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# Decision making in complex collaborative engineering design.

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# DECISION MAKING IN COMPLEX COLLABORATIVE ENGINEERING DESIGN

by

Jing Gao

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# ABSTRACT

Engineering design process has often been an independent decision-making process, in which mainly design engineers are involved. With the market globalization and increasing competition, in order to fully satisfy the customers' requirements, products become more and more customized and complex. Therefore, it is impossible for most design tasks to be performed following traditional procedures to meet those requirements. An integrated approach is needed to deal with this issue.

Currently, there are many researchers working on complexity, collaboration, negotiation, and decision-making problems respectively. But none of the researchers considered all of them together. This should be the approach to solve the problem since it is unavoidable to have complexity, collaboration, negotiation and decision-making process in most of engineering designs. In this research, the different definitions of complexity are reviewed and a definition of complexity from collaboration point of view is given. In the meantime, the research goes through collaboration and negotiation methodologies and tools in engineering design process. The decision-making techniques in engineering design are also reviewed. A flowchart is constructed to guide engineers or managers in the engineering design process.

A case study, based on a real-world project, compares traditional engineering design approach with the new approach using Analytical Hierarchy Process (AHP) methodology approach for efficient decision-making process of material selection.

The second case study shows how improvements are made by using ECN (Engineering as Collaborative Negotiation) methodology instead of classical decision analysis in a shaft tolerance design process.

# ACKNOWLEDGMENTS

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

People in nearly every occupation and every walk of life have to make decisions. Engineering design has often been a decision-making process. People always need to make decisions collaboratively, especially for the complex problems of collaborative engineering design process. Collaboration takes place not only within organizations, but also between and among them. Although, a lot of researchers worked in these fields, they dealt with complexity, collaborative design, and decision making separately. Therefore, an integrated solution is needed to solve the complex collaborative engineering design problem and helps engineers or managers go through the process in a whole.

## 1.2 Research Motivation

With the increasing market competition, in order to meet customers' requirements, the products become more and more complex. It is impossible for a single individual to finish the entire job in most situations. There is a need for collaboration. Collaborative engineering design problems always involve stakeholders with their various perspectives. Customers, managers, designers, and manufacturing engineers and others play their various roles in the design process. During this complicated and dynamic process, one of the major roles of the stakeholders is to make their decisions with respect to the product, the design process, and the design team. The inconsistency of stakeholders' objectives is a basic characteristic of collaborative design and causes the additional complexity in it. The collaborative design could be viewed as a multi-objective decision-making process, by which multiple stakeholders use their different experience, viewpoint and preferences to manage interests in order to achieve the common goal.

Product development cycles are tightened to the minimum and subjected to a growing competitive pressure, in parallel product and process design complexities are increasing. The various design actors, provided with diverse expertise and culture, are therefore invited to collaborate more and more closely in order to perform an effective product design [Robin, 2004]. The more complex the system or process is, the more difficult it is to make the right decision. But the companies increasingly have to deal with complex problems. How can good decisions be made in the complex system in an efficient way? Efficient frameworks or methodologies are needed to lead stakeholders to perform from problem identification to good results.

Through literature review I found out there is no research going through all four aspects: complexity, collaboration, negotiation, and decision-making (Table 1.1). In Table 1.1, indicates the different researches' domains, methods, or tools used. The reader is encouraged to come back to this table after reading Chapter 2, 3, 4 and 5 for a better understanding of the Table 1.1.

## Table 1.1 Literature Review Summary

| Authors [Year] | Complexity | Collaboration | Negotiation | Decision-making |
|---|---|---|---|---|
| Adelson, B. [1999] | | Framework | Framework | |
| Al-Harbi, K. [2001] | | | | AHP |
| Beer, S. [1970] | General | | | |
| Biondi, D. [1999] | | Co-design | | Group |
| Braha, D., Maimon, O. [1998] | Design | | | |
| Bushong, J.G. et al. [1999] | | | | TOC |
| Calinescu, A. et al. [1997, 2001] | Manufacturing | | | |
| Campbell, M. et al. [2001] | | A-design | | |
| Danesh, M. and Jin, Yan [2001] | | Network | | Concurrent Engineering |
| Efstathiou J. [2002] | Manufacturing | | | |
| El-Haik, B., Yang, K. [1999] | Design | | | AD |
| ElMaraghy, W.H. and Urbanic, R. J. [2003, 2004] | Manufacturing | | | Index |
| Feizelle, G. [1998] | Manufacturing | | | |
| Flood, R.L., and Carson, E.R. [1988] | General | | | |
| Frizelle, G.D.M. [1996] | Manufacturing | | | Entropy |
| Fromme, J. [2004] | General | | | |
| Gell-Mann, M. [1995] | General | | | |
| Gino, F. [2002] | General | | | Entropy |
| Größler, A., Grübner, A., and Hasenpusch, J [2003] | Manufacturing | | | |

| | | | | |
|---|---|---|---|---|
| Hammond, J. H. [2001] | | Review | | |
| Harvey, C. M. [1997] | | Model | | |
| Hay. D. [2000] | | | | Zachman |
| Huang, G Q. et al. [2002] | | Web-based | | |
| Klir, G. [1985] | General | | | |
| London, S. [1996] | | Survey | | |
| Lu, S. C-Y [1999, 2002, 2003] | | ECN | ECN | ECN |
| Maier, J. and Fadel, G. [2003] | Design | | | |
| May, Daniel C-M. et al. [2003] | CoCoMo | CoCoMo | | |
| Miyazaki, K. and Kijama, K. [2000] | Manufacturing | Culture Conflict | | |
| Morowitz, H. [1995] | Manufacturing | | | |
| Pahng, F., Bae, S., and Wallace, D. [1998] | | Web-based | | DOME |
| Parunak, V. [1993] | Manufacturing | | | |
| Pena-Mora, F. and Wang, C. [1998] | | Methodology | Model | CONVINCER |
| Phal, G. and Beitz, W. [1998] | | Systematic Approach | | Phal&Beitz |
| Raiffa, H. [2002] | | Game Theory | Win-Win | Group |
| Roberts, N. C. and Bradley, R. T. [1991] | | Review | | |
| Rodríguez-Toro, C. et al. [2002] | Design | | | |
| Saaty, TL [1980] | | | | AHP |
| Shen, W. and Barthès, J. [1996] | | Framework | | |
| Simon, H. A. [1996] | Architecture | | | |
| Singh, N. [1996] | | Concurrent Engineering | | Concurrent Engineering |

| | | | | |
|---|---|---|---|---|
| Straus, D. [2002] | | Principles | Principles | Process Map |
| Suh, Nam P. [1999, 2003] | AD | | | AD |
| Summers, J., Shah, J. [2003] | Design | | | |
| Turban, E. and Aronson, J. E. [2001] | | GSS | Negotiator Pro | DSS |
| Urbanic, R. J. [2002] | Manufacturing | | | |
| Wang, L. et al. [2002] | | Summary | | |
| Wiendahl, H. P. and Scholtissek, P., [1994] | Manufacturing | | | |
| Wood, D. J. and Gray, B. [1991] | | Review | | |

Where:

AD—Axiomatic Design

AHP—Analytical Hierarchy Process

CoCoMo—Complexity, Collaboration and Modeling

DOME—Distributed Object-based Modeling and Evaluation

DSS—Decision Support Systems

ECN—Engineering as Collaborative Negotiation

GSS—Group Support Systems

TOC—Theory of Constraint

## 1.3 Research Objective

This research aims at integrating collaboration, negotiation, and decision-making tools and methodologies to deal with complex engineering design problems.

In short, complex problems require identifying and articulating multiple problem representations, and tools to assist this, to be able to make the right decisions. The purpose of this research is to find the efficient way to direct managers or engineers to make a good decision for complex problems through collaboration and negotiation and decision support system. Working together to solve a problem, envision a future, or make a decision can actually be an enjoyable and even an energizing experience.

## 1.4 Research Approach

My research started at the definition of complexity in order to get an overview of different complexity concepts. For complex problems, multidisciplinary stakeholders are often involved. It will need to collaborate well through negotiation in order to make good decisions to reach the common ground. My research will involve the following contents. Please refer to Figure 1.1.

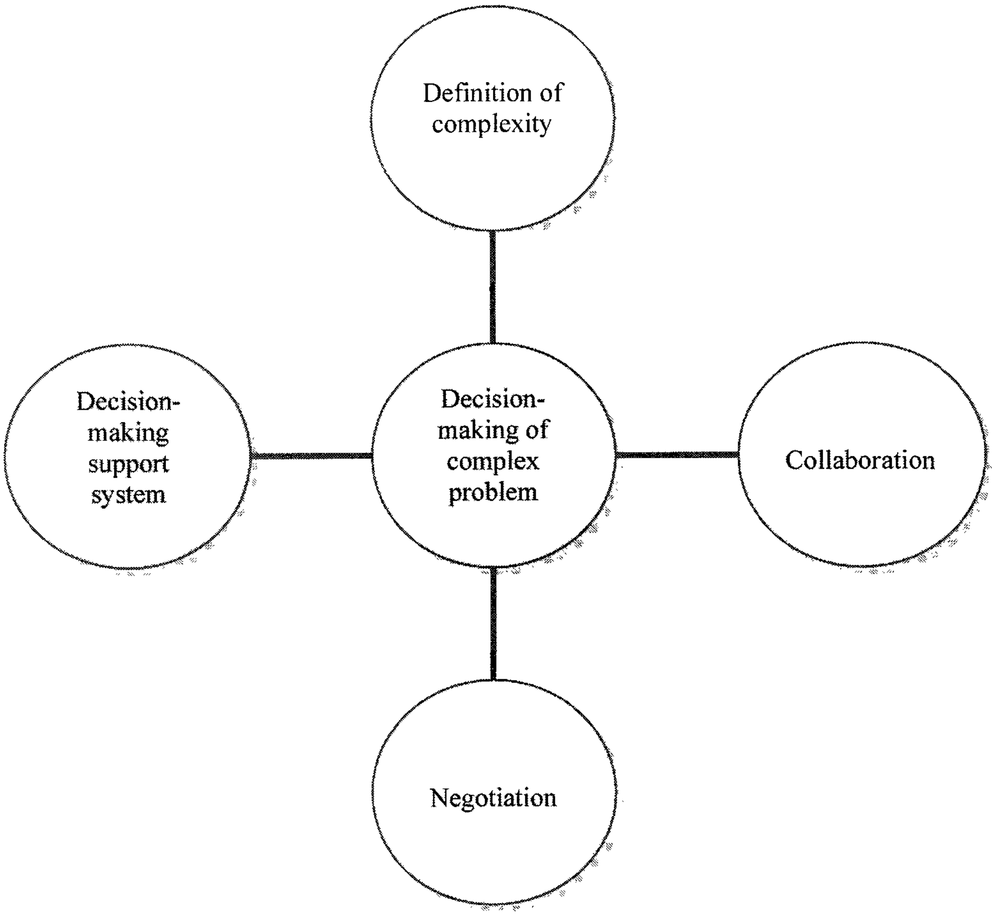


**Figure 1.1 Research Contents**

In the following chapters, the above contents will be discussed in detail respectively. The different definitions of complexity are reviewed and a definition of complexity from collaboration point of view is given. In the meanwhile, the research goes through collaboration and negotiation methodology and tools in engineering design process. The decision-making techniques are also reviewed. A flowchart is constructed to guide engineers or managers in engineering design process.

A case study based on a real-world project, compares traditional engineering design approach with the new approach which using Analytical Hierarchy Process (AHP) methodology approach for efficient decision-making process of material selection.

The second case study shows how improvements are made by using ECN (Engineering as Collaborative Negotiation) methodology instead of classical decision analysis in a shaft tolerance design process.

## 1.5 Thesis Report Organization

This thesis report is divided into 6 chapters:

- Chapter 1 gives introduction of this research. It includes research motivation, research objective, and research approach.
- Chapter 2 presents an overview of definitions of complexity and gives a new definition of complexity from a collaboration point of view. The relationship between entropy and complexity is discussed. A complexity detector is constructed based on the new definition.
- Chapter 3 presents a literature survey covering collaboration and negotiation methodologies and tools.
- Chapter 4 discusses the decision-making process in collaborative engineering design.
- Chapter 5 provides an overview of the methods of integrating collaboration, negotiation and decision-making process. A flowchart is created to guide

engineers or managers to go through engineering design process. Two case studies are given.

- Chapter 6 concludes this research and also highlights the significance of the research contributions and those can be expected in the future works.

# CHAPTER 2

# COMPLEXITY

## 2.1 Introduction

In the past several decades, complexity research has been a main topic in the engineering field. With the increasing competition, products are becoming more and more complex in order to meet customers' requirements. Complexity research is now receiving increased attention. In the following sections, the definitions of complexity will be reviewed and redefined according to this research domain, which is collaborative design.

## 2.2 Definitions of Complexity

In order to understand complexity, it is necessary to find out what complexity is. But it is difficult to find a clear, concise, and precise definition of the term complexity since it exists everywhere. Also, something is complex if it cannot be described in a simple way. Many researchers tried to define complexity based on the characteristics of complexity in the context of their own research fields. But not a single definition seems comprehensive enough to suit all the situations where complexity exists. It seems that adding different definitions can only approximate a general definition of complexity. But it is essential to give a definition of complexity before posing the question regarding how to measure and manage it. Please note that complexity management is out of the scope of this research.

According to Webster's Third International Dictionary [Webster, 2002], “complexity is being marked by an involvement of many parts, aspects, details, notions, and necessitating earnest study or examination to understand or cope with. Complexity has many varied interrelated parts, patterns, or elements and consequently is hard to fully understand.”

Many researchers gave different complexity definitions. A typical response to the definition of complexity is that “complexity has many possible meanings” [Klir, 1985]. The earlier definition given by Beer [1970] is that “complexity is a measure of variety of states in the system”. Flood and Carson [1988] said, "in general, we seem to associate complexity with anything we find difficult to understand." This involves people perceiving things. Since we understand things through our personal, subjective perception of how things are objectively, we each perceive things differently. Murray Gell-Mann [1995] stated in his paper, What is Complexity, that “you need a measure to describe what is meant by complexity: the length of the most concise system description or the length of a concise description of the system’s regularities.”

Miyazaki and Kijima [2000] classified complex situations on a two dimensional space, i.e., object-related and human-related complexity, as shown in the Figure 2.1. They stated, “Complexity of an object is in the eyes of the observer.” It is absolutely true because people with different background and knowledge have different opinions for a problem.

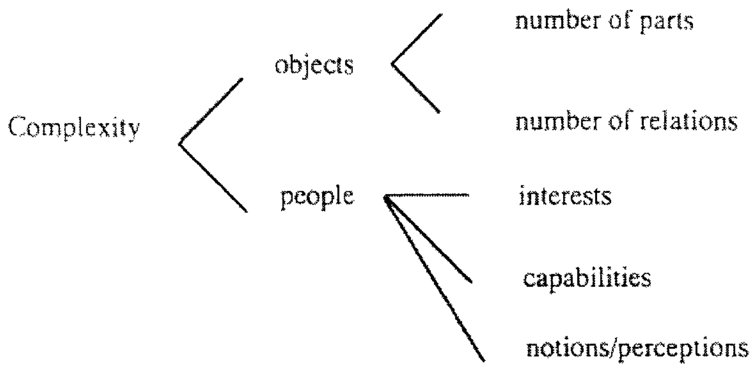


**Figure 2.1 Disassembly of Complexity [Miyazaki, 2000]**

Some researchers even tried to avoid giving a precise definition of complexity. Herbert A. Simon defines complexity in the book, the Architecture of Complexity [Simon, 1996], as a property of complex systems. He says, "I shall not undertake a formal definition of complex systems. Roughly, by a complex system I mean one made up of a large number of parts that interact in a non-simple way."

There are many different definitions that exist. The questions are what the basic or most fundamental definitions of complexity are and what the essence of complexity is. In the following sections, I will go through some definitions in design and manufacturing domains.

### 2.2.1 Complexity in Design

Braha and Maimon [1998] believed that design complexity was either artifact complexity or design process complexity. There are two kinds of complexity discussed. One is Structural Design Complexity, which is a function of the design's information content. The other is Functional Design Complexity, which defines information in the functional way. A design complexity may be said to be a function of its probability of successfully achieving the required specifications.

Suh [1999] defined the complexity in the context of axiomatic design as "a measure of uncertainty in achieving a set of specific functions or functional requirements (FR)." Complexity is related to information, which is defined as a logarithmic function of the probability of achieving the FRs. The greater the information required achieving the FRs of a design, the greater is the information content, and thus the complexity. It relates with information entropy that will be discussed later. The author classified the complexity as time-independent complexity and time-dependent complexity. In the time-independent situations, it was shown that there were two kinds of complexities: real complexity and imaginary complexity, which are orthogonal to each other. In the time-dependent complexity arena, it was shown that there were two different kinds of complexities: combinatorial complexity and periodic complexity. It was shown how a coupled system was being decoupled through design changes and how a combinatorial complexity problem could be changed into a periodic complexity design problem. The classification of complexity according to Suh is shown in Figure 2.2.

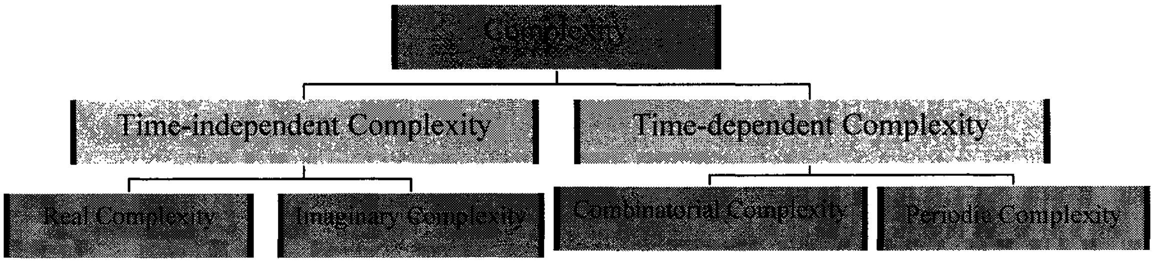


**Figure 2.2 Classification of Complexity [Suh, 1999]**

El-Haik and Yang [1999] stated that "the development of a precise definition and measure of complexity in engineering design is a pre-requisite to facilitate its minimization effort." They explored components of complexity in engineering design as variability, vulnerability and correlation (Figure 2.3).

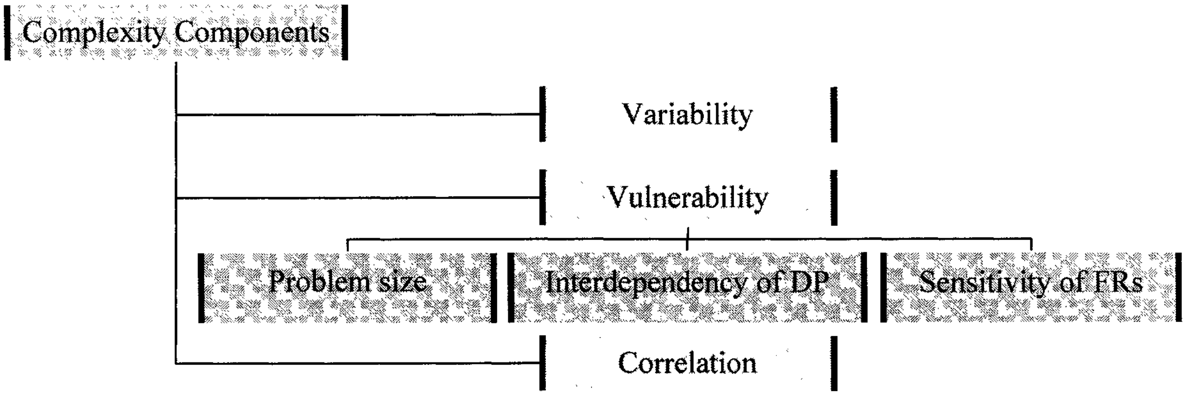


**Figure 2.3 Complexity Components [El-Haik and Yang, 1999]**

Maier says that people need not focus on just artifacts, or just artifacts, or just problems, or just solution procedures. He addressed complexity in design by proposing a designer-artifact-user system that was defined as the complex system of interest. Maier stated that people should focus on not only artifacts or just problem or just solution procedures but also the stakeholders as well. There are at least three major subsystems in every design:

1) The designer(s) of the artifact,

2) The artifact(s) being designed, and

3) The user(s) of the artifact.

I quote a sentence from Phal and Beitz [1998] to summarize design complexity, "Complexity in design has many facets, including the lack of transparency of the transfer functions between inputs and outputs in the functional structure, the relative difficulty of employed physical processes, and the relatively large number of assemblies and components involved."

### 2.2.2 Complexity in Manufacturing

Calinescu et al. [2001] defined manufacturing complexity as "a systemic characteristic that integrates several key dimensions of the manufacturing environment which include size, variety, concurrency, objectives, information, variability, uncertainty, control, cost and value."

According to Morowitz [1995], the complex systems share certain features like having a large number of elements, possessing high dimensionality and representing an extended space of possibilities. A manufacturing system can be characterized by two kinds of features. The first is the increasing variety and the second is the uncertainty that may come from unplanned events such as plant breakdowns, shortages and unbalanced flow etc.

ElMaraghy and Urbanic [2003, 2004] stated "three types of complexity to be considered in a manufacturing environment: product complexity, process complexity and operational complexity, and each one flow into the other" as shown in Figure 2.4, where "product complexity is a function of the material, design and special specifications for each component within the product, process complexity is a function of the product, the volume requirements, and the work environment and operational complexity is a function of the product, process and production logistics."

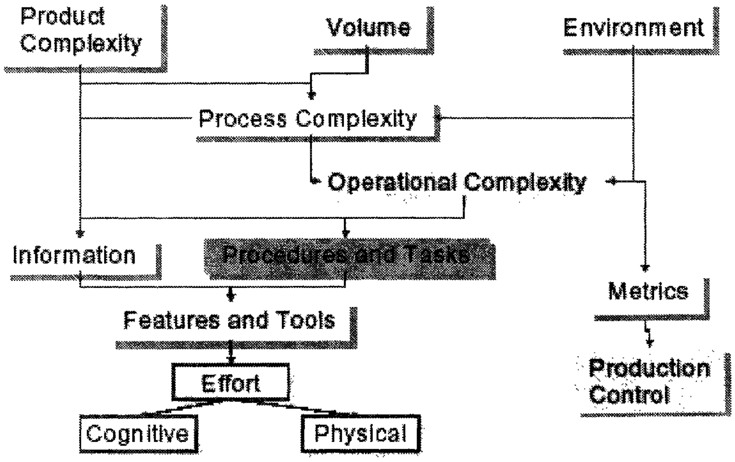


**Figure 2.4 Manufacturing Complexity Cascade [ElMaraghy and Urbanic, 2003]**

Efstathiou [2002] stated that manufacturing systems were the combination of social and technical systems in complex and interesting ways. He pointed out that there was a tradeoff between flexibility and complexity in manufacturing systems. The introduction of flexibility into manufacturing systems will increase the complexity, but to solve some problems we need flexible manufacturing systems. There are two statements by the author:

1) If a manufacturing system is too simple to solve problems, then make it more complex.
2) If a manufacturing system is too complex to cope with the problems, then make it simpler.

Complexity is a double-edged sword. Too little, and the facility becomes too rigid and inflexible. Too much, makes the facility too difficult and stressful to control, with too much energy dissipated on solving recurring problems instead of focusing on value-adding activities.

Feizelle [1998] published a book, The Management of Complexity in Manufacturing: A Strategic Route Map to Competitive Advantage through the Control and Measurement of Complexity, which gave a road map that followed two guiding principles: simplification followed by control and prevention rather than cure (Table 2.1).

**Table 2.1 Strategic Route Map [Feizelle, 1998]**

| **Strategy** | **Structural Complexity** | **Operational Complexity** |
|---|---|---|
| | Simplification | Management & Control |
| **Prevention** | Better design | Improved reliability |
| **Cure** | Restructuring | Enhanced planning and scheduling |

The arrows dedicated the priority of the procedures, i.e. better design is the first step to start. Try to prevent complexity instead of curing it after it happened.

### 2.2.3 Definition of Complexity from Collaborative Point of View

Through the review of different definitions of complexity in design and manufacturing, we can see that the definition of complexity depends on the domains or objectives of the application. In different domain, the meaning of complexity will be different. In general, I simply disassemble complexity to two aspects, objects and stakeholders (Figure 2.5).

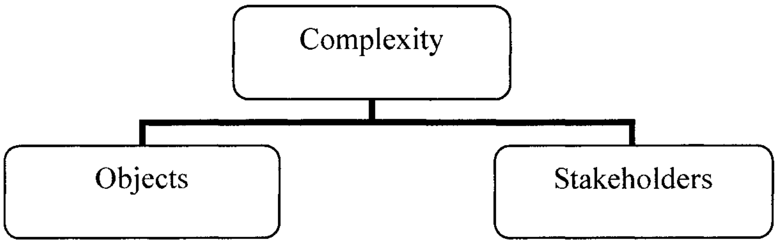


**Figure 2.5 Disassembly of Complexity**

There are two states for objects:

State 1: A lot of objects are involved, but simple.

State 2: Very few objects are involved, but complex.

For stakeholders, it depends on stakeholders to feel that a problem is simple or complex according to their knowledge and background.

Since this research context is in collaborative design domain, it is necessary to give a definition of complexity from a collaborative point of view. The definition of complexity is given in this domain as:

"Complexity is a relative concept. It can be called as a complex problem if stakeholders cannot handle objects individually either because of inner factors like stakeholders' knowledge or outer factors like due dates."

## 2.3 Entropy and Complexity

Complexity is always related with information content of a design. So is the entropy. Now take a look at the relationship between the complexity and entropy. Information content is defined as a reduction in uncertainty. The uncertainty preceding the occurrence of an event is usually termed entropy. The term entropy always comes with the information measurement of complexity. Information theory provides a way of quantifying the information content received, so that the quantity of information received is equal to the reduction in entropy. What is entropy and how it relates with complexity? And is it an efficient way to measure complexity?

### 2.3.1 Definition of Entropy

The entropy indicates the expected amount of information mediated in time necessary to describe the state of a system. In other words, "the entropy is essentially the amount of information that we need to obtain in order to understand what is happening in a system" [Gino, 2002]. The concept of entropy is adapted from its theoretical and mathematical basis to its practical application in measuring complexity. Entropy, as a measure of complexity, is defined as a measure of the variety associated with uncertainty in a system. The entropic measure is rooted in information theory, where it is defined as the expected amount of information necessary to describe the state of the system.

### 2.3.2 History of Entropy

Entropy is a term that comes from the study of thermodynamics. At the end of the 19th century, people like Boltzmann, Carnot, Gibbs and Clausius were all working in this field. Shannon [1949] has been the first one to introduce the concept of measurement of the information amount through the entropy, with his work 'The mathematical theory of communications'. He borrowed the notion of entropy from the thermodynamics in order to use it in the theory of communications and information developed by him. His idea is to use the entropy as a measure of the amount of information passed from an emitter to a receiver. Moreover, Shannon refers to the entropy as an index of the uncertainty level of a stochastic process. The theory of information, therefore, as developed by Shannon, provides a measure of how much information must be associated to a certain state of affairs. The entropy concept is defined formally as follows: given a set of events $E = e_1, e_2 \ldots e_n$ and the a priori probabilities of taking place of these events $P = \{p_1, p_2 \ldots p_n\}$ where $p_i \geq 0$ and $\sum p_i = 1$, the entropy function is defined as equation (2.1):

$$H = -\sum_{i=1}^{n} p_i \log_2(p_i) \tag{2.1}$$

### 2.3.3 From Entropy to Complexity

A paper dealing with complexity in the context of axiomatic design by El-Haik and Yang [1999] used Boltzmann entropy as the complexity measure. El-Haik et al. used

Boltzmann entropy as the complexity measure to evaluate engineering design since it can deal with continuous random variable. Engineering design can be modeled as the mapping between the functional requirements (FRs) in the functional domain and the design parameters (DPs) in the physical domain and through the mapping between the DPs and the process variables (PVs) in the process domain. In an engineering design, the array of FR is used to characterize the design objective. So the Boltzmann entropy of FR is a good measure of complexity for engineering design.

Frizelle and Woodcock [1994] developed a formal mathematical approach based on an entropic model of the factory. The entropic complexity method considers that complexity management is about looking at the progress of parts through manufacturing operations, and measuring the obstacles, i.e. the machines that extend the lead-time. Please refer the original paper for the formulae.

ElMaraghy and Urbanic [2003] assumed that "basic elements of complexity consist of three factors: the absolute quantity of information, the diversity of information and the information content", as illustrated in Figure 2.6. They stated that "Complexity is associated with understanding and managing a large volume or quantity of information, as well as a large variety of information." The approach to quantitate the complexity will be discussed in next section.

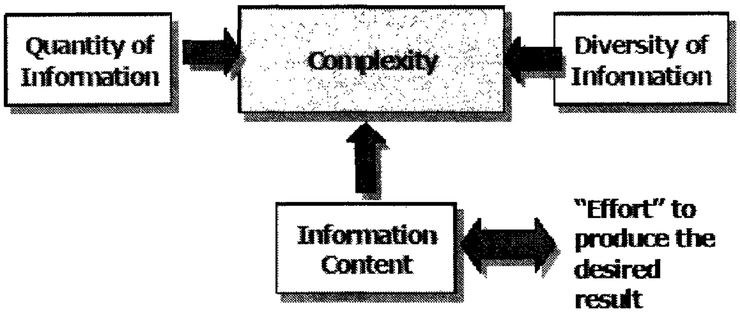


**Figure 2.6 Elements of Complexity [ElMaraghy and Urbanic, 2003]**

Entropy measure focuses on the information side of complexity. From the information point of view, it gives an indication on the amount of information necessary in order to manage and to control the system.

## 2.4 Complexity Index

In this section, an index of product complexity created by ElMaraghy and Urbanic [2003] is introduced.

The product complexity is represented by the product complexity index, $CI_{product}$, and is a function of the product information entropy, $H_{product}$, the product diversity ratio $D_{Rproduct}$ and the product relative complexity coefficient $c_{j,product}$. The value of the relative product complexity coefficient is based on general manufacturing principles and is independent of the process type or the volume. Its value increases with the effort required to produce the final part. Using utility charts, the product complexity index

$CI_{product}$ was determined to be a combination of the diversity ratio and the relative complexity, and scaled by its information entropy as[1]:

$$CI_{product} = (D_{R_{product}} + c_{j,product}) * H_{product} \qquad \text{or} \tag{2.2}$$

$$CI_{product} = (\frac{n}{N} + c_{j,product}) * \log_2(N+1) \tag{2.3}$$

Where:

$$H_{product} = \log_2(N+1) \tag{2.4}$$

$$D_{R_{product}} = \frac{n}{N} \tag{2.5}$$

$$C_{j,product} = \sum_{f=1}^{F} x_f * c_{f,feature} \tag{2.6}$$

$$c_{f,feature} = \frac{F_N * F_{CF} + S_N * S_{CF}}{F_N + S_N} \tag{2.7}$$

$$F_{CF} = \sum_{j=1}^{J} factor\_level_j \tag{2.8}$$

$$S_{CF} = \sum_{k=1}^{K} factor\_level_k \Big/ K \tag{2.9}$$

n –the quantity of unique information

N –the total quantity of information

$c_f$ –the relative feature complexity coefficient

$x_f$ –the percentage of the $x^{th}$ dissimilar feature

$F_N$ –the quantity of features

$F_{CF}$ –the feature complexity factor

---

[1] In section 2.4, all formulas are taken from ElMaraghy and Urbanic [2003].

$S_N$ –the quantity of specification checks

$S_{CF}$ – the specification complexity factor

$J$ –the number of categories

$Factor\ level_j$ –the factor for the $j_{th}$ category

$K$ –the number of specifications

$factor\_level_k$ –the factor for the $k_{th}$ specification

Next, they developed a methodology to generate the product complexity index $CI_{product}$ as below [ElMaraghy and Urbanic, 2003]:

1. Define the multi-tier ranking system to be used, like low-medium-high or 1-10 scale.
2. Determine the total number $N$ of the entire individual feature information, components, subcomponents, etc. and from equation (2.4), calculate $H_{product}$.
3. Determine the specific quantity $n$ of each diverse feature defined in step 2, and from equations (2.4) and (2.5), calculate the product diversity ratio $D_{Rproduct}$.
4. Define the number and type of diverse "aspects" for evaluating the features *(J)* and the specifications *(K)* associated with manufacturing the product.
5. Generate the $FxJ$ feature matrix and the $FxK$ specification matrix and assign the appropriate complexity levels into each cell.
6. Calculate the product complexity coefficient $c_{j,product}$ as defined by equations, (2.6) – (2.9).
7. Calculate the product complexity index $CI_{product}$ as defined by equations (2.2) and (2.3).

In the original paper, an example was given using above methodology. The process complexity was also calculated by similar way. Since measurement and management of complexity are beyond this research, the purpose of introducing this index here is to show that there are ways to calculate complexity. The interested readers are encouraged to refer to the reference paper.

## 2.5 Collaborative Complexity Detector

The definition of complexity in collaborative point of view is given. Although, how can stakeholders tell whether a problem is complex or not? In this research, a complexity detector is constructed according to the collaborative complexity definition to guide stakeholders go through the decision process.

According to the definition of complexity from collaborative point of view, the key to complexity detector is to tell whether the project needs team performance or not. To construct complexity detector, the logic is very simple. First, we need to know the objective of the project and then match to the related people or departments. Second, the due day of the project must be clarified. The available budget for the project should also be considered. According to the database of the average cost for the stakeholders and work efficiency, tell if individual can do the project or not. Thus, the project can be decided whether complex or not. The complexity detector is shown in Figure 2.7.

## 2.6 Summary

In this chapter, the different definitions of complexity mainly in design and manufacturing were reviewed. A new definition of complexity from collaborative point of view was given as: Complexity is a relative concept. It can be called as a complex problem if stakeholders cannot handle objects individually no matter because of inner factors like stakeholders' knowledge or outer factors like due day.

The relationship of entropy and complexity is discussed. One of complexity measure approach based on the information entropy, complexity index is reviewed.

A conceptual complexity detector is developed to help managers and engineers tell whether a project is complex or not.

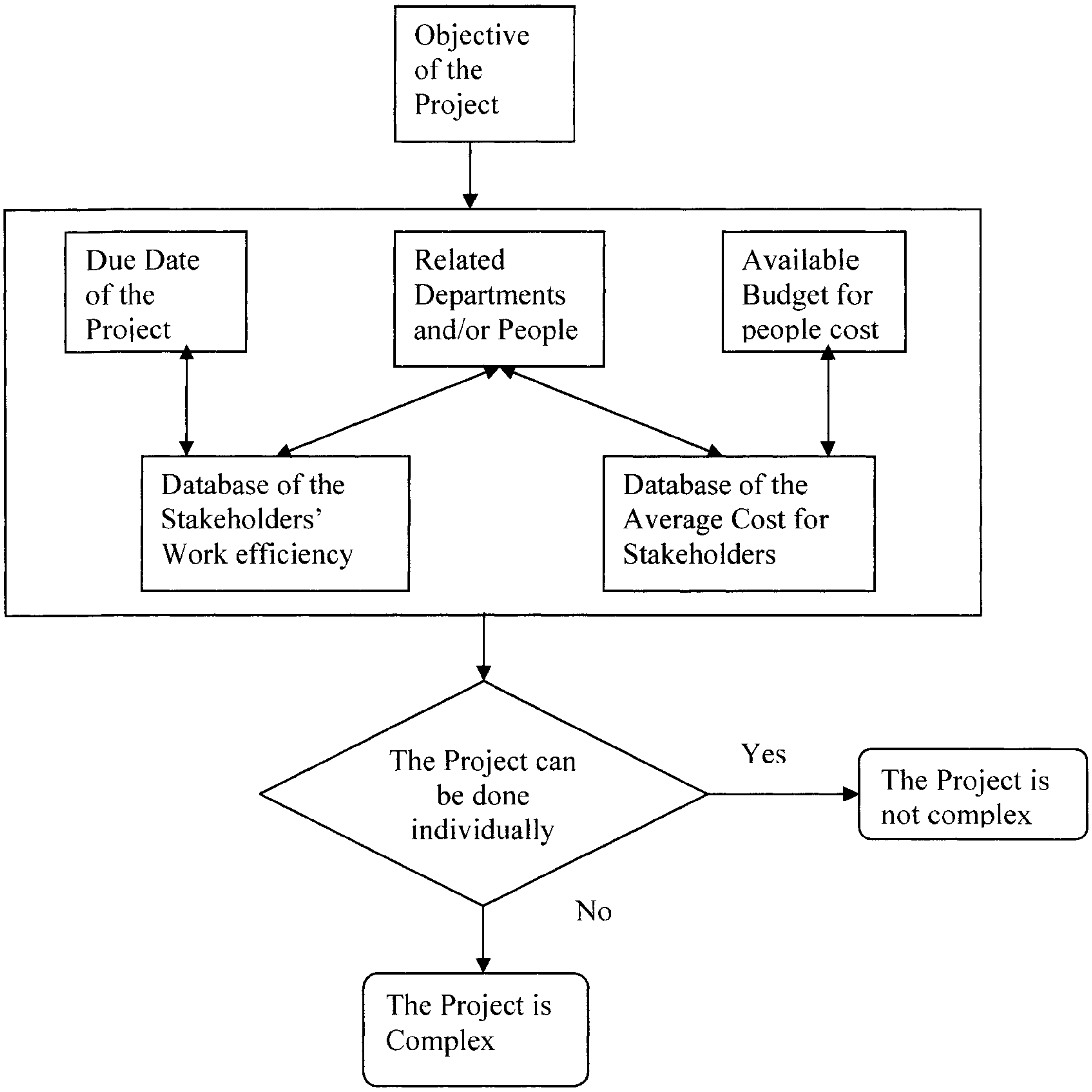


**Figure 2.7 Collaborative Complexity Detector**

# CHAPTER 3

# COLLABORATION AND NEGOTIATION

## 3.1 Introduction

From the definition of complexity from collaborative point of view, it is true that most engineering design is a complex process, especially in the current competitive environment. During the process, many people with various backgrounds and experiences, even from different countries are involved. They have different views to the product and the organization. The design process therefore becomes a complicated multi-objective decision making process. How to communicate, cooperate and negotiate is a problem that many companies are facing. In the following sections, some definitions of collaboration and negotiation are reviewed, why collaboration and negotiation are needed, and how people approach.

## 3.2 Definitions of Collaboration and Negotiation

### 3.2.1 What is Collaboration?

The term collaboration is derived from the Latin verb *collaborare*, which means to labor together. There are several definitions of collaboration within the literature.

Wood and Gray [1991] said that any definition must be able to answer the following questions: Who is doing what, with what means, toward what ends? They wrote the definition as follows:

> "Collaboration occurs when a group of autonomous stakeholders of a problem domain engage in an interactive process, using shared rules, norms, and structures, to act or decide on issues related to that domain."

Stakeholders may have shared or differing interests in a problem domain and these interests may change over time. Some degree of autonomy is required, or else stakeholders "merge" rather than "collaborate." Rules for governing interactions must be implicitly or explicitly agreed upon. Acting or deciding is needed to reach a common objective.

Lang et al. [2002] described collaboration as an activity where a large task achieved by a team. Often the task is only achievable when the collective resources are assembled. Collaboration requires successful and efficient sharing of knowledge, negotiation, coordination and management of activities. Distributed design teams are carrying out engineering design in an effort to use expert human resources more efficiently. The support needs of distributed design are reviewed from a cognitive viewpoint using five broad categories: design methodology, collaboration, teamwork, knowledge management and design representation. Successful collaboration requires effectiveness in a number of areas:

- Cognitive synchronization/reconciliation,
- Developing shared meaning,
- Developing shared memories,
- Negotiation,
- Communication of data, knowledge, information,
- Planning of activities, tasks, methodologies,
- Management of tasks.

Roberts and Bradley [1991] constructed the definition of collaboration as:

> "Collaboration is a temporary social arrangement in which two or more social actors work together toward a singular common end requiring the transmutation of materials, ideas, and/or social relations to achieve that end."

Collaborative endeavors generally share a number of basic characteristics [London, 1996]:

- The problems are ill defined, or there is disagreement about how they should be defined.
- Several stakeholders have a vested interest in the problems and are interdependent.
- These stakeholders are not necessarily identified a priori or organized in any systematic way.
- There may be a disparity of power and/or resources for dealing with the problems among the stakeholders.

- Stakeholders may have different levels of expertise and different access to information about the problems.
- The problems are often characterized by technical complexity and scientific uncertainty.
- Differing perspectives on the problems often lead to adversarial relationships among the stakeholders.
- Incremental or unilateral efforts to deal with the problems typically produce less than satisfactory solutions.
- Existing processes for addressing the problems have proved insufficient.

### 3.2.2 What is Negotiation?

Researchers did not commonly define negotiation in research papers in engineering domain. In my understanding, negotiation is a process in which two or more stakeholders exchange ideas or services because conflict happens among stakeholders and attempt to agree upon the same goal. Negotiations are common in engineering design, especially on large projects, and are typically conducted informally. Often, negotiation is used to handle the imprecision or uncertainty that is inherent in the design process. A process in which the interests of the parties provide the basis for the resolution of differences drives design negotiation.

## 3.3 Why Collaborate and Negotiate?

In today's competitive environment, people's skills, knowledge and access to information become more important. With the product becoming more and more complex, it is impossible for engineers to finish jobs individually in most situations. We need a cross-functional or multidisciplinary team to do the job efficiently. With the emergence of information technology and the convergence of computer networking and telecommunication technologies, it is no longer a requirement for people or cooperative companies to be located in the same place to communicate. Instead, people or companies that are geographically dispersed can engage in collaborative arrangements to increase their agility.

Collaboration and Negotiation are needed because:

- Competing goals
- Competition for resources, collaboration allows companies to share resources and core competencies
- Cultural differences
- Power discrepancies
- The boundaries among business, government and labor
- Increasing competitive pressures
- Rapid economic and technological change
- Global interdependence
- Faster time to market

## 3.4 How to Collaborate and Negotiate?

In order to collaborate and negotiate, we need have some tools or methodologies. Now there are some available tools and methodologies like:

- Whiteboard
- Computers: nowadays, there are not only traditional desktop and laptop available but also Tablet PC [Microsoft Window XP, 2004], which is the evolution of a laptop.
- Internet
- Group meeting
- Framework, Concept map
- E-mail, V-mail
- Computer conference

### 3.4.1 Internet Approach and Framework Approach

Amount of information is available on the internet. Most information is free to all users, some require membership and usually some form of payment. Data quality may vary from source to source. The university and government's sources are more trustful.

Team members may be in different locations and work at different time zones with different emphasis on the aspects of the project. They need to communicate, collaborate and access a diverse set of information sources in multiple formats--people perform group work or teamwork. Turban [2001] gave some characteristics of group work as following:

- Group members may be located in different places.
- Group members may work at different times.
- Group members may work for the same or for different organizations.
- The group can be permanent or temporary.
- The group can be at any managerial level or span levels.
- There can be synergy (process and task gains) or conflict in the group work.
- There can be gains and/or losses in productivity from group work.
- The task might have to be accomplished very quickly.
- It may be impossible or too expensive for all the team members to meet in one place.
- Some of the needed data, information, or knowledge may be located in many sources, several of which are external to the organization.
- The expertise of non-team members may be needed.

The communication and collaboration among team members is a critical aspect. It needs appropriate methods and technologies for groups to collaborate to reach the common ground efficiently and effectively.

Groupware is one of the answers. Groupware refers to software products that provide collaborative support to groups. Groupware provides a mechanism for teams to share opinions, data, information, knowledge, and other resources. Different collaborative computing technologies support group work in different ways, depending on the time/place category in which the work occurs, the purpose of the group, and the task.

Some popular groupware systems like Lotus Notes/Domino Server, Netscape Collabra Server, Microsoft Netmeeting, and GroupSystems. Those groupware systems have the similar structure. Using GroupSystems as an example, the major Group Support System (GSS) activities is shown in Figure 3.1.

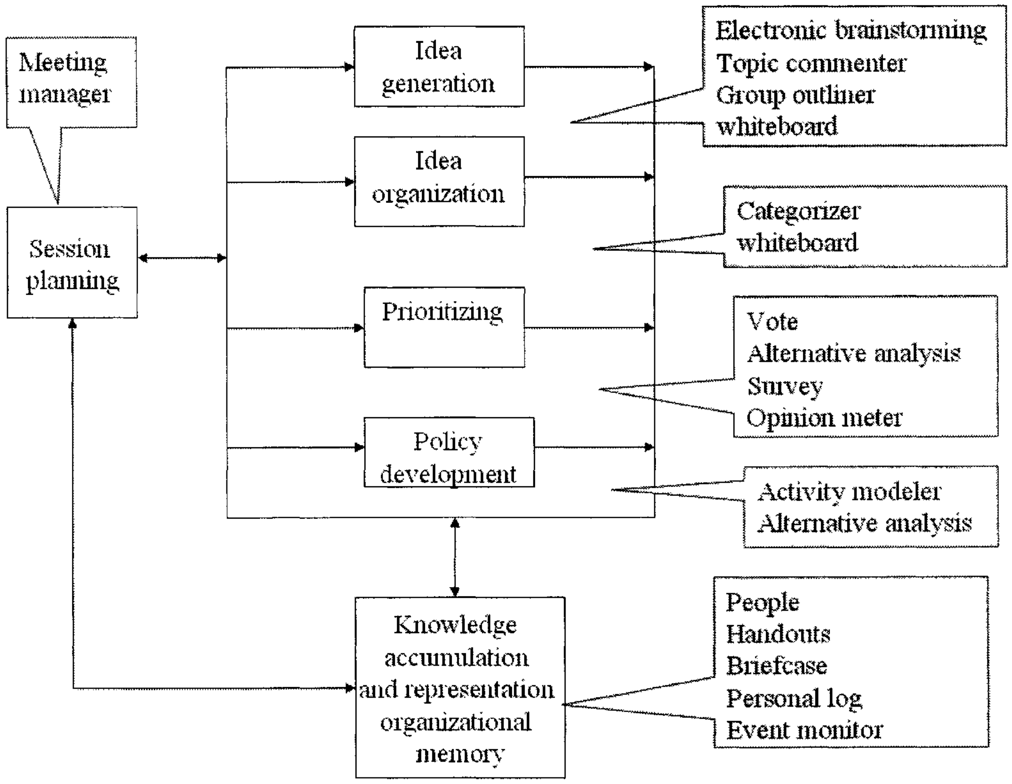
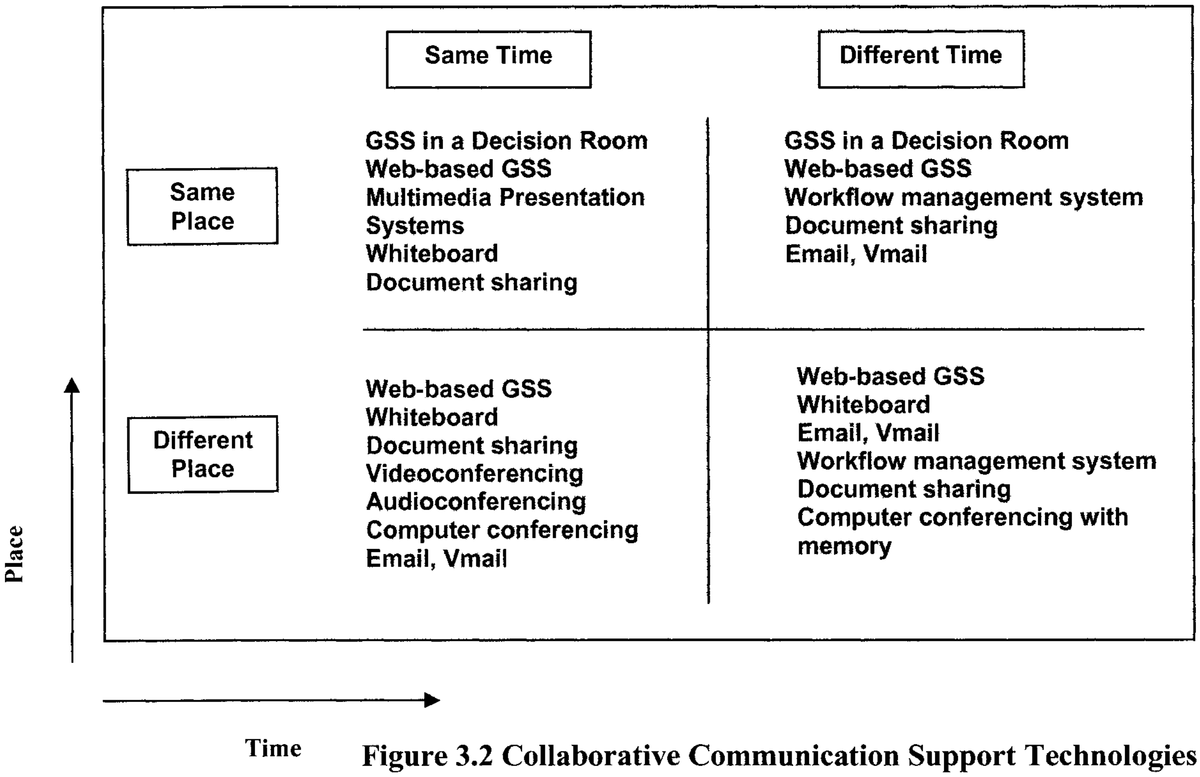


**Figure 3.1 Structure of GroupSystems [Turban, 2001]**

Collaboration involves more than one organization, which is able to integrate their ideas and knowledge into an end product no matter where the organizations locate. According to different places or times, Turban summarized some collaborative computing support technologies along two dimensions of time and place (Figure 3.2).



| | Same Time | Different Time |
|---|---|---|
| Same Place | GSS in a Decision Room<br>Web-based GSS<br>Multimedia Presentation Systems<br>Whiteboard<br>Document sharing | GSS in a Decision Room<br>Web-based GSS<br>Workflow management system<br>Document sharing<br>Email, Vmail |
| Different Place | Web-based GSS<br>Whiteboard<br>Document sharing<br>Videoconferencing<br>Audioconferencing<br>Computer conferencing<br>Email, Vmail | Web-based GSS<br>Whiteboard<br>Email, Vmail<br>Workflow management system<br>Document sharing<br>Computer conferencing with memory |

**Figure 3.2 Collaborative Communication Support Technologies along Time/Place [Turban, 2001]**

The four cells of the Figure 3.2 are explained as follows:

- Same time/same place: participants meet face-to-face in one place at the same time, as in a traditional meting or decision room.
- Same time/different place: participants are in different places, but they communicate at the same time, for example, with videoconferencing.
- Different time/same place: people work in shifts. One shift leaves information for the next shift.
- Different time/different place: participants are in different places. They send and receive information at different times. This occurs when team members are traveling, have conflicting schedules, or work in different time zones.

Straus [2002] stated five Principles of Collaboration in his book, How to Make Collaboration Work: Powerful Ways to Build Consensus, Solve Problems, and Make Decisions, as:

1) Involve the relevant stakeholders

    1.1) Four types of stakeholders

    - Those with the formal power to make a decision
    - Those with the power to block a decision
    - Those affected by a decision
    - Those with relevant information or expertise

    1.2) Involve stakeholders (Figure 3.3)

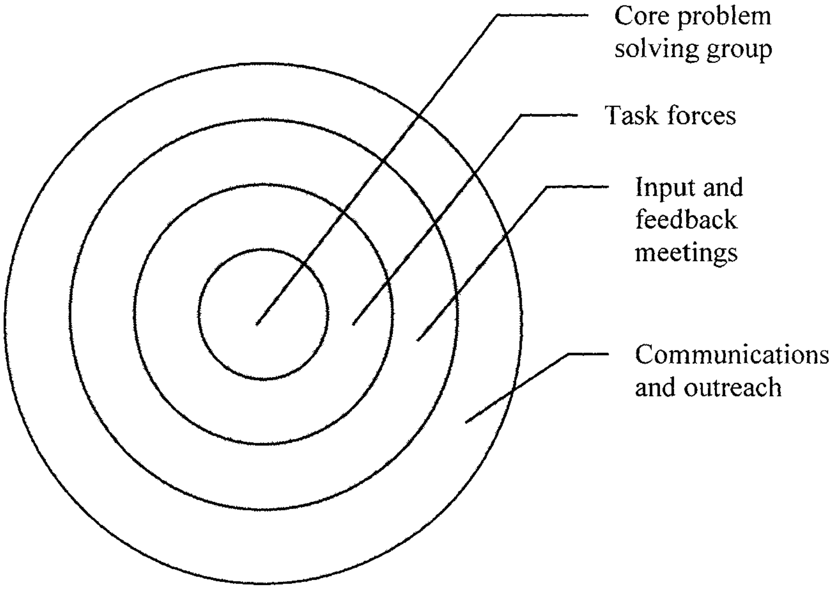


**Figure 3.3 Rings of Involvement [Straus 2002]**

2) Build consensus phase by phase
3) Design a process Map
4) Designate a process facilitator
5) Harness the power of group memory

Harvery [1997] constructed a Collaboration Process. I revised as Figure 3.4.

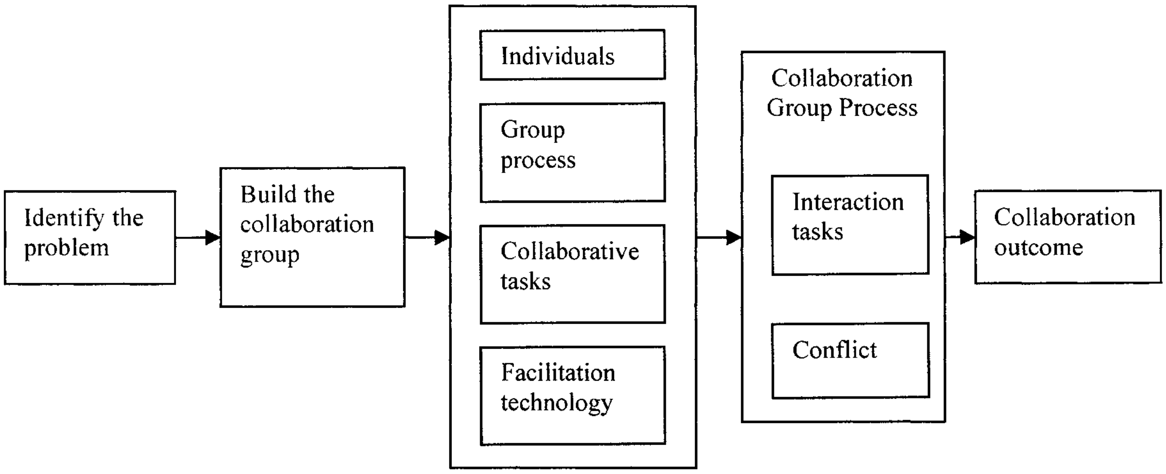


**Figure 3.4 Collaboration Process [Revised from Harvery, 1997]**

In order to solve the conflict during collaboration and make the collaborative process more effective and efficient, better methodologies are needed. Pena-Mora et al. [1998] generated a generic negotiation model shown in Figure 3.5. The model consists of five basic elements:

1) Project: the project data offer the environment of the conflict;
2) Participants: the participants expose the different attitudes in conflict situations due to their different interests to the issues;
3) Negotiation process: this is a iterative process to exchange the participants preferences;
4) Collaborative negotiation methodology: it provides suggestions to participants on how they can collaborate to resolve the conflict;

5) Outcome: shows the final agreement determined by the interactive process following the methodology in the project environment.

Pena-Mora et al. [1998] proposed a Collaborative Conflict Resolution Methodology and a computer agent named CONVINCER based on negotiation theory, game theory and generic negotiation model. The Collaborative Conflict Resolution Methodology includes five steps:

1) Build decision trees
2) Select payoff function form and weighting for all players
3) Finding maximum payoff combinations
4) Obtain suggested outcome using backward induction
5) Judge whether the outcome is influenced by insufficient knowledge and strategies

The Figure 3.6 gives the detail descriptions of the steps.

Adelson [1999] applied a theory-based framework of collaborative negotiation to some of the disputes that regularly arise during design. A collaborative negotiation tool like NegotiationLens may have been able to resolve a number of the conflicts, which arose within and between the groups working on the Integrated Work Set project.

The framework, embodied in the system NegotiationLens, has four facets:

1) Provides a negotiation method intended to produce gain for all parties.
2) Provides an efficient process for conflict resolution.
3) Develops working alliances.
4) Lets parties decide quickly when they should go their separate ways.

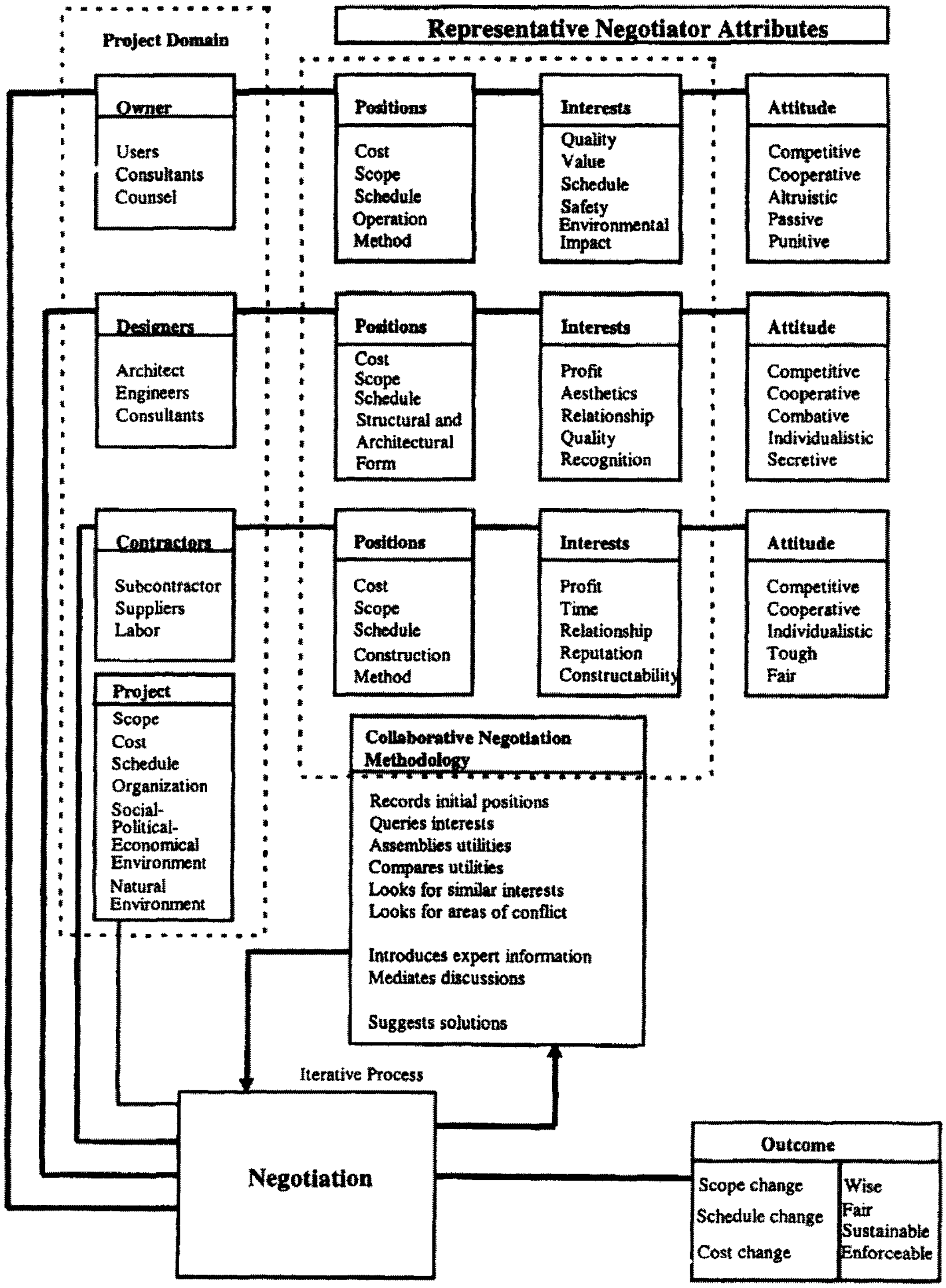


Figure 3.5 Generic Negotiation Model [Pena-Mora et al., 1998]

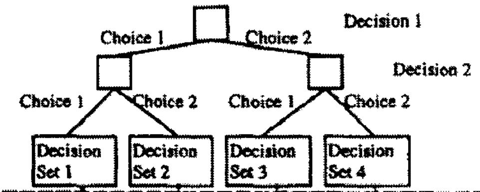
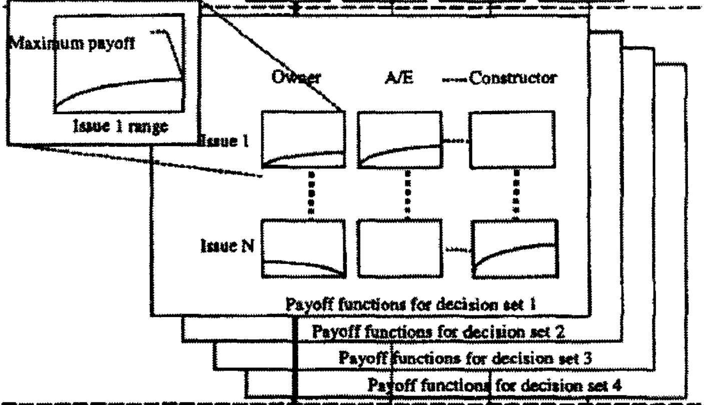
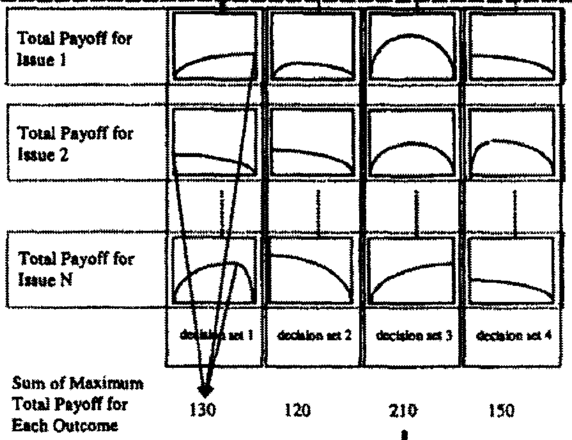
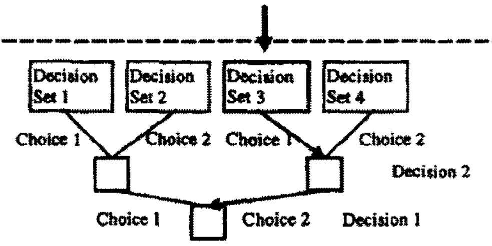
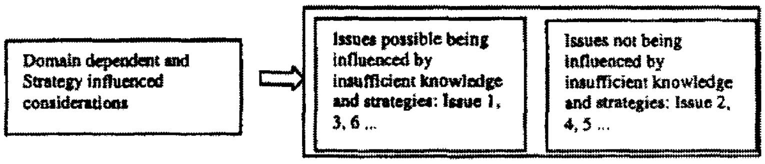
| | |
|---|---|
| Step 1. Build Decision/Game Trees: Draw decision tree based on the decisions and choices of the players. |  |
| Step 2. Select Payoff Function Form and Weighting for All Players According to Game Theory and Generic Negotiation Model: Give every issue of each player a payoff function and weighting according to the attitude and preferences of players in the game and generic negotiation model. |  |
| Step 3. Finding Maximum Payoff Combinations: For each outcome, find the total payoff of all players in every issue. The most beneficial (maximum total payoff) point in each issue can be obtained. The settlement point can be determined from those points. Then sums up the entire maximum total payoffs and obtain the payoff for every decision set. |  |
| Step 4. Obtain Suggested Decision Set Using Backward Induction: Using backward induction to obtain the combination of most beneficial choices. |  |
| Step 5. Judge Whether the Outcome Is Influenced by Insufficient Knowledge and Strategies |  |

Figure 3.6 Five Steps in Methodology for Collaborative Conflict Resolution [Pena-Mora et al., 1998]

Huang [2002] reported on the development of a web-based framework—CyberReview—a central portal for supporting collaborative product design review. Figure 3.7 shows an overview of the CyberReview system. CyberReview is a web site that serves two main groups of users. One is the group of designers or product development team who submit designs (in the form of documents) for review. The other group is the committee established for reviewing a design project. CyberReview provides a repository for archiving the design and review documents for both groups.

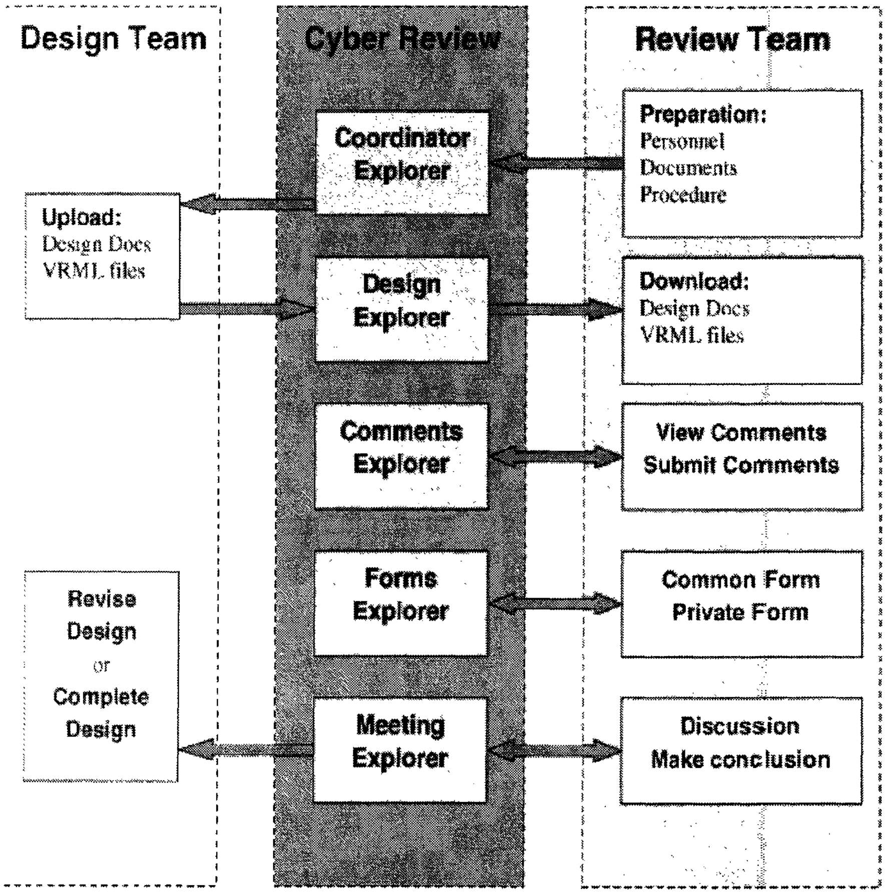


**Figure 3.7 CyberReview Framework [Huang, 2002]**

With the advent of the Internet and World Wide Web, and the availability of object-oriented technology, major CAD developers have come up with new generation CAD tools that can handle information sharing such as AutoCAD ® (Autodesk). Other systems include ArchiCAD ® for teamwork (Graphisoft) and MicroStation ProjectBank ® (Bentley Systems). These systems focus on how the CAD file formats can be shared or published over a network for collaborative use to replace the traditional view of CAD as individual desktop processing with a radical view of CAD as collaborative computing. They have the features for industrial data communications and information exchanges over the Internet.

### 3.4.2 Engineering as Collaborative Negotiation (ECN) Approach

In the past, engineering has been treated as only applied sciences. However, for today, an engineer must be an incorporator of social and technical, i.e. a negotiator. But, how the negotiators collaborate to achieve the common goal of the team is still an issue. It calls for the need of extending the engineering from "Engineering is applied science" to "Engineering as Collaborative Negotiation". The Engineering as Collaborative Negotiation (ECN) paradigm encourages engineers to use various negotiation approaches and techniques to make the decisions.

#### 3.4.2.1 What is Engineering as Collaborative Negotiation?

ECN is a new decision-making style that uses both technical (sciences of nature) and non-technical (sciences of artificial) knowledge.

- ECN is an interactive co-construction, give-take process, via which agreements and compromises among competing perspectives and multiple stakeholders are gradually arrived through conflict managements.
- ECN is best suited for team decision-making tasks in highly complex and dynamic systems.

The definition of ECN given by Lu [2003] is:

"ECN is a socio-technical decision-making activity, where a team of stakeholders with different expertise and mixed motives engage in interactive and joint conflict resolutions to co-construct consensual agreements of some engineering matter."

Lu [2002] stated five key premises of ECN:

1) One should negotiate when things are still soft
    - negotiation (not computation) is needed at early stages
2) One should first suffice, then optimize
    - negotiate acceptable solutions, then select the best
3) One should "interact" rather than "iterate"
    - bi-directional relationships are useful at early stages
4) One should always leave rooms for others
    - Intervals/sets are better than single point specifications
5) One should always prepare for later "regrets"
    - Keep track of decision rationales for later uses

Based on Lu [2002], the engineering development history is as follows (Figure 3.8):

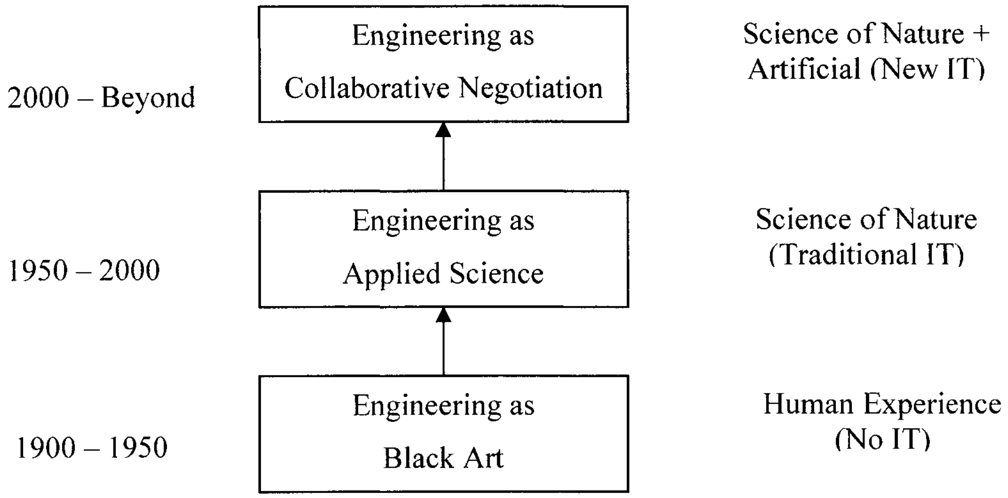


**Figure 3.8 Engineering Development History [Adopted from Lu, 2002]**

From 1900 to 1950, engineering is as black art, there is no Information Technology (IT), and decisions were made based on human experience. From 1950 to 2000, engineering is as applied science, the traditional IT was used, or we can say that it is science of nature approach. Since 2000, engineering is as collaborative negotiation which is a new IT or science of nature and artificial approach. So we can say that engineering is not about guessing, computing, drafting or searching. It is about collaborative negotiation.

In the past work of the IMPACT Research Laboratory [Lu, 1999], a Socio-Technical design framework was created. The Socio-Technical framework is based on the acceptance that collaborative engineering design is a human-based, interdisciplinary and socio-technical activity. Figure 3.9 shows the framework structure. The Socio-technical

Framework addresses the fundamental characteristics of collaborative engineering design. The framework illustrates that collaborative engineering design is a human-based socio-technical activity. There are two levels in the framework. The lower level represents the design environment, the communications in which a specific design is to take place. The upper level shows the socio-technical co-construction during a specific design process. Initiated by a design objective, the design evolves in the upper level whose outputs constitute the design result, and feed-backs to the evolution of the design environment and the design campaign itself. The co-construction which occurs in the upper level may be envisioned as that relevant at the product and process level, while that which occurs in the lower level may be envisioned as that relevant at the system level.

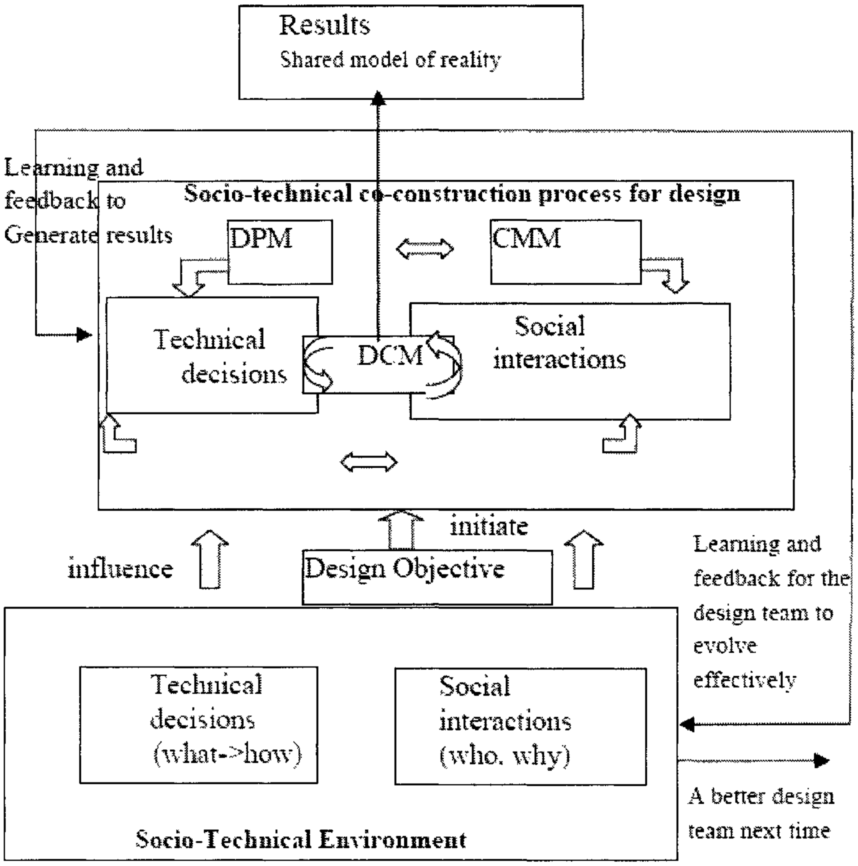


Figure 3.9 Socio-Technical Design Framework [Lu, 1999]

In ECN research, the focal point is on stakeholders' collaborative behaviors to deal with various mixed (i.e., common and conflicting) motives in engineering decisions with not only all social, economical, and technical (S.E.T.) knowledge but also the ability to negotiate effectively with other stakeholders.

The above Socio-Technical framework results in a design process architecture, which expressively depicts various elements and their relationships in collaborative design. The architecture is shown in Figure 3.10.

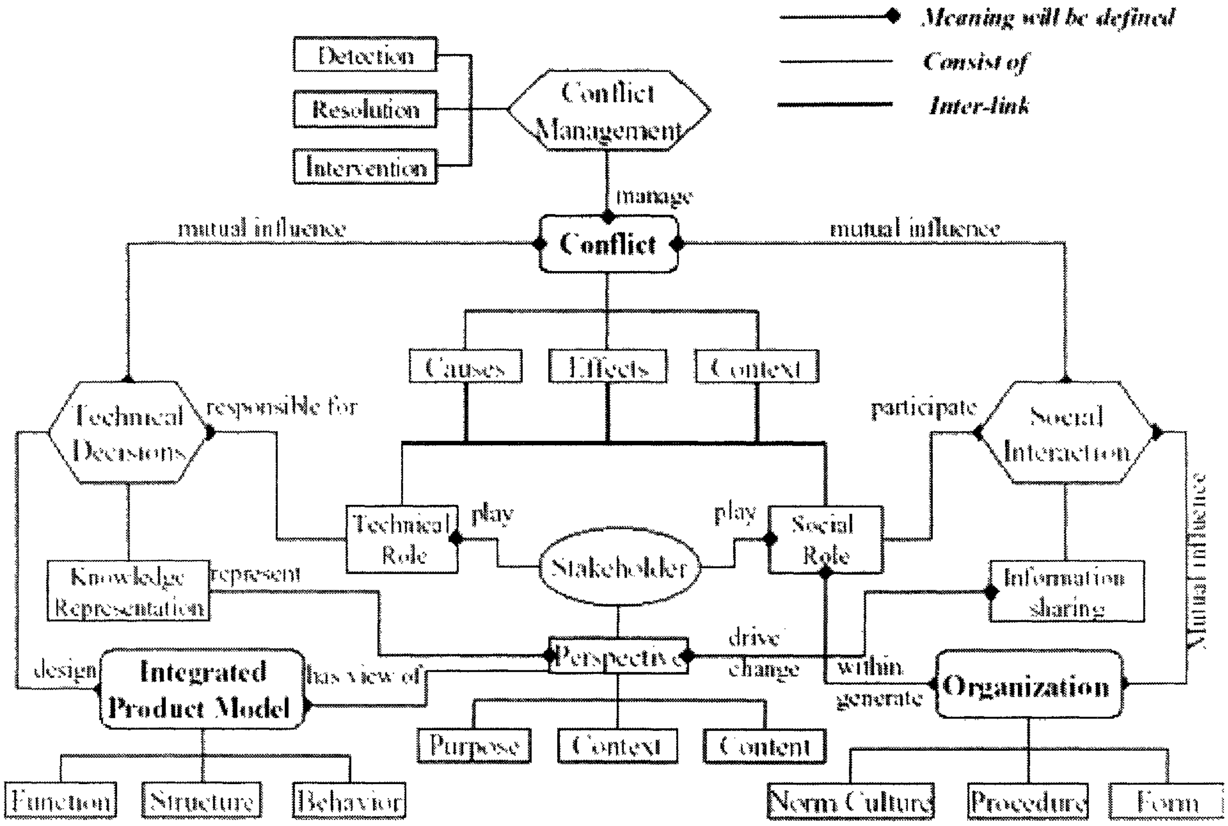


**Figure 3.10 Socio-Technical DPM Architecture [Lu et al., 1999]**

The goal of ECN research is to establish a new engineering decision-making foundation that is effective in supporting joint decisions to achieve the maximal (i.e., purposeful) solutions in collaborative engineering.

#### 3.4.2.2 Engineering as Collaborative Negotiation vs. Traditional Engineering

Lu [2003] compared the difference between ECN and the traditional views of engineering decision making according to a few features (Table 3.1).

**Table 3.1 Traditional Engineering vs. ECN [Lu, 2003]**

| The Traditional Engineering Viewpoints | The ECN Viewpoints |
|---|---|
| Seek correct answers | Obtain consensual agreements |
| Mixed normative and prescriptive | Mixed descriptive and perspective |
| Technical | Socio-technical |
| Focused on consistent theories | Focused on conflict resolutions |
| Sciences of the nature | Sciences of the nature and the artificial |
| Application/integration of existing knowledge | Co-construction of new knowledge |
| Iterative analysis | Joint synthesis |
| Optimal | Suffice (minimal), acceptable |
| Decision knowledge | Decision style |

It is very important to clarify the scope of ECN research. Comparing with the existing methodologies DFX, concurrent engineering, project management, ECN should cover all of them (Figure 3.11).

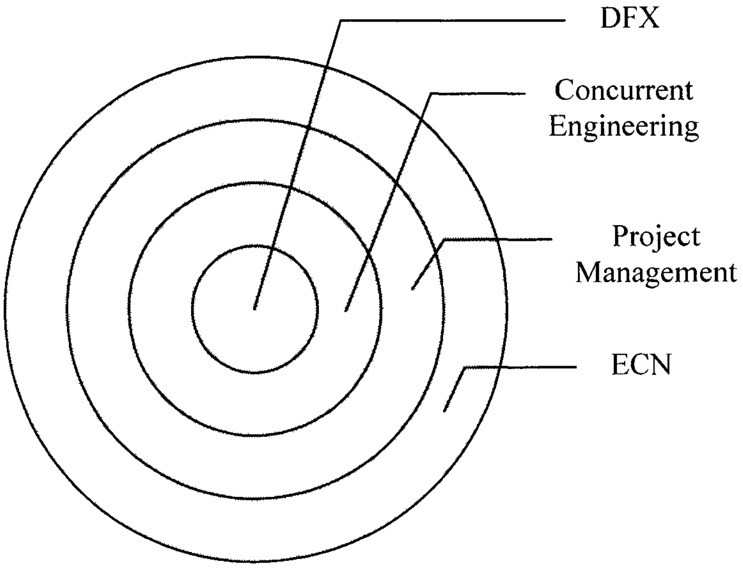


**Figure 3.11 The Scope of ECN [ElMaraghy and Urbanic, 2004]**

#### 3.4.2.3 Engineering as Collaborative Negotiation Rules for Participants

ECN process involves multi-discipline participants, and facilitating the group's selection. It is essential to create a set of ground rules to insure an orderly and fair process. Based on the characteristics of ECN, the rules for participants are created as follows:

1) It is the obligation for all participants to attend all the meetings on time and everyone should give their opinion during the meeting.
2) The chairperson is responsible for organizing the meeting, and makes sure that the meeting follows the rules. But he/she has no right to make the final decision.
3) Try to get information as much as possible and encourage wild even exaggerated ideas from different disciplines.
4) Do not criticize other participants' ideas, but negotiate.
5) To negotiate at early stages, do not wait until the last result.
6) Negotiate first to get acceptable solutions, and then select the best.
7) When some methodologies are used to support ECN decision making, make sure every participant understand the principles and rules. A briefly training is needed if it is necessary.
8) Always keep asking "Can it be better?"
9) Integrate multiple factors into an optimal solution and the final result should meet win-win situation for all participants.

## 3.5 Summary

In Chapter 3, the definitions of collaboration and negotiation, the benefit of them, and different approaches regarding to engineering field are reviewed. There are many methodologies and tools available for collaboration, but not negotiation. However, negotiation is a critical process in the engineering processes.

ECN approach is a new methodology for collaboration and negotiation for engineering design. It is also a new decision-making style that uses both technical (sciences of nature) and non-technical (sciences of artificial) knowledge. It is different from traditional engineering style. Because ECN process involves multi-discipline participants, and facilitating the group's selection, a set of ground rules for ECN are created. ECN will continue to be discussed in the next chapter.

# CHAPTER 4

# DECISION MAKING IN COLLABORATIVE DESIGN

## 4.1 Introduction

In complex processes, effective collaboration among the stakeholders is necessary. With the increasing complexity, group decision-making seems more and more important with good collaboration and negotiation. However, group decision-making also has its disadvantages. The distributed perspectives among the stakeholders cause many defections and inconsistencies in design. That makes the multi-objective decision-making process more complicated than the individual ones. To understand and support this process, it requires an objective and comprehensive study of why and how the decisions are made in the design organization.

Collaborative design is conducted by a group of stakeholders with different goals. There are two categories of goals in collaborative design, the individual goals and the organization goals. Customers, managers, design engineers, and manufacturing engineers etc. have different perspectives. Customers present their preferences about the product and wish the corporation to provide the better quality good with low price. Owners of companies also have their important voice in design process, such as to make more profit. Design engineers might view functionality more important. Even within same kind of technical roles, the stakeholders may have different behavior for the knowledge and personality differences. It is obvious that the design goals may not be just to maximize the profit of the company. The design group as an organization also has its goals. The goals of the design group can be simply conceived of as a derivative of the individual goals of the stakeholders. Conflicts among the individual goals and the organization goals are frequently occurring.

Although the stakeholders are supposed to make decisions to satisfy their goals and the organization goals, sometime they face the obstacles to make the decisions. The reasons are various:

- The goals of the individuals are not always well defined. In the early design stage of design, this happens frequently for the concepts of the product had not been clearly figured out.
- The norms, rules, and the coherent culture of the organization will force the individuals to adjust their goals to conform the organization goals.
- Designers only have limited knowledge and computational ability. They usually make decisions by the sensible outcome or by experience.
- In large system design, a lot of uncertain issues are involved and the decisions become fuzzy.
- The probability of the final outcome is hard to be evaluated in the early stages of design. Stakeholders are more intent to select the satisfactory options, rather than to maximize their utilities.

In section 4.2, some decision support methodologies and tools will be briefly reviewed. Some will be described in detail in section 4.3, 4.4 and 4.5.

## 4.2 Decision Support Methodologies and Tools Review

### 4.2.1 Brainstorming

Brainstorming is a method for generating ideas in a group situation, such as choosing a project to work on, determining possible causes and/or solutions to problems, planning out the steps of a project.

### 4.2.2 Customer Surveys and Interviews

Customer surveys and interviews are the good ways to gather information of the customers' needs. It can be difficult to get accurate customer information. In companies, there should be general customer data available from previous surveys and interviews. However, companies will need to update the data when they have a new project, to find out what customers exactly need.

### 4.2.3 Quality Function Deployment (QFD)

QFD is a method used to identify customer attributes and to create the relation between customer attributes and design parameters. The main part of QFD process is a planning tool called the "house of quality" (Figure 4.1)

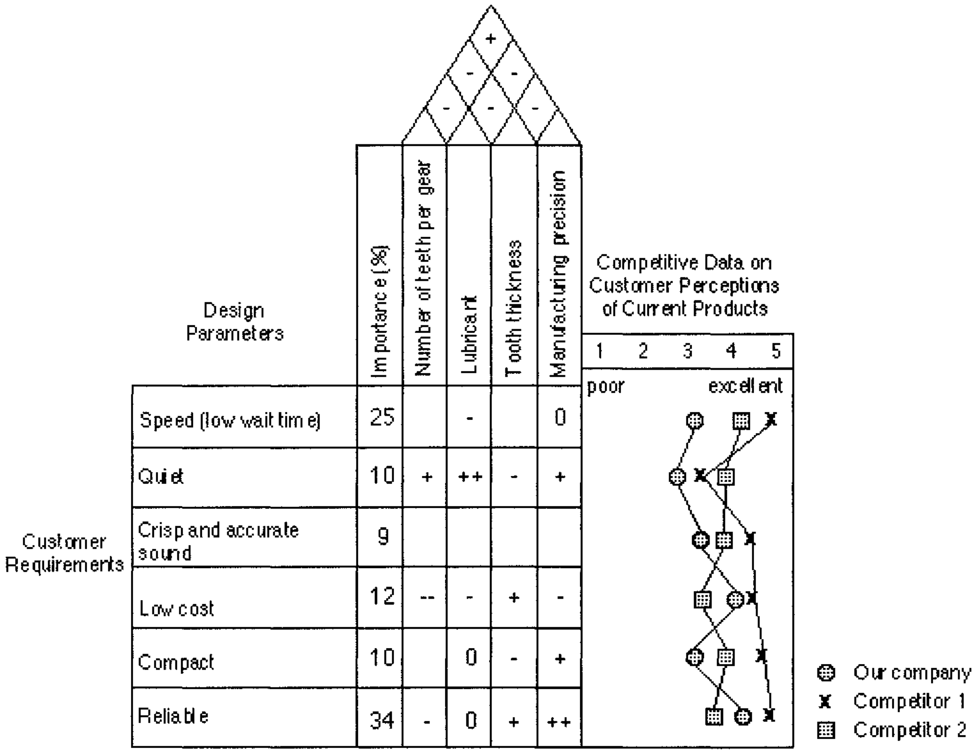


**Figure 4.1 House of Quality [Wheelwrigh and Clark, 1992]**

### 4.2.4 Strategic Options Development and Analysis (SODA)

SODA was originally developed by Colin Eden at the University of Bath [Eden, 1990]. SODA uses interview and cognitive mapping to capture individual views of an issue. Group maps constructed through the aggregation of individual cognitive maps are used to facilitate negotiation about value/goal systems, key strategic issues, and option portfolios. COPE cognitive mapping software was created specifically for use with SODA. COPE is used to map individual cognitive maps of the problem space and then to combine those individual maps into a group map that can highlight both areas of consensus and areas of disagreement.

### 4.2.5 Balanced Scorecard

The balanced scorecard is a strategic approach and performance management system [Kaplan and Norton, 2004]. It forces managers to look at the business from four important perspectives and links performance measures by requiring firms to address four basic questions (Figure 4.2):

- How do customers see us? - Customer perspective
- What must we excel at? - Internal perspective
- Can we continue to improve and create value? - Innovation & learning perspective
- How do we look to shareholders? - Financial perspective

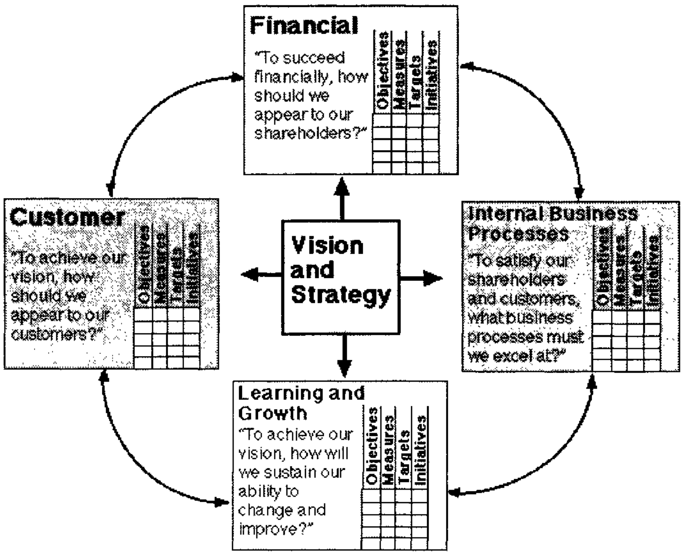


**Figure 4.2 Balanced Scorecard [Kaplan and Norton, 2004]**

### 4.2.6 Development Funnel

The development funnel provides a graphic structure for thinking about the generation and screening of alternative development options, and combining a subset of these into a product concept in a very simple way [Wheelwrigh and Clark, 1992]. A variety of different product and process ideas enter the funnel for investigation, but only a fraction become part of a full-fledged development project (Figure 4.3).

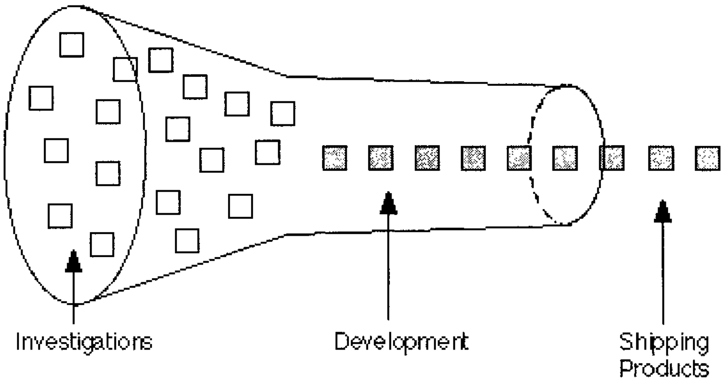


**Figure 4.3 Development Funnel [Wheelwrigh and Clark, 1992]**

Managing the development funnel involves three different tasks or challenges.

1) Widen the mouth of the funnel - the organization must expand its knowledge base and access to information in order to increase the number of new product and new process ideas.
2) Narrow the funnel neck - ideas generated must be screened and resources focused on the most attractive opportunities.
3) Ensure that the selected projects deliver on the objectives anticipated when the project was approved.

### 4.2.7 Critical Path Analysis (CPA)

CPA is a network map which traces the work from a departure point of a project to the final completion objective (Figure 4.4).

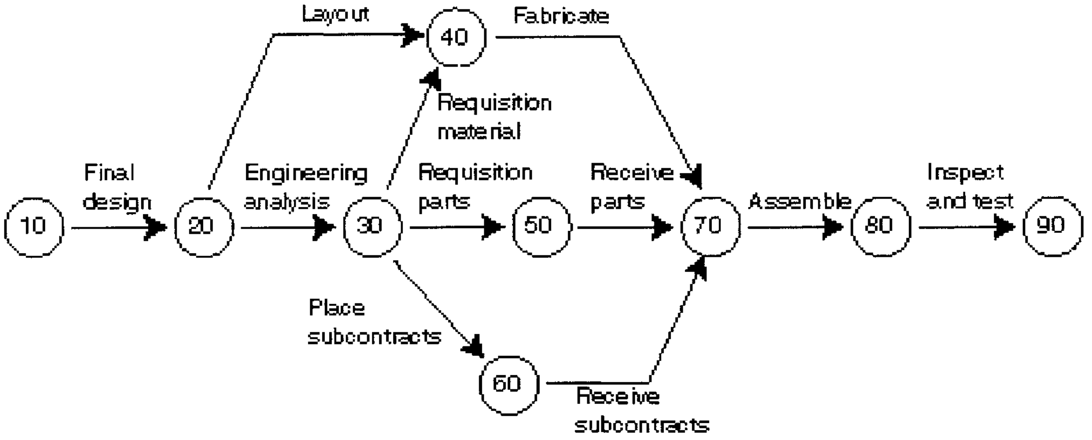


Figure 4.4 Critical Path Analysis Map [Riggs, J. L., 1987]

In CPA an activity is represented by a line or arrow. This line or arrow connects two events. Each event is a specific point in time, marking the beginning and/or end of an activity. The network may also include time/calendar information (including boundaries) and hence deadline data.

### 4.2.8 Strategic Assumptions Surfacing and Testing (SAST)

SAST was developed in the US by Richard Mason, Ian Mitroff, and Jim Emshoff [Mason et al., 1981]. It is a process which reveals the underlying assumptions of a policy or plan and helps create a map for exploring them.

SAST has five phases:

1) Key individuals from across company functions are formed into small (6 - 8 people) groups
2) Each group meets separately and begins to identify the assumptions inherent in the issue (from their viewpoint)
3) Dialectic debate within each group
4) Dialectic debate between groups
5) Final synthesis

### 4.2.9 Strategic Choice Approach

The Strategic Choice Approach is used in face to face meetings of a decision making group [Friend and Hickling, 1987]. It is viewed as an ongoing process in which the planned management of uncertainty plays a crucial role. There are three key elements of analysis which are used in structuring problems and working towards decisions:

- The Decision Area
- The Comparison Area
- The Uncertainty Area - divides into three broad categories
    1) Uncertainties to do with the working environment
    2) Uncertainties to do with guiding values
    3) Uncertainties to do with related choices

### 4.2.10 Decision Tree

Decision trees represent a disjunction of conjunctions of constraints on the attribute-values of instances. Decision trees classify instances by sorting them down the tree from the root node to some leaf node, which provides the classification of the instance. Each node in the tree specifies a test of some attribute of the instance, and each branch descending from that node corresponds to one of the possible values for this attribute.

An instance is classified by starting at the root node of the decision tree, testing the attribute specified by this node, then moving down the tree branch corresponding to the value of the attribute. This process is then repeated at the node on this branch and so on until a leaf node is reached (Figure 4.5).

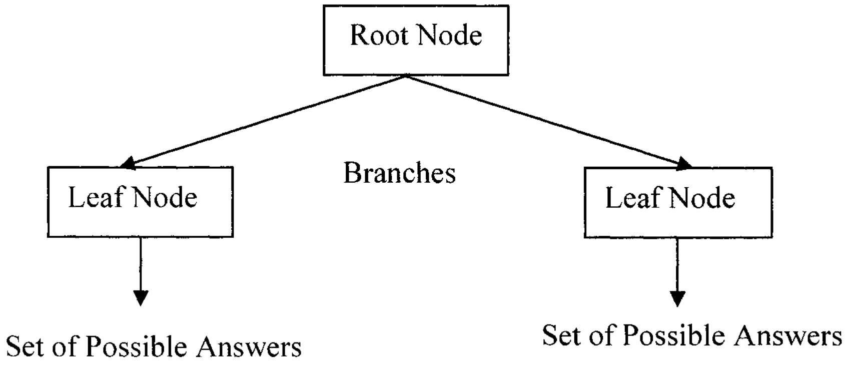


**Figure 4.5 Decision Tree**

## 4.3 A Roadmap of Engineering Decision Paradigms

Lu [2003] summarized decision styles and created a roadmap of engineering decision paradigm. Before going through the roadmap, first take a look at engineering decision styles.

### 4.3.1 Engineering Decision Styles

Researchers in decision sciences have long established the following three different types of decision scenarios:

i. Individual decisions – where an unitary decision maker, or a team of decision makers that poses as an undivided entity speaking in a monolithic voice, makes decisions with or without the consideration of uncertainties and risks. When making decision individually, one employs the tools, techniques, and methods of decision analysis.

ii. Interactive decisions – one of group decisions according to Raiffa [2002], where rational choices made separately by multiple cooperative or non-cooperative individuals in a sequential or simultaneous manner interact to produce joint outcomes (i.e., payoff) for all parties involved. When using group decision making, it will involves more complexity than individual decision-making. In general, there are two approaches developed in examining group decision-making: the theory of games and the theory of negotiation. In the domain of interactive decision-making, the theory of non-cooperative games is adopted.

Non-cooperative game theory deals largely with how intelligent individuals interact with one another in an effort to achieve their own goals.

iii. Joint decisions – the other of group decisions, where concerned parties make mutually agreed-upon joint decisions through full, open, reciprocal, and (preferably) truthful communications to resolve competing interests and create new alternatives. In the domain of joint decision, the theory of negotiation is adopted.

Actually, we can say that there are two types of decision making in general: individual and group decision-making, then splitting group decision-making into interactive decisions and joint decisions (See Figure 4. 6 for the taxonomy of decision-making). It is easy to get confused with interactive decisions and joint decisions. Both game and negotiation theories involve group activities. Games involve multiple individuals making separate decisions that interact. The payoffs for each individual are dependent not only on their own decision, but also on the decisions of the other individuals, and vice versa. In contract, negotiations involve multiple individuals cooperating to arrive at a joint decision. The joint decision entails joint consequences, or payoffs, for each individual.

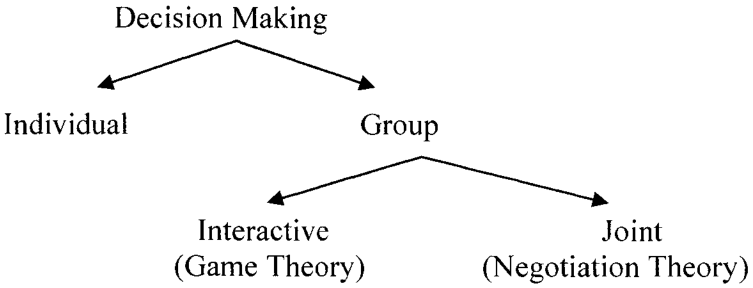


**Figure 4.6 Taxonomy of Decision Making**

In the past, individual engineering decisions were made separately, and then when necessary, were joined together by system integration efforts. This traditional engineering paradigm was replaced by the concurrent engineering paradigm, where multiple interacting life-cycle decisions are made in parallel, as much as possible, in order to reduce the lead-time. After concurrent engineering, collaborative engineering has been proposed as a new engineering paradigm, where joint decisions are made by a group of interested stakeholders. Table 4.1 summarizes these intriguing correlations between decision science scenarios and engineering decision styles.

**Table 4.1 Decision Science Scenarios and Engineering Decision Styles [Lu, 2003]**

| Decision Science Scenario | Engineering Decision Style |
|---|---|
| Individual decisions | Traditional (sequential) engineering |
| Interactive decisions | Concurrent (simultaneous) engineering |
| Joint decisions | **Collaborative engineering** |

### 4.3.2 The Roadmap and Examples

#### 4.3.2.1 The Roadmap

Lu [2003] constructed a 2-D roadmap to define the different engineering decision – making paradigms, as shown in Table 4.2.

**Table 4.2 Roadmap of Engineering Decision Paradigms [Lu, 2003]**

| Knowledge Type<br>Decision Type | | Knowledge independent of human opinions | Knowledge resulted from human agreements |
|---|---|---|---|
| | | **Sciences of The Nature** | **Sciences of The Artificial** |
| | | **The Minimal Engineering Solutions** | **The Maximal Engineering Solutions** |
| **Traditional Engineering** | **Individual Decisions** | **a.** Physical laws expressed by mathematics | **d.** Classical decision analysis |
| **Concurrent Engineering** | **Interactive Decisions** | **b.** Modeling systems | **e.** (Non-cooperative) Game theory approaches |
| **Collaborative Engineering** | **Joint Decisions** | **c.** Analysis of systems of network of dependencies | **f.** Collaborative negotiation paradigm |

#### 4.3.2.2 Examples

According to my understanding about the roadmap of engineering decision paradigms, I give an example for each cell of Table 4.2.

**a. Design a Bolt to Join Two Pieces of Parts Together**

Calculate the dimension required according to standard raw materials, then select standard screw type according to function requirement and select the standard head shape of bolt according to the function required an the wrench space limitation.

### b. Redesign a Shaft Box

A company wants to redesign a shaft box for one of their major product. Because entire processes from design to final product will be within this company. The company feels really convenience and beneficial to form a concurrent engineering design team to increase the reliability and performance capability of the design parameters.

As the principal of concurrent engineering, the design is not only for the parameter and function design but also the design for manufacturing, the design for assembling, and the design for the quality assurance. For example, the positional tolerance of the case used in the design is related to the testing process and eventually will affect the final assembly result. Therefore, the design engineer will not indicate the parameter of that tolerance himself/herself; he or she has to discuss the parameter with the testing engineer, manufacturing engineer and final assembling engineer together in a concurrent engineering meeting. From the design engineer's point of view, he or she feels that tighter tolerance will be better since it will make sure any part pass the test and will have no problem for the final assembly. The engineer who is in charge of the final assembly strongly agrees with this idea. But on the other hand, the testing engineer and the manufacturing engineer will not agree with the tight tolerance because tighter tolerance means higher manufacturing cost and harder test performing. To solve this disagreement, the participants of the problem decide to do a cost-benefit analysis to indicate the trade-off between the cost and the accuracy. The result is shown as in the Figure 4.7. The middle point of the cost and accuracy trade-off figure is the best point can be accepted by all of the participants with reasonable cost and defect rate.

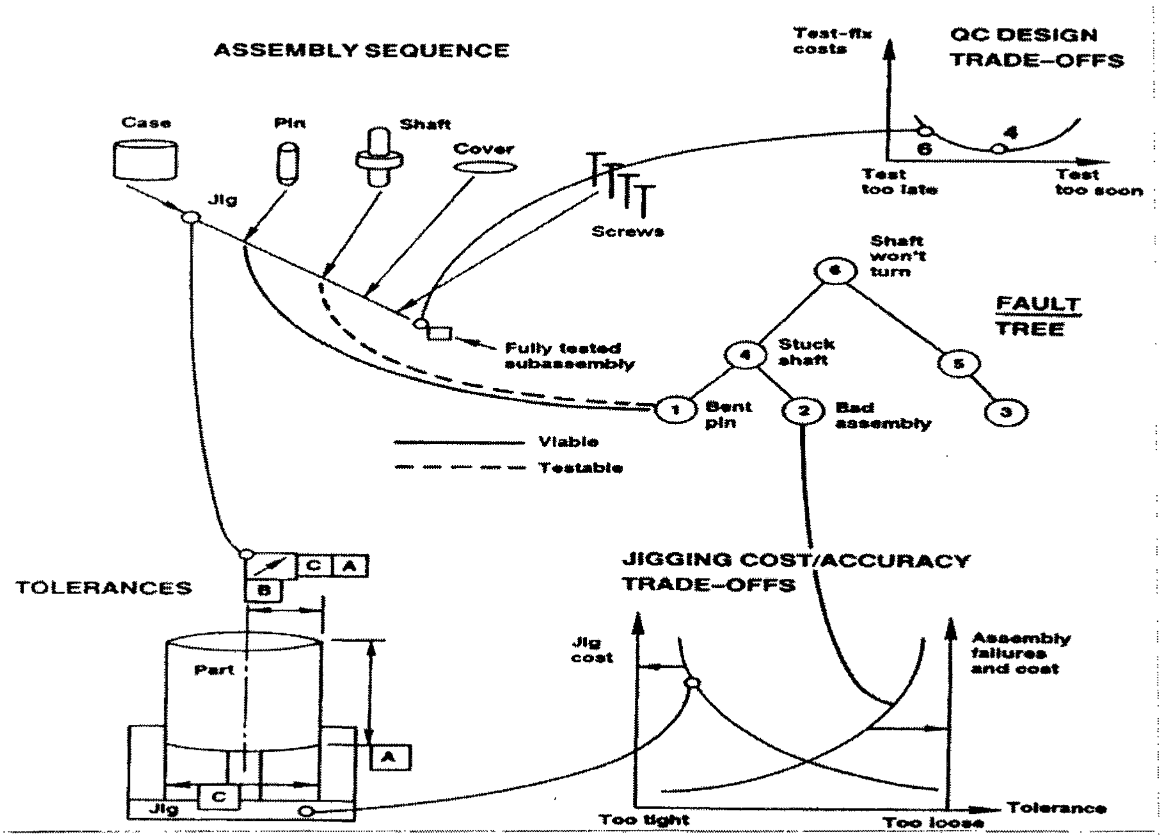


**Figure 4.7 Redesign Process of a Shaft Box** [Whitney, D., 1988]

Design for assembling is also part of the design process that is covered by concurrent engineering methodology. During this assembling sequence design process, the design engineer wants to add a testing process for the pin and shaft which are used in the product since the major failure method is the shaft stuck or shaft will not turn after assembling. The concurrent engineering team which has testing engineer, assembling engineer, quality engineer, and design engineer involved indicated there are two primary reasons for the failure by using Fault Tree model, one is the bad assembly which already be solved at the last concurrent engineering meeting, the other is the bend bin used in the assembly without checking. Therefore the testing process for the pin is essential. But the issue is when parts should be sent for the testing? The testing engineer points out that it is too costly to do the test at the very late step even though it is easy to do it, but on the other hand, it is not reliable if do the test too soon. The assembling engineer also gives the point of cost at each step in case disassembly needed. And the quality engineer has a certain bottom line for the defect rate required. According to the information, the concurrent engineering team indicates a trade-off figure for the test time and the cost spent. This figure has the optimal solution, which integrates manufacturing concerned, quality required, testing performed and so on, the make the design engineer have a clear picture to indicate the assembling and testing sequences.

Through this case, the concurrent engineering methodology shows its advantages at many points. The core of this methodology is to have participants who are or will be involved into the project meet together at individual point during design process to avoid the further possible conflicts, and also to get the best cost-benefit result through analyzing integrated information from different disciplines. But the disadvantages of this methodology is that there are still limitation for information resources, since only directly related department or engineer will attend the concurrent engineering meeting for specific problem, and therefore the solution may be not the best solution.

### c. Design Inner Anti-Wear Cast Steel Linings for Ball-mill Machines

A concentrating mill company imported a series of ball-mill machines from a foreign supplier. The contract indicated that the company has the option to select other spare parts supplier after the machine normally run over half year. The company assigned the design and development task of a major consuming part, a set of inner anti-wear cast steel linings, to one of their domestic tier one supplier.

In order to successfully satisfy the customer requirements, a multi-discipline cross-functional design team was formed. The team included a project engineer, a design engineer, a material engineer, a manufacturing engineer and a marketing person. The project engineer was in charge of the entire project, the design engineer was in charge of the original linings measurement and dimension identification, the material engineer was in charge of the raw material selection and the steel melting process control, the manufacturing engineer was in charge of the casting, trimming and heat treatment, the marketing person was in charge of raw material purchasing, finished good checking, delivering and final assembling. But they all interacted within each action during the total design process.

All team participants started working together at the same point which following the identification of each design parameter. For example, the design engineer wanted the finished linings can reach surface hardness 50 HRC and impact power 50 $J/mm^2$ to satisfy the expected anti-wear and anti-crash capability. The design engineer proposed this requirement with possible adjustments to the other team members to do the feasibility evaluation. The material engineer proposed several candidate materials which can reach the point under certain casting or heat treatment conditions that were offered by the manufacturing engineer, the candidate materials were also limited by the information from the marketing person which is about the supplying and purchasing situation. The project engineer analyzed cost-benefit of different alternatives. The finial decision, which not only indicated the best suitable parameters for surface hardness and impact power but also indicated the type of raw material, metal melting process, linings casting process, heat treatment process, and the possible selling price, came from the integrated information supplied by each participant. The design team used same methodology to deal with different problems during design process such as dimension and tolerances identification and keep on-going refining to the design until the product launched.

During this design process, it seems that the duties of each participant following certain sequence rather than can be done together. But actually the entire design team still worked together from the starting point by following the system of network of dependencies. This methodology gives the opportunity for the designers to understand the overall constrains and possibilities during the design process, therefore the design solutions are the best solution not only for the design stage but also for the following stages. Also this methodology gives the opportunity to the other participants who involved in the design process to understand the requirements from design point of view; therefore the focus of the following steps becomes clearer. The disadvantage of this methodology is that the lack of internal optimizing process at each engineer's point of view. That may cause the bias which comes from personal experience or preference to the final solution, in other word, the solution may not be the best solution since the sub solutions which support the final solution are not the optimized solution but come from the personal opinions.

### d. Tolerance Selection

Most of design processes follow this procedure at early time, e.g. the case in the case study 2. The design engineers get the specification requirements from marketing department, after calculation and comparison with previous experiences; they indicated the optimal solution of 25 ± 0.03mm. This solution is sent to the manufacturing department of the manufacturer through the marketing department of the buyer side. The manufacturing department will only challenge this order if it is not producible. Otherwise they will try to find out the suitable machines and producing sequences for this product. The process department will accept the order from manufacturing department with no doubt. They only try to figure out the best solution to produce this product with the lowest cost and the highest quality. Only if they find that the quality and the cost of this product are not satisfied during the producing, they will ask the manufacturing department to refine the producing sequences and the machine selected. The manufacturing department will try to refine the solution or talk to the marketing department about the issues of later delivery, increased cost, bad quality, etc. If the manufacturing department can not get a better solution, the marketing department will take to the buyer's marketing department about refining the design and other issue such as cost and lead time. The marketing department of the buyer side will transform the question to the design department to see the possibility of refinement of the design. This sequence will repeat until get a satisfied solution of both sides.

The characters of this methodology are the sequences are fixed, each department involved in the process only has chance to talk to the department which directly related to them. And the solution made by each department is limited in their own area without concerning entire related factors. Therefore, it is time consuming to solve a problem and with higher cost.

### e. Design an Electric Sewing Machine

A leading sewing machine company intends to introduce a new product to keep its market sharing. For the new product, what kind of features should be added in or what changes should be made is the most important issue to determine if the company can occupy or extent the current market sharing.

In current market situation, the company has two options: one is to introduce a brand new machine with more new features; the other is to introduce a refined product with limited additional features. Both options have different advantages and risks. And the company does not know what other companies are going to do with those options. In order to pursue the maximal profit and keep in the situation with no failure, the company chooses Non-cooperative Game Theory as the decision-making tool to decide the development strategies for the new product.

In the analysis by using Non-cooperative Game Theory, the company knows that they occupies about 30% of local market sharing, a major competitor occupies about 25% of local market sharing. From historical records, the company knows that it has 60% success rate for introducing a brand new product, and the competitor has 50% success rate. The company also needs to know what kind of features probably customers need or want. From the survey done by marketing department, the technical department transfers the voice of customers to the technical features and evaluates the manufacturing feasibility for each feature. In the meantime, the accounting department calculates the approximate cost for developing and manufacturing those features. After gathering above information, marketing department performs another customer survey to investigate the customers' reaction for those new features at unspecified price. Therefore, the company knows what kind of situation they will be in by selecting different options, and also for the competitor. The final integrated information generates the following game box (Table 4.3) and the game relationship tree (Figure 4.8) to present the payoff by different situations.

**Table 4.3 Payoff Matrix**

| Competitor<br>Company | | More Features | | Few Features |
|---|---|---|---|---|
| | | Success | Failure | |
| More Features | Success | 30, 25 | 40, 10 | 35, 20 |
| | Failure | 20, 35 | 20, 20 | 20, 25 |
| Few Features | | 25, 35 | 30, 20 | 25, 20 |

From the payoff matrix and the game relationship tree result, the company has a clear picture about where they should go. Since to introduce more features has higher payoff (29) than to add few features (26.25), it means that the company should introduce a brand new product with more new features no matter what the competitor is going to do.

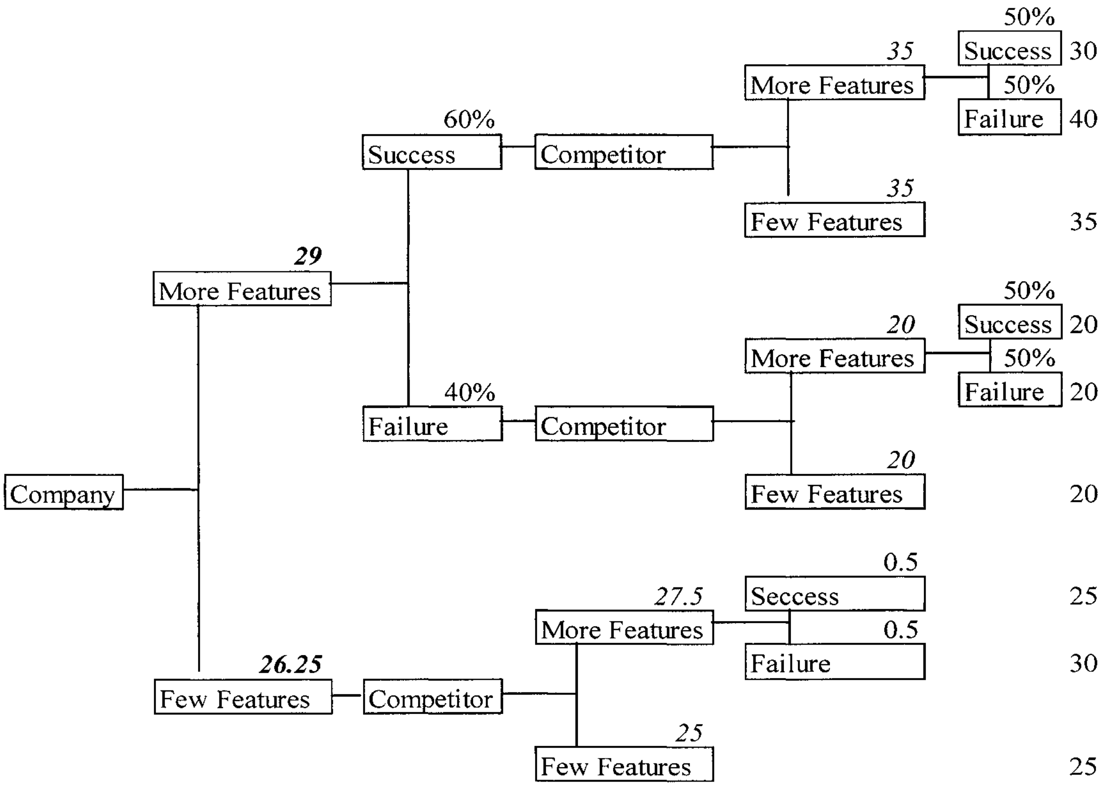


**Figure 4.8 Game Relationship Tree**

The Non-cooperative Game Theory gives the company the opportunity to look over entire different situations at enterprise level to decide the further development strategies based on no failure situation. But because of the lack of cooperation with the competitors, company can not reach the win-win situation in the market to lead customers rather than leaded by customers.

### f. Energy-Smart Vehicles Design

Vehicle emissions are a major source of global air pollution today. Recent advances in fuels and vehicle designs are making it easier for consumers to buy energy-smart cars.

Because energy-smart cars are quiet new products in the vehicle market and it has too many directed and indirected relationships with other fields. The design stage is the most important step in its development process. In this situation, using ECN methodology to organize the design process is the best solution.

A multi-disciplines cross-functions team will be formed at the beginning. The team should include the experts or engineers who may come from different companies, different countries, or even speak different language from different technical area, such as mechanical, electrical, material, chemical, environmental, marketing, customer service, safety, supplying, accounting, etc.

The design objects may have the following constrains from social, technology, and economic:

**Social Aspects – Human**

- Safety concerned
    - Driving safety
    - Power resource safety
- Comfortableness
- Appearance

**Social Aspects – Environment**

- New pollution
- Environmental protection laws

**Technology Aspects**

- Speed
- Accelerate capability
- Continue driving distance
- Load capability

**Economic Aspects**

- Affordable price
- Energy resource
- Energy supplying system

The design team may face the following problems during the design process:

1) How much will cost for the new car?
2) How much will cost for the new fuel per unit or per 100 kilometers?
3) Is that widely supplied for the new fuel around the country or certain area?
4) What will be the average driving distance for the full energy car?
5) How easy to get the new fuel from nature or through producing?
6) Does the emission obey the environmental standard and without generate new pollution?
7) What is the average speed of the car using new fuel? Slower or faster?
8) Does the car look strange because the equipment for the new fuel on the car?
9) Is the car comfortable like the general car?
10) Is the new fuel safe? (exploration, radiation, etc)
11) Are the physical, chemical characters stable with the weather change?

As we can see, the ECN methodology in this design process gives the chance to aggregate all the necessary information at early design stage. The design team can have the optimal solution for each sub-object and support the core object to get the optimal solution. The ECN methodology takes care of a lot of human factors, environmental factors, marketing factors in the design to make sure that the design will meet what customers really want and need. The ECN methodology deals with problems from customer's point of view, which will guarantee the new product which will be accepted by customers after it is introduced.

ECN methodology requires all participants in the team no matter where they come from, buyer side or seller side or even from competitor, they should only have one common goal. They will share the information among them and also share the profit in the future. And there are no boundaries between any two disciplines or fields, the interaction and communication should have at any time when it is necessary. All of those makes ECN methodology can handle those really complex multi-discipline design tasks in this tightly competitive global market.

## 4.4 Theory of Constraints (TOC)

### 4.4.1 What is Theory of Constraints?

The Theory of Constraints is an overall philosophy developed by Dr. Eliyahu M. Goldratt [Goldratt's Marketing Ltd., 2004], usually applied to running and improving an organization. TOC consists of Problem Solving and Management/Decision-Making Tools called the Thinking Processes (TP). Dr. Goldratt said: Powerful solutions start with the right questions. TOC is applied to logically and systematically answer these three questions essential to any process of ongoing improvement:

- What to change? Identify the core conflict or problem (the constraint) i.e. Consensus and Focus.
- To what to change? Construct a complete solution.
- How to cause a change? Devise plans for implementing the solution and achieving buy-in where necessary i.e. Communication and Collaboration.

The Thinking Processes can be used to significantly enhance vital management skills, such as:

- Win-win conflict resolution,
- Effective communication,
- Team building skills,
- Delegation,
- Empowerment.

### 4.4.2 The Five Focusing Steps

There are five focusing steps in TOC. The steps are as follows:

Step 1 Identify the System's constraints (Find the problem).

Here a process is analyzed so that a task or activity that limits the productivity of an entire system can be identified. A system constraint may be identified by a long queue of work or long processing times.

Step 2 Decide how to exploit the systems constraints (Define the causes and cures).

In this step, decisions must be made on how to modify or redesign the task or activity so that work can be performed more effectively and efficiently.

Step 3 Subordinate everything else to the above decision. (Involve/train others)

Now, management directs all its efforts to improving the performance of the constraining task or activity and any other task or activity and any other task or activity that directly affects the constraining task or activity.

Step 4 Elevate the system's constraint (Document improvement).

In this step, additional capacity is obtained that will increase (elevate) the overall output of the constraining task or activity. This differs from step 2 in that the added output comes from additional purchased capacity, such as buying a second machine tool or implementing a new information technology.

Step 5 If, in the previous step, a constraint has been broken, go back to step 1 but do not allow inertia to cause a new constraint (Celebrate success).

This sets up a process of ongoing improvement. As a result of the focusing process, the improvement of the original constraining task or activity may cause a different task to become a constraining task or activity. Inertia could blind management from taking steps to improve the system's output now limited by a new constraint.

During the process, do not say:

A) It is not our fault.

B) Our problems are different.

C) Do not have time.

D) Policy will not let us.

E) Management will not support us.

### 4.4.3 Theory of Constraints Examples

#### 4.4.3.1 Example 1

Here is an example that shows how to implement the five steps to eliminate a Non-Value Added Process [Theory of Constraint, 2004]:

**Identify** - Moving parts to a final inspection area after the last operation was found to be a waste of space and motion. Final inspection time was stealing from in-process.

**Exploit** - Parts moved to final inspection would be improved if already bought off, and then moved to shipping (save time involved). The vibratory generated parts were too fast to keep up with final inspection. The carousel seemed like a hard place to conduct final inspections.

**Subordinate** - Inspectors were trained to final inspect at the last operation, material handlers to move parts to a shipping staging area? Vibratory operators were trained to conduct their own final inspection. The carousel turned out to be a non-issue.

**Elevate** - During September 75% of the final inspections were done at the last operation, saving space and motion.

**Inertia** - Keep working through constraint to accomplish 100% compliance, with no extra conveyance or space.

### 4.4.3.2 Example 2

In order to show how TOC can lead to decisions that improve industry profitability, the following example[2] gives the numerical comparison before and after applying TOC in a small business.

Daufel Enterprises is a small business that produces hand-tied fishing flies. Quality and speed are two issues that conflict in this business. The faster a tier can construct a fly, the more profitable. However, if speed is the only focus, quality will suffer. And

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[2] This example is taken from Bushong, J. G. et al [1999].

the other thing is that Daufel brothers must personally tie the flies or quality will suffer. In their business, therefore, the brothers' time is the constraint factor.

The Table 4.4 illustrates the throughput per hour for the five most popular flies constructed by the Daufel brothers.

**Table 4.4 Determination of Throughput per Hour [Bushong, J. G. et al, 1999]**

| | Hare's Ear | Pheasant Tail | Compara Dun | Thorax Dun | Woolly Bugger |
|---|---|---|---|---|---|
| Sales price per dozen | 12 | 12 | 12 | 12 | 12 |
| Hook | 1.59 | 1.59 | 1.07 | 1.07 | 1.19 |
| Thread | 0.06 | 0.04 | 0.10 | 0.06 | 0.09 |
| Tail | 0.21 | 0.38 | 0.25 | 0.25 | 0.50 |
| Other | 0.37 | 0.17 | 0.40 | 1.59 | 0.93 |
| Total direct materials | 2.23 | 2.18 | 1.82 | 2.97 | 2.71 |
| Shipping | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 |
| Total variable cost per dozen | 2.35 | 2.30 | 1.94 | 3.09 | 2.83 |
| Contribution margin(throughput) per dozen | **9.65** | **9.70** | **10.06** | **8.91** | **9.17** |
| Contribution margin percent | 80.4% | 81% | 84% | 74% | 76% |
| Production hours per dozen | 0.4 | 0.33 | 0.5 | 0.6 | 0.33 |
| Throughput per labor hour | **24.13** | **29.39** | **20.12** | **14.85** | **27.79** |

The Table 4.5 compares the apparent profitability of the various flies based on traditional contribution margin analysis with the profitability of the various flies based on constraint analysis. They were surprised that the Compara Dun, which has the highest contribution margin, ranked next to last based on throughput per labor hour because it required the second highest amount of the brothers' time. The Woolly Bugger, which had the next to lowest contribution margin, had the second highest throughput per hour.

**Table 4.5 Profitability Rank [Bushong, J. G. et al, 1999]**

| | Throughput per dozen | Contribution margin per dozen |
|---|---|---|
| Pheasant Tail | 1 | 2 |
| Woolly Bugger | 2 | 4 |
| Hare's Ear | 3 | 3 |
| Compara Dun | 4 | 1 |
| Thorax Dun | 5 | 5 |

The brothers desired to continue producing all of the current models, while increasing their profitability. With this objective in mind, it was suggested that the brothers explore the possibility of increasing the price of the less profitable flies. It suggests that the Daufel brothers should consider raising the price of the Thorax Dun, Compara Dun, and Hare's Ear to $14.00 per dozen and the price of the Woolly Bugger to $12.50 per dozen. Table 4.6 shows the throughput per dozen based on the new sales prices. According to this table, simply switching 500 productive hours per year from the Compara Dun to the Pheasant Tail would result in increased profitability of over $4,600 per year.

From this example, we can see that a simple constraint analysis will help company to quantify its institutive feel and make precise adjustments. TOC is a big field which cannot be explained in detail through a section, but my purpose is to show that TOC is one of good ways to make decisions. Also there are commercial companies which offer constraint analysis to improve companies' profitability, such as CPA, CIRAS.

**Table 4.6 Revised Throughput per Hour [Bushong, J. G. et al, 1999]**

| | Hare's Ear | Pheasant Tail | Compara Dun | Thorax Dun | Woolly Bugger |
|---|---|---|---|---|---|
| Sales price per dozen | 14 | 12 | 14 | 14 | 12.50 |
| Hook | 1.59 | 1.59 | 1.07 | 1.07 | 1.19 |
| Thread | 0.06 | 0.04 | 0.10 | 0.06 | 0.09 |
| Tail | 0.21 | 0.38 | 0.25 | 0.25 | 0.50 |
| Other | 0.37 | 0.17 | 0.40 | 1.59 | 0.93 |
| Total direct materials | 2.23 | 2.18 | 1.82 | 2.97 | 2.71 |
| Shipping | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 |
| Total variable cost per dozen | 2.35 | 2.30 | 1.94 | 3.09 | 2.83 |
| Contribution margin(throughput) per dozen | **11.65** | **9.70** | **12.06** | **10.91** | **9.67** |
| Contribution margin percent | 83.2% | 81% | 86% | 78% | 77% |
| Production hours per dozen | 0.4 | 0.33 | 0.5 | 0.6 | 0.33 |
| Throughput per labor hour | **29.13** | **29.39** | **24.12** | **18.18** | **29.30** |

In essence, if you want more of your goal, you must identify your constraint, focus on it, and follow through. That is the essence of TOC!

## 4.5 Analytical Hierarchy Process (AHP)

There is a popular tool for decision-making process, Analytical Hierarchy Process (AHP). In the following sections, what is AHP, its benefit, procedures and software will be introduced.

### 4.5.1 What is Analytical Hierarchy Process?

AHP is a powerful and flexible decision making process that was developed by Saaty [1980]. AHP provides a proven, effective means to deal with complex decision making which involves multiple criteria. AHP can assist with identifying and weighting selection criteria, analyzing the data collected for the criteria and expediting the decision-making process. AHP can be used to obtain group judgments through consensus.

### 4.5.2 Benefits of Analytical Hierarchy Process

Decision-makers always bases on their knowledge and experience when they make judgments, then makes decisions accordingly. The AHP approach agrees well with the behavior of decision-makers. The strength of this approach is that it organizes tangible and intangible factors in a systematic way, and provides a structured yet relatively simple solution to the decision-making problems. In addition, by breaking a problem down in a logical fashion from the large, descending in gradual steps, to the smaller and smaller, one is able to connect, through simple paired comparison judgments, the small to the large. AHP helps capture both subjective and objective evaluation measures, providing a useful mechanism for checking the consistency of the evaluation measures and alternatives suggested by the team thus reducing bias in decision making. Combined with meeting automation, organizations can minimize common pitfalls of team decision making process, such as lack of focus, planning, participation or ownership, which ultimately are costly distractions that can prevent teams from making the right choice.

### 4.5.3 Steps for Applying Analytical Hierarchy Process

Saaty [1980] developed the following steps for applying the AHP:

1) Define the problem and determine its goal.
2) The next step is for the team to decompose the goal into its constituent parts, progressing from the general to the specific. In its simplest form, this structure comprises a goal, criteria and alternative levels. Each set of alternatives would then be further divided into an appropriate level of detail, recognizing that the more criteria included, the less important each individual criterion may become. In the other words, structure the hierarchy from the top (the objectives from a decision-maker's viewpoint) through the intermediate levels (criteria on which subsequent levels depend) to the lowest level which usually contains the list of alternatives.
3) Then assign a relative weight to each one. Each criterion has a local (immediate) and global priority. The sum of all the criteria beneath a given parent criterion in each tier of the model must equal one. Its global priority shows its relative importance within the overall model. Construct a set of pair-wise comparison matrices (size n * n) for each of the lower levels with one matrix for each element in the level immediately above by using the

relative scale measurement shown in Table 4.7. The pair-wise comparisons are done in terms of which element dominates the other.

4) In doing pair-wise comparison to relate n activities, n (n - 1) judgments are required to develop the set of matrices in step 3. The main diagonal of a matrix must consist of 1. Insert the appropriate reciprocals for the reverse comparison in each pair-wise comparison.
5) Hierarchical synthesis is now used to weight the eigenvectors by the weights of the criteria and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy.

**Table 4.7 Pair-wise Comparison Scale for AHP Preferences [Saaty, 1980]**

| Numerical rating | Verbal judgments of preferences |
|---|---|
| 9 | Extremely preferred |
| 8 | Very strongly to extremely |
| 7 | Very strongly preferred |
| 6 | Strongly to very strongly |
| 5 | Strongly preferred |
| 4 | Moderately to strongly |
| 3 | Moderately preferred |
| 2 | Equally to moderately |
| 1 | Equally preferred |

6) Since AHP conducts a pair-wise comparison, only two factors are considered at the same time, it is very easy to build an inconsistent matrix. For example, first give A = 3 B, A = 6 C, then should be B = 2 C. but if only B and C are considered, B = 3 C could be given. In this case, the matrix will not be

consistent. This happens frequently and the consistency can be calculated using an inconsistency ration CR. Satty [1980] stated that "It turns out that the consistency of a positive reciprocal matrix is equivalent to the requirement that its maximum eigenvalue $\lambda_{\max}$ should be equal to n. It is also possible to estimate the departure from consistency by the difference $\lambda_{\max}$ - n divided by n – 1." Consistency index, CI is shown as follows(4.1):

$$CI = (\lambda_{\max} - n)/(n-1) \tag{4.1}$$

Where n is the matrix size

Judgment consistency can be checked by taking the CR of CI with the random consistency RI in Table 4.8.

$$CR = CI/RI \tag{4.2}$$

**Table 4.8 Average Random Index [Saaty, 1980]**

| **Size of matrix** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Random Index** | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1 |

The CR is acceptable, if it does not exceed 0.10. If it is more, the judgment matrix is inconsistent. To obtain a consistent matrix, judgments should be reviewed and improved. A detail calculation steps for CR is demonstrated in case study 1 (Chapter 5).

7) Steps 3-6 are performed for all levels in the hierarchy.

### 4.5.4 Analytical Hierarchy Process Software

The AHP allows group decision making, where group members can use their experience, values and knowledge to break down a problem into a hierarchy and solve it by the AHP steps. Brainstorming and sharing ideas and insights (inherent in the use of Expert Choice in a group setting) often leads to a more complete representation and understanding of the issues. Fortunately, there is no need to implement the steps manually. Professional commercial software, Expert Choice [Expert Choice, 2004], developed by Expert Choice, Inc., is available on the market which simplifies the implementation of the AHP's steps and automates many of its computations. The following suggestions and recommendations are suggested in the Expert Choice software manual.

a. Group decisions involving participants with common interests are typical of many organizational decisions. Even if we assume a group with common interests, individual group members will each have their own motivations and, hence, will be in conflict on certain issues. Nevertheless, since the group members are supposed to be striving for the same goal and have more in common than in conflict, it is usually best to work as a group and attempt to achieve consensus. This mode maximizes communication as well as each group member's stake in the decision.

b. An interesting aspect of using Expert Choice is that it minimizes the difficult problem of group-think or dominance by a strong member of the group. This occurs because attention is focused on a specific aspect of the problem as judgments are being made, eliminating drift from topic to topic as so often happens in group discussions. As a result, a person who may be shy and hesitant to speak up when a group's discussion drifts from topic to topic will feel more comfortable in speaking up when the discussion is organized and attention turns to his/her area of expertise.

c. When Expert Choice is used in a group session, the group can be shown a hierarchy that has been prepared in advance. They can modify it to suit their understanding of the problem. The group defines the issues to be examined and alters the prepared hierarchy or constructs a new hierarchy to cover all the important issues. A group with widely varying perspectives can feel comfortable with a complex issue, when the issue is broken down into different levels. Each member can present his/her own concerns and definitions. Then, the group can cooperate in identifying the overall structure of the issue. In this way, agreement can be reached on the higher-order and lower-order objectives of the problem by including all the concerns that members have expressed. The group would then provide the judgments. If the group has achieved consensus on some judgment, input only that judgment. If during the process it is impossible to arrive at a consensus on a judgment, the group may use some voting technique, or may choose to take the average of the judgments. The group may decide to give all group members equal weight, or the group members could give them different weights that reflect their position in the project. All calculations are done automatically on the computer screen.

d. The Group Meeting: While Expert Choice is an ideal tool for generating group decisions through a cohesive, rigorous process; the software does not replace the components necessary for good group facilitation. There are a number of different approaches to group decision-making, some better than others. Above all, it is important to have a meeting in which everyone is engaged, and there is buy-in and consensus with the result.

## 4.6 Summary

In chapter 4, we looked at the different engineering decision styles and the roadmap of engineering decision paradigms created by Lu [2003]. And examples were given for each cell of the roadmap.

TOC as a thinking process is briefly reviewed. It guides participants to think "correctly". TOC is applied to logically and systematically answer these three questions essential to any process of ongoing improvement: What to change? To what to change? How to cause a change? Two examples show that how TOC can help industries and companies get improvements.

AHP as a group decision making tool provides a proven, effective means to deal with complex decision making which involves multiple criteria. Professional commercial software, Expert Choice, developed by Expert Choice, Inc. simplifies the implementation of the AHP's steps and automates many of its computations. It will be used to make decision for the case study 1 in the next chapter.

# CHAPTER 5

# INTEGRATION OF DECISION-MAKING IN COMPLEX COLLABORATIVE DESIGN

## 5.1 Introduction

So far we got a good view of complexity, collaboration, negotiation and decision-making respectively. It is not the main purpose of this research. As described in Chapter 1, this research aims at integrating collaboration, negotiation and decision-making tools and methodologies to deal with complex engineering design problems.

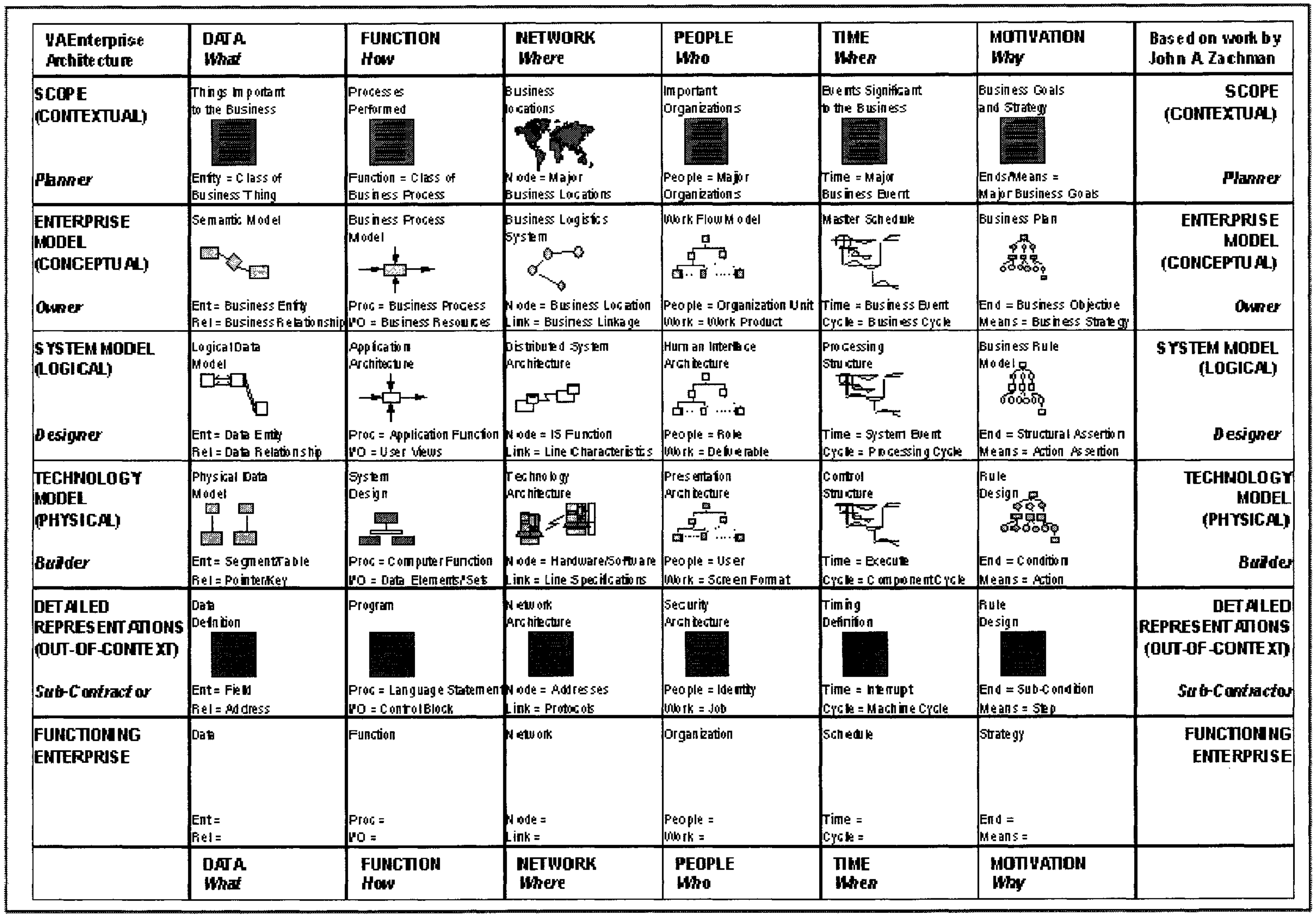
## 5.2 Zachman Framework

For integration purpose, a framework is a good way/tool to organize any form of meta-data for the enterprise. It can provide a basic structure which supports the organization, access, integration, interpretation, development, management, and changing of a set of architectural representations of the organizations information systems. Such objects or descriptions of architectural representations are usually referred to as artifacts. The framework, then, can contain global plans as well as technical details, lists and charts as well as natural language statements. Any appropriate approach, standard, role, method, technique, or tool may be placed in it. The classic example is Zachman framework for information systems architecture - first proposed in 1987 and later extended in 1992. It is an approach used for developing and/or documenting enterprise-wide information systems architecture (Table 5.1).

But, the Zachman Framework is not just a 6 x 6 matrix, it can be seen as a structured, multidimensional management framework that helps organizations plan, design and implement complex. Zachman framework is a popular way to organize the whole project or process. It gives the big picture of whole. But the problem is that it is not quiet clear about the sequence, in the other words, it does not guide stakeholders well. In the next section, a new approach is given.

## 5.3 A New Approach to Integrate Complexity, Collaboration, Negotiation and Decision-making Process

In order to express clearly the approach, the first work is to construct a simple flowchart for collaborative decision-making process as Figure 5.1. The process starts from receiving the objective of a problem, then tell if the problem is complex according to complexity detector which is constructed in chapter 2. After that, if the problem is complex, build team(s). During collaborative activities, conduct negotiation when conflict appears. Finally get the outcome.



| **VAEnterprise Architecture** | **DATA** *What* | **FUNCTION** *How* | **NETWORK** *Where* | **PEOPLE** *Who* | **TIME** *When* | **MOTIVATION** *Why* | **Based on work by John A Zachman** |
|---|---|---|---|---|---|---|---|
| **SCOPE (CONTEXTUAL)**<br>***Planner*** | Things Important to the Business<br>Entity = Class of Business Thing | Processes Performed<br>Function = Class of Business Process | Business locations<br>Node = Major Business Locations | Important Organizations<br>People = Major Organizations | Events Significant to the Business<br>Time = Major Business Event | Business Goals and Strategy<br>Ends/Means = Major Business Goals | **SCOPE (CONTEXTUAL)**<br>***Planner*** |
| **ENTERPRISE MODEL (CONCEPTUAL)**<br>***Owner*** | Semantic Model<br>Ent = Business Entity<br>Rel = Business Relationship | Business Process Model<br>Proc = Business Process<br>I/O = Business Resources | Business Logistics System<br>Node = Business Location<br>Link = Business Linkage | Work Flow Model<br>People = Organization Unit<br>Work = Work Product | Master Schedule<br>Time = Business Event<br>Cycle = Business Cycle | Business Plan<br>End = Business Objective<br>Means = Business Strategy | **ENTERPRISE MODEL (CONCEPTUAL)**<br>***Owner*** |
| **SYSTEM MODEL (LOGICAL)**<br>***Designer*** | Logical Data Model<br>Ent = Data Entity<br>Rel = Data Relationship | Application Architecture<br>Proc = Application Function<br>I/O = User Views | Distributed System Architecture<br>Node = IS Function<br>Link = Line Characteristics | Human Interface Architecture<br>People = Role<br>Work = Deliverable | Processing Structure<br>Time = System Event<br>Cycle = Processing Cycle | Business Rule Model<br>End = Structural Assertion<br>Means = Action Assertion | **SYSTEM MODEL (LOGICAL)**<br>***Designer*** |
| **TECHNOLOGY MODEL (PHYSICAL)**<br>***Builder*** | Physical Data Model<br>Ent = Segment/Table<br>Rel = Pointer/Key | System Design<br>Proc = Computer Function<br>I/O = Data Elements/Sets | Technology Architecture<br>Node = Hardware/Software<br>Link = Line Specifications | Presentation Architecture<br>People = User<br>Work = Screen Format | Control Structure<br>Time = Execute<br>Cycle = Component Cycle | Rule Design<br>End = Condition<br>Means = Action | **TECHNOLOGY MODEL (PHYSICAL)**<br>***Builder*** |
| **DETAILED REPRESENTATIONS (OUT-OF-CONTEXT)**<br>***Sub-Contractor*** | Data Definition<br>Ent = Field<br>Rel = Address | Program<br>Proc = Language Statement<br>I/O = Control Block | Network Architecture<br>Node = Addresses<br>Link = Protocols | Security Architecture<br>People = Identity<br>Work = Job | Timing Definition<br>Time = Interrupt<br>Cycle = Machine Cycle | Rule Design<br>End = Sub-Condition<br>Means = Step | **DETAILED REPRESENTATIONS (OUT-OF-CONTEXT)**<br>***Sub-Contractor*** |
| **FUNCTIONING ENTERPRISE** | Data<br>Ent =<br>Rel = | Function<br>Proc =<br>I/O = | Network<br>Node =<br>Link = | Organization<br>People =<br>Work = | Schedule<br>Time =<br>Cycle = | Strategy<br>End =<br>Means = | **FUNCTIONING ENTERPRISE** |
|  | **DATA** *What* | **FUNCTION** *How* | **NETWORK** *Where* | **PEOPLE** *Who* | **TIME** *When* | **MOTIVATION** *Why* |  |

Table 5.1 The Zachman Framework [Zachman, 2004]

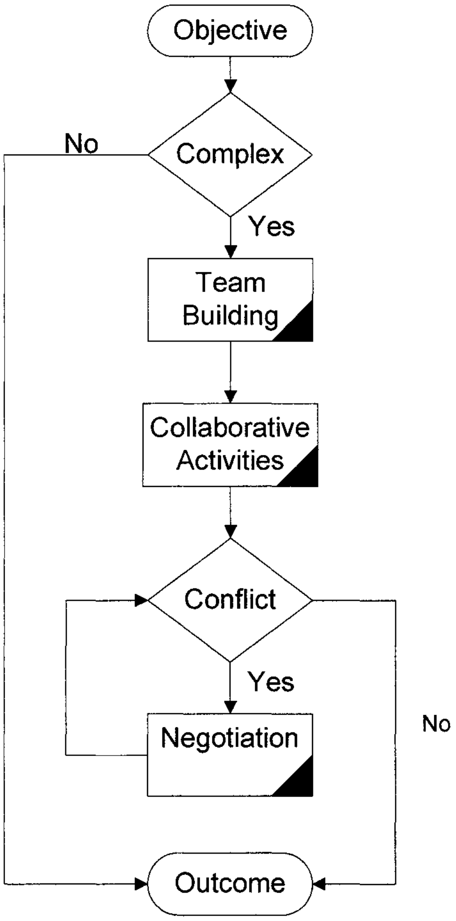


**Figure 5.1 Collaborative Decision-Making Flowchart**

In order to give a clear view about the collaborative decision-making process, a detailed flowchart with the possible methodologies and tools is constructed in Figure 5.2.

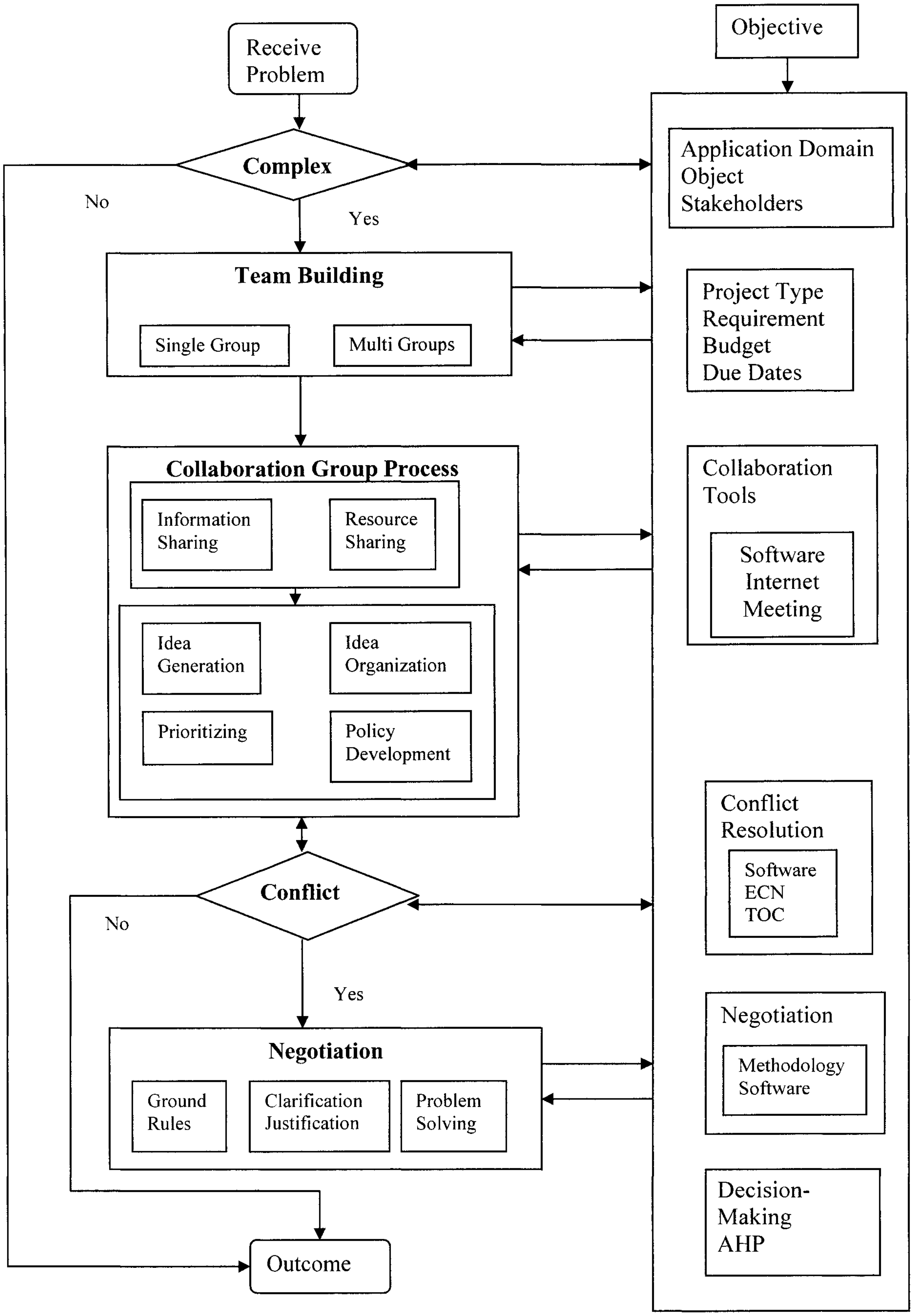


Figure 5.2 Detailed Flowchart of Collaborative Decision-making

## 5.4 Case Study 1

In this section, a case study of material selection for tandem mill work roll in a project will be discussed. It bases on a real-world project, Continuous Pickling Line and Tandem Mill, which is a cooperative project between a Chinese steel company and Germany company.

### 5.4.1 Introduction of Continuous Pickling Line and Tandem Mill Project

The purpose of Continuous Pickling Line and Tandem Mill Project is to reduce the cycle time and increase the quality. Figure 5.3 describes the old process for rolling steel in a Chinese steel company. The process need two separated mills and it takes twice reel off and reel on. It not only wastes the time but also increases the damage rate during moving between two mills. The goal is to deduct the processes in the rectangle in Figure 5.3. After modification, the new system is shown in Figure 5.4.

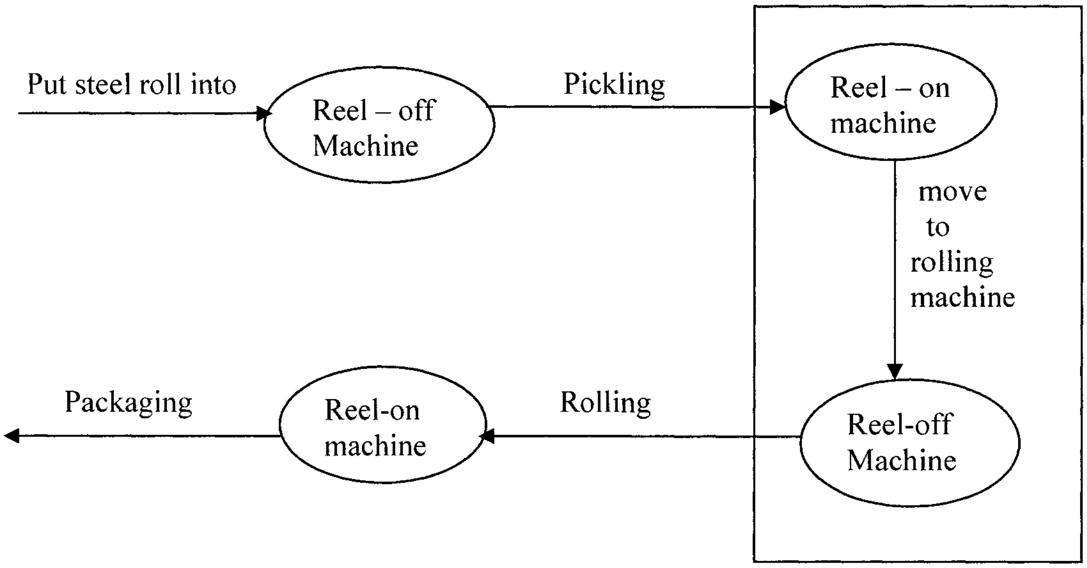


Figure 5.3 Old Systems

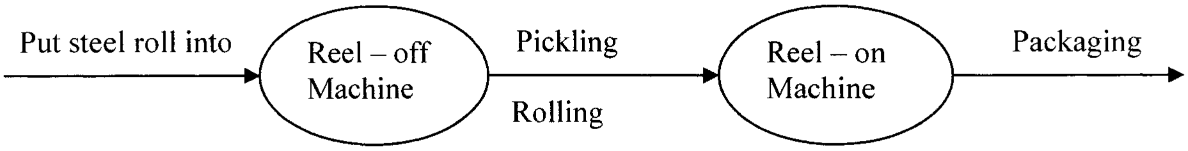


Figure 5.4 New Systems

### 5.4.2 Decision-making for Material Selection of Work Roll in Cold Rolling Tandem Mill

Schematic of Coupled Continuous Pickling Line and Tandem Mill after modification is shown in Figure 5.5. From this figure we can see that there are ten work rolls in Mill Line. So work rolls are very important consuming part in cold-rolling operations. The quality and working life of work rolls will significantly affect the quality of finial product and entire system product efficiency. Commonly used materials for work rolls of Tandem Mill in cold rolling are:

- Indefinite chill (grain iron)
- High-chrome iron
- Forged steel

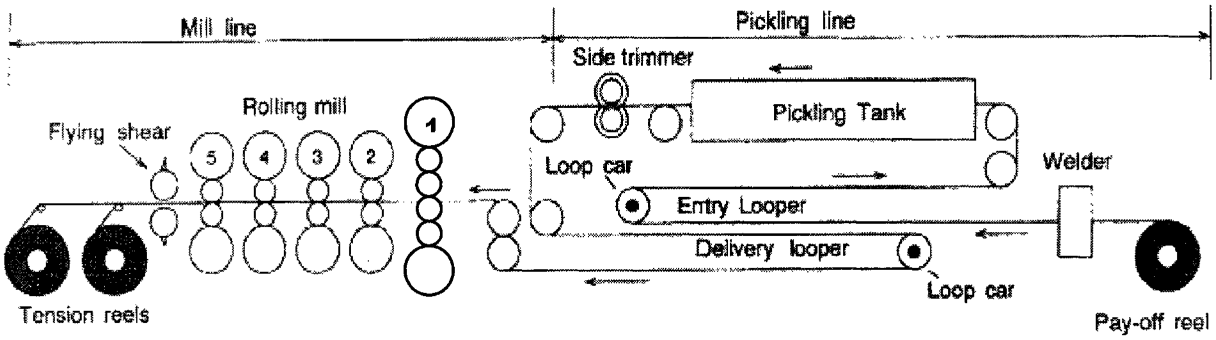


Figure 5.5 Schematic of Continuous Pickling Line and Tandem Mill

#### 5.4.2.1 Problem Statement

In a regular meeting during the design process, a material engineer from buyer[3] side suggested the material of the work roll should be chosen according to the current buyer's capability and material market situation. That means buyer wants to manufacture the work roll by the local manufactures in the future and use the material which can be bought from local steel market rather than continually purchase the consumed work rolls from the supplier which is indicated by the seller[4]. But the design engineer from seller side insisted in to use the work roll, which need to be imported from other country, for the reason of the capacity of entire system must be balanced and the durable quality of that work rolls.

The material engineer from buyer side was prefer to use forged steel to make the work rolls since they had used this kind of material for work rolls making for a while with mature experiences and technology. The material could be bought from internal enterprise and the manufacturer also belonged to the same enterprise so that they did not need to worry about the supplying problem and technical support. Even though the lifetime of the work rolls may reduce a little bit but if compare with the other factors, the decision should be made on this material.

The design engineer from seller side used some data to explain why he preferred to choose high-chrome iron as the material of work rolls as follows (Table 5.2 and Table 5.3):

---

[3] Buyer represents a Chinese Steel Company.
[4] Seller represents a Germany Company.

**Table 5.2 The Average Data Using Forged Steel Rolls [Robert, 1988]**

| Present work rolls | **Forged steel rolls** |
|---|---|
| Mill production | 500,000 ton/year = 100 ton/hr |
| Number of stands | 6 |
| Total working time | 7000hr/year |
| Present roll life | 80,000 ton/roll (50,000 ton/roll + 30,000 ton/roll after rehardening) |
| Present mill down time for roll changes | 10% of total work hr = 700 hr/year |
| Present total mill down time | 30% of total work hr = 2100 hr/year |
| Present roll changes | Rolls are changed in one stand at a time |
| Present roll consumption | 48 roll/year |
| Allowance to cover fixed costs | $50 /ton |
| Present roll purchase costs | $10,000/roll + $2500/roll for the rehardening |

**Table 5.3 The Average Compression Data Using High-chrome Iron Rolls [Robert, 1988]**

| Present work rolls | **High-chrome iron rolls** |
|---|---|
| Roll purchase costs | $13,500/roll<br>35% increasing per roll, no rehardening costs |
| Roll life | 160,000 ton/roll<br>100% increasing |
| Roll consumption | 50% decreasing |
| Roll changes | 50% decreasing |
| Mill down time due to roll changes | 10% Vs. 5% of total work hr |
| Decrease in direct roll costs | $0.7/ton (= $300,000/year) |
| Decrease in total roll costs | **$4.30/ton (=$2.4 million/year)** |

In the case of the disagreement in the meeting, the host of the meeting wrote an integrated report according to the information from both sides and submitted it to the upper level manager. From the integration factors in the Table 5.2 and Table 5.3, the high-chrome iron roll had the low cost. But from single factor of roll purchase cost, the forged steel roll is much cheaper. So the final decision was made as using high-chrome iron rolls for regular production and using forged steel rolls for spare parts.

#### 5.4.2.2 Process Analysis

From collaboration and negotiation points of view to look at this material selection process, we can say that collaboration and negotiation in this decision making process did not work very well.

First of all, from the material engineer of buyer side, he did not have enough evidences to proof the benefits of using forged steel rolls and use related technical data to support his solution. But from the seller side, they only focused on obviously beneficial evidences which may lead to incorrect direction of the final decision, such as life time, change over time, purchase cost, etc. but other potential influential factors like quality, reliability, etc.

Secondly, the argument did not have a consistent goal but each side only tried to maximize their own benefit. The goal of the argument should be set as finding an optimal solution that can maximize the benefit (not just money, also including potential benefits) with the lowest investment (not just cost, also including potential related factor such as quality).

### 5.4.2.3 New Process Using Flowchart and Analytical Hierarchy Process Methodology

According to the flowchart (Figure 5.2), first, clarify the objective is to choose suitable material for work rolls of Tandem Mill in cold rolling. Based on the complexity detector developed in Chapter 2, this problem is complex because it has to involve more than one stakeholder. The next step is to build a team. A chief design engineer, a design engineer from seller side, and a project engineer, a mechanical engineer, a material engineer from buyer side, total five engineers are chosen to take part in this material selection decision-making process. They all have plenty of experiences and knowledge about the issue they will discuss. They also have enough knowledge and experiences about management methodologies and decision making tools. And they are willing to work together to find out the best solution. From the problem statement, there is a disagreement with the material and this conflict has to be solved by the team. Since this material selection involves multi criteria, the team agrees to use AHP to solve this problem.

The first meeting for this specific issue by using AHP methodology included the following contents:

- Making the agreement of using AHP methodology to solve this problem.
- Setting the consistent goal of the argument.
- Find out the significant factors which will influence the consistent goal.
- Assign the task to participants to identify the importance among factors and the preference of each factor to the alternatives.

The results of meeting were as follows:

- Got the consistent goal is to select the best suitable material with the lowest direct and indirect cost for the work rolls of 4 ~ 6 High, 5 Stands Cold Rolling Tandem Mill according to the machine specification and the implementing situations.
- Selected the significant factors:

  Due to the reason that each participant may have different view of point for the significant factors which are going to have the influence to the consistent goal, the chair of the meeting decided to use a brainstorming methodology to select the factors and then weighted them after the factors were identified. Table 5.4 summarized the engineers' selections from their own opinions.

The significant factors are chosen if they have more than two votes by the engineers. The finial significant factors are:

1) Reliability
2) Quality
3) Life time
4) Purchasing cost
5) Shipping cost
6) Lead time
7) Technical advantage
8) Technical support
9) Change over cost

**Table 5.4 The Significant Factors Selection Chart**

| Engineers | Chief Design Engineer | Design Engineer | Project Engineer | Mechanical Engineer | Material Engineer |
|---|---|---|---|---|---|
| Chosen Factors | Reliability | Technical advantage | Quality | Quality | Life time |
| | Quality | Reliability | Life time | Change over cost | Quality |
| | Life time | Quality | Lead time | Life time | Reliability |
| | Technical advantage | Purchasing cost | Reliability | Lead time | Purchasing cost |
| | Purchasing cost | Life time | Change over cost | Technical support | Shipping cost |
| | Technical support | | Shipping cost | Manufacturing capability | Physical characters |
| | Lead time | | Technical support | | |

For the reason of simplification, all of participants agree to integrate factors to two categories; one is manufacturing consideration which including reliability, quality, life time, technical advantage, and technical support. The other one is marketing consideration which including purchasing cost, shipping cost, lead time, and change over cost. So, the hierarchy of the material selection can be constructed as Figure 5.6.

After first meeting for two or three days, participants came back to have the second meeting. They submitted the comparison results to the meeting chair after carefully analyzing the factors. The importance rating for manufacturing consideration part results are shown in Table 5.5 ~ Table 5.9. One thing should be mentioned here is about inconsistency ratio, the ratio should not excess 0.1. Otherwise, the result cannot be trusted. Inconsistency ratio can be calculated by the AHP software, Expert Choice, and I include them in the tables.

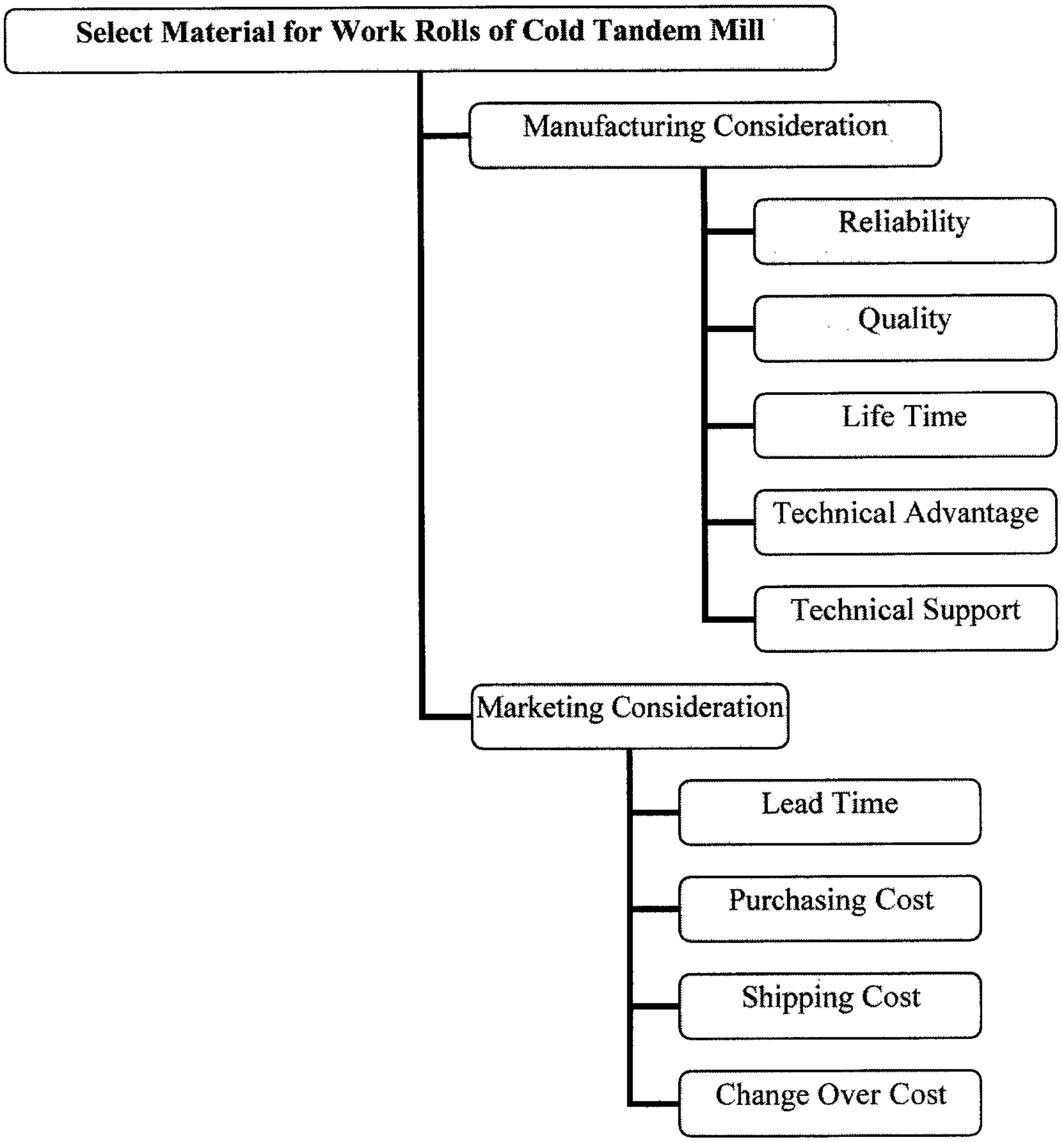


Figure 5.6 AHP Decision Hierarchy of Material Selection for Work Rolls

**Table 5.5 Chief Design Engineer Importance Rating for Manufacturing Consideration**

| **Chief Design Engineer** | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Reliability | 1 | 1.2 | 3 | 7 | 3 |
| 2. Quality |  | 1 | 3 | 5 | 2 |
| 3. Life time |  |  | 1 | 2 | 1 |
| 4. Technical advantage |  |  |  | 1 | 1/2 |
| 5. Technical support |  |  |  |  | 1 |
| Inconsistency Ratio | 0.00 |  |  |  |  |

**Table 5.6 Design Engineer Importance Rating for Manufacturing Consideration**

| **Design Engineer** | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Reliability | 1 | 1 | 2 | 3 | 1 |
| 2. Quality |  | 1 | 1 | 1.1 | 3 |
| 3. Life time |  |  | 1 | 2 | 2 |
| 4. Technical advantage |  |  |  | 1 | 3 |
| 5. Technical support |  |  |  |  | 1 |
| Inconsistency Ratio | 0.13 |  |  |  |  |

**Table 5.7 Project Engineer Importance Rating for Manufacturing Consideration**

| **Project Engineer** | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Reliability | 1 | 3 | 1 | 7 | 3 |
| 2. Quality |  | 1 | 3 | 5 | 2 |
| 3. Life time |  |  | 1 | 3 | 3 |
| 4. Technical advantage |  |  |  | 1 | 1/2 |
| 5. Technical support |  |  |  |  | 1 |
| Inconsistency Ratio | 0.10 |  |  |  |  |

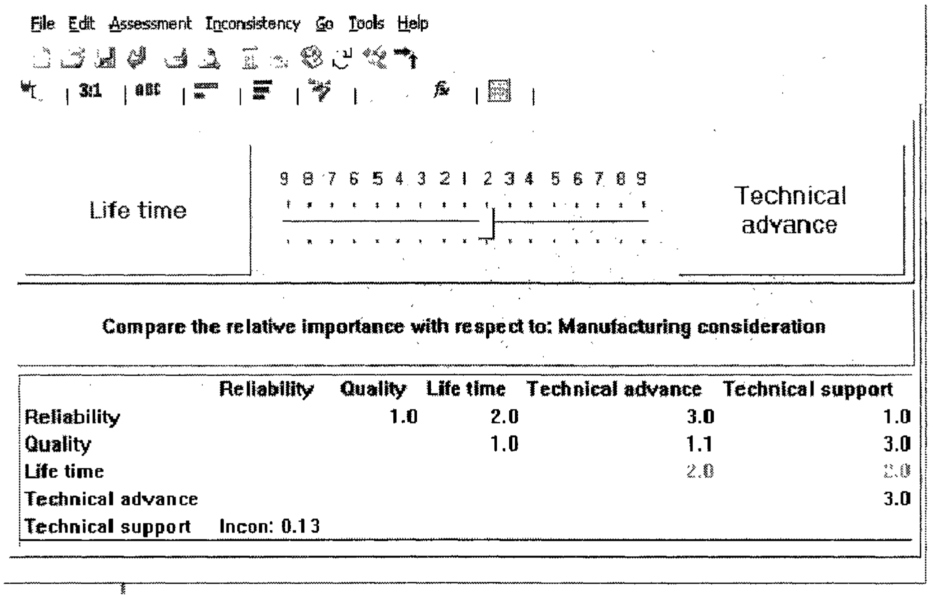
**Table 5.8 Mechanical Engineer Importance Rating for Manufacturing Consideration**

| **Mechanical Engineer** | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Reliability | 1 | 2 | 2 | 2 | 2 |
| 2. Quality |  | 1 | 3 | 1 | 1 |
| 3. Life time |  |  | 1 | 2 | 2 |
| 4. Technical advantage |  |  |  | 1 | 1 |
| 5. Technical support |  |  |  |  | 1 |
| Inconsistency Ratio | 0.08 |  |  |  |  |

**Table 5.9 Material Engineer Importance Rating for Manufacturing Consideration**

| Material Engineer | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Reliability | 1 | 1 | 1 | 1 | 5 |
| 2. Quality |  | 1 | 3 | 1.5 | 3 |
| 3. Life time |  |  | 1 | 2 | 3 |
| 4. Technical advantage |  |  |  | 1 | 1 |
| 5. Technical support |  |  |  |  | 1 |
| Inconsistency Ratio | 0.08 |  |  |  |  |

After reviewing all the ratios, there is one ratio which excesses 0.1 (Table 5.6). The snapshot of this matrix is shown in Figure 5.7. It means that the consistency of this matrix is not acceptable and needs to be modified.



Compare the relative importance with respect to: Manufacturing consideration

|  | Reliability | Quality | Life time | Technical advance | Technical support |
|---|---|---|---|---|---|
| Reliability |  | 1.0 | 2.0 | 3.0 | 1.0 |
| Quality |  |  | 1.0 | 1.1 | 3.0 |
| Life time |  |  |  | 2.0 | 2.0 |
| Technical advance |  |  |  |  | 3.0 |
| Technical support | Incon: 0.13 |  |  |  |  |

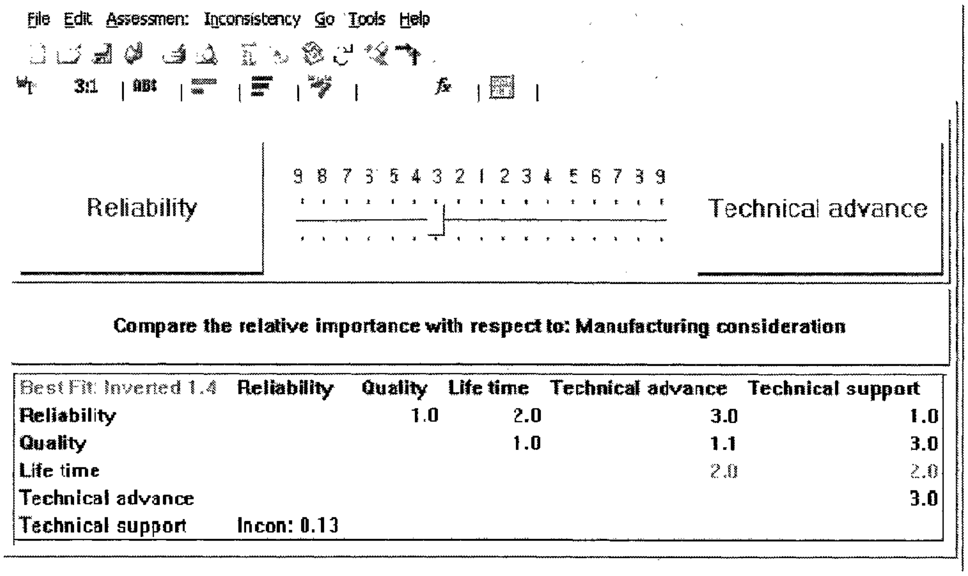
**Figure 5.7 Snapshot of Inconsistent Matrix in Expert Choice (Table 5.6)**

In the matrices, the given values are unavoidably influenced by personal preference and professional characteristics. In Table 5.6, it obviously shows that the design engineer is more preferred to the technical advance rather than life time. There is a confliction between technical advance and life time. If a product has a long life time, it probably will not keep its technical advance as lately developed similar products. As design engineers, the innovative career and the working environment in which they can easily receive new technologies and knowledge make them have this inconsistent result.

Since Table 5.6 is given by the design engineer in the group, this table is sent back to the design engineer to make the adjustment. The design engineer carefully analyzes the factors according to his knowledge and working experiences. The design engineer then used the AHP software, Expert Choice, to calculate the inconsistency ratio to improve the feasibility.

It should be mentioned here that the software, Expert Choice has a function called 'best fit' which can help decision makers decide the feasible value for a matrix. The design engineer first uses the software to help him making the adjustment. The software gives the first choice is to change the comparison value between reliability and technical advance from 3.0 to inverted 1.4 (Figure 5.8). Although the design engineer wants to assign a high importance to technical advance, the reliability still should be the first important factor to be concerned. Therefore, the first choice given by software is not acceptable.

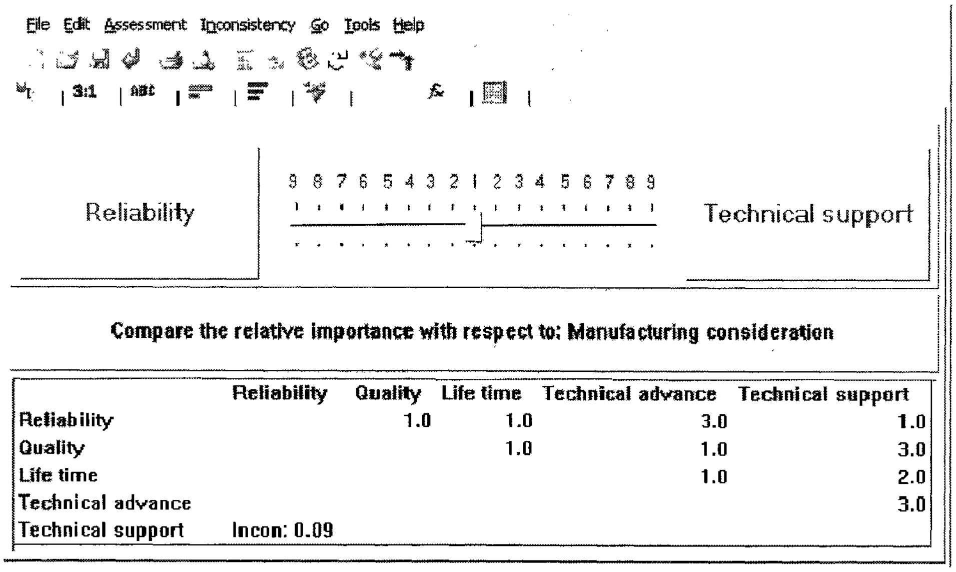
Since the suggestions come from software which only considers the mathematical consistency, it could not really help the design engineer to make a satisfied adjustment. It needs a self negotiation process for the design engineer. The design engineer once again puts entire factors on the table and makes the adjustment of the comparison value, reliability, life time and technical advantage. This inconsistency ratio is 0.09 which is acceptable as shown in Figure 5.9.



Compare the relative importance with respect to: Manufacturing consideration

| Best Fit: Inverted 1.4 | Reliability | Quality | Life time | Technical advance | Technical support |
|---|---|---|---|---|---|
| Reliability | | 1.0 | 2.0 | 3.0 | 1.0 |
| Quality | | | 1.0 | 1.1 | 3.0 |
| Life time | | | | 2.0 | 2.0 |
| Technical advance | | | | | 3.0 |
| Technical support | Incon: 0.13 | | | | |

Figure 5.8 Snapshot of Suggestion Matrix in Expert Choice



Compare the relative importance with respect to: Manufacturing consideration

| | Reliability | Quality | Life time | Technical advance | Technical support |
|---|---|---|---|---|---|
| Reliability | | 1.0 | 1.0 | 3.0 | 1.0 |
| Quality | | | 1.0 | 1.0 | 3.0 |
| Life time | | | | 1.0 | 2.0 |
| Technical advance | | | | | 3.0 |
| Technical support | Incon: 0.09 | | | | |

Figure 5.9 Snapshot of Modified Matrix in Expert Choice

Now all the inconsistency ratios are not greater than 0.1, then calculate the average importance ratings (Table 5.10).

**Table 5.10 Average Importance Rating for Manufacturing Consideration**

| **Average** | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Reliability | 1 | 1.6 | 1.6 | 4 | 2.8 |
| 2. Quality | | 1 | 2.6 | 2.7 | 2.2 |
| 3. Life time | | | 1 | 2 | 2.2 |
| 4. Technical advantage | | | | 1 | 1.2 |
| 5. Technical support | | | | | 1 |
| Inconsistency Ratio | 0.03 | | | | |

The importance of rating for marketing consideration part is shown from Table 5.11 to Table 5.16.

**Table 5.11 Chief Design Engineer Importance Rating for Marketing Consideration**

| **Chief Design Engineer** | 6 | 7 | 8 | 9 |
|---|---|---|---|---|
| 6. Lead time | 1 | 1/3 | 1.5 | 3 |
| 7. Purchasing cost | | 1 | 3 | 3 |
| 8. Shipping cost | | | 1 | 1/2 |
| 9. Change over cost | | | | 1 |
| Inconsistency Ratio | 0.09 | | | |

**Table 5.12 Design Engineer Importance Rating for Marketing Consideration**

| **Design Engineer** | 6 | 7 | 8 | 9 |
|---|---|---|---|---|
| 6. Lead time | 1 | 1 | 2 | 3 |
| 7. Purchasing cost | | 1 | 3 | 3 |
| 8. Shipping cost | | | 1 | 1/3 |
| 9. Change over cost | | | | 1 |
| Inconsistency Ratio | 0.09 | | | |

### Table 5.13 Project Engineer Importance Rating for Marketing Consideration

| **Project Engineer** | 6 | 7 | 8 | 9 |
|---|---|---|---|---|
| 6. Lead time | 1 | 1.5 | 3 | 5 |
| 7. Purchasing cost | | 1 | 3 | 3 |
| 8. Shipping cost | | | 1 | 1/3 |
| 9. Change over cost | | | | 1 |
| Inconsistency Ratio | 0.10 | | | |

### Table 5.14 Mechanical Engineer Importance Rating for Marketing Consideration

| **Mechanical Engineer** | 6 | 7 | 8 | 9 |
|---|---|---|---|---|
| 6. Lead time | 1 | 2 | 5 | 1 |
| 7. Purchasing cost | | 1 | 1.5 | 1/1.5 |
| 8. Shipping cost | | | 1 | 1/5 |
| 9. Change over cost | | | | 1 |
| Inconsistency Ratio | 0.02 | | | |

### Table 5.15 Material Engineer Importance Rating for Marketing Consideration

| **Material Engineer** | 6 | 7 | 8 | 9 |
|---|---|---|---|---|
| 6. Lead time | 1 | 2 | 2 | 2 |
| 7. Purchasing cost | | 1 | 2 | 1 |
| 8. Shipping cost | | | 1 | 1/2 |
| 9. Change over cost | | | | 1 |
| Inconsistency Ratio | 0.02 | | | |

### Table 5.16 Average Importance Rating for Marketing Consideration

| **Average** | 6 | 7 | 8 | 9 |
|---|---|---|---|---|
| 6. Lead time | 1 | 1.4 | 2.7 | 2.8 |
| 7. Purchasing cost | | 1 | 2.5 | 2.13 |
| 8. Shipping cost | | | 1 | 0.4 |
| 9. Change over cost | | | | 1 |
| Inconsistency Ratio | 0.04 | | | |

For the manufacturing consideration and marketing consideration importance ratio, refer to Table 5.17. Preferences for forged steel rolls and high-chrome iron rolls are shown in Table 5.18.

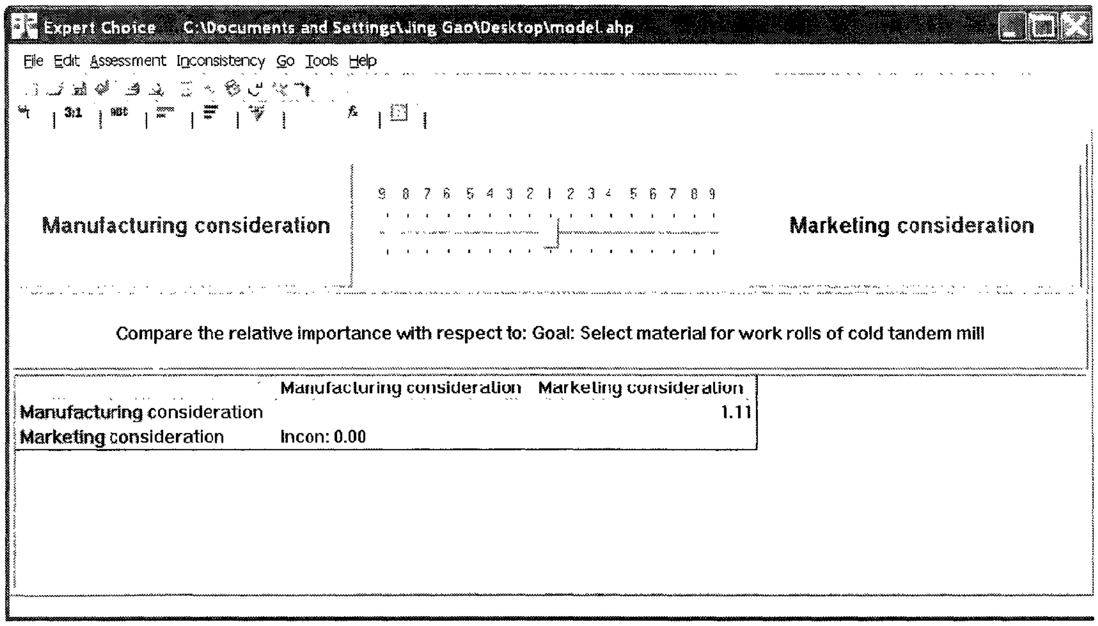
**Table 5.17 Importance Rating Manufacturing Consideration vs. Marketing Consideration**

| **Manufacturing Consideration /Marketing Consideration** | |
|---|---|
| Chief Design Engineer | 1.00 |
| Design Engineer | 1.50 |
| Project Engineer | 1.00 |
| Mechanical Engineer | 0.83 |
| Material Engineer | 1.20 |
| **Average** | **1.11** |

**Table 5.18 Preferences for Forged Steel Rolls and High-Chrome Iron Rolls**

| **Forged steel rolls/High-chrome iron rolls** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Chief Design Engineer | 1.50 | 0.30 | 0.20 | 0.50 | 3.00 | 5.00 | 5.00 | 5.00 | 0.20 |
| Design Engineer | 1.00 | 0.20 | 0.14 | 0.20 | 2.00 | 3.00 | 3.00 | 3.00 | 0.14 |
| Project Engineer | 1.00 | 0.33 | 0.20 | 0.50 | 5.00 | 5.00 | 7.00 | 5.00 | 0.33 |
| Mechanical Engineer | 3.00 | 0.67 | 0.25 | 0.50 | 5.00 | 5.00 | 7.00 | 5.00 | 0.20 |
| Material Engineer | 2.00 | 0.33 | 0.20 | 0.33 | 4.00 | 5.00 | 5.00 | 5.00 | 0.20 |
| **Average** | **1.70** | **0.37** | **0.20** | **0.41** | **3.80** | **4.60** | **5.40** | **4.60** | **0.21** |

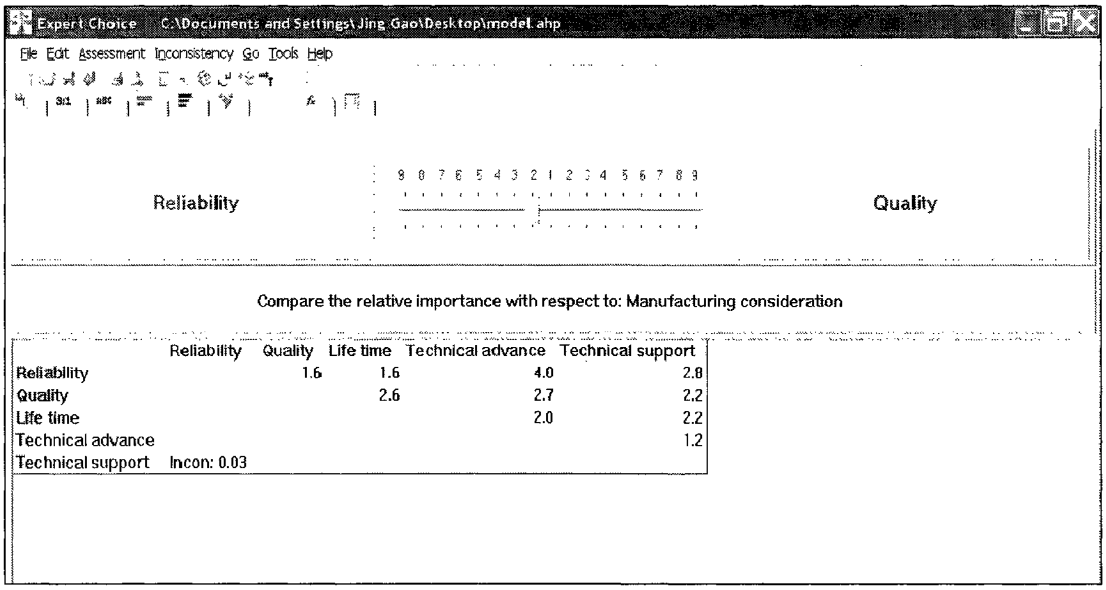
The snapshots of the matrix with inconsistency ratios are shown in Figure 5.10 ~ Figure 5.12. Inconsistency ratios are located at the left-hand bottom in the matrix.



Compare the relative importance with respect to: Goal: Select material for work rolls of cold tandem mill

| | Manufacturing consideration | Marketing consideration |
|---|---|---|
| Manufacturing consideration | | 1.11 |
| Marketing consideration | Incon: 0.00 | |

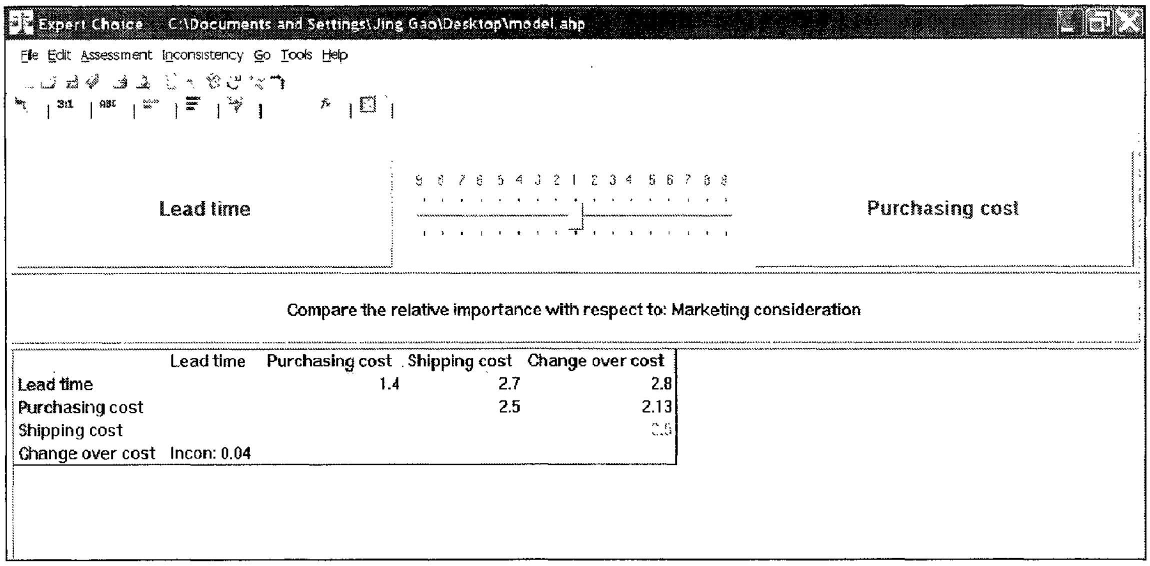
Figure 5.10 Snapshot of Relative Importances with Respect to Goal



Compare the relative importance with respect to: Manufacturing consideration

| | Reliability | Quality | Life time | Technical advance | Technical support |
|---|---|---|---|---|---|
| Reliability | | 1.6 | 1.6 | 4.0 | 2.8 |
| Quality | | | 2.6 | 2.7 | 2.2 |
| Life time | | | | 2.0 | 2.2 |
| Technical advance | | | | | 1.2 |
| Technical support | Incon: 0.03 | | | | |

Figure 5.11 Snapshot of Relative Importances with Respect to Manufacturing Consideration



Compare the relative importance with respect to: Marketing consideration

| | Lead time | Purchasing cost | Shipping cost | Change over cost |
|---|---|---|---|---|
| Lead time | | 1.4 | 2.7 | 2.8 |
| Purchasing cost | | | 2.5 | 2.13 |
| Shipping cost | | | | 2.5 |
| Change over cost | Incon: 0.04 | | | |

Figure 5.12 Snapshot of Relative Importances with Respect to Marketing Consideration

In order to demonstrate the calculation steps for the inconsistency ratio CR and verify the results given by the software, Expert Choice, the detail of calculation process for one matrix (Figure 5.10) will be given. Table 5.19 is the pair-wise comparison matrix for Table 5.6.

**Table 5.19 Pair-wise Comparison Matrix**

| | Reliability | Quality | Life time | Technical advantage | Technical support |
|---|---|---|---|---|---|
| Reliability | 1 | 1 | 1 | 3 | 1 |
| Quality | 1 | 1 | 1 | 1 | 3 |
| Life time | 1 | 1 | 1 | 1 | 2 |
| Technical advantage | 1/3 | 1 | 1 | 1 | 3 |
| Technical support | 1 | 1/3 | 1/2 | 1/3 | 1 |
| Column Sum | 4 1/3 | 4 1/3 | 4 1/2 | 6 1/3 | 10 |

Next step is to develop a normalized matrix by dividing each number in a column of the pair-wise comparison matrix by its column sum. And then develop the priority vector by averaging each row of the normalized matrix. These row averages form the priority vector of alternative preferences with respect to the particular criterion. The values in this vector sum to 1. Then, develop a priority Matrix (Table 5.21) by multiplying the priority vector (from Table 5.20) by the pair-wise comparison matrix (Table 5.19). And sum the row of Table 5.21 to get the overall priority vector. Average the $\lambda$ by n and get $\lambda_{max}$. According to the formula (4.1) and (4.2) , calculate the CR, where RI = 1.12 for n = 5 (Table 4.8).

$$CI = (\lambda_{max} - n)/(n - 1) = (5.4105 - 5)/(5-1) = 0.1026$$

$$CR = CI/RI = 0.1026 /1.12 = 0.0916$$

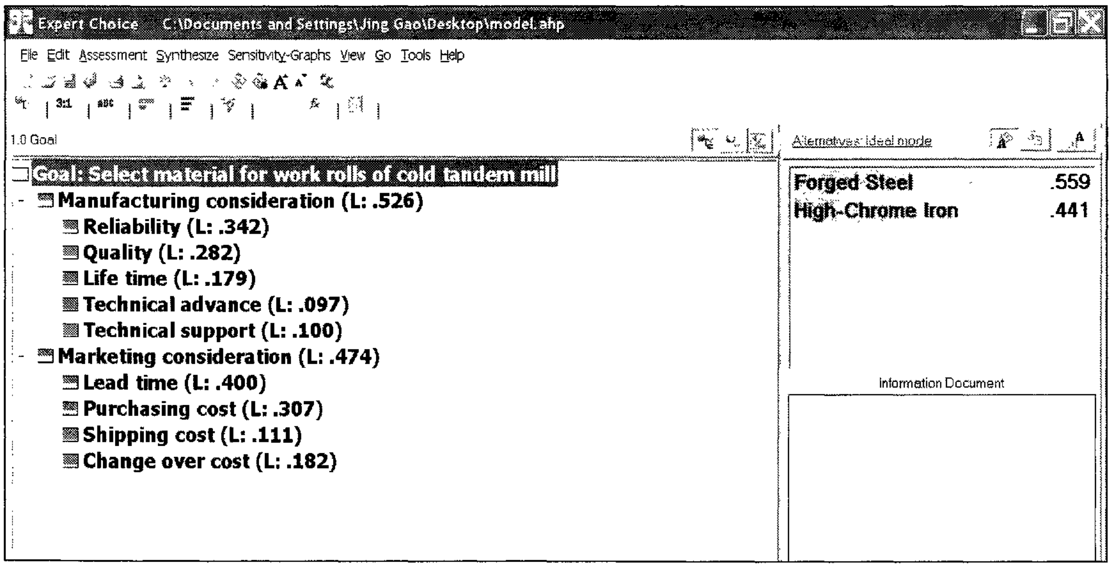
**Table 5.20 Normalized Matrix**

| | Reliability | Quality | Life time | Technical advantage | Technical support | Priority Vector |
|---|---|---|---|---|---|---|
| Reliability | 0.2308 | 0.2308 | 0.2222 | 0.4737 | 0.1000 | 0.2515 |
| Quality | 0.2308 | 0.2308 | 0.2222 | 0.1579 | 0.3000 | 0.2283 |
| Life time | 0.2308 | 0.2308 | 0.2222 | 0.1579 | 0.2000 | 0.2083 |
| Technical advantage | 0.0769 | 0.2308 | 0.2222 | 0.1579 | 0.3000 | 0.1976 |
| Technical support | 0.2308 | 0.0769 | 0.1111 | 0.0526 | 0.1000 | 0.1143 |
| Column Sum | 1 | 1 | 1 | 1 | 1 | 1 |

### Table 5.21 Priority Matrix

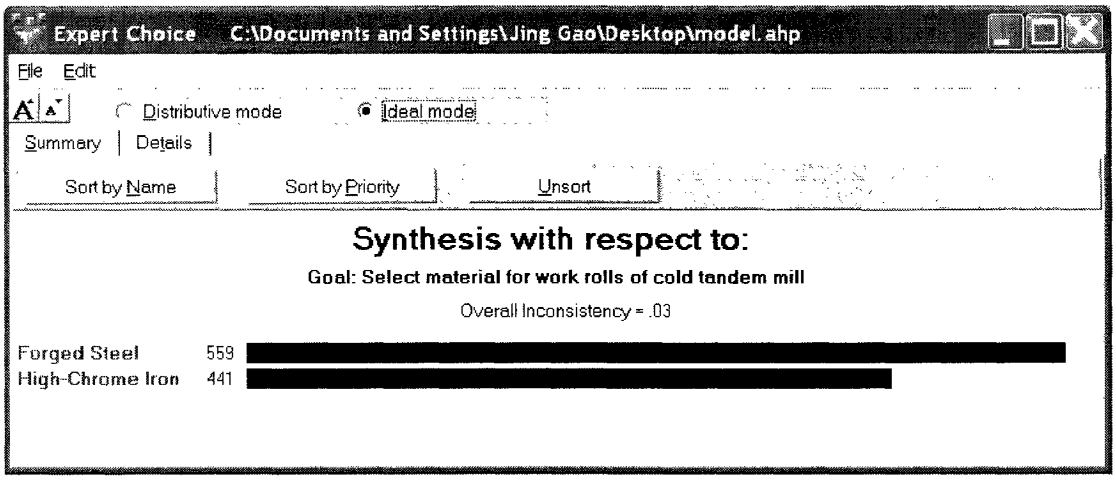
| | Reliability | Quality | Life time | Technical advantage | Technical support | Overall Priority Vector | λ |
|---|---|---|---|---|---|---|---|
| Reliability | 0.2515 | 0.2283 | 0.2083 | 0.5927 | 0.1143 | 1.3951 | 5.5475 |
| Quality | 0.2515 | 0.2283 | 0.2083 | 0.1976 | 0.3429 | 1.2286 | 5.3807 |
| Life time | 0.2515 | 0.2283 | 0.2083 | 0.2083 | 0.2286 | 1.1251 | 5.4003 |
| Technical advantage | 0.0838 | 0.2283 | 0.2083 | 0.1976 | 0.3429 | 1.0609 | 5.3700 |
| Technical support | 0.2515 | 0.0761 | 0.1042 | 0.0659 | 0.1143 | 0.6119 | 5.3541 |
| | | | | | Sum of λ | | 27.053 |
| | | | | | $\lambda_{max}$ = Sum of λ/n | | 5.4105 |

The result is the same as the software gives. So verify all the matrix using Expert Choice and get the results that all the inconsistency ratios are not greater than 0.1. The matrices are all considered consistent and can be used for running Expert Choice to calculate. The results are shown in Figure 5.13.



Goal: Select material for work rolls of cold tandem mill
- Manufacturing consideration (L: .526)
  - Reliability (L: .342)
  - Quality (L: .282)
  - Life time (L: .179)
  - Technical advance (L: .097)
  - Technical support (L: .100)
- Marketing consideration (L: .474)
  - Lead time (L: .400)
  - Purchasing cost (L: .307)
  - Shipping cost (L: .111)
  - Change over cost (L: .182)

| | |
|---|---|
| Forged Steel | .559 |
| High-Chrome Iron | .441 |



● Ideal mode

**Synthesis with respect to:**

**Goal: Select material for work rolls of cold tandem mill**

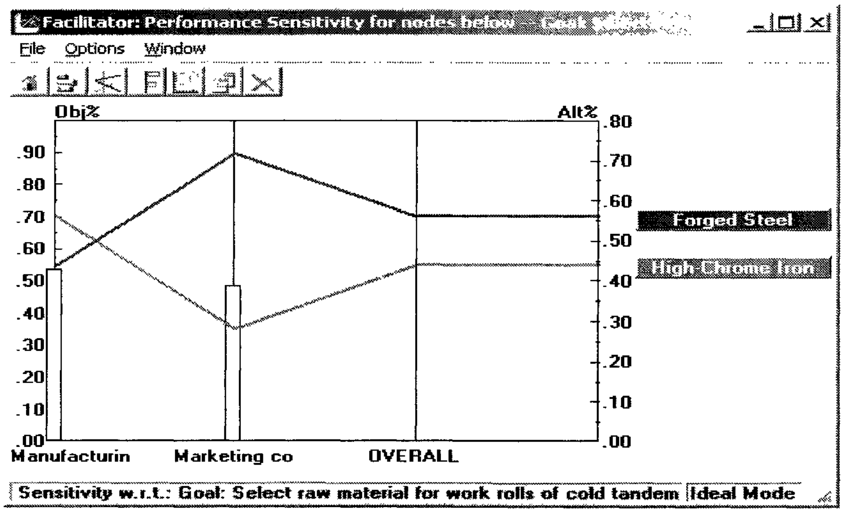
Overall Inconsistency = .03

| | |
|---|---|
| Forged Steel | 559 |
| High-Chrome Iron | 441 |

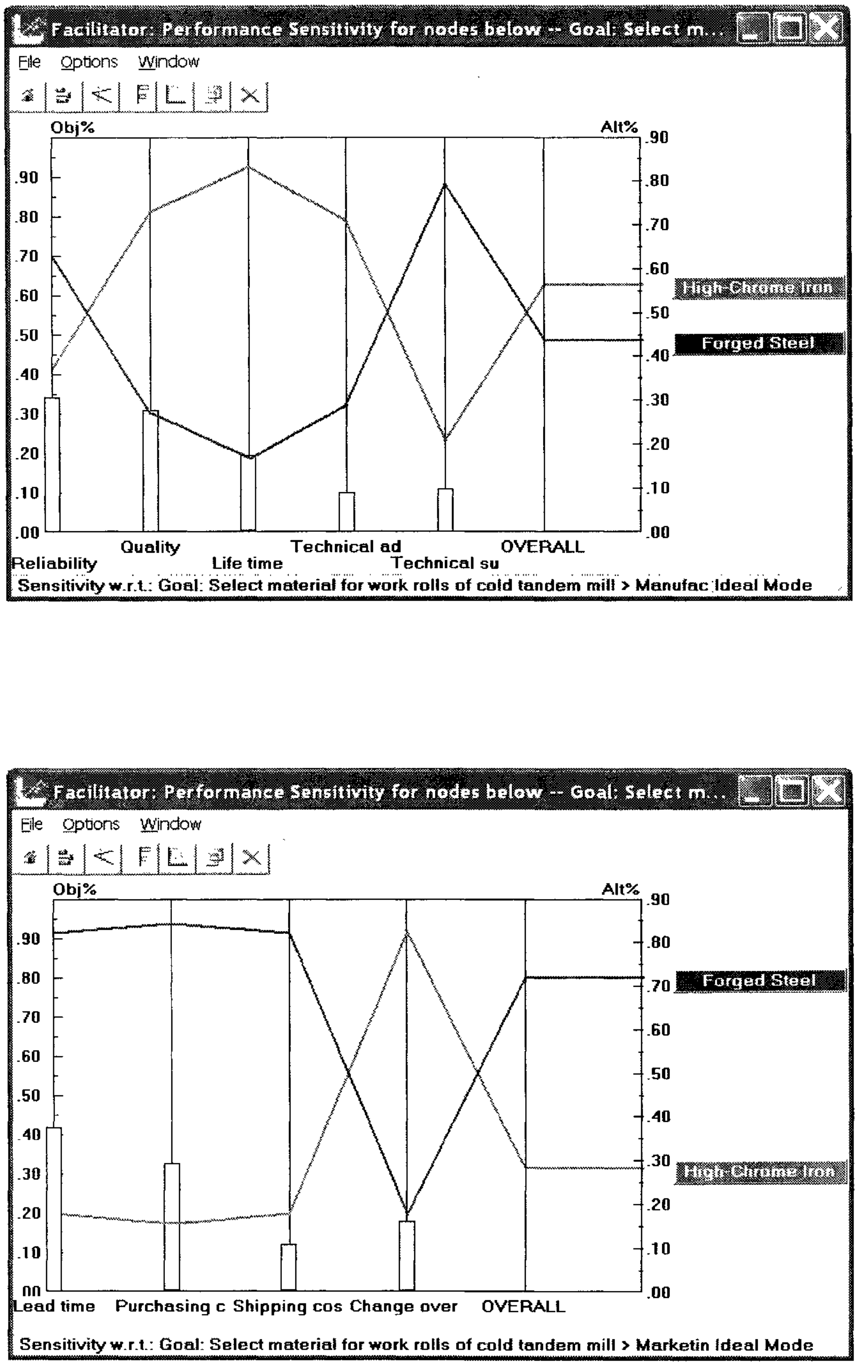
Figure 5.13 Snapshots of Results from Expert Choice

### 5.4.2.4 Results and Conclusions

From Figure 5.13, the result shows that the forged steel had the high value so this kind of material should be chosen. But we can see that this result is opposite to the result from experience without considering more factors. Some snapshots of expert choice performance sensitive are shown in Figure 5.14.



Sensitivity w.r.t.: Goal: Select raw material for work rolls of cold tandem | Ideal Mode



Facilitator: Performance Sensitivity for nodes below -- Goal: Select m...

Sensitivity w.r.t.: Goal: Select material for work rolls of cold tandem mill > Manufac Ideal Mode

Facilitator: Performance Sensitivity for nodes below -- Goal: Select m...

Sensitivity w.r.t.: Goal: Select material for work rolls of cold tandem mill > Marketin Ideal Mode

Figure 5.14 Snapshots of Expert Choice Performance Sensitivity Analysis

In order to see the tendencies of the results with changing manufacturing consideration and marketing consideration, the bars of manufacturing consideration and marketing consideration in the first figure of Figure 5.14 are dragged up and down , then get four scenarios which are shown in Table 5.22.

**Table 5.22 Scenarios with Different Consideration Weight**

| | Unit (%) | | | |
|---|---|---|---|---|
| Forged Steel Preference | 46.3 | 48.8 | 51.4 | 55.3 |
| High Chrome Iron Preference | 53.7 | 51.2 | 48.6 | 44.7 |
| Marketing Consideration | 10 | 20 | 30 | 40 |
| Manufacturing Consideration | 90 | 80 | 70 | 60 |

Figure 5.15 (a) shows the tendency to select different raw materials following the consideration weights changing for marketing and manufacturing. The vertical axis of the coordinator indicates the percentage of preference for both of the considerations. The horizontal axis of the coordinator indicates different scenarios of the material selected when the considerations of marketing and manufacturing are changed. The specific point is indicated which presents the equal preference for either raw material when the manufacturing consideration is 75.7%, i.e. marketing consideration is 24.3%. And finding this point is the main purpose to draw these two figures. At this break even point, the two considerations have the same priority and you can not make the decision based on the present data. In this case, more factors have to be considered to make the final decision.

Figure 5.15 (b) represents similar information as Figure 5.15 (a). The two triangles show the percentage change of the marketing and manufacturing considerations which are changed correspondingly.

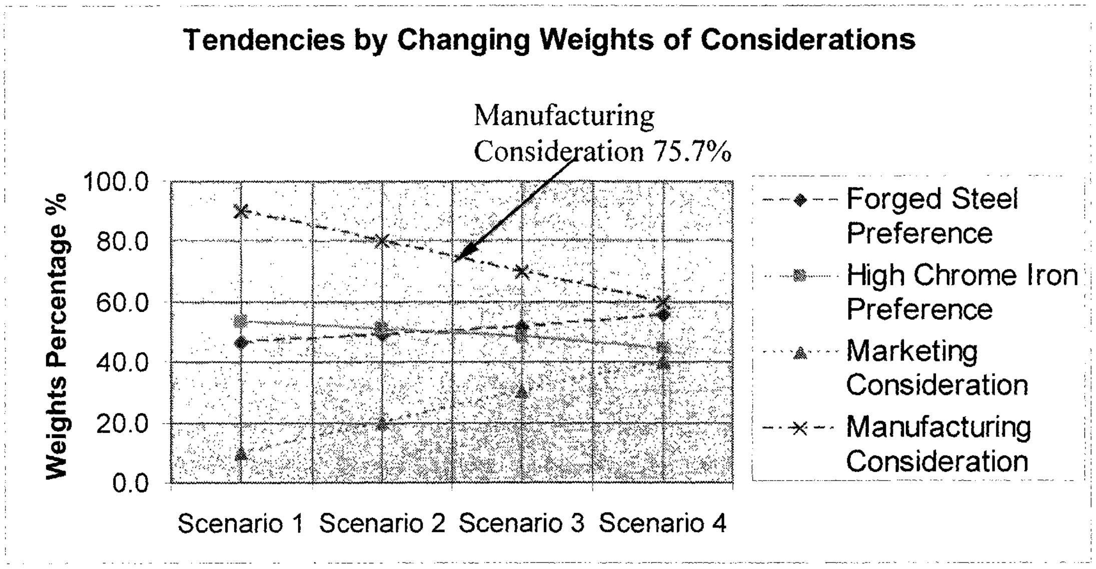


Figure 5.15 (a) Tendencies by Changing Weight of Considerations

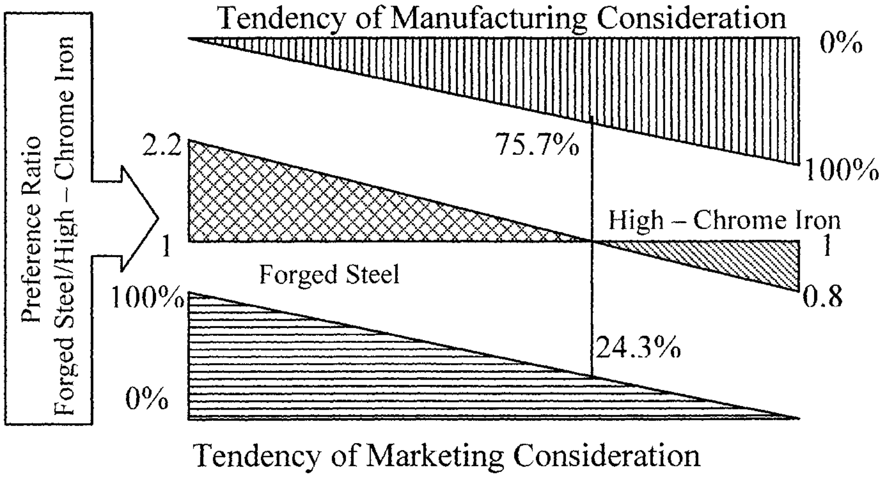


Figure 5.15 (b) Tendencies by Changing Weight of Considerations

The middle part shows the preference change using the ratio of forged steel and high – chrome iron which represents that when the marketing consideration is 100%, i.e. no consideration for the manufacturing, the preference of the forged steel is 2.2 times of high – chrome iron. And when the manufacturing consideration is 100%, i.e. no consideration for the marketing, the preference of the forged steel is 0.8 times of – chrome iron. Also the figure indicates the break even point at 75.7% manufacturing consideration and 24.3% marketing consideration which is the preferences of using forged steel and high – chrome iron are equivalent.

## 5.5 Case Study 2

In case study 2, the approaches using classical decision analysis and ECN methodology for tolerance selection process are presented.

### 5.5.1 Problem Statement

A company received a demand of 1000 units of a turned cylindrical part (shaft). The design department from the buyer side defined a need for this cylindrical part to be finished to $\Phi 25 \pm 0.03$ mm. [5]

---

[5] This case is modified according to the book, *Systems approach to computer-integrated design and manufacturing.* [Singh, N., 1996]

### 5.5.2 Classical Decision Analysis Approach

The design department of the buyer side recommended a shaft dimension and tolerance of Φ25 ± 0.03 mm. This requirement was transmitted to the manufacturing engineering department through both sides marketing department. In the classical decision analysis approach, it is a design specification driven process. The process engineer assumed that the tolerances were driven by performance requirements, and a manufacturing process is selected that will meet the design specification, manufacturing engineers accepted these specifications and attempted to find the best manufacturing technology to accommodate the request made by design. They would challenge the specification to their own side marketing department only if the design was not producible. In this situation both sides marketing department would communicate each other by transforming the information from manufacturing department and design department to further discuss the possibility to produce this product.

To visualize the design process using Classical Decision Analysis, I constructed a Classical Decision Analysis Design Process Map (Figure 5.16). Drawing on the preceding analysis, manufacturing engineers decided to produce the parts on a turret lathe because the desired tolerances can be obtained. The process average and the standard deviation were estimated to be 25 and 0.03 mm, respectively. Other relevant data are:

Unit cost of raw material = $10.00

Unit salvage value = $2.00

Unit processing cost = \$7.00 (fixed cost without considering the influence of other factors such as ordering lot size, rework cost, energy cost, etc.)

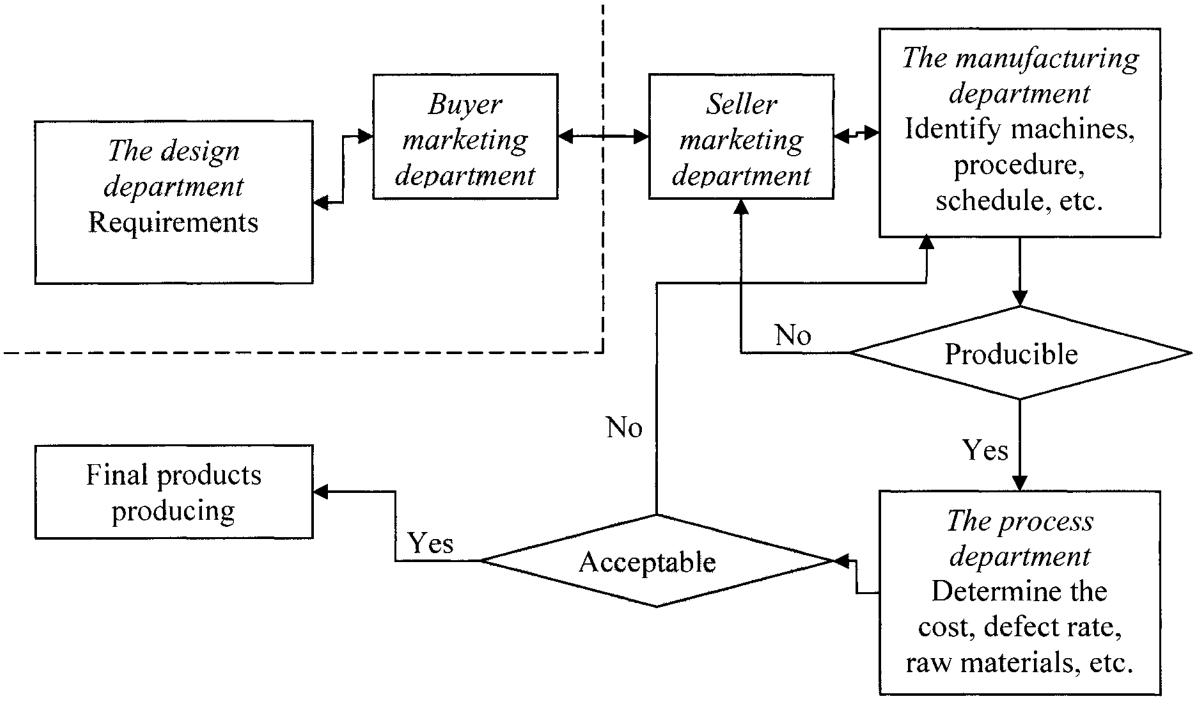


Figure 5.16 Classical Decision Analysis Design Process Map

## ***Mathematic equations***

The process engineers determined the unit cost of output, number of units of scrap generated, and number of raw units required to produce 1000 finished units using a mathematic model as follows (5.1):

$$Z_{jk}^{u} = {t_k^u - \mu_j}\Big/{\sigma_j}\ , \qquad Z_{jk}^{l} = {t_k^l - \mu_j}\Big/{\sigma_j} \tag{5.1}$$

Where $t_k^u$ and $t_k^l$ represent the upper and lower tolerance limits, respectively, for a component shaft for the k^th^ alternative system of tolerances. $\mu_j$ and $\sigma_j$ represent the standard deviation and the process mean of the output dimension of the shaft, respectively, for the j^th^ manufacturing option. Assuming the dimensions is normally distributed. We have $Z_{jk}^{u}$ and $Z_{jk}^{l}$ designate the standard normal varieties for the upper and lower tolerance limits, respectively for the k^th^ alternative system of tolerances using the j^th^ manufacturing option.

$$X_{jk}^{o} = k_{jk}^{i} X_{jk}^{i} - k_{jk}^{s} X_{jk}^{s} + k_{jk}^{i} f\left(Y_{jk}^{i}\right) \tag{5.2}$$

$$k_{jk}^{s} = \frac{SC_{jk}}{1 - SC_{jk}} = \frac{\Phi\left(Z_{jk}^{l}\right) + 1 - \Phi\left(Z_{jk}^{u}\right)}{\Phi\left(Z_{jk}^{u}\right) - \Phi\left(Z_{jk}^{l}\right)} \tag{5.3}$$

$$k_{jk}^{i} = 1 + k_{jk}^{s} = \frac{1}{\Phi\left(Z_{jk}^{u}\right) - \Phi\left(Z_{jk}^{l}\right)} \tag{5.4}$$

Where

$X_{jk}^{i}$, $X_{jk}^{o}$ and $X_{jk}^{s}$ are the unit average cost of input, output, and scrap, respectively

$f(Y_{jk}^{i})$ is the processing cost per unit

$k_{jk}^{s}$ and $k_{jk}^{i}$ are the technological coefficients per unit output to represent the scrap generated (units below the lower tolerance limit and units above the upper tolerance limit) and the input requirements, respectively

$SC_{jk}$ is the fraction of scrap

$\Phi()$ is the cumulative density function of the standard normal variety

***Unit cost and scrap calculations***

As a turret lathe was the first manufacturing technology option, j = 1, assuming dimension and tolerance Φ25 ± 0.03 mm as the first design option, k = 1. All parts above and below the tolerance limits were scrapped. For the given data, we got $Z_{11}^{u} = 1.00$ and $Z_{11}^{l} = -1.00$. Therefore, from the normal distribution tables, the percentage of items above the upper limit equals to 15.87 and the percentage of items below the lower tolerance limit equals to 15.87. The total percentage of rejects was 15.87 + 15.87 = 31.74. Accordingly,

Technological coefficient of scrap, $k_{11}^{s} = \dfrac{SC_{11}}{1 - SC_{11}} = \dfrac{0.3174}{1 - 0.3174} = 0.4649$

Technological coefficient of input, $k_{11}^{i} = 1 + k_{11}^{s} = 1 + 0.4649 = 1.4649$

Number of units scrapped, $Y_{11}^{s} = k_{11}^{s} Y_{11}^{o} = 0.4649 \times 1000 \approx 465$

Number of raw units (input) required, $Y_{11}^{i} = k_{11}^{i} Y_{11}^{o} = 1.4649 \times 1000 = 1465$

$$X_{11}^{o} = k_{11}^{i} X_{11}^{i} - k_{11}^{s} X_{11}^{s} + k_{11}^{i} f\left(Y_{11}^{i}\right)$$

Unit output cost, $= 1.4649 \times 10.00 - 0.4649 \times 2.00 + 1.4649 \times 7.00$

$= 23.97$

As the result of the calculations, we can see that the unit finished product cost would be as high as \$23.97 and the scraps would be as high as 465 units for producing 1000 satisfied parts. Those results would eventually lead to reexamination of the process and design specifications. In the classical decision analysis approach there is no formal mechanism for considering these aspects simultaneously. Therefore, the process of change may take significant time. During that period, the system normally operates at significantly low performance levels, that is, higher rejects, unit costs, and lead time.

### 5.5.3 Engineering as Collaborative Negotiation Approach

ECN approach is based on cross-functional and multi-disciplinary teams at different levels optimization representing various functional areas including social and economic factors. Therefore, the ECN methodology cuts across functional boundaries of an organization at the enterprise level with the concerning of human resource and global environment and competition. Also as the ECN methodology, it breaks the boundaries between the buyer and seller, the entire team only has one goal which is to purses the optimized solution and at meanwhile to share all resource and profit. I constructed ECN design process map to show how all stakeholders involved (Figure 5.17). Those ECN rules created in section 3.4.2.3 should be followed.

In this case, the marketing people, design team, manufacturing engineer group, and all stakeholders in the product development process met together to discuss integrating issues of functional design, manufacturing, quality control, customer service, and so on.

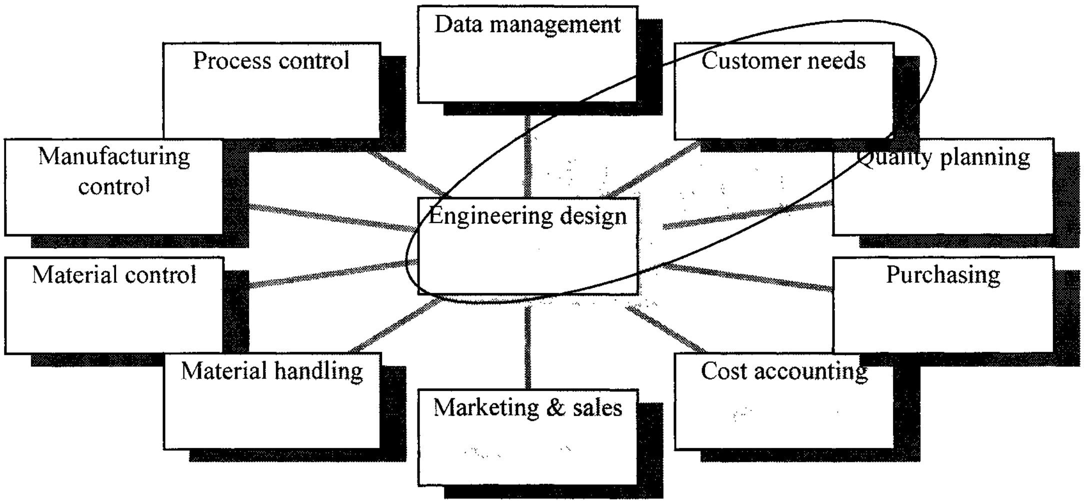


Figure 5.17 ECN Design Process Map

This multifunctional team was responsible for addressing various issues:

- The marketing services of design side found that the tolerance range of Φ25 ± 0.03 mm may be too tight through market research and customer survey.
- The quality department complained that the rejection rate was too high.
- The manufacturing planning department wanted to use machine tools with better process capabilities.
- The purchasing department could not buy so many raw shafts because of the restricted availability of such steel.

This process leaded to a sequence of interactions that were documented in the following sets of meetings of the ECN team.

### 5.5.3.1 Engineering as Collaborative Negotiation Team Meeting 1

The team began by agreeing to hold the shaft dimensions to Φ25 ± 0.03 mm by the reason to purse a better quality even though the marketing services of design side found that the tolerance range maybe too tight. The manufacturing department recommended an engine lathe after comparing among entire available resources, which has higher process capability resulting in a process standard deviation of 0.02 mm to avoid the high rejection rate, however, the processing cost increased to $9.00 per unit from the previous $7.00. Other data were the same as before. The unit cost of output, number of units of scrap generated, and number of raw units required to produce 1000 finished units were determined as follows:

***<u>Unit cost and scrap calculations</u>***

Because the engine lathe was the second manufacturing technological alternative, we have j = 2. Also, k = 1, because there was no change in the design specifications, $Z_{21}^{u} = 1.5$, $Z_{21}^{l} = -1.5$

Percent rejection above the upper limit equals to 6.7, percent rejection below the lower limit equals to 6.7, total percent rejection = 13.34, $k_{21}^{s} = 0.1547$, $k_{21}^{i} = 1.1547$. Accordingly,

Number of units scrapped, $Y_{21}^{s} = k_{21}^{s} Y_{21}^{o} = 0.1547 \times 1000 = 154.7 \approx 155$

Number of raw units (input) required, $Y_{21}^{i} = k_{21}^{i} Y_{21}^{o} = 1.1547 \times 1000 = 1154.7 \approx 1155$

With the considering of the influence of economies of scale of production, the process cost would be $f\left(Y_{21}^{i}\right) = 9.00 + 0.002 Y_{21}^{i} = 9.00 + 0.002 \times 1155 = \$11.31$

$$X_{21}^{o} = k_{21}^{i} X_{21}^{i} - k_{21}^{s} X_{21}^{s} + k_{21}^{i} f\left(Y_{21}^{i}\right)$$

Unit output cost, $= 1.1547 \times 10.00 - 0.1547 \times 2.00 + 1.1547 \times 11.31$

$= \$24.297$

### 5.5.3.2 Engineering as Collaborative Negotiation Team Meeting 2

The quality and purchasing departments were still not satisfied with the amount of scrap generated, and the marketing department felt that the unit cost was still too high. As a consequence of this feedback from marketing, the design engineers believed that the customer requirements can be met with tolerance limits of Φ25 ± 0.04 mm. And engine lathe was to be used to manufacture the component. Other data were the same as before. The unit cost of output, number of units of scrap generated and number of raw units required to produce 1000 finished units were calculated as follows:

***Unit cost and scrap calculations***

In this case j= 2, k= 2. Using a procedure similar to that used in meeting 1, we obtained:

Number of units scrapped, $Y_{22}^{s} = k_{22}^{s} Y_{22}^{o} = 0.0456 \times 1000 = 45.6 \approx 46$

Number of raw unit (input) required $Y_{22}^{i} = k_{22}^{i} Y_{22}^{o} = 1.0456 \times 1000 = 1045.6 \approx 1046$

With the considering of the influence of economies of scale of production, the process cost would be $f\left(Y_{22}^{i}\right) = 9.00 + 0.001 Y_{22}^{i} = 9.00 + 0.001 \times 1046 = \$10.046$

$$X_{22}^{o} = k_{22}^{i} X_{22}^{i} - k_{22}^{s} X_{22}^{s} + k_{22}^{i} f\left(Y_{22}^{i}\right)$$

Unit output cost $= 1.0456 \times 10.00 - 0.0456 \times 2.00 + 1.0456 \times 10.046$

$= \$20.869$

### 5.5.3.3 Engineering as Collaborative Negotiation Team Meeting 3

The cross-functional multi-disciplinary team compared the results of the two meetings and sought reductions in the cost of manufacturing, the number of rejects, and consequently the number of pieces of raw shaft material required. Although the number of rejects had been reduced considerably, quality level was still not acceptable to the buyer side. The survey had been done by the marketing department from buyer side showed that the customers were willing to pay more per unit with a higher reliability. The team explored the possibility of using an automated screw machine (ASM), whose process capability was much better than that of an engine lathe. This would, however, increased the unit processing cost.

For the ASM the standard deviation was now 0.01mm and the unit processing cost was \$12.00. Other data were the same as in the previous meetings. In this meeting the team wanted to know the unit cost of output, number of units of scrap generated, and number of raw units required to produce 1000 finished units considering both Φ25 ± 0.03 mm and Φ25 ± 0.04 mm as tolerance limits. The relevant calculations are as follows:

***Unit cost and scrap calculations***

For the tolerance limit of Φ25 ± 0.03 mm, and automated screw machine, we had k = 1, j = 3,

Number of units scrapped, $Y_{31}^{s} = k_{31}^{s} Y_{31}^{o} = 0.0027 \times 1000 = 2.7 \approx 3$

Number of raw unit (input) required $Y_{31}^{i} = k_{31}^{i} Y_{31}^{o} = 1.0027 \times 1000 = 1002.7 \approx 1003$

With the considering of the influence of economies of scale of production, the process cost would be $f(Y_{31}^{i}) = 12.00 - 0.002 Y_{31}^{i} = 12.00 - 0.002 \times 1003 = \$9.994$

$$X_{31}^{o} = k_{31}^{i} X_{31}^{i} - k_{31}^{s} X_{31}^{s} + k_{31}^{i} f(Y_{31}^{i})$$

Unit output cost $= 1.0027 \times 10.00 - 0.0027 \times 2.00 + 1.0027 \times 9.994$

$= \$20.043$

For the tolerance limit of Φ25 ± 0.04 mm, and automated screw machine, we had k = 2, j = 3,

Number of units scrapped,

$$Y_{32}^{s} = k_{32}^{s} Y_{32}^{o} = 0.000 \times 1000 = 0.00$$

$$K_{32}^{i} = 1 + 0.00 = 1.00$$

Number of raw unit (input) required $Y_{32}^{i} = k_{32}^{i} Y_{32}^{o} = 1.00 \times 1000 = 1000$

With the considering of the influence of economies of scale of production, the process cost would be $f(Y_{32}^{i}) = 12.00 - 0.003 Y_{32}^{i} = 12.00 - 0.003 \times 1000 = \$9.00$

$$X_{32}^{o} = k_{32}^{i} X_{32}^{i} - k_{32}^{s} X_{32}^{s} + k_{32}^{i} f\left(Y_{32}^{i}\right)$$

Unit output cost $= 1.00 \times 10.00 - 0.00 \times 2.00 + 1.00 \times 9.00$

$= \$19.00$

### 5.5.4 Results and Conclusions

The result of applying ECN methodology is shown in Table 5.23. The figures of cost deduction and detect deduction by using ECN approach are shown in Figure 5.18 and Figure 5.19.

**Table 5.23 Results of Applying ECN Methodology**

| | **Meeting 1** | **Meeting 2** | **Meeting 3** | |
|---|---|---|---|---|
| **Situations** | Engine lathe & Original tolerance | Engine lathe & Modified tolerance | ASM & Original tolerance | ASM & Modified tolerance |
| **Fixed Processing Cost** | \$9 | \$9 | \$12 | \$12 |
| **Actual Processing Cost** | \$11.31 | \$10.046 | \$9.994 | \$9.00 |
| **Scrapped Number** | 155 | 46 | 3 | 0 |
| **Number of Raw Units Required** | 1155 | 1046 | 1003 | 1000 |
| **Unit Output Cost** | \$24.297 | \$20.869 | \$20.043 | \$19 |

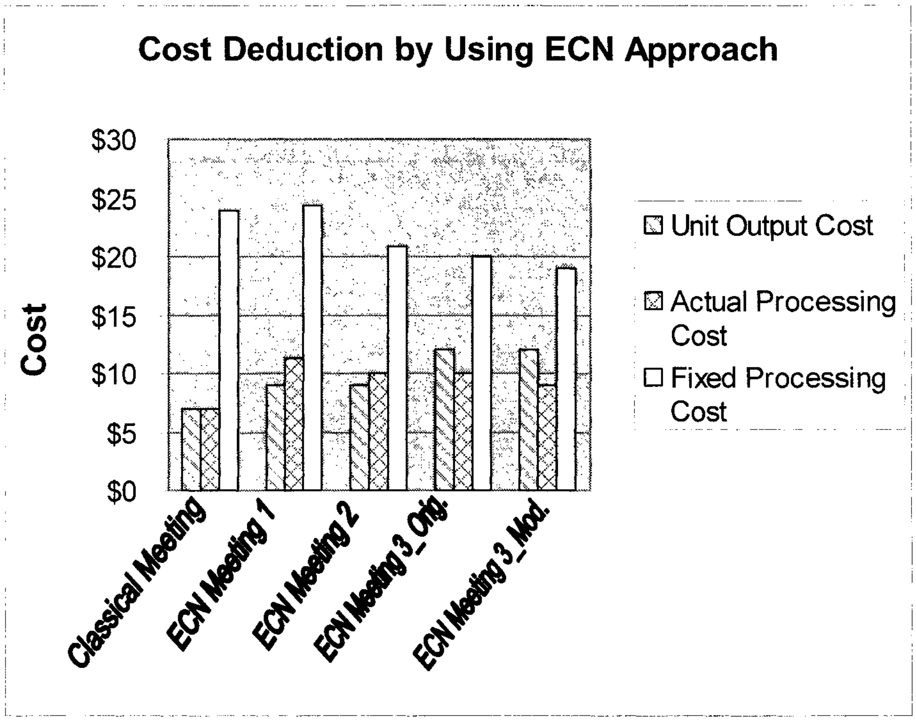


Figure 5.18 Cost Deduction by Using ECN Approach

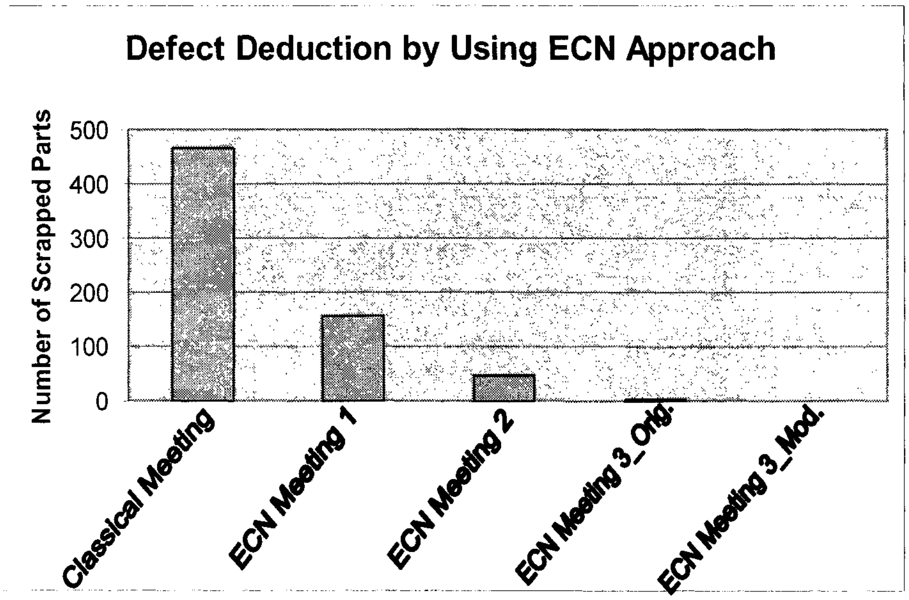


Figure 5.19 Defect Deduction by Using ECN Approach

In traditional classical decision analysis method, there is no collaborative among different disciplines and functions. Whole departments involved in the product development process only follow a pre-dedicated procedure. Even though each department may have their own optimized solution at their stage, it is a great possibility to be an incorrect decision for the finial solution. In that case, it takes a very long time to go through the cycle again to correct the problem and even the problem can not be solved since the lose of the information during the transforming one by one.

The sequence of meetings of ECN engineering team has led them to understand the collaboration and negotiation among design, manufacturing, marketing, cost-benefit, etc by simultaneously considering all of those issues. It gives the chance to make the correct decision at the early stage of a new product by introducing all related departments to involve in. Even though it usually takes longer time than traditional decision making process, it actually saves a lot of time at the following stages, such as manufacturing planning, process planning, purchasing planning, and so forth since all those departments are already involved at the beginning and the problems that will appear at their stages are solved at the same time. By following ECN methodology, all involved departments have a clear picture about the entire process. The design team finally decided the tolerance specifications as $\Phi 25 \pm 0.04$ mm, and the actual unit cost of the finial product was only \$19.00.

# CHARPTER 6

# CONCLUSIONS AND FUTURE WORKS

## 6.1 Results and Conclusions

Through the case study 1 of material selection for Continuous Pickling Line and Tandem Mill Project, we can see that the collaboration and negotiation for decision-making process in engineering design are very important. The different decision can be made without collaboration and negotiation. And in case study 2, the improvement for the cost deduction was obvious after using ECN methodology. The cost reduced from \$23.97 to \$ 19.00.

The conclusions for this research are:

- For complex engineering design, collaboration and negotiation are essential;
- How to collaborate and negotiate depends on what the problem is and in what situation;
- Without or lacking of collaboration and negotiation can lead to inaccurate, even wrong, decision(s).

## 6.2 Contributions

The contributions of this research can be summarized as follows:

- A new definition of complexity was in the collaborative context as: Complexity is a relative concept. It can be called as a complex problem if stakeholders cannot handle objects individually no matter because of inner factors like stakeholders' knowledge or outer factors like due day;
- A complexity detector was conceptually created to be used as telling whether a problem is complex or not from collaborative point of view;
- Confirmed that the importance of collaboration and negotiation in decision making process for engineering design;
- In order to insure an orderly and fair ECN process, a set of ground rules are created;
- A detailed flowchart was constructed to guide mangers and engineers to go through the whole process from receiving problem to make the reasonable decision;
- Case study 1 which was based on a real-world project compared traditional engineering design approach with the new approach using AHP for efficient decision-making process of material selection. Sensitivity analysis was made to show how the decision will be changed with the factor weights;
- Case study 2 showed how using ECN methodology instead of classical decision analysis in a shaft tolerance design process made improvements.

## 6.3 Future Works

In this research, the complexity problems in engineering design and related fields are reviewed, and a complexity detector is constructed in Chapter 2 to give a guideline for stakeholders to determine complexity conceptually from general point of view. A quantitive complexity detector needs to be built in the further work to classify the different complexity levels in detail. Various methodologies and tools should also be testified and abstracted to find out an integrated optimal approach to measure and manage the complexities.

Suh [2003] defined complexity as "a measure of uncertainty in achieving a set of specific functions or functional requirements (FR)". How to measure and manage complexity based on FR is a topic for further research.

ECN still is a new theory and an on-going research topic. A more detail definition of ECN is needed. The methodologies and tools used in ECN are still under construction and need be further developed. Also the ECN rules for participants need to be further developed. There are so many methodologies and tools used in engineering design decision-making process. How to make ECN unique and can ideally solve the complexity issues in engineering design at a joint decision level are also parts of future work.

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