + 0.5/6 + 0.4/7 + 0.3/8 + 0.2/9 + 0.1/10 + 0.0/11$$

In this example + denotes the union operator. The fuzzy set *Small* is depicted graphically in Figure A.1.

When the universal set and the corresponding fuzzy subset are continuous (rather than discrete in nature), the fuzzy subset $\widetilde{A}$ may be expressed as:

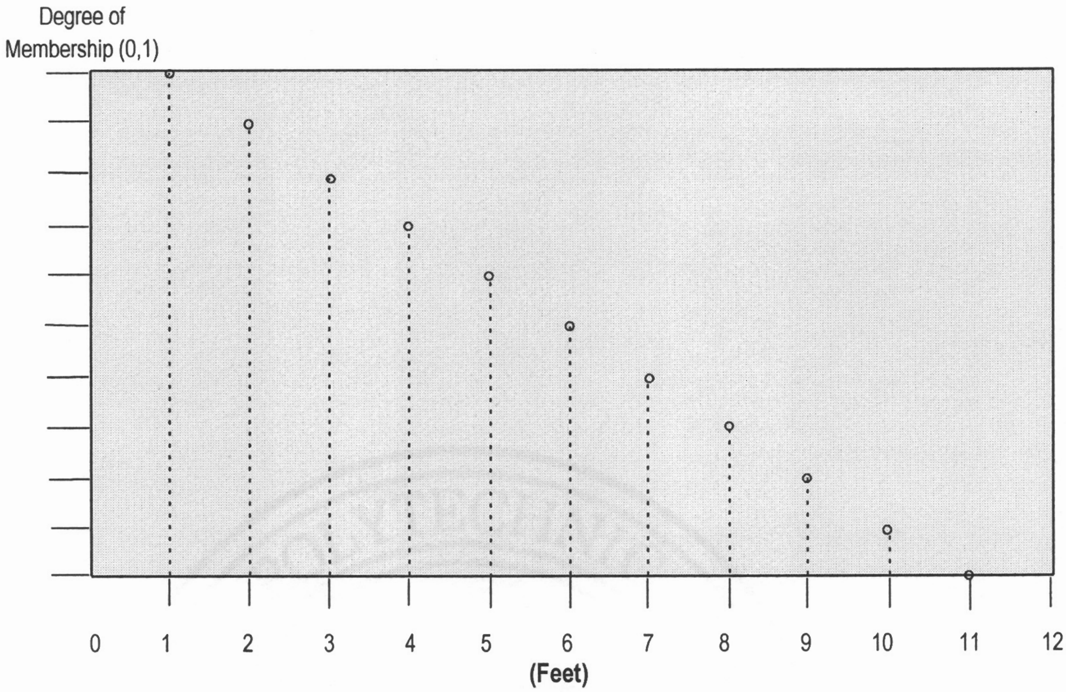

Figure A.1. Graphical depiction of the discrete fuzzy subset *Small*.

$$\tilde{A} = \int_x \mu_{\tilde{A}}(x_n) / x_n$$

The continuous fuzzy subset *Small* is represented in Figure A.2.

Selected operations on fuzzy subsets. Given a universal set E and two fuzzy subsets $\tilde{A}$ and $\tilde{B}$, selected operations on these fuzzy subsets may be expressed as:

1. *Inclusion*. $\tilde{A}$ is included in $\tilde{B}$,

$$\tilde{A} \subset \tilde{B}, \; if \;\; \mu_{\tilde{A}}(x) \leq \mu_{\tilde{B}}(x), \; \forall x \in E$$

$\tilde{A}$ is strictly included in $\tilde{B}$,

$$\tilde{A} \subset\subset \tilde{B}, \; if \;\; \mu_{\tilde{A}}(x) < \mu_{\tilde{B}}(x) \; at \; least \; once$$

2. *Equality*. Sets $\tilde{A}$ and $\tilde{B}$ are equal,

$$\tilde{A} = \tilde{B}, \; if \; and \; only \; if, \; \mu_{\tilde{A}}(x) = \mu_{\tilde{B}}(x), \; \forall x \in E$$

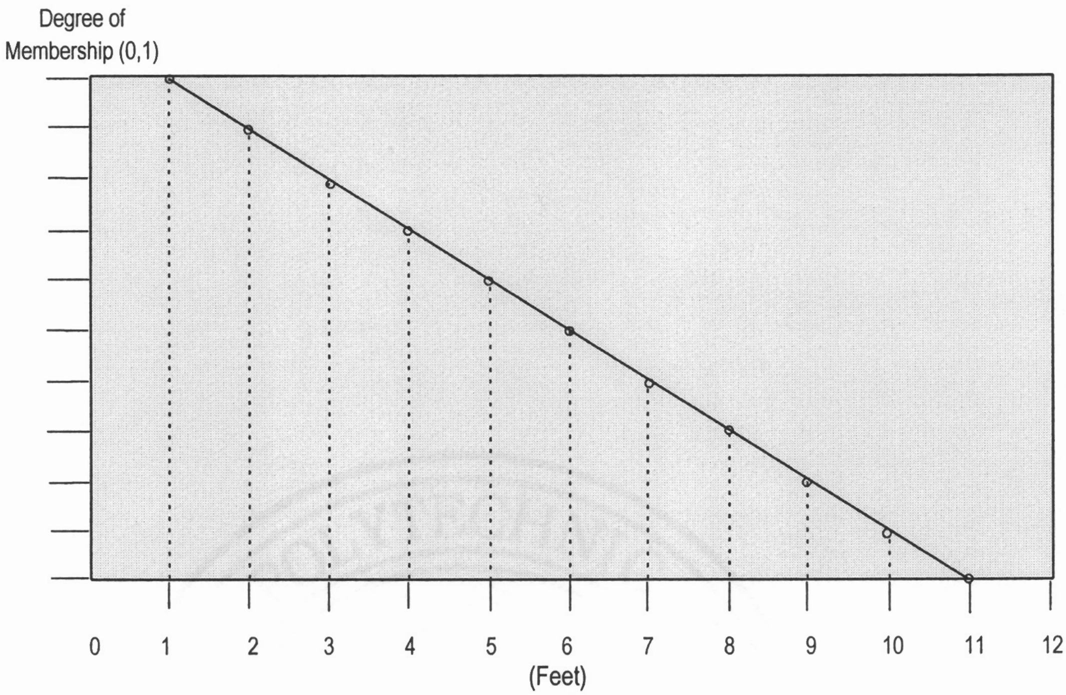

Figure A.2. Graphical depiction of the continuous fuzzy subset *Small*.

3. *Complementation*. Sets $\tilde{A}$ and $\tilde{B}$ are complementary,

$$\tilde{A} = \overline{\tilde{B}} \,/\, \tilde{B} = \overline{\tilde{A}},\ if\ and\ only\ if, \mu_{\tilde{A}} = 1 - \mu_{\tilde{B}},\ \forall x \in E$$

4. *Intersection*. Intersection between two fuzzy sets $\tilde{A}$ and $\tilde{B}$ is denoted and defined as,

$$\tilde{A} \cap \tilde{B}$$

where,

$$\mu_{A \cap B}(x) = Min\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)\}$$

5. *Union*. Union between two fuzzy sets $\tilde{A}$ and $\tilde{B}$ is denoted and defined as,

$$\tilde{A} \cup \tilde{B}$$

where,

$$\mu_{\tilde{A}\cup\tilde{B}}(x) = Max\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)\}$$

6. *Disjunctive Sum.* The disjunctive sum of two fuzzy sets $\tilde{A}$ and $\tilde{B}$ is denoted and defined as,

$$\tilde{A} \oplus \tilde{B} = (\tilde{A} \cap \bar{\tilde{B}}) \cup (\bar{\tilde{A}} \cap \tilde{B})$$

Selected concepts and definitions from the field of fuzzy subsets. Relevant concepts and pertinent definitions are listed below.

1. *Support of a fuzzy subset.* The support of a fuzzy subset $\tilde{A}$ is defined as the traditional crisp set A which contains all elements for which $\mu_{\tilde{A}}(x)$ is greater than zero. This is shown in Figure A.3 and may be expressed as:

$$A_{Support\ \tilde{A}} = (x, \forall \mu_{\tilde{A}}(x) > 0\ and\ \forall x \in E)$$

given that,

$$\tilde{A} = (x | \mu_{\tilde{A}}(x), \forall x \in E)$$

2. *Normality of a fuzzy subset.* A fuzzy subset $\tilde{A}$ is normal if there is at least one element, *x*, for which the characteristic function $\mu_{\tilde{A}}(x)$ assumes a value equal to 1. This is shown in Figure A.3, and may be expressed as:

$$\tilde{A}\ is\ normal\ if\ \vee \mu_{\tilde{A}}(x) = 1,\ \forall x \in E$$

3. *α-level sets of a fuzzy subset.* The concept of α-level sets can be generalized from the concept of support of a fuzzy subset. Support of a fuzzy subset is it's α-level set at α equal to zero. An α-level set of a fuzzy subset $\tilde{A}$ is a crisp traditional set A^{α} defined at any level or degree of membership. α conveys the level or degree of membership as depicted in Figure A.4. This concept may be expressed as:

$$A^{\alpha} = (x | \mu_{\tilde{A}}(x) \geq \alpha, \forall x \in E), \alpha = [0,1]$$

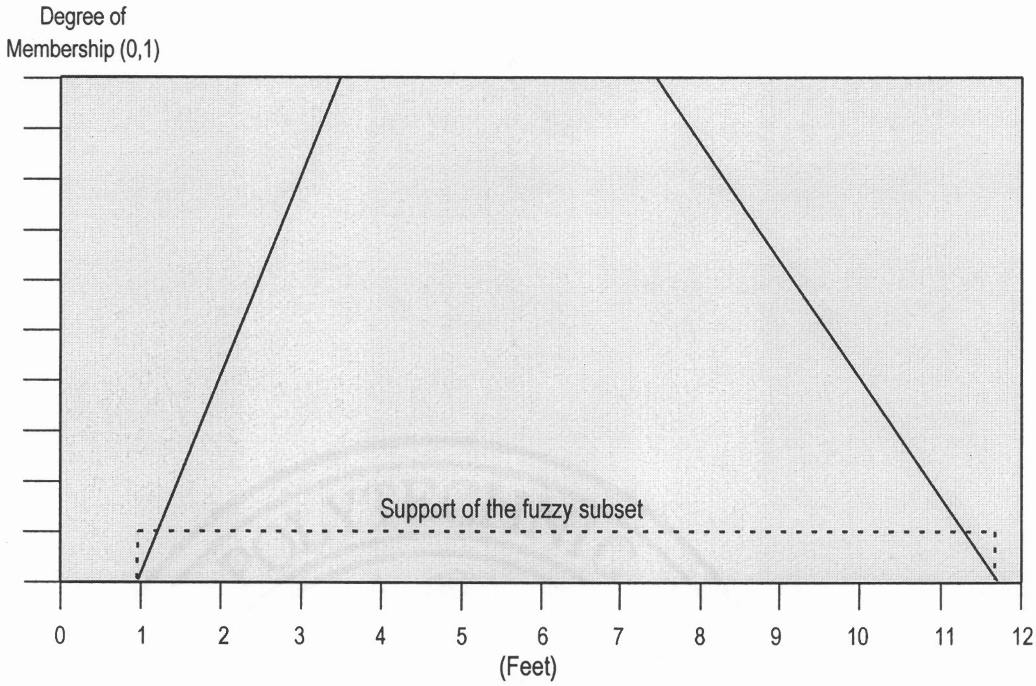

Figure A.3. Support of a normal fuzzy subset.

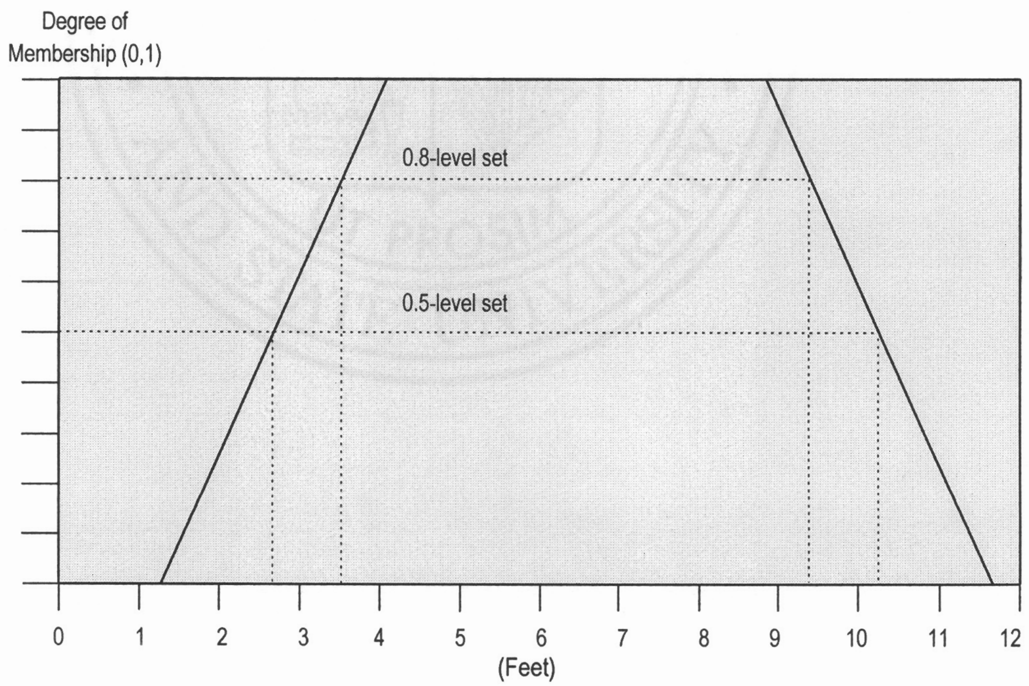

Figure A.4. Graphical depiction of α-level sets.

In accordance with the illustration in Figure A.4, the two α-level sets may be expressed as:

$$A^{0.8} = [3.6, 9.1] \; and \; A^{0.5} = [2.7, 11.3]$$

4. *Convexity of a fuzzy subset.* A fuzzy subset is defined as being convex if every α-level set of this fuzzy subset is a closed interval in the universe of discourse. This may be expressed as:

$$\mu_{\tilde{A}}[\lambda x_1 + (1-\lambda)x_2] \geq \mu_{\tilde{A}}(x_1) \wedge \mu_{\tilde{A}}(x_2)$$

For x_1 *and* $x_2 \in E$, *and* $\forall \lambda \in [0,1]$. The fuzzy subset depicted in Figure A.4 is convex since all its α-level sets form closed intervals on the real number line.

A.3. THE CONCEPT OF FUZZY NUMBERS

Within the broad domain of fuzzy set theory and fuzzy logic, fuzzy subsets which are convex, normal, and defined on a totally ordered universe of discourse (such as the set of real numbers, the set of natural numbers, or the set of all integers) are called fuzzy numbers. Fuzzy numbers are a special case of fuzzy subsets and the calculus developed to manipulate and work with fuzzy numbers is called fuzzy arithmetic. Only a selected and relevant set of operations on fuzzy numbers will be reviewed herein. For a more exhaustive treatise on the subject refer to [Kaufmann and Gupta, 1991]. The examples in this section were adapted from this source.

Operations pertaining to addition, subtraction, multiplication, and division of fuzzy numbers will be reviewed first, followed by brief discussions on the concept of a maximum/minimum fuzzy number, the max-min convolution in fuzzy arithmetic, and the normalization of a probabilistic measure in order to translate it into a fuzzy profile or a subjective valuation.

Addition of two or more fuzzy numbers. The addition of two fuzzy numbers, $\tilde{A}$ and $\tilde{B}$, may be expressed as:

$$\tilde{C} = \tilde{A} + \tilde{B}$$

such that $\mu_{\tilde{C}}(z) = \underset{z=x+y}{\vee}(\mu_{\tilde{A}}(x) \wedge \mu_{\tilde{B}}(y))$

Equivalently, the addition operation may also be expressed in terms of α-level sets for the two fuzzy numbers $\tilde{A}$ and $\tilde{B}$ as:

$$C^{\alpha} = A^{\alpha} + B^{\alpha} = (x_1^{\alpha}, x_2^{\alpha}) + (y_1^{\alpha}, y_2^{\alpha}) = [(x_1^{\alpha} + y_1^{\alpha}), (x_2^{\alpha} + y_2^{\alpha})]$$

Given that $A^{\alpha} = (x_1^{\alpha}, x_2^{\alpha})$ *and* $B^{\alpha} = (y_1^{\alpha}, y_2^{\alpha})$

As an example, consider the following two triangular fuzzy numbers (also see Figure A.5):

$$\begin{aligned} \mu_{\tilde{A}} &= x/3 + 5/3, && -5 \le x \le -2 \\ &= -x/3 + 1/3 && -2 \le x \le 1 \\ &= 0, && \textit{anything else} \end{aligned}$$

$$\begin{aligned} \mu_{\tilde{B}} &= x/7 + 3/7, && -3 \le x \le 4 \\ &= -x/8 + 12/8, && 4 \le x \le 12 \\ &= 0, && \textit{anything else} \end{aligned}$$

The above equations can be adapted to represent the two fuzzy numbers in terms of their α-levels as:

$$\textit{For } \tilde{A}, \alpha = x_1^{\alpha}/3 + 5/3 \textit{ and } \alpha = -x_2^{\alpha}/3 + 1/3$$
$$\textit{For } \tilde{B}, \alpha = y_1^{\alpha}/7 + 3/7 \textit{ and } \alpha = -y_2^{\alpha}/8 + 12/8$$

Therefore,

$$A^{\alpha} = (x_1^{\alpha}, x_2^{\alpha}) = [(3\alpha - 5), (-3\alpha + 1)],$$
$$\textit{and } B^{\alpha} = (y_1^{\alpha}, y_2^{\alpha}) = [(7\alpha - 3), (-8\alpha + 12)]$$

Having reduced both fuzzy numbers to their respective α-level representations, they can be added as:

$$
\begin{aligned}
C^{\alpha} &= A^{\alpha} + B^{\alpha} \\
&= [(3\alpha - 5), (-3\alpha + 1)] + [(7\alpha - 3), (-8\alpha + 12)] \\
&= [(10\alpha - 8), (-11\alpha + 13)]
\end{aligned}
$$

Using the approach applied earlier, the α-level representation of $\widetilde{C}$ can be translated back into the membership level representation and expressed as:

$$
\begin{aligned}
\mu_{\widetilde{C}}(z) &= z/10 + 8/10, & -8 \le x \le 2 \\
&= -z/11 + 13/11, & 2 \le x \le 13 \\
&= 0, & \textit{anything else}
\end{aligned}
$$

The above operation is depicted in Figure A.5.

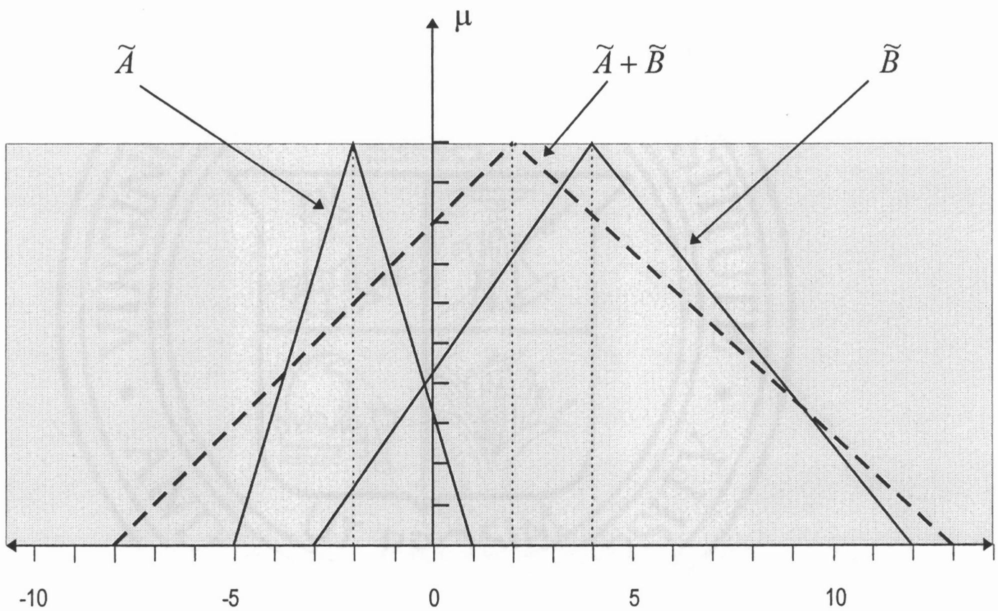

Figure A.5. Addition of two fuzzy numbers.

Subtraction of two fuzzy numbers. The procedure for adding fuzzy numbers can be easily extended to the subtraction of two fuzzy numbers, and expressed as:

$$\widetilde{C} = \widetilde{A} - \widetilde{B}$$

such that $\mu_{\widetilde{C}}(z) = \vee_{z=x-y} (\mu_{\widetilde{A}}(x) \wedge \mu_{\widetilde{B}}(y))$.

Equivalently, the subtraction operation may also be expressed in terms of α-level sets for the two fuzzy numbers $\widetilde{A}$ and $\widetilde{B}$ as:

$$C^{\alpha} = A^{\alpha} - B^{\alpha} = (x_1, x_2) - (y_1, y_2) = [(x_1 - y_1), (x_2 - y_2)]$$

Given that $A^{\alpha} = (x_1, x_2), and\ B^{\alpha} = (y_1, y_2)$.

Multiplication of fuzzy numbers. Let $\widetilde{A}$ and $\widetilde{B}$ be two fuzzy numbers, then their multiplication may be expressed as:

$$\widetilde{C} = \widetilde{A} \cdot \widetilde{B}$$

such that $\mu_{\widetilde{C}}(z) = \underset{z=x \cdot y}{\vee} (\mu_{\widetilde{A}}(x) \wedge \mu_{\widetilde{B}}(y))$.

Equivalently, the multiplication operation may also be expressed in terms of α-level sets for the two fuzzy numbers $\widetilde{A}$ and $\widetilde{B}$ as:

$$C^{\alpha} = A^{\alpha} \cdot B^{\alpha} = (x_1^{\alpha}, x_2^{\alpha}) \cdot (y_1^{\alpha}, y_2^{\alpha}) = [(x_1^{\alpha} \cdot y_1^{\alpha}), (x_2^{\alpha} \cdot y_2^{\alpha})]$$

given that $A^{\alpha} = (x_1^{\alpha}, x_2^{\alpha})\ and\ B^{\alpha} = (y_1^{\alpha}, y_2^{\alpha})$.

To illustrate, consider two triangular fuzzy numbers (also see Figure A.6):

$$\begin{aligned} \mu_{\widetilde{A}} &= x - 2, && 2 \le x \le 3 \\ &= -x/2 + 5/2 && 3 \le x \le 5 \\ &= 0, && anything\ else \end{aligned}$$

$$\begin{aligned} \mu_{\widetilde{B}} &= x/2 - 3/2, && -3 \le x \le 4 \\ &= -x + 6, && 4 \le x \le 12 \\ &= 0, && anything\ else \end{aligned}$$

The above equations can be adapted to express the two fuzzy numbers in terms of α-levels, as:

$$For\ \widetilde{A}, \alpha = x_1^{\alpha} - 2\ and\ \alpha = -x_2^{\alpha}/2 + 5/2$$
$$For\ \widetilde{B}, \alpha = y_1^{\alpha}/2 - 3/2\ and\ \alpha = -y_2^{\alpha} + 6$$

Therefore,

$$A^\alpha = (x_1^\alpha, x_2^\alpha) = [(\alpha + 2), (-2\alpha + 5)], \textit{ and}$$
$$B^\alpha = (y_1^\alpha, y_2^\alpha) = [(2\alpha + 3), (-\alpha + 6)]$$

Having reduced both fuzzy numbers to their respective α-level representations, they can be multiplied as:

$$\begin{aligned} C^\alpha &= A^\alpha \cdot B^\alpha \\ &= [(\alpha + 2)\cdot(2\alpha + 3)], [(-2\alpha + 5), (-\alpha + 6)] \\ &= [(2\alpha^2 + 7\alpha + 6), (2\alpha^2 - 17\alpha + 30)] \end{aligned}$$

The output fuzzy number can now be synthesized by solving these quadratic equations and delineating the two roots. In this example, the roots are:

$$(-7 + \sqrt{1 + 8z}) / 4 \textit{ and } (17 - \sqrt{49 - 8z}) / 4$$

Using the approach applied earlier, the α-level representation of $\widetilde{C}$ can be translated back into the membership level representation and expressed as:

$$\begin{aligned} \mu_{\widetilde{C}}(z) &= (-7 + \sqrt{1 + 8x}) / 4, & 6 \le z \le 15 \\ &= (17 - \sqrt{49 + 8x}) / 4, & 15 \le z \le 30 \\ &= 0, & \textit{anything else} \end{aligned}$$

This multiplication operation is depicted in Figure A.6.

Division of two fuzzy numbers. The procedure for multiplying fuzzy numbers can be extended to the division of two fuzzy numbers as:

$$\widetilde{C} = \widetilde{A} \div \widetilde{B}$$

such that $\mu_{\widetilde{C}}(z) = \vee_{z = x/y} (\mu_{\widetilde{A}}(x) \wedge \mu_{\widetilde{B}}(y))$.

Equivalently, the division operation may also be expressed in terms of α-level sets for the two fuzzy numbers $\widetilde{A}$ and $\widetilde{B}$ as:

$$C^\alpha = A^\alpha \div B^\alpha = (x_1^\alpha, x_2^\alpha) \div (y_1^\alpha, y_2^\alpha) = [(x_1^\alpha / y_2^\alpha), (x_2^\alpha / y_1^\alpha)],\ y_2^\alpha > 0$$

given that $A^\alpha = (x_1^\alpha, x_2^\alpha) \textit{ and } B^\alpha = (y_1^\alpha, y_2^\alpha)$.

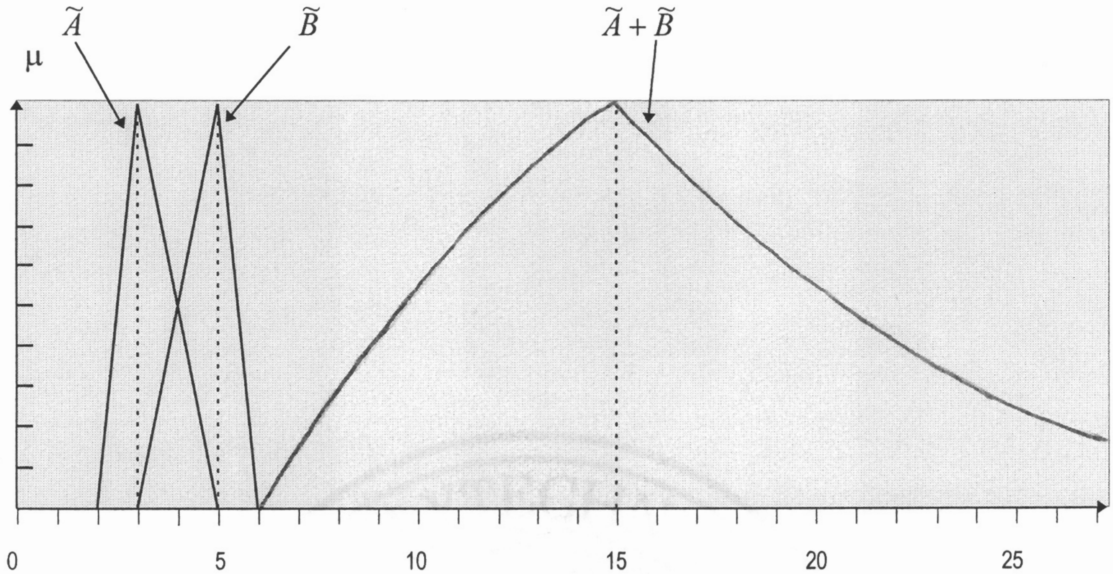

Figure A.6. Multiplication of two fuzzy numbers.

Minimum and maximum of fuzzy numbers. Unlike the set of real numbers, natural numbers, or integers, fuzzy numbers do not possess total order and are not always comparable. At best, fuzzy numbers display partial order. In other words, it may be stated that $\widetilde{A} \leq \widetilde{B}$, if and only if:

$$x_1^\alpha \leq y_1^\alpha \;\; and \;\; x_2^\alpha \leq y_2^\alpha$$

given that $A^\alpha = (x_1^\alpha, x_2^\alpha) \; and \; B^\alpha = (y_1^\alpha, y_2^\alpha)$.

The fuzzy minimum of two fuzzy numbers $\widetilde{A}$ and $\widetilde{B}$ is expressed as:

$$Fuzzy\;Minimum\,(\widetilde{A}\;and\;\widetilde{B}) = A^\alpha \wedge B^\alpha = [(x_1^\alpha \wedge y_1^\alpha),(x_2^\alpha \wedge y_2^\alpha)]$$

given that $A^\alpha = (x_1^\alpha, x_2^\alpha) \; and \; B^\alpha = (y_1^\alpha, y_2^\alpha)$. Similarly, the fuzzy maximum of two fuzzy numbers $\widetilde{A}$ and $\widetilde{B}$ is expressed as:

$$Fuzzy\;Maximum\,(\widetilde{A}\;and\;\widetilde{B}) = A^\alpha \vee B^\alpha = [(x_1^\alpha \vee y_1^\alpha),(x_2^\alpha \vee y_2^\alpha)]$$

given that $A^\alpha = (x_1^\alpha, x_2^\alpha) \; and \; B^\alpha = (y_1^\alpha, y_2^\alpha)$.

The fuzzy minimum and fuzzy maximum operations are depicted in Figures A.7 and A.8, respectively.

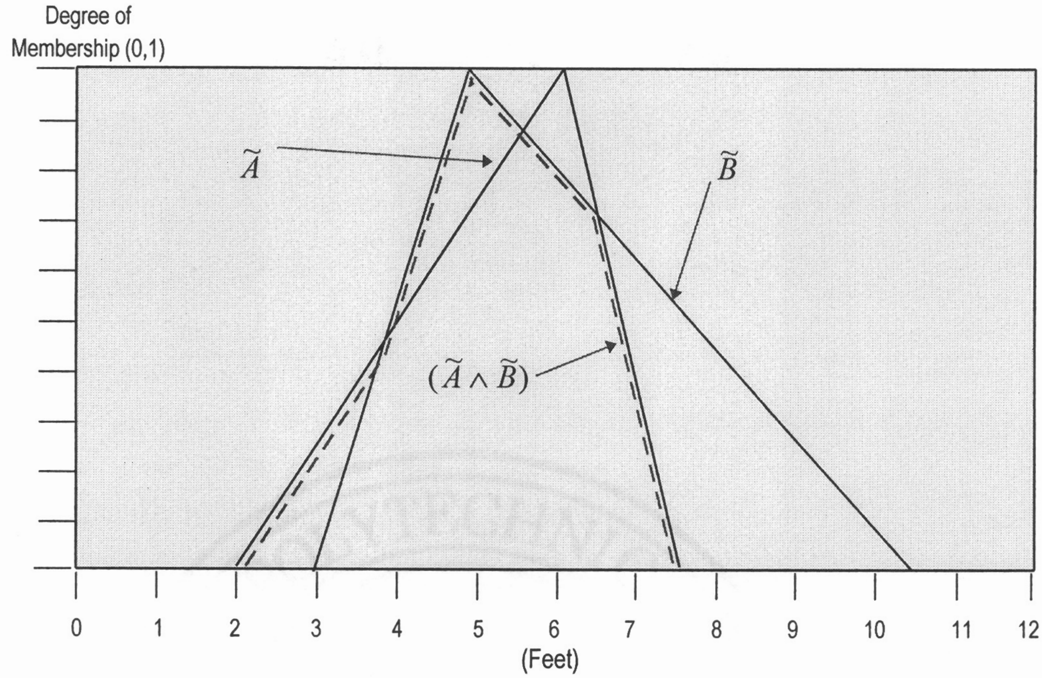

Figure A.7. Fuzzy minimum of two fuzzy numbers.

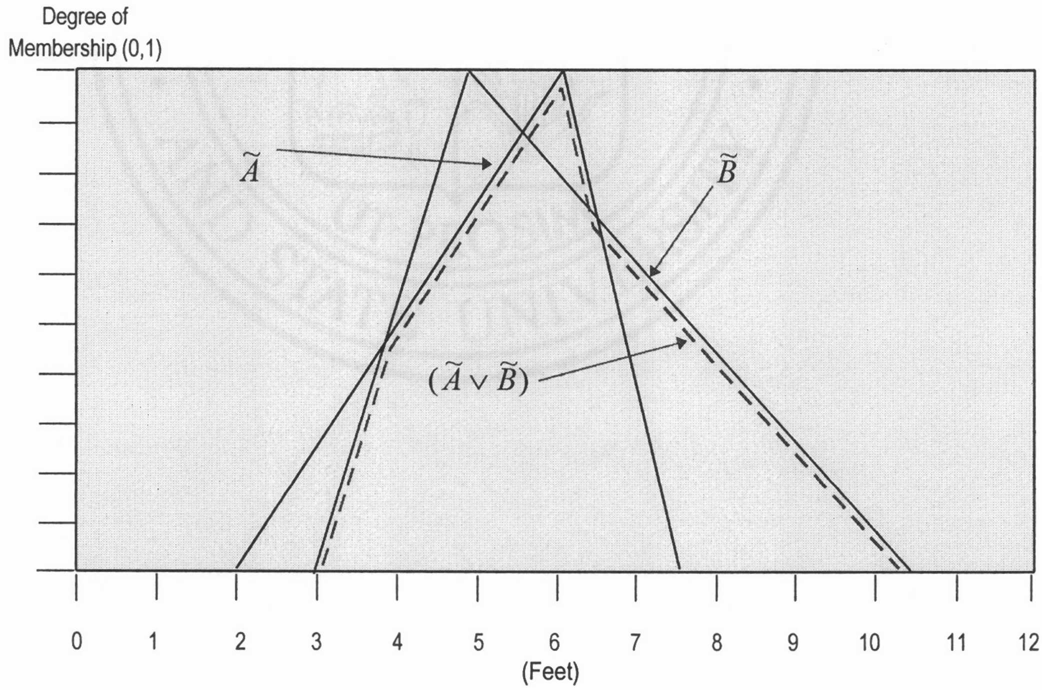

Figure A.8. Fuzzy maximum of two fuzzy numbers.

Convolution of fuzzy numbers and random numbers. When represented in terms of their membership or characteristic functions, fuzzy numbers are manipulated or operated upon through the use of the *Max-Min Convolution*. This was depicted in various preceding sub-sections.

In order to summarize its utilization and to distinguish it from the convolution used in probability theory, operations on fuzzy numbers may be represented as:

$$\forall x, y, z \in (Set \;\; of \;\; real \;\; numbers)$$

$$\mu_{\tilde{C}}(z) = \underset{z=x+y}{\vee}(\mu_{\tilde{A}}(x) \wedge \mu_{\tilde{B}}(y)) \qquad (Addition)$$

$$\mu_{\tilde{C}}(z) = \underset{z=x-y}{\vee}(\mu_{\tilde{A}}(x) \wedge \mu_{\tilde{B}}(y)) \qquad (Subtraction)$$

$$\mu_{\tilde{C}}(z) = \underset{z=x \cdot y}{\vee}(\mu_{\tilde{A}}(x) \wedge \mu_{\tilde{B}}(y)) \qquad (Multiplication)$$

$$\mu_{\tilde{C}}(z) = \underset{z=x \div y}{\vee}(\mu_{\tilde{A}}(x) \wedge \mu_{\tilde{B}}(y)) \qquad (Division)$$

$$\mu_{\tilde{C}}(z) = \underset{z=x \wedge y}{\vee}(\mu_{\tilde{A}}(x) \wedge \mu_{\tilde{B}}(y)) \qquad (Fuzzy \;\; Minimum)$$

$$\mu_{\tilde{C}}(z) = \underset{z=x \vee y}{\vee}(\mu_{\tilde{A}}(x) \wedge \mu_{\tilde{B}}(y)) \qquad (Fuzzy \;\; Maximum)$$

Contrary to the the *Max-Min Convolution* used in fuzzy arithmetic, the convolution used to manipulate and operate on random variables is the *Sum-Product Convolution*.

Normalization of a probability density function. There often arises a need to address fuzzy and probabilistic measures in combination (addition, multiplication, etc.). This can be achieved through the conversion of a probabilistic measure into a fuzzy valuation by normalizing the associated probablity density function.

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VITA

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