COMPUTER SIMULATION AND OPTIMIZATION
FOR
ECONOMIC RAW MATERIAL SELECTION

by

Ruilin Chen

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

Doctor of Philosophy
in
the Department of Mechanical and Industrial Engineering
University of Manitoba
Winnipeg, Manitoba

February, 1994
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BY

RUILIN CHEN

A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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The sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work.

John Von Neumann

ABSTRACT

This dissertation concentrates on a sole subject - economic raw material selection techniques for engineering manufacturers. To approach the problem of economic raw material selection, a generalized economic model for raw material selection is proposed. A realistic example is presented and some significant variables and relationships are investigated. Afterwards, an analytical method is followed to give a series of mathematical equations for determining the optimal material quality level. Certain serious limitations are pointed out regarding practical application of this approach. To overcome the difficulty, a computer simulation model integrated with two optimization techniques is provided to identify the optimum raw material properties for the particular case. Two system modeling approaches are developed to simulate costs incurred during material purchasing, impact of manufacturing processes and impact of product quality in order to select the most suitable raw material and supplier available for the particular application. Finally, an Abductive Network Method - an "expert system" type of approach - is used for the raw material selection problem with "fuzzy" inputs. This research is based on a realistic example in order to indicate its practical usefulness.

ACKNOWLEDGMENT

I convey my deep sense of appreciation and gratitude to my research co-advisors, **Professor Ostap Hawaleshka** and **Dr. Doug Strong**. They have been great friends, philosophers and guides throughout my program from beginning to end. My debt of thanks for what they have done for me at this important stage of my career, is immense. I will always remember their encouragement, their patience and their kindness. Special thanks are due to **Dr. Strong** for his efforts to guide my research towards this real and important industrial problem.

Sincere thanks are extended to the member of my committee, **Dr. Kedar Tandon**, professor in Metallurgy, and **Dr. C. R. Bector**, professor in Management Science for their generous guidance and input in the thesis. Deep appreciation is extended to my external examiner, **Dr. Gerry V. Price**, the president of E. H. Price Ltd., for his comments, valuable discussions and careful review of the thesis.

Special thanks are also due to the assistance I received from the employees at E. H. Price Ltd. I especially extend my appreciation to Mr. Tim Mitchell (Manufacturing Engineering Manager), Mr. Othmar Furer (Manufacturing Manager), Mr. James Smith (Industrial Engineer) and Mrs. Henrietta Rother (Account Representative of the Namasco Steel Service Center) for the contribution to the practical aspect of this research.

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CHAPTER 1

INTRODUCTION OF THE PROBLEM

The subject of this research is to systematically study a common problem faced by manufacturers: the selection of the most suitable raw material for a particular application. The organization of the thesis and an introduction of this problem are given in this Chapter.

1. 1. ORGANIZATION OF THE THESIS

The objective of this research is to develop a systematic approach to the economic raw material selection problem and, in the process, to show the usefulness of this approach by means of a practical industrial example. The thesis is organized as follows:

Chapter 1 describes the organization of the thesis and introduces the problem of economic raw material selection.

Chapter 2 follows with a review of related literature and research. Its purpose is to evaluate the present state-of-the-art in this field, in order to allow us to identify areas that seem to require further work and a promising research direction.

Chapter 3 is devoted to the construction of an economic model for raw material selection. In the discussion, we set up our new raw material selection criterion and also provide an novel approach for the cost impact calculation of the raw material used in the manufacturing processes.

Chapter 4 and Chapter 5 are devoted to the investigation and data collection of a realistic industrial example, which provides the database for our work as given in subsequent chapters. Chapter 4 first states the raw material properties and their inter-relationships, then proceeds to the cost relationship analysis between raw material properties and the various manufacturing costs. Chapter 5 discusses the purchasing operations for raw materials and the costs related to the material purchasing processes. These two chapters provide the necessary background material for our computer simulation and optimization approaches.

Chapter 6, 7, 8 and 9 constitute our contributions to this field of knowledge.

Chapter 6 provides a series of mathematical relationships used for calculating the expected cost impact of raw materials and determining their optimal quality level using an analytical approach. This exercise, on one hand, from a special approach, provides some generalized useful equations; on the other hand, indicates the strict limitations of the analytical approach in real practice. It also provides a basis for the computer simulation and optimization approaches in later Chapters.

Chapter 7 deals with the combination of computer simulation and two different optimum-seeking techniques for the identification of the optimum raw material properties for the industrial case discussed. This approach overcomes the difficulty of using analytical approaches and provide a clear view of the optimal raw material properties for the particular application.

The most suitable raw material and supplier selection using two computer simulation techniques is shown in Chapter 8. The simulation models constructed in this Chapter can re-generate the purchasing and manufacturing process as well as the real-time costs. It may be used to assist the industrial practitioner with economic raw material selection.

Chapter 9 uses a knowledge-based system - the Abductive Network Method [2] to approach this same raw material selection problem with "fuzzy" inputs. This approach sees the raw material selection problem from another angle, and can be used even if the cost relationship between the raw material properties and manufacturing process is implicit, but qualitatively known in a fuzzy manner.

The last Chapter - Chapter 10, re-states the nature of this research, as well as the conclusions and contributions of this research work.

1. 2. INTRODUCTION

Raw materials have a considerable influence on the cost of engineering (manufactured) products. This is because their cost often represents a high proportion of the total product cost, and also because their processability affects the level and productivity of the capital and labor required for their conversion into the final shape. For typical engineering industries, the direct cost of materials can represent 30 to 70 % of the value of production. In many cases, raw material properties also have significant effects on the manufacturing process and on the final product quality itself. As the cost impact of both material and material properties can be so important, it is worthwhile, indeed imperative, to optimize their selection and use, in order to achieve the best overall application cost.

One can describe the various impacts of raw material applications in manufacturing situations as follows (see Figure 1.1):

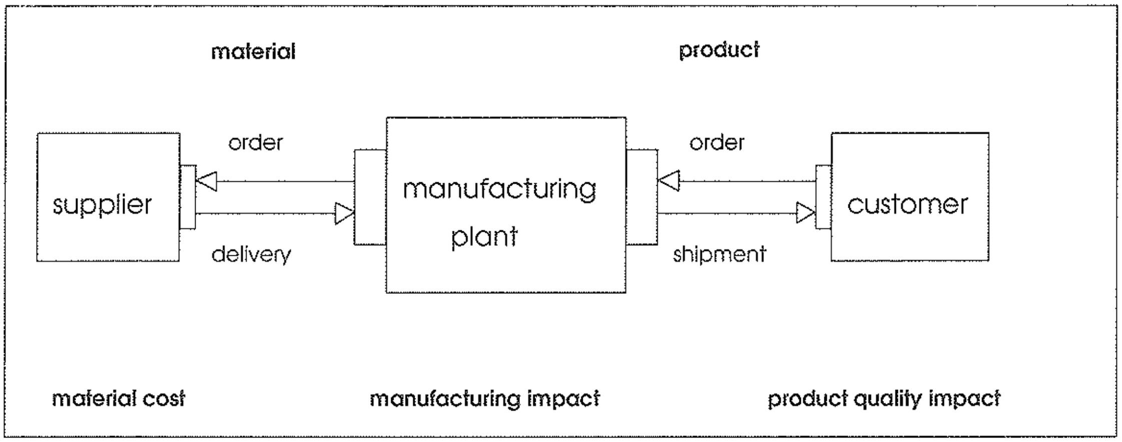


Figure 1.1 Areas of Impact of Materials

As we know, different raw materials have different market prices. The material purchasing process and its handling cost are also different if one deals with different material suppliers. In manufacturing, different materials may have varying impacts on the manufacturing processes themselves, due to the material's workability, machinability and, its effect on the quality of the various production operations. Their impact on the final product quality, may affect the customer's acceptance of the product.

Effectively selected materials must satisfy both technical requirements and economic requirements. From the "production process point of view" the material needs to be transformed easily into its final shape with the desired level of quality; in addition, the overall combination of the material cost and its cost impact due to its effect on the process should be at the lowest level possible.

We are concerned here with the following: a thorough investigation of the economic raw material selection problem and of its governing parameters and, as a result, the development of a systematic method to analyze this problem. Ultimately we are interested in providing the industrial decision-maker with a useful tool for economic raw material selection. Throughout, we will be using a real industrial example as the vehicle for our work.

1. 3. PROBLEM STATEMENT

Raw material selection is a complicated problem. To provide a systematic guide for industrial practice, we divide this raw material selection problem into two sub-problems for discussion: one is the identification of the optimum raw material characteristics (common at the product design stage) from the material requirements of the manufacturing processes and product quality; the other one is the practical selection of the most suitable raw material from materials available (commonly of interest at the purchasing stage). The data used for first problem is only a part of that required for the analysis of the second problem since the second problem needs detailed information about material characteristics and material available suppliers.

1. 3. 1 Identifying the Most Suitable Material

To make an effective raw material selection, one must first understand the relationships between its properties and its area of application (or utilization). Different processes may require different properties. Consider the following simple example: in sheet metal pressing (processing) applications, "ease of bending" requirements favor thinner metal and lower yield strength. On the other hand, final product handling requirements may favour thicker metal and higher yield strength (see Figure 1.2). Even in this simple example one can note conflicting requirements for material properties. The general problem we are addressing is, of course, significantly more involved.

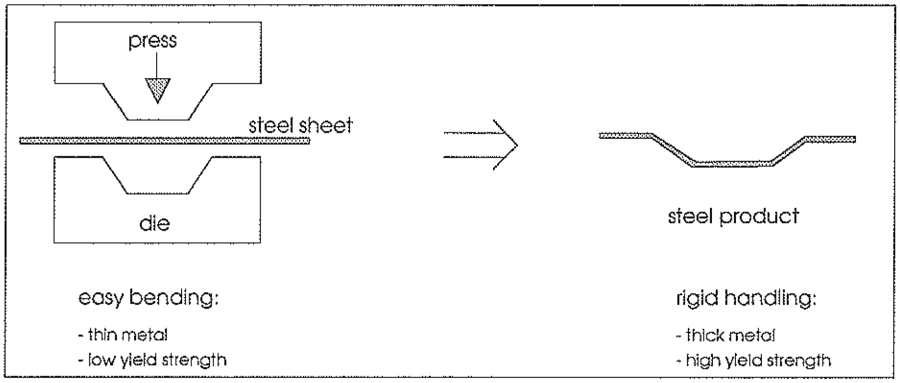


Figure 1.2 Material Characteristics Requirements

After understanding the relationships between a material's properties and its application process, one can then assess the seriousness (cost impact) of the effect of material properties on each production process in which that particular material participates. In general, raw material of overall high quality is usually more expensive than low quality material. The same (more expensive) material may, however, make the production process easier, less costly or improve the final product quality. This is typical of engineering "trade-off" situations. In order to balance the material expenses and their production impact, we need to eliminate those expenses which do not bring more value or benefit to the application. We must then balance the cost between the raw material properties themselves and the impacts of the material on the downstream application processes, including the manufacturing process and final product quality (see Figure 1.3).

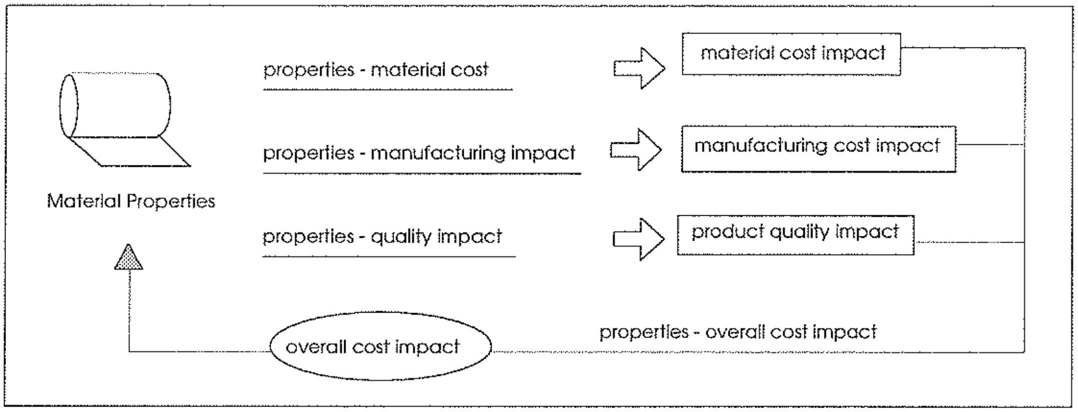


Figure 1.3 Economic Selection For Material Properties

1. 3. 2 Material And Supplier Selection:

After having identified and understood the raw material requirements, one is ready to: 1. choose right material from among those available, and 2. the right supplier for the material. Different suppliers may provide different materials with different quality, different handling processes, different minimum order amounts, different lead times, different purchasing bonuses, etc. These variances all affect the actual material cost in the purchasing process. The properties themselves, of the materials available, may follow different statistical distributions. A useful way to study these relationships involves the use of simulation techniques. The right material and the right supplier chosen must be the ones which result in the lowest overall cost (see Figure 1.4) in terms of actual material cost, manufacturing cost impact and product quality cost impact..

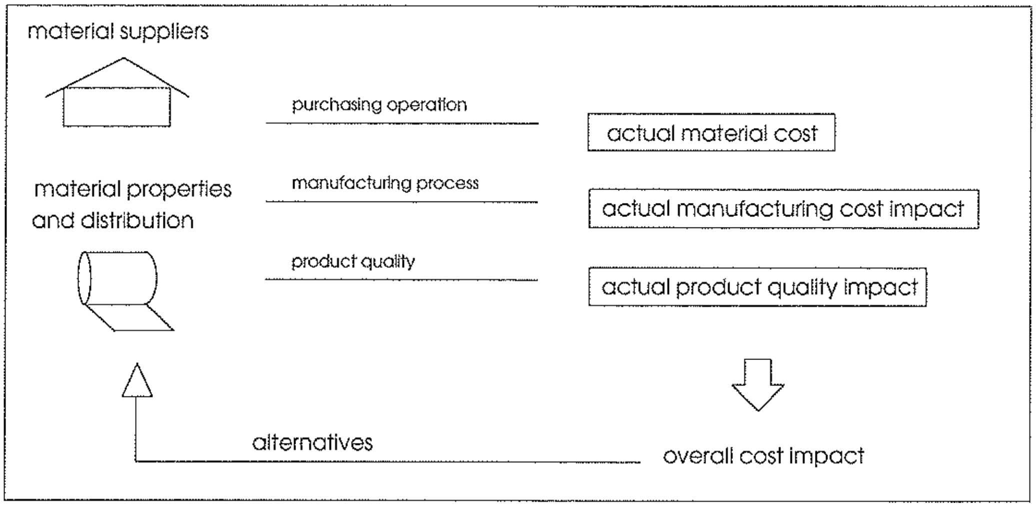


Figure 1.4 Economic Selection of Raw Material and Supplier

1. 4. RESEARCH STRATEGY AND TOOLS

In our systematic study of the raw material selection problem, the following steps (or strategies) and related tools are used:

Raw Material Selection Criteria:

An economically and technically based material selection criterion (defined as the overall total cost) is proposed to judge the suitability of a raw material for a particular application. A practical "process by process" and "parameter by parameter" approach is suggested to analyze the cost impact of materials on the manufacturing processes in which they participate.

Information Gathering and Analysis:

The gathering of appropriate and useful information and its analysis constitute the major and most difficult aspects of this research since, at the corporate level, there is rarely direct information and data available at all, or available in usable form. Our targets then consist of defining related important variables of the various processes and to investigate the relationships between the material properties and their impacts on the production processes to which this material is subjected. One of the frustrating aspects of this work is that many problems related to the impact of materials on manufacturing processes are described in a very "fuzzy" or vague terminology such as "low" or "very high" by production experts one consults.

Analytical Approach:

An analytical approach has been used to identify the optimum raw material characteristic and to calculate the cost impact of the material on the production processes affected. In this approach, we assume that the cost impact of material properties on their application processes is known or can be determined. In the case of a raw material with a single quality characteristic, a raw material with multiple characteristics, but independent of each other, or a raw material with multiple characteristics, that linearly and interactively affect the cost of their application process, the above analytical approach can provide a mathematical solution (i.e.: optimum quality level) in an analytical format or by means of a simple search algorithm. The application of this analytical approach is limited since the material properties (characteristics) may, in an actual case, be more complicated and not behave in the way assumed above.

System Simulation and Optimization:

With the data gathered above, we can use a computer simulation approach to model the material cost and the cost impact of raw material properties on manufacturing processes and product quality. Combining this simulation with an optimum search algorithm, we can identify the most suitable raw material properties for a particular application. After that, we can experiment with certain ranges of material properties around this optimum point in order to identify a possible suitable range of raw material properties for that application. The result of this analysis should give an effective basis for a company's policies regarding their practices for raw material selection.

Manufacturing Operations Modeling:

After we obtain the information and identify the raw material properties requirements, we can select the most suitable materials and material supplier. Since there always exists a certain uncertainty regarding material properties (i.e.: with the statistical distribution of the quality characteristics) and their cost impact, we use computer simulation method to model the cost impact on the purchasing process, the manufacturing process, and product quality. The overall cost impact can thus be determined, and the most suitable material and supplier can be identified.

Application of a Knowledge-Based Approach - Abductive Network Method [2] :

We have used an abductive network to approach this raw material selection problem. As we know, some industrial problems (system) cannot be explicitly defined or analyzed due to the limitation of our knowledge (too complicated), the associated effort requirements or cost constraints. We treat the problem as a "system". The abductive network approach can help us to transfer the valuable experience of "experts" to a systematically synthesized network, which gives us an opportunity to address the problem from another direction.

CHAPTER 2

SURVEY OF RELATED LITERATURE

This chapter presents a survey and analysis of published research literature dealing with the raw material selection problem and associated techniques. The purpose of this study is to evaluate the present state-of-the-art in this field, in order to allow us to identify areas that seem to require further work and a promising research direction.

The literature dealing with raw material selection and techniques can be classified into four categories: 1. value analysis techniques for material selection, 2. industry practice in material selection, 3. analytical economic material selection models and 4. computer simulation in the analysis of quality problems. These four groups of literature are individually reviewed and discussed in this chapter.

2.1 VALUE ANALYSIS FOR RAW MATERIAL SELECTION

Value Analysis is an organized and systematic study of the function of a material, part, component, or system in order to identify areas of unnecessary cost that could be eliminated without impairing the usefulness of the item evaluated. Value analysis is concerned with function, cost and value; it attempts to identify any possible way through which savings that can be achieved. It identifies unnecessary costs that do not add value, and it develops acceptable performance at a lower cost. Value Analysis measures the functional usefulness of items, processes, or procedures so that greatest value is obtained for the money spend. Better value is obtained by either by improving the function without increasing the cost or, by reducing the cost without impairing the function. The emphasis here, is not only on the cost, but also on value.

Four publications related to value engineering (analysis) techniques include the work by ASTME [99] in 1967, Heller [36] in 1971, Raven [77] in 1971 and Miles [60] in 1972. The above four publications, systematically present (from different perspectives) the techniques and methods of Value Analysis in industrial, military and other applications. Even a cursory review of the principles of value analysis leads us to the conclusion that its main precepts could be applied effectively to the problem of "intelligent" raw material selection. One example in material selection using value analysis was actually given in Miles' book. Based on the analysis of the problem, he stated that, by selecting "the" most appropriate material from among a large selection of possible materials, it is possible to eliminate many of the unnecessary costs incurred in purchasing.

The ASTME book describes the value analysis techniques in terms of the following general steps:

1. Select the product for value analysis
2. Determine and evaluate the function, assign dollar or cost equivalent
3. Develop alternative means to achieve the required function
4. Select alternatives, measure benefit, follow-up

These principles can be applied to raw material selection. Of course, some special aspects of the "function" and "cost" need to be clarified according to real cases and conditions encountered.

In 1966, Sharp [88], in his book "Engineering Materials: Selection and Value Analysis", discussed the considerations required in applying value analysis to material selection. At first, he stated some basic ideas of value analysis for material selection, then he pointed out the possible affect of raw materials on the actual design of the product and on the fabrication process itself. Afterwards, he gave some basic economic ideas for material selection from a pallet of different engineering material properties and their market prices. He stated that, in selecting a raw material, it is important to ensure that one is not paying for more properties than is actually required. Further, he stated that the material selected must be such that the total cost (material cost plus its manufacturing impact cost) leads to the most economic combination. He also suggested that the selection of the most suitable material for a given application depends not only on material properties but also upon the most suitable design and production method. Based on that, in assessing the economics of any given application, it is necessary to consider not only the basic material cost but also the fabrication and finishing cost involved when a given material is used. These statements are excellent guidelines for effective economic material selection by using the principles of value analysis.

In 1979, Farag [22] in his book "Materials and Process Selection in Engineering", further extended Sharp's ideas. He devoted several chapters to deal especially with the general ideas for raw material selection as well as for the selection of production process. He also pointed out that the selection of raw materials should also consider production processes involved, and that there is an interactive relationship between the raw material properties and the processes. He further proposed that the production process needs to be adapted to the requirements of the raw materials used. He proposed the following step-by-step method for economic raw material selection:

1. Analysis of material requirements
   Function requirements
   Processability requirements
   Material costs
   Reliability requirements
   Service requirements
2. Classification of material requirements
3. Development of alternative solutions

4. Evaluation of alternative materials
5. Decision regarding the optimum material

The above steps are very similar to the general value engineering (analysis) steps, but are adapted to fit the economic material selection case.

He stated that, since the material price is related to material properties then, for a particular material application, a cheaper material might not actually be the right choice if it turns out to be difficult and expensive to process.

In 1984, Thuesen et al. [100], restated that, from an "economics" point of view, when two or more materials may serve equally well from a function standpoint, the relationship of their cost, availability, and processing cost impact should be considered in determining which one is chosen. He pointed out that, in some cases, the decision to substitute one material for another may result in an entirely different sequence of processing. He also stated that to determine the comparative economic desirability of two materials, it is necessary to make a detailed study of the costs that arise when each is used.

In summary, the value analysis literature gives us the basic concepts and general ideas to be followed during the raw material selection process, but falls short regarding detailed measures or procedures. These clearly need to be further investigated for better understanding of the problem and for real, in-depth industrial applications.

2.2 INDUSTRIAL MATERIAL SELECTION PRACTICE

In material selection practice, manufacturers increasingly have come to realize that the material specification should depend on the manufacturing requirements as well as product design requirements.

In 1966, Swaton and Weaver [94] suggested a five step approach to supplier quality control. These are:

1. Categorize materials
2. Determine quality requirements to impose on manufacturers
3. Apply these requirements to the purchase document
4. Plan for and receive procured hardware
5. Follow up on correct procured hardware

These steps can be considered as a generalized rule for raw material selection practice. Manufacturers have also become increasingly aware that it is very difficult to define the "real quality requirements" for the materials.

In 1967, Burr [11] suggested that, when making the material selection, the desired distribution of material characteristics should be specified, rather than only the maximum and minimum limits, since maximum and minimum specification are often misused and misinterpreted in industry and do not emphasize what is actually important. By placing the emphasis where it belongs, it is possible to be more realistic and to achieve greater economies. In the same year, King [52] proposed a "new approach", claimed to be different from the usual material selection practice. In his paper, he stated that the traditional approach for vendor selection includes a vendor survey and vendor rating based on the results of inspection of received materials. He believes the concern over quality should ideally result in the manufacture of optimally controlled products, not merely specification-oriented conforming product. This idea is exactly the same as Burr's [11] suggestion. An example was given in his paper for comparison of the final product performance with two kinds of raw material distributions: a permissive (uniform) distribution and a superior (normal) distribution. From the results of the example, the material with the normal distribution gives a much more stable final product performance value than the material with a uniform distribution. He stressed that the raw material selection should be based on the performance of the material throughout the production process.

More recently, many researchers and practitioners have been questioning the use of interval specifications as a quality standard. In 1982, Shaw [89] pointed out that quality should be determined on the basis of the consumer's satisfaction; thus, an assessment of the consumer's perception of quality is needed for establishing an appropriate, modern quality standard. Unfortunately, he didn't consider that the material price and manufacturing cost are related to the material quality although this relationship can be very important in many cases. In the same year, Bhuyan [9] suggested that the consumer has some "ideal" value for the quality characteristic, and the consumer's satisfaction is inversely proportional to the deviation between the ideal value and the quality perceived by the consumer. Bhuyan's idea is further extended by Taguchi. In 1984, Taguchi [95] suggested that quality should be measured in monetary units and that quality cost, the cost incurred because of imperfect material quality, should be approximated by a quadratic function of the quality deviation from the ideal value. Taguchi's quality cost concept has drawn increasing attention in the last few years although quality cost concepts can be traced back to Juran's (1951) well known handbook [42] for quality control. This type of quality cost formulation is very valuable in concept. On the other hand, it is noticed that manufacturers may have difficulties to determine the real sources of the various costs that are incurred due to the improper of material characteristics.

In 1984, Pettit [73] considered the vendor evaluation problem. In his method, he identified four areas for evaluation: material quality, material price, material performance and facility capability. His approach is the most sophisticated among existing vendor selection procedures which generally concentrate mainly on evaluating the vendors' production processes without considering the interaction with producer's (buyer's) own production, quality requirements, control, and sales systems. However, estimation of the material quality cost is still a very difficult task because purchased items are often used as part of the production process and it is hard to isolate their effect on the quality cost of an individual material.

2.3 RAW MATERIAL SELECTION MODEL

Although there are not many mathematical or analytical models directly dedicated to the topic of optimal raw material selection, some techniques are reviewed here because they are closely related to our topic and deal with optimization techniques for material or production quality control.

For years, researchers have used various mathematical formulae trying to guide optimal quality control levels and material requirements from an economic perspective in order to achieve maximum profit. In many of these mathematical formulations, it is assumed that the most desirable values of the parameters of the distribution of the material quality (properties) are given and that the actual problem is to optimize the production processes or procedures for controlling the product quality.

In 1962, Bettes [8] treated a somewhat simplified version of the above problem by considering the simultaneous choosing of the optimal upper specification limit and the process level. His work showed that a normal statistical distribution for quality deviation may be used to solve some problems in manufacturing to give a certain quality specification (for quality control) in order to minimize the cost. In 1951, Springer [91] treated this problem under the assumption of constant net income functions with both upper and lower specification limits. He also assumed a gamma distribution to represent the quality characteristic. The solution he reached can not be easily applied due to the complexity of the resulting mathematical expressions. In 1977, Hunter and Kartha [41] solved the problem with one specification limit, assuming the net income function for accepted items to be linearly decreasing (expressing the give-away costs), and constant for rejected items. There is, however, no explicit solution for their assumed conditions. Nelson [67], in 1978, provided an approximate solution to what he claims to be "at least two decimal accuracy". In 1979, Nelson [68] also constructed a homograph to Springer's solution, thus making easier to use. In 1984, Carlsson [13] assumed that the quality characteristic is one-dimensional and normally distributed with a known variance. He further assumed that the net income function is a piece-wise linear function of the quality characteristic and that all items are inspected. The solution he reached is still not explicit enough to be useful for industry. In the same year, Bisgaard et al. [10] formulated another implicit solution for a similar problem.

Although the techniques mentioned above may be academically and mathematically sound and could be adapted for our economic raw material selection approach, they are however difficult to apply in an industrial setting. The main reasons for this are: 1. They make too many assumptions for the mathematical formulation, many of which may not be true, or not exactly true, in real industrial cases; 2. The solutions are too complicated to apply since most do not provide clearly usable expressions. As a result, these approaches do not give us the ability to deal with real situations effectively and easily.

In 1988, Tang [96] proposed an economic model for vendor selection. Two decision factors are considered in the model: price and material quality. In the formulation of the model, material quality is expressed in terms of monetary units, then combined with price to establish a cost-effective decision criterion for vendor selection. In his model the material quality cost is expressed by Taguchi's generalized arbitrary quadratic cost function: $c_0(y) = a(y - t)^2$, in which the consumer's ideal value of y is assumed to be t.

Assuming the raw material parameter follows a normal distribution and having a defined target value for a particular application, and using the above quadratic quality cost function, Tang [96] formulated a mathematical model to express the quality cost of a raw material. This value, combined with the raw material price, forms Tang's raw material selection criterion. In his paper, he also gave an example, using a FORTRAN program, to calculate the raw material quality costs and select the better material from among two candidate materials.

In order to support his formulation, Tang [96] mentioned that Taguchi's method [95] had been successfully used by many Japanese companies and that it has proven to be a cost-effective method for improving manufacturing processes and product field performance. In his paper, he also described the effect of the interaction between the manufacturing process r(x) and the raw material performance characteristic value x to the final product performance characteristic value y. Figure 2.1, shown in his paper, follows:

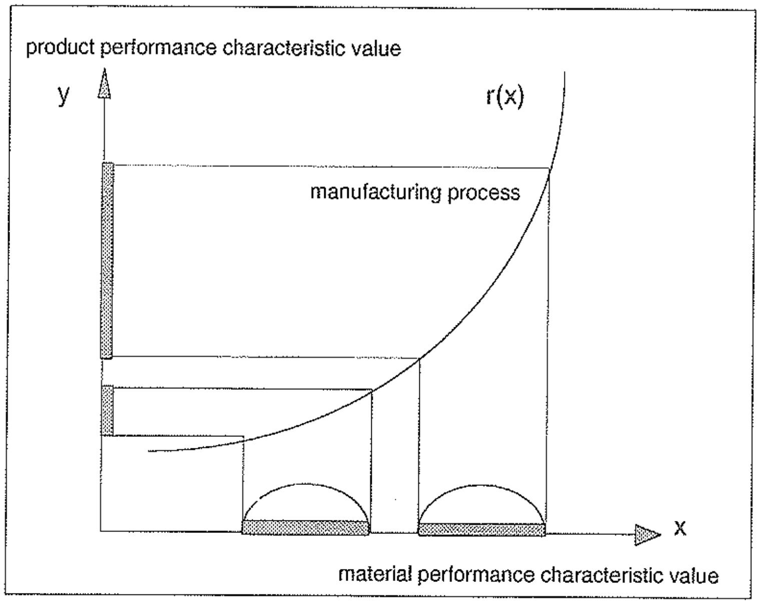


Figure 2. 1 Relationship between Material Characteristic Value and Product Characteristic Value

Figure 2.1 shows that the manufacturing process r(x) plays a very important role in the selection of the material quality characteristic. Since the effect of material properties on manufacturing processes vary with different situations, his mathematical formulation does not include the impact of the manufacturing process on his raw material selection criterion, but includes a vague quadratic quality cost function. The contribution of Tang's model lies in his transferring of the raw material economic selection idea to a systematic and scientific decision process by mathematical expressions and calculations.

Even so, Tang's model [96] exhibits several problems, which strongly detract from their industrial application.

First, using Taguchi's quality loss function [95, 96] as the material cost cannot always represent the real cost effect of the selected material. In 1992, Sprow [92] pointed out that, although the concept of the quality loss function is very good, "nobody knows the actual loss-function curve, it is a concept nobody can define, and it would be different for every product. The basic message is simple, there is no need to complicate it with loss function.". In industrial situations, the total cost effect of a selected material depends on many factors, which include the manufacturing process, product function, customer requirements, etc. Thus, the cost effect of material may not be a well defined quadratic curve, but could be made up of step lines or any type of curves, or mixed combinations. To analyze the total cost effect, we need to dig in for a more detailed analysis that reflects real circumstances.

Second, Tang's model [96] only considered the effect of one raw material performance characteristic value (parameter) on the material cost or cost effect in its application. In actual cases, several material parameters may affect the total cost effect (costs on production processes as well as on product quality) of the material.

Third, Tang [96] mentioned the cost effect of the interaction of manufacturing process and material only in conceptual terms. In many industrial cases, the manufacturing processes are quite complex, different processes may "prefer" different raw material parameters and the related effects on cost may be different for each process.

As a result, Tang's mathematical model is not really satisfactory for use in industrial material selection.

2.4 COMPUTER SIMULATION IN THE ANALYSIS OF QUALITY PROBLEMS

Because of the complexity of industrial problems, mathematical and optimization models and techniques usually have difficulty in representing most industrial quality problems. In order to approach real industrial problems, computer simulation becomes an increasingly attractive method. In 1977, Lester et al. [54] pointed out that simulation can be used to imitate real world relations, and the greater the similarity of the simulation variables to actuality, the more useful will be the study. A sampling plan for material quality inspection and product quality inspection is given by them as an example in the search for the optimal amount of inspection required for raw materials as well as for each production operation. From successive outputs of their simulation runs, an optimal procedure for quality inspection is revealed. In 1978, Dalal [18] gave a case study of a simulation example to search for optimal production and process control in order to achieve a better quality product. A dynamic mathematical simulation model helped the manufacturer (in this example) to select the optimal operating conditions. In 1984, Buzacott and Cheng [12] used computer simulation to model quality control system in an assembly line. The simulation model enables the user to answer questions such as: where to carry out the tests and the inspections? How much inspection and testing is required? What incoming quality should be required of each component? What quality level should be sought of the individual processes? and so on. Their quality simulation model can serve as a powerful tool for users to gain insight about the behavior of the system and to explore the optimal process parameters of each process as well as the structure of the system. (In fact, this is what we are interested in as well). In the same year, Peters and Williams [72] used computer simulation as a tool to establish an effective quality program for the inspection and testing of critical product attributes. Their simulation model can answer "when and where" in the production process should the actual inspection be performed. It appeared plausible that not all potential quality checking location are economically equivalent; more likely, given differentials in cost structures and process characteristics, some combinations of inspection sites may prove to be economically preferable to others. Five heuristics were evaluated and the economic trade-off relevant to a given inspection plan were investigated. Some similar quality inspection planning approaches using computer simulation were also given by Palaniswami and Hassan [70] in 1988 and by Saxena et al. [85] in 1990.

In summary, we can conclude that computer simulation, as an approach to economic quality inspection planning has been widely studied, recognized and proven to be useful to industry. Unfortunately, much of the simulation work in this area is only limited to problems of quality inspection planning. No simulation work in the published literature has been found to be directly related to economic raw material selection problems. We believe that computer simulation, can be a very powerful tool to effectively study and assist in making cost effective material selection decisions.

2.5 CONCLUSIONS

The literature related to value analysis provides general guidelines for raw material selection, but no detail method is available. The literature related to industrial practice looks at the problem mainly from an every day practice point of view to judge the material available from suppliers, but systematic cost structures to minimize to overall total cost, have not been given. The literature related to material selection models does provide some mathematical optimization and economic formulations, but too many assumptions make these models ineffective in representing the reality of industrial problems and the solutions are always too implicit to be applied and easily understood. The literature related to computer simulation mainly concentrates on economic inspection planning. No work is found on the economic raw material selection problem. We thus conclude that, although some research work has been done, there are no systematic approaches available to provide some generalized guidance for this common industrial problem.

In this research, we will absorb some useful ideas from the literature and develop a systematic, effective and applicable economic raw material selection strategy. The main aspects of our research are:

1. We have used the basic ideas of value analysis. To define a better material, we consider whether it brings more benefit or value than the "extra" expenses associated with it. In our model, we consider all types of cost impacts of a material on its application process. Our raw material selection criteria is defined as its "total overall cost impact".

2. To indicate its industrial application, we use a realistic example for most of our analysis. We first define or analyze the requirements for the material quality, then, provide a systematic solutions for this particular problem.

3. A new analytical approach is demonstrated to guide this raw material selection approach. A series of equations are developed which can be used for raw material selection practice. We also realize that the application of this approach is limited since certain assumptions must be adopted for this approach.

4. We use computer simulation and optimization techniques in our analysis. This techniques can model the material application processes and the simulate various costs incurred, and can provide a systematic and advanced tool for detailed analysis of this complicated problem.

5. A knowledge-based approach - abductive network approach is applied in this research. We demonstrate the usefulness of this method in the raw material selection problem. Some advantages of this technique are also addressed.

CHAPTER 3

AN ECONOMIC MODEL FOR RAW MATERIAL SELECTION

An economic model for raw material selection is presented in this chapter. The model considers three decision factors: raw material cost, additional manufacturing costs due to material characteristics, and additional product quality cost incurred due to inappropriateness of raw material quality. The "additional manufacturing cost" may include items such as: extra operator costs, extra machine costs and extra quality costs.

3.1. INTRODUCTION

Typically, an end product consists of an assembly of many separate components. Since each part may have its own specific function(s) within the product design, each may have individual raw material requirements. These requirements are mainly due to the specific part's manufacturing process as well as its specific quality requirements. Raw material of inferior quality may cause material losses, production delays, unnecessary machine costs and possibly result in a poor quality end product. On the other hand, without a thorough and systematic analysis of raw material quality requirements, the effort to produce a product of high quality may result in unnecessary expenditures on raw materials of higher quality than are really needed. This may adversely affect the product and make it uncompetitive in the market. Technically and economically correct raw material selection can, on one hand, satisfy local manufacturing requirements as well as meeting customer concerns, while at the same time, reduce unnecessary costs incurred by purchasing "overqualified" supplies.

The aim of this chapter is to introduce a technically and economically appropriate model for the selection of raw material quality, optimally satisfying the technical requirements of the specific manufacturing process as well as meeting the product's specifications and the customer's needs, at minimum cost.

From our literature review in Chapter 2, we noted that Tang [96] proposed an economic model for vendor selection in 1988. His model was based on material price and material quality. In his paper, Tang suggested in passing, that material quality be expressed in monetary units. He established a cost-effective decision criterion model by combining the material quality and price in an analytic format. He mentions a special computer program for the cost calculation of a simple example. But, as stated by us previously, there are some limitations in his model. First, Tang's model includes only the cost of product quality, but not the production cost nor other costs. Second, the Taguchi quality cost function [95] used by Tang [96] cannot always represent the real quality cost exactly. In many real cases, the cost function needs to be modified or deduced from real circumstances. Third, Tang only considered the effect of one raw material parameter on material cost. In most real cases, however, several material properties may affect production process and product quality at the same time. These real limitations make applications of Tang's model very difficult, or even impossible, in real manufacturing environments.

To make such an analysis more applicable, our approach attempts to include all cost factors associated with a raw material that may have some effect on the manufacturing process and product quality. Our model allows the consideration of all cost parameters of interest, including Taguchi's quality cost function. In addition, our model allows for the influence of many material parameters and permits the interaction between them. We believe that, although these modifications may make our proposed model somewhat more complex, it may, as a result, be more applicable and more realistic.

3.2 APPROACH STRATEGY

In order to select an appropriate material, one should consider its unit cost and its eventual impact on the proposed manufacturing process and manufacturing (i.e. end product) costs. Here, manufacturing costs include, among others, operator costs (cost due to operator's time), machine costs (cost due to machine maintenance and supplies) as well as quality costs (cost due to quality problems). We believe these three costs essentially cover all pertinent costs typically associated with raw materials. If one wishes to consider other special costs, these can be easily added, since the model is an open one. In all of the costs mentioned above, only "additional" costs (i.e.: costs incurred above the normal costs due to non-ideal raw material conditions) are included in our cost calculation. The cost for ideal raw material conditions is not included in the model. This approach allows us to reduce the requirements for cost information to a minimum. For example: if because of working with some inferior quality material an operator needs two minutes to finish an operation, but needs only one minute when working with a material of ideal quality, the "additional cost" - or operation time, is only one minute. Hence, the operator cost in our calculations would be the cost for the "extra" one minute, and not for the total two minutes required for the task.

Assuming that a product part uses some raw materials, there are several quality parameters to be considered for each. The raw material cost is decided by these parameters and by their degree of variation on the market. Each material parameter has its own effect on the manufacturing processes to which the material will be subjected, and on the product properties (including cost) required by the customer. Parameters may interactively influence the manufacturing process(es). To address this, we develop a "mixed" parameter as the acting parameter, in order to analyze the material's effect on the cost. We define those parameters which directly affect the processes as acting parameters whether they are single or mixed parameters. To analyze the costs associated with the raw material, we need to analyze the effect of each of these acting parameters on each of the associated processes and on the resulting costs.

3.3 THE PROPOSED RAW MATERIAL SELECTION MODEL

Assumptions:

A-1: Assume that there are n manufacturing processes (called p_1, p_2, ...,p_n) associated with each raw material.

A-2: Assume that each raw material has m acting parameters called r_1, r_2, ..., r_m.

A-3: Assume that the operator cost, machine cost and quality cost in process i on parameter j at the condition given by the parameter values at a point "x" are given by $O_{ij}(x)$, $M_{ij}(x)$ and $Q_{ij}(x)$ respectively (see Fig. 3. 1).

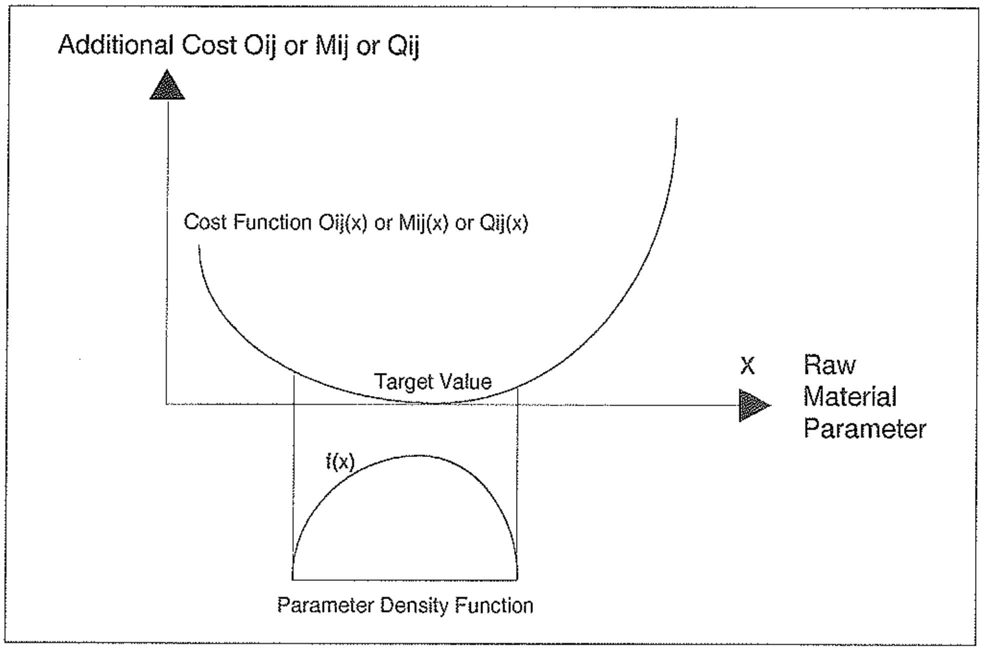


Figure 3. 1 Additional Cost Function Related to Raw Material Parameter

When the value of parameter x changes, all the costs associated with this particular raw material may change accordingly. When this value of parameter x is at the "ideal" level, all of the associated costs would be at a minimum level (remembering that costs, in our case, mean "above-normal" costs).

The cost per unit of raw material is labeled as RMC.

RMC includes direct raw material price as well as various material handling costs before it is used.

Typical material parameter ranges are taken as:

Parameter 1: from a_1 to b_1;

Parameter 2: from a_2 to b_2;

......

Parameter m: from a_m to b_m.

Assume that the raw material parameters r_1, r_2, ..., r_m fit distributions: $f_1(x)$, $f_2(x)$, ... $f_m(x)$ respectively (Fig. 3. 2).

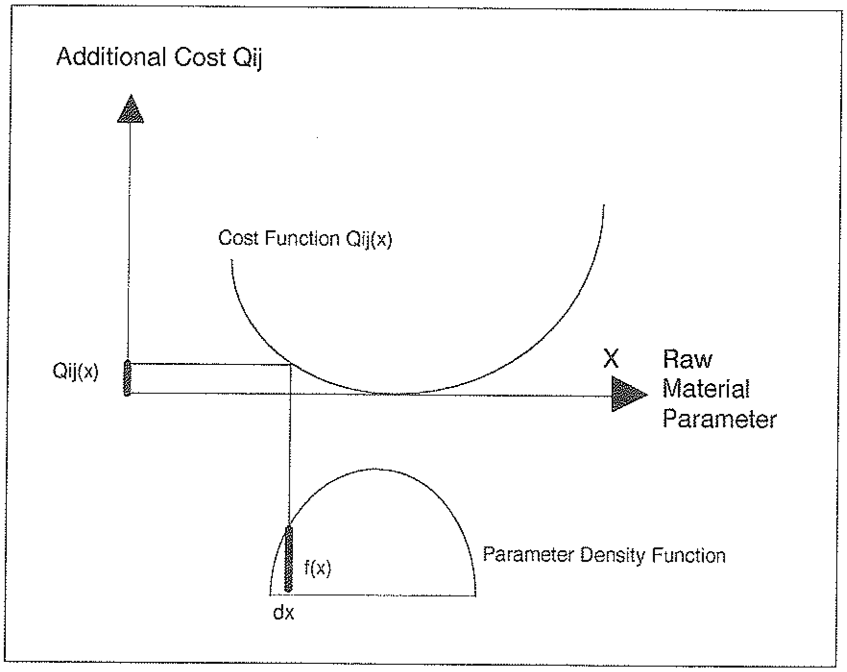


Fig. 3. 2 Additional Manufacturing Cost Calculation

As stated previously, the manufacturing cost in process i associated with parameter j for each material includes the "extra" operator cost, machine cost and quality cost.

From Fig. 3.2 -- we can express, for parameter 1 on process 1, the manufacturing cost as:

$$\int_{a_1}^{b_1}\{O_{11}(x)+M_{11}(x)+Q_{11}(x)]df_1(x) \tag{3.1}$$

For parameter 1 on process 2, the manufacturing cost is:

$$\int_{a_1}^{b_1}[O_{21}(x)+M_{21}(x)+Q_{21}(x)]df_1(x) \tag{3.2}$$

For parameter 1 on process n, the manufacturing cost is:

$$\int_{a_1}^{b_1}[O_{n1}(x)+M_{n1}(x)+Q_{n1}(x)]df_1(x) \tag{3.3}$$

Hence, for parameter 1, the total manufacturing cost MC on all processes associated with this material can be expressed as:

$$MC1=\sum_{i=1}^{n}\int_{a_1}^{b_1}[O_{i1}(x)+M_{i1}(x)+Q_{i1}(x)]df_1(x) \tag{3.4}$$

Similarly, for parameter m, the total manufacturing cost over all processes associated with this material is:

$$MCm=\sum_{i=1}^{n}\int_{a_m}^{b_m}[O_{im}(x)+M_{im}(x)+Q_{im}(x)]df_m(x) \tag{3.5}$$

For all parameters from r_1 to r_m, overall associated processes p_1 to p_n, the total manufacturing cost is then:

$$MC=\sum_{j=1}^{m}MC_j \tag{3.6}$$

$$MC = \sum_{j=1}^{m} \sum_{i=1}^{n} \int_{a_j}^{b_j} [O_{ij}(x) + M_{ij}(x) + Q_{ij}(x)] df_j(x) \qquad (3.7)$$

The raw material selection criterion (RMSC) can be defined by:

$$\mathrm{RMSC} = \mathrm{RMC} + \mathrm{MC} + \mathrm{QC} \qquad (3.8)$$

QC: Quality Cost of the Final Product

QC represents the impact of the raw material on final product quality. This cost may include the cost of product rejection by customers and the cost of detrimental impact on company image caused by a poor quality final product. This cost also indicates the above "normal" cost due to the use materials with non-ideal properties.

If several possible raw materials are available for selection, the raw material with the lowest RMSC value would be the best candidate since it would offer the lowest total cost.

In order to make high-quality decisions, it seems logical to require high-quality information inputs. Hence, for this type of analysis, in which the various costs form the basis for the analysis, the correct raw material selection depends clearly on the accuracy of the cost information.

Under realistic conditions, the material parameter variations may follow normal (or any other) distributions while costs may follow various types of functions (continuous, step, etc.). This may make our MC expression very complex and difficult to formulate in an analytic form. This difficulty does not really affect the solution of the underlying problem since the actual analysis is quite straightforward.

In order to solve such realistic, complex problems, we suggest that computer simulation would probably be the most suitable method to proceed with our proposed cost calculation model. Computer simulation can easily handle any type of raw material parameter distribution to represent real statistical conditions. From the parameter distribution and associated cost data from the function, the manufacturing cost can be obtained easily. The raw material selection criterion (RMSC) can be obtained accordingly. Each product part needs to be analyzed separately as regards its planned manufacturing process to find which raw materials fits most economically. The combined information can provide a very useful input into the product's manufacturing and decision-making process.

3.4 MIXED INDEX HANDLING

It is common that manufacturing cost is affected by the combination of several raw material properties interactively. A realistic example is that the machine (die) wear of a press in a pressing operation is affected by both sheet thickness and steel hardness [24, 90]. In industrial cases, raw material properties may interactively work together in many ways to affect the manufacturing cost. It could be difficult to analyze the real impact of each material property on the additional manufacturing cost separately simply because each acts interactively with others. Two typical problems are introduced here to show some techniques in dealing with these problems.

One case is when two (or more) material properties may work together in a similar way to affect the manufacturing process. For example, sheet metal in pressing operation, the **thickness** and **yield strength** are two material properties affecting the formability [90]. The thicker the sheet metal and higher its yield strength, the more difficult it is to bend the metal sheet. Since they work together to affect the formability, we cannot find out their relationships with the formability individually; we need to determine a mixed index to represent the effect of both of them together. Assuming x_1 represents yield strength and x_2 represents thickness, then the mixed parameter x can be expressed as $x = f(x_1,x_2)$. A useful method that may be used to determine the relationships between x and x1 and x2, is to set the two parameters x_1, x_2 at several levels, and carry out a series of bending experiments, and then to correlate the relationship between the two properties and the mixed index - formability of metal sheet. After knowing the relationships, the statistical distribution of parameter x can be obtained through simulation analysis or analytical analysis of the two known statistical distributions x1 and x2. The additional manufacturing cost MC_{ij} can be expressed and analyzed as $MC_{ij} = g(x)$. Then, g(x) is the function relating the material mixed index (combination of steel hardness and thickness) and the extra manufacturing cost.

Another case considers the situation when two (or more) properties may work interactively in a dependent way to affect the manufacturing process. As we stated before, we cannot analyze them individually, simply because they work interactively. One example of this, for our case, would be the welding operation for connecting two sheet metals. The **thickness & hardness** together with the **amount of oil** on the sheet metal interactively affect the weldability [24, 27]. If the welding energy is too large, the welding heat may burn through the sheet (which counts as defect). If the energy is too low, the welding strength between sheet metals may be not enough (also resulting in a defect). The thicker and harder metal can withstand higher energy levels that result in a stronger weld. Heavy oil coatings require high welding energy to burn through the oil film before the real welding starts. As a result, we can identify several possible cases in this situation:

1. Thick and hard metal sheet with a little oil on the sheet: a perfect welding can be achieved.

2. Thin and soft metal with a little oil on the sheet as well as thick and hard metal with heavier amount of oil on the sheet: may achieve a good weld if the proper welding energy is used.

3. In the case of thin and soft metal with a high amount of coating oil on the metal sheet, direct welding may cause either a "burn through" or a "missed weld" since thin and soft metal can only withstand a low welding energy level while a large oil amount on the

metal sheet requires a much higher energies to burn off the oil before the actual welding process.

Thus, the weldability depends on the relationship between the thickness & hardness and the oil amount on the metal sheet.

Assume x represents the combination of yield strength and thickness and y represents the amount of oil. The base relationship for a marginal weld between them could be expressed as x = f(y), which means that, for a certain oil amount y on the metal sheet, the weldable thickness and yield strength of the metal should be equal to or larger than x.

This relationship also may be obtained by a series of welding experiments. The method requires the setting of the parameters at several levels in order to determine the relationship between the mixed index and the "oil amount" in the welding process. From the above analysis, we know that two (or more) parameters need to be used at same time in order to analyze the cost. The extra manufacturing cost MC_{ij} can be expressed by $MC_{ij} = g(x,y)$. The g(x, y) is the combination effect of the raw material parameters x and y on the extra manufacturing cost.

In practical situations, the interaction between the properties of the raw material may be more complicated than illustrated in the two examples above. However, based on the above approaches and through an analysis of their relationships, the correct expression between parameters may be determined for further manufacturing cost analysis.

3.5 CONCLUSION

A new raw material selection model is proposed. The criterion for the selection of technologically and economically optimal raw materials is the combination of material cost, extra manufacturing cost and quality cost of final product. The extra manufacturing cost is based on costs associated with any specific raw material obtained from detailed analysis of the manufacturing process to which that raw material will be subjected. The actual manufacturing costs used in our model are the "excess" costs experienced as a result of that raw material's incomplete compliance with "ideal" specifications and is expressed in terms of "extra" operator costs, "extra" machine costs and "extra" quality costs.

Due to the complexity of real industrial problems in terms of the expression of all required factors in the appropriate analytic relationships, we suggest that they be solved by means of computer simulation methods.

CHAPTER 4

CASE ANALYSIS: PART 1

MANUFACTURING PROCESS AND PRODUCT QUALITY ANALYSIS

The Chapter 4 and Chapter 5 deal with the collection and organization of data for use in the subsequent simulation study. The data collected in this study was obtained from the following sources: 1. Literature review; 2. Conversations with the manufacturer; and 3. Our best educated estimations. The data collected is only a rough estimation of the actual case. They are only used as a background material for our approaches.

In this chapter, various manufacturing problems related to material properties are described, and the relationships between material properties and their effect on different manufacturing processes are analyzed.

4. 1. GENERAL STATEMENT

The following discussion uses our industrial example as a vehicle.

The manufacturing process for the ceiling diffuser products can be simplified as shown in Figure 4.1:

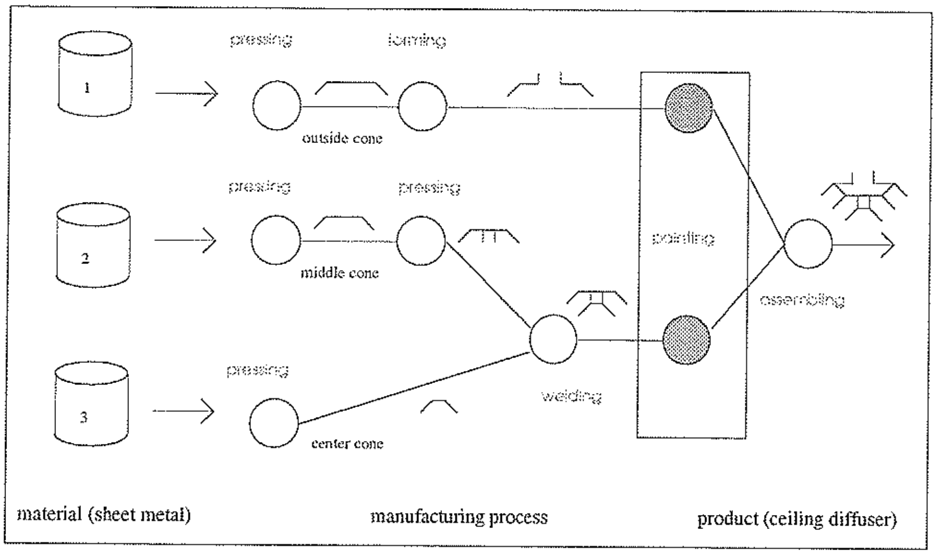


Figure 4.1 A Simplified Ceiling Diffuser Production Line

From Figure 4.1, it can be seen that the ceiling diffuser product is assembled from three main parts: the outer cone, the middle cone and the inner cone (as well as some other small components). Due to the thickness of the sheet required, the raw materials for these three cones are all cold rolled (instead of hot rolled) low carbon steel sheet. After the pressing, forming, welding, painting and assembly operations, the product, then, is ready for packaging and shipping. Since each part experiences different manufacturing processes and plays different functional roles in the final product, each has different raw material sheet properties requirements. Our example analysis concentrates on the material requirements for the Outer Cone of the ceiling diffuser.

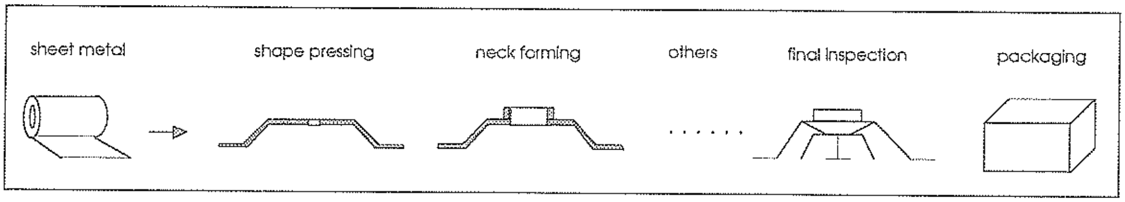


Figure 4. 2 Manufacturing Operations of the Outer Cone

We can see that the sheet metal for the outer cone experiences pressing, forming, painting, final assembly, final inspection and packaging operations. Pressing, forming, final inspection and packaging operations (see Figure 4.2) are our interests in this analysis since we believe the painting and assembly operations are not (or not significantly) affected by the sheet metal properties. Our analysis concentrates on how sheet metal properties affect the operations.

4. 2 SHEET METALS

There are two types of processes to produce sheet metal: hot rolling and cold rolling. As it is known that the variation of properties is greater for hot rolled than cold rolled materials [58] and that the hot rolled method is limited to producing relatively thick sheet metals (> 1.2 mm or > 0.045 in.). For the ceiling diffuser application, only cold rolled low carbon steel (0.35 - 2.0 mm or 0.014 to 0.082 in.) can be considered.

Low carbon steel sheet comes in three types of quality: commercial quality, draw quality, and draw quality special killed. Each of these three types of products also has a series of grades corresponding to the carbon contents in the metal [46]. Since different materials have different chemical components, their mechanical properties are different (see Figure 4.3).

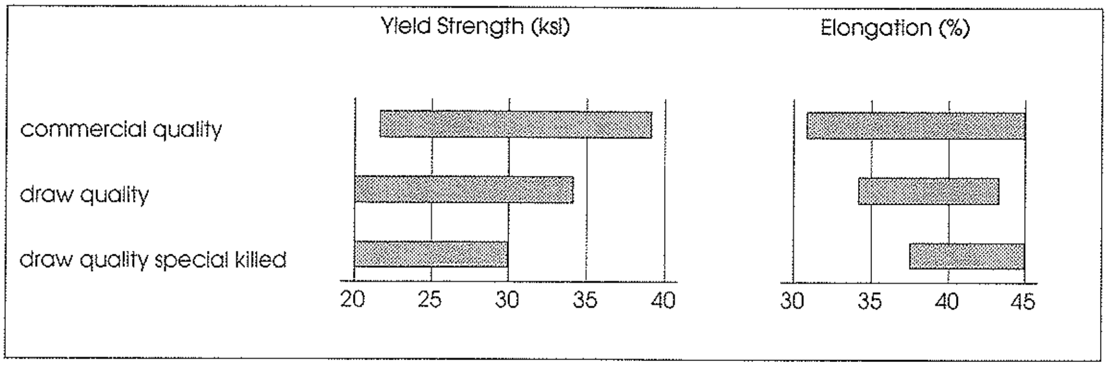


Figure 4.3 Two Mechanical Properties of Three Types of Sheet Metals

Since commercial quality materials exhibit the biggest variations and widest ranges of properties, they, of course, have the lowest price in the market. Draw quality special killed sheet metals exhibit the least variation and show the narrowest range of properties. Draw quality sheet metals lie in the middle. Among these three general quality types, there is a significant overlap of property values for all qualities. The higher the quality, the better and more uniform the properties. For example, in the commercial quality, the total elongation (important to shape formability) is in the range of 32% to 45%. In draw quality, the total elongation is in the range of 34% to 43%. It is possible for a company to buy a material with a low price but still with adequate quality specifications if the company knows the real technical requirements of the material for a particular application.

Both commercial quality and draw quality sheet metals exhibit the problem of "aging" [46,83,90]. The aging problem has two affects on the application of the metal: one is a loss of ductility and the other results in stretcher straining and fluting problems during forming. To avoid or reduce the effect of aging, some or all of the following measures may be used:

1. Prompt use of sheets;
2. Effective roller leveling;
3. Reduction of delay between draws;
4. Avoiding exposure of sheet to over-heating condition.

For different application, different mechanical properties are preferred. For bending processes, the thickness and the yield strength of the sheet metal are considered to be the most important factors. For drawing or stretching processes, the elongation, thickness and hardening exponent are considered to be most important. The most common parameters for description of sheet metals include: tensile strength, yield strength, uniform elongation, total elongation, hardness and thickness.

4. 3. MATERIAL CHARACTERISTICS

4.3.1 Material Characteristics

There are many characteristics which can be used to describe the properties or characteristics of sheet metals. These include chemical content (carbon content, etc.), mechanical properties (tensile strength, yield strength, total elongation, uniform elongation etc.), formability (form limited diagram, hardening exponent, strain limiting coefficient, cup-height etc.), and other properties (thickness, width, hardness etc.).

To a general manufacturer of steel sheet products, the material hardness and material thickness are the most common characteristics used for material testing due to the easiness of their measurement. The problem is that these two characteristics are not good enough to make effective predictions and can not be directly related to its manufacturing processes. If suitable facilities for sheet material testing are available, more material characteristics can be examined and thus provide more information to assess the impact of those materials on the manufacturing processes and product quality. Unfortunately, some properties are very difficult to obtain, or the general manufacturer may not have the facilities to do the testing. To best describe the effect of materials on their application, we choose here three material quality parameters to describe the sheet material: material thickness, material yield strength and total elongation. These three parameter are relatively easy to get and most importantly, from the investigation of previous research work, can be used effectively to describe the impact effect of the sheet material on the applications investigated.

4.3.2 Relationships Between Yield Strength and Total Elongation

The yield strength and total elongation are two of the mechanical properties we consider. These two properties are closely related to each other. Generally speaking, if a metal has high yield strength, it will have a low total elongation value.

In some application, we may have different expectations or preferences about different properties. For instance, if we need a metal to have good stretchability, we expect the metal to have a higher percent total elongation; but, if we need a metal piece to have a solid structure for handling, we require a metal with higher yield strength. If we need both of them at the same time, then we need to make some trade-off between these two properties. The material which best satisfies the requirements should have adequate total elongation as well as enough yield strength. To make an effective selection, we need to understand the relationship between the mechanical properties of the metals in detail.

There is no clear or explicit relationship between these two properties, but we know they relate to each other. A simple method to find their relationship is to make a series of experiments on sheet metals for these two properties, then relate the properties data in a linear or quadratic form. The more data collected for the analysis, the more accurate a relationship may be reached.

The data used for our analysis is based on the data presented by Hecker [34] in 1977. The data is shown in Appendix A. All materials tested are low carbon steel sheet and the tensile specimens were prepared in accordance with ASTM specification E-8. The specimens were tested at a strain rate of 2×10^{-3} /s. All properties data are an average value of tests taken at 0, 45 and 90 degrees to the rolling direction.

The yield strength (ksi) and total elongation data [34] are shown in Figure 4.4:

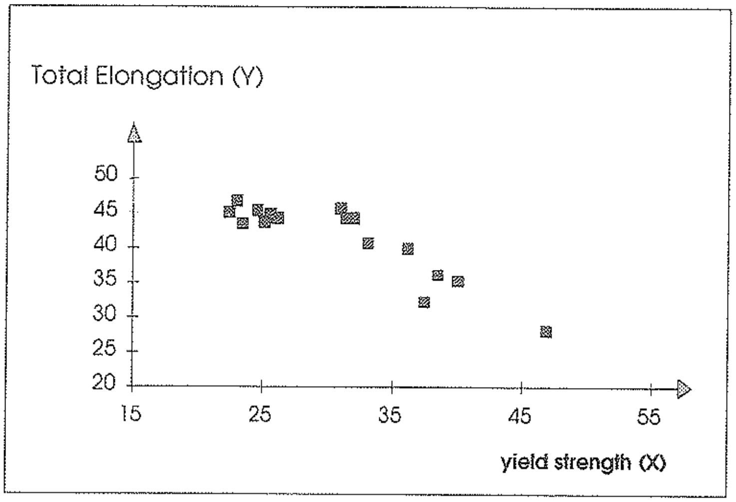


Figure 4.4 Total Elongation and Yield Strength of Low Carbon Sheet Steel

We assume that, X represents yield strength (ksi); Y represents total elongation (%); a linear equation Y = a + bX represents the relationship between yield strength and total elongation. From a least-square approach used to correlate these data, we obtained:

a = 61.89, and b = - 0.67. The resulting linear equation becomes,

Y = 61.89 - 0.67 X with a correlation coefficient of - 0.8943, estimated standard error of slope = 0.0865, estimated standard error of intercept = 2.73, estimated standard error of estimate = 2.475, and percent of variance explained = 0.7997.

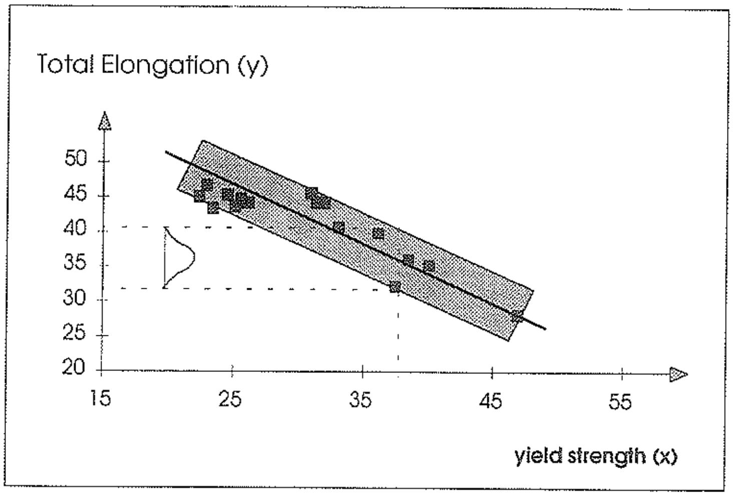


Figure 4.5 Relationship Between Yield Strength and Total Elongation

Using the above approach, if we know the yield strength X, we can predict the possible range of the total elongation Y of the metal with a desired confidence.

For a 100(1-α) percent confidence, the interval for the value y at a fixed x can be described as:

$$y = \overline{y} \pm t_{\frac{\alpha}{2}}(n-2)(\text{estimated standard deviation of } \overline{y})$$

For the above condition of n - 2 = 15, with a 95% confidence level (α equals 0.05), we obtained the value of $t_{\frac{0.05}{2}}(15)$ equal to 2.13 from the t-distribution table. Since the estimated standard deviation of $\overline{y}$ is 2.475, therefore, the value of $t_{\frac{\alpha}{2}}(n-2)(\text{estimated standard deviation of } \overline{y})$ reaches 5.27.

So, the following relationship between yield strength x and total elongation y is obtained:

$$y = 61.89 - 0.67x \pm 5.27$$

4. 4. PROBLEM INTRODUCTION

To understand the impact of sheet metal material on the manufacturing processes and quality aspects, we need to analyze all possible problems caused by material properties. The sheet material properties here include metal thickness, yield strength and total elongation.

As we mentioned before, only the operations related to the sheet metal raw material properties are of interest to us. As for affected manufacturing operations, we are interested in the shape pressing operation (to form the right shape), the neck forming operation (to form the neck), the packaging operation and the final quality.

We can classify problems caused by sheet metal material into three categories: personnel involvement (operator cost), machine involvement (machine cost) and quality involvement (quality cost).

The information presented in this section mainly comes from the conversations with production workers, engineering staff and management personnel [24]. Some simplistic analysis of these problems and their related cost impact estimations are given in the next section.

a) In the shape pressing operation, the analysis can be done as follows:

(i) operator cost (reason: pickup problem)

Pickup problems in the shape pressing operation reduce the production rate or productivity. It is due to the metal being too thin and/or with too low a yield strength, so that the metal sticks on the press or die after the pressing operation [27]. At that point, one needs to manually separate the part and the die (or press) after the press is released.

(ii) machine cost (reason: extra die wear)

Very high pressing forces used in the pressing operation increase the machine wear, the machine and die maintenance costs and, to some extent, reduce the useful life time of the press and the die used [24]. High press forces are caused by the metal being too thick and the yield strength being too high, therefore a higher force [90,101] is needed to bend or stretch the metal to the required shape.

(iii) quality cost (reason: shape springback)

If the springback problem effect is too serious, the shape of the part may affect the acceptance of the product [24]. Springback problems are mainly due to the metal having too much yield strength [90]. Since we only deal with low carbon steel sheet (with relatively low yield strength) and the shape of the end product is not very critical for its application, this problem is not serious enough to be considered here [24].

b) In the neck forming operation, the analysis is as follows:

(i) operator cost (reason: pickup problem)

This is the same problem as discussed in the shape pressing operation. The effect of this problem is not serious enough [24] to be considered in this operation in this example.

(ii) machine cost (reason: extra die wear)

This is the same problem as discussed in the shape pressing operation.

(iii) quality cost (reason: problem of neck cracking)

Neck rips caused during the neck forming process reduce the level of customer acceptance. They are caused by the metal being too brittle (low elongation) for the stretch it is required to undergo [46,47,48,49,50,51,59]. This problem is less likely to occur if the material ductility (total elongation) increases and the material thickness increases [59]. Ripping problems are also less likely to occur as the neck diameter increases and the neck height decreases because the required proportional amount of stretch is reduced.

c) In the packaging operation, the analysis is as follows:

(i) packing cost (reason: extra packing material and effort)

Product packaging is a decision based on the metal thickness. When the metal is too thin, extra packaging material and effort is required [24], thus resulting in more sophisticated packaging necessary to prevent bending during shipping. The packing cost is more likely to increase as the material thickness decreases.

d) In the final quality inspection operation

(i) final quality cost (reason: part rigidity cost)

Poor final product rigidity increases the product shipment damage, product installation damage and adversely affects the company's image [24]. The product rigidity is affected by the metal thickness and yield strength [101]. Although the product structure design affects the product rigidity (a box like shape is more rigid than a flat surface), the thicker and the higher yield strength of the material. the better rigidity of the product [101].

e) Product acceptance by customers

Unsatisfactory product quality in the eyes of the customer may increase the overall product cost and reduce the company's image to customers [24]. There are three possible problems related to our analyzed part.

(i) the shipment damage problem [24]:

It is less likely to occur as the product rigidity (the combination of material thickness and the material yield strength) increases [101]. It is also affected by the packaging design.

(ii) the installation damage problem [24]:

It is less likely to occur as the product rigidity (the combination of material thickness and the material yield strength) increases [101]. It is also affected by the product structure design.

(iii) the neck ripping problem [24]:

The neck ripping defects will be less likely if the company has tighter inspection criteria. It is also less likely if the material has better stretchability and the product has a lower stretch requirement [27].

In the modern competitive manufacturing environment, a zero defect level is the target for many companies and the defects should not fall into the customers' hands. In our later investigations, we assume all of the problems which may be received by the customers can be inspected and eliminated before the products are shipped to the customers. In our case, if the final inspection (rigidity) is tight enough and the packing is safe enough, the shipment damage and installation damage should be avoided. If the neck forming quality is inspected strictly enough, the product with a ripped neck would not get into the customers' hands. We assume hereafter that the customers always receive quality products and thus, customer acceptance will no-longer be discussed in cost terms.

The problems presented above are real concerns to manufacturer. Selecting the right material may help to eliminate or to reduce the above problems and related costs.

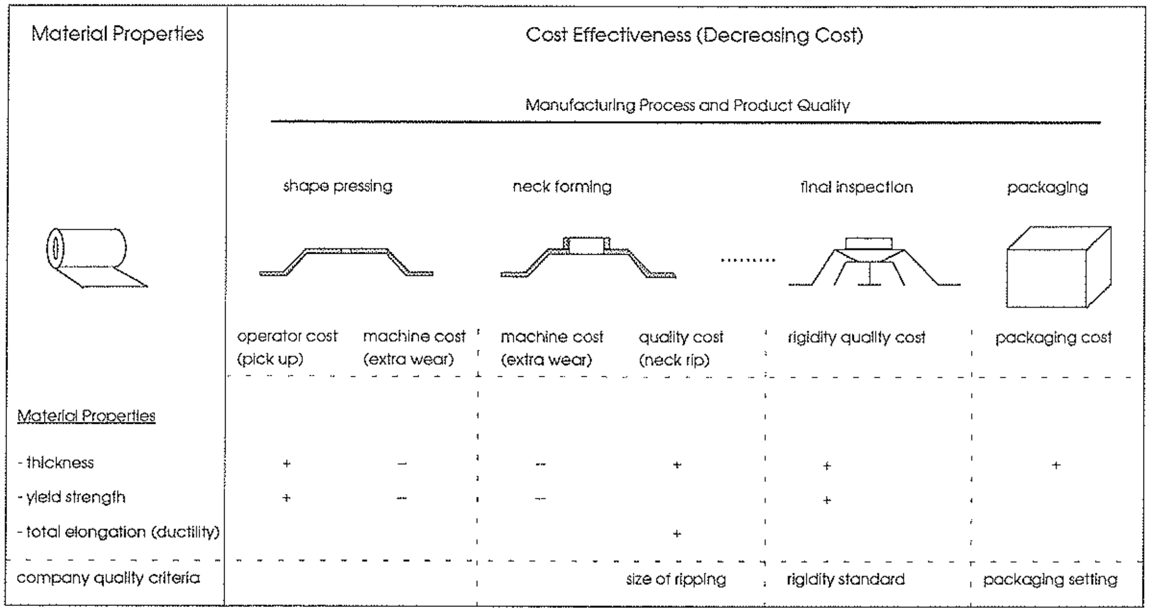
4.5 PROBLEM ANALYSIS

As discussed in the previous section, material properties have certain impacts on various costs in the manufacturing processes. To analyze the seriousness of these cost impacts, we need to address these problems in more detail.

Due to its length, this detailed analysis is given in Appendix F.

4. 6 CONCLUSION

In conclusion, a review of all manufacturing problems we have discussed are given as follows (Figure 4.6):



	shape pressing		neck forming		final inspection	packaging
	operator cost (pick up)	machine cost (extra wear)	machine cost (extra wear)	quality cost (neck rip)	rigidity quality cost	packaging cost
Material Properties						
- thickness	+	—	--	+	+	+
- yield strength	+	--	--		+	
- total elongation (ductility)				+		
company quality criteria				size of ripping	rigidity standard	packaging setting

Figure 4.6 Summary of the analysis of the manufacturing problems

In Figure 4.6, the negative sign "--" means negative impact on the cost and the positive sign "+" means positive impact on the cost. The most suitable material for this application would then be the material with the lowest overall cost which includes the manufacturing and product quality costs discussed above, and the raw material cost itself.

CHAPTER 5

CASE ANALYSIS: PART 2
PURCHASING PROCESS ANALYSIS FOR SHEET MATERIAL

This chapter is the continuation of the previous chapter on data collection and organization. It deals with the material purchasing operation and the related costs. Two kinds of material suppliers and the related purchasing processes are presented. The various costs incurred during material purchasing operations are also discussed (the data shown in this chapter are based on conversations with employees of a local material supplier as well as on our best educated estimation).

5. 1 INTRODUCTION

In general, for a particular type of raw material, manufacturers have some alternatives to purchase from several different suppliers. Effective selection of materials and suppliers sometimes may significantly reduce purchasing operation expenses as well as reduce manufacturing process costs affected by the materials purchased .

The raw material used for the case analyzed by us is cold rolled low carbon steel sheet. This type of metal is a typical material for steel sheet products and is usually available from several suppliers. Different suppliers may offer similar materials (with slightly different properties) with different market prices. Different handling processes may be involved in dealing with different suppliers. For an economic selection of raw materials, there is a need to understand the various costs incurred during purchasing operations from different suppliers. This is a part of the information needed for the identification of the most suitable supplier and material available.

5. 2 COSTS IN PURCHASING OPERATIONS

To understand the true material cost, we need to investigate the purchasing process in detail. From analysis of a typical purchasing operation cycle (from one material ordering to the next), the costs during the whole purchasing process can be categorized into the following sub-costs:

Order Cost: the cost for ordering a certain amount of material. This cost may contain telecommunication costs, market investigation costs, personal visit costs and other related costs [24,25]. In the case we discuss, the order cost is assumed to be \$ 100.00 per order if the material is ordered directly from a local warehouses [26]. It is assumed to be \$250.00 per order in ordering from steel mills [26].

Material Cost: The direct material cost is related to the material unit price. This cost may be affected by quantity, grade (commercial, draw and draw quality special killed) and listed specifications [24,25] such as thickness (since the material is paid by weight);

Transportation Cost: The cost for transporting the material from the steel mill to the warehouse or/and from the warehouse to the manufacturing plant;

Slitting Cost: The cost for slitting the sheet metal material to a specified width;

Holding Cost: The cost for holding the material in inventory. This includes interest money invested in material as well as storage expenses [24], if applicable. Here, we only consider the first one, the interest expenses. Interest of 10 % for material expenses is assumed in our analysis [24,25,26].

Out-of-Stock Cost: The cost due to the need to cease production of a particular product because there is no material available in the inventory. This cost varies according to circumstances [26]. For a general manufacturing company, one always tries to keep some extra material in stock to avoid the out-of-stock problem [24,25].

Although we only cited a few costs for consideration in our analysis, other purchasing operation costs could also be considered for our simulation analysis (in a later chapter). In a complicated manufacturing environment, all these costs may be changing with time and with different circumstances. This makes the material and supplier selection in real circumstances more dynamic and more challenging.

5. 3 THE PURCHASING PROCESS FOR TWO TYPICAL SUPPLIERS

There are two typical types of suppliers available for the sheet metal product: the local warehouse and the steel mill. The purchasing process for similar material from different suppliers may be different. For each type of supplier, the purchasing procedure is more or less the same. For our analysis, we take two sheet metal suppliers: Namasco - a local warehouse (Winnipeg, MB) and Stelco - a steel mill (Hamilton, Ontario).

5.3.1 Purchasing From a Local Warehouse

The purchasing process from the warehouse for each cycle can be described as follows:

When the sheet metal in the inventory stock of the manufacturing plant is lower than pre-defined level, the company gives an order to a particular warehouse. It takes about 6 days for the sheet slitting process and then takes about another 4 days for the delivery of the slitted material to the manufacturing plant. The material price includes the original material price plus the slitting cost (packing and freight cost is included in the slitting cost). The warehouse can monitor the sheet thickness for the company at no extra charge. The warehouse can also provide the chemical contents information of the metal with no extra charge. The information regarding the mechanical properties of the sheet metal may need to take 1 more week's time, and at extra charge, since the testing is done by an outside consulting firm. The manufacturer receives the sheet metal material to back up the inventory and to feed the production. The purchasing loop is described as in Figure 5. 1:

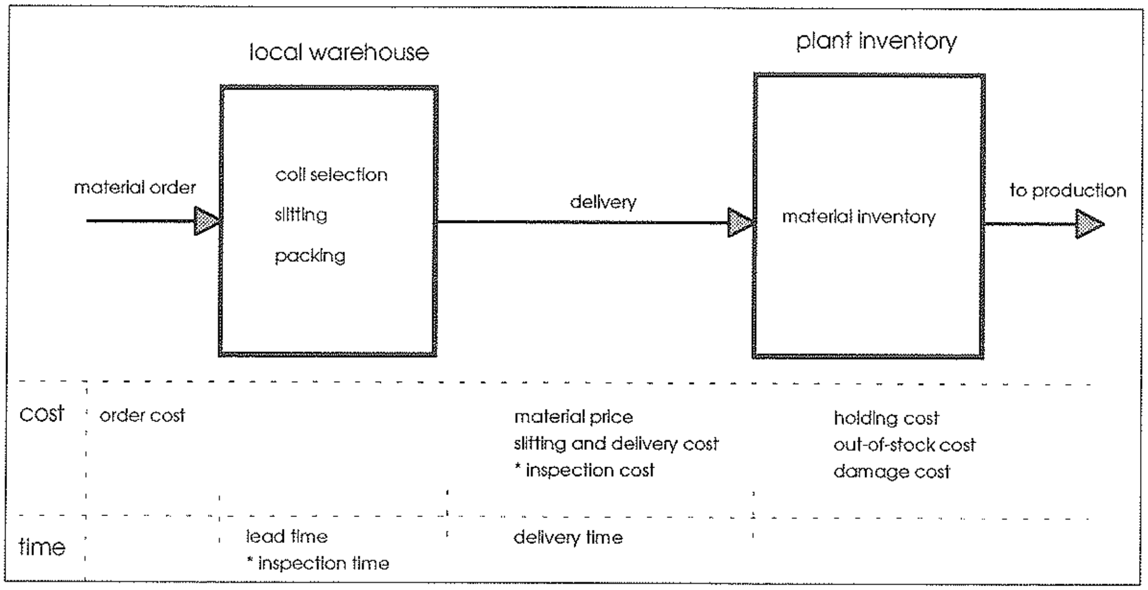


Figure 5.1 Purchasing Process 1 (Local Warehouse As material Suppler)

5.3.2 Purchasing From a Steel Mill

The purchasing process from a steel mill for each cycle can be described as follows:

When the sheet metal in inventory of the manufacturing plant is lower than a certain level, the company gives an order to a particular steel mill. It takes about 6 to 8 weeks for material processing and it takes about 7 days to ship the material from the mill to a local warehouse. The warehouse does the sheet slitting work for about 6 days and then, takes about another 4 days for the delivery to the plant. The material price for the mill only includes the pure material cost, not the transportation nor the waste material in slitting. The material slitting cost in the warehouse is for material slitting, re-packing and freight. The warehouse can also monitor the sheet thickness and provide the chemical contents for the company at no extra charge. The inspection of mechanical properties may need 1 more week time and an extra charge, since the testing is done by an outside consulting company. The company receives the sheet metal material to feed the production. The purchasing loop is described as following Figure 5. 2:

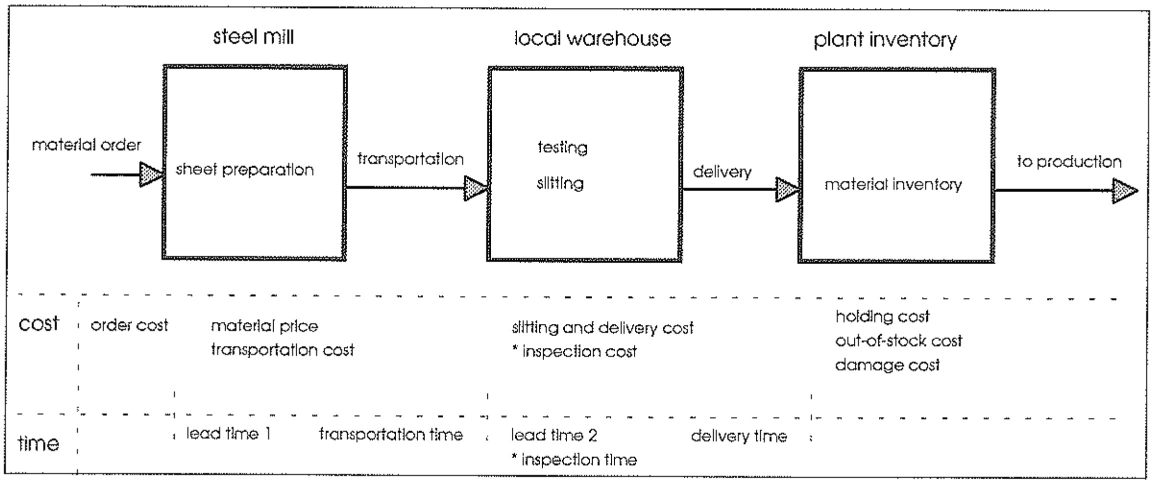


Figure 5.2 Purchasing Process 2 (Steel Mill As Material Supplier)

5. 4 MATERIAL PROPERTIES, LEAD TIME, PRICE AND RELATED COSTS

Material Properties:

The raw material used for the outer cone of ceiling diffusers is a low carbon steel sheet. The normal thickness [24] for the material is from 0.024" (24 thou) to 0.031" (31 thou). The quality of material varies [24,25] from coil to coil, and varies even within one coil.

In general, raw materials (sheet metal) from the local warehouse have larger variations [24] since one warehouse usually contains all kinds of materials (variations of thickness, grade, stocking time etc.). More careful selection in terms of material properties is necessary for those demanding quality. On the contrary, raw materials (sheet metal) from steel mills usually have a more stable quality [24] since they are directly from the steel producer.

The quality we mentioned above lies mainly in the variation of sheet thickness and the formability of the sheet metal. To get a general feeling for the sheet thickness, when one orders 24 thou thick metal, the real thickness what one usually receives is in the range of 23 to 25 thou; sometimes, it may reach 21 to 27 thou [24].

Lead Time:

The warehouse offers much shorter lead time: about 6 days for material selection and slitting, plus 4 days time for coil delivery [24,25]. The total time for ordering from a warehouse to receiving the material is thus about 10 days;

The lead time to order material from a steel mill is much longer: it takes about 8 to 12 weeks for steel processing [24,25]; In some special cases, it can reach 30 weeks (over half a year). Then, it takes about 7 days' shipping time from the steel mill to a local warehouse. Further, the local warehouse still needs another 6 days for sheet slitting and also, 4 extra days for coil delivery.

Material Price:

Some of the aspects of the two types of raw material suppliers in terms of material price are similar: the material price changes with different material grade (type), material thickness and the order quantity [24,25]:

- the thicker the sheet metal ordered, the lower the price per pound [25] is since less rolling is required.

- there are three quality levels for cold rolled steel sheets: commercial quality, draw quality and draw quality special killed [24,25,58]. Commercial quality has the widest specification and, of course, the lowest price. Draw quality has better forming quality and comes with a higher price. Draw quality special killed has experienced the de-oxidization process (aluminum killed), so it has a more stable quality (no aging problem), and comes with the highest price. In each quality level, there are different grades (carbon contents are different too), but they are all at the same price level.

- In order to attract more customers and increase sales, large orders usually obtain some price discount.

Material From a Local Warehouse:

Following are some typical relationships between material thickness and sheet metal price for materials from a local warehouse [25]:

thickness (thou)	24	30	60	100
price (ç/lb. for cold rolled)	34	33	32	31

Similarly, some typical relationships [25] between material types and sheet metal prices (thickness is 24 thou):

type:	commercial	draw quality	draw quality special killed
price (ç/lb.)	34	35.5	36.5

The above material prices mentioned are for general cases. For the same material with normal price of 34 ç/lb. sheet metal, one may have the opportunity to get it for just 32 or 33 ç/lb. in a good deal. This usually happens when some customer over-ordered some type of sheet, which he does not needed anymore. For some low stock and high demand sheet metal, the price can rise up to 39 or 40 ç/lb. [25].

Steel price also changes with time. When market demand increases, the price is higher; but when market demand decreases, the price is lower [25]. For sheet metal material with normal price of 34 ç/lb., the price may reach 35ç/lb. the next month. For some low demand material (e.g.: when after one year in stock, the metal still can't sell), the warehouse may "eat the cost" and offer it at a very low price to get rid of the unwanted inventory [25].

For our analysis, only the normal condition for material price is considered.

Material From A Steel Mill:

As for the local warehouse, the material price in the steel mill changes with different material grades (type), material thickness and ordering quantity.

Since steel mills are producers of steel sheet, they only accept large orders [25]. They require a bigger order amount for each order and have a minimum order amount per year.

For the sheet metal we mentioned, one can obtain similar material (with tight specification) 24 thou thickness for only 24 ç/lb. from the steel mill under the condition of a minimum order of 1000 tons per year [25].

Transportation Cost:

If one orders material from a local warehouse, one does not need to pay for the transportation cost since the slitting cost covers the transportation cost in the warehouse.

The transportation cost between the steel mill to a local warehouse is not covered by neither steel mill nor local warehouse, so the customer pays for the transportation cost if ordering the material from a steel mill. From Hamilton to Winnipeg, transportation can be by train or by truck. Since the steel mill usually has a deal with the train company, the transportation cost by train is lower than by truck. The rough cost for transportation from Hamilton to Winnipeg is about 2.5 ç/lb. by train [25]. By truck, the cost would be 3 ç/lb. ($3.00/100 lb. for a 35-ton truck load) [25].

Slitting Cost:

In the warehouse, the calculation of the slitting cost is according to the time spent on the slitting process [25]. This process includes machine setup time and real slitting time. Machine setup time for two widths is about 0.5 hour. The slitting time depends on the slitting amount, the general slitting rate is about 22 min. per ton. The real cost for the slitting process is calculated at $3.0/min. (the time includes setup time and the slitting run time).

Material From a Local Warehouse:

After the above calculation, the warehouse adds 18% to cover overhead on the slitting cost for the customers who order the material directly from the warehouse [25]. The slitting cost also includes coil packing and freight. For a very large quantity and for favored customers, overhead can be reduced to 10% (not considered here).

The slitting waste (off-cut) during the slitting process is the responsibility of the warehouse, and not the expense of customer. So the material price does not include the material off-cut, "one just pays for what is received".

Material From Steel Mill:

The calculation for the material slitting cost is the same as for material purchased from a warehouse, but the overhead cost added on is 100% instead of 18% [25].

The slitting waste (off-cut) will be the responsibility of the customer. The material price paid to the steel mill includes the whole material weight ordered, "one pays for what is ordered". The slitting waste [25] may be quite significant (on average 5% of the whole steel weight ordered) if the customer cannot use off-cut or cannot find someone who needs the off-cut. If the offset is salable, the warehouse may take the material with 50% off the original price for the off-cut after it is slit in the local warehouse.

Order Cost:

If one orders the material from a local warehouse, the ordering cost per order is usually much less than the ordering cost from a steel mill [25].

Holding Cost:

Since a long lead time is required if the material is ordered from a steel mill, a very large inventory is necessary to maintain the production. The holding cost, of course, is then much higher in these circumstances than when ordering smaller quantities of the material directly from local warehouse [24,25,27].

Out-of-Stock Cost:

The out-of-stock problem exists when no more material is available for production and the manufacturer waits for the ordered material. The reason for this problem is an incorrect estimate of the lead time or the large variation of the lead time which makes it difficult for the manufacturer to correctly estimate the lead time. Although, in the condition of ordering material from steel mill, this problem is more likely, the out-of-stock cost depends mainly on the company's inventory policy. The more material inventory it decides to keep in stock, the lesser is the chance of this problem happening.

5. 5. COMPARISON OF THE TWO TYPES OF SUPPLIERS

We conclude this chapter by making a comparison for the two types of suppliers. As we discussed in this chapter, the purchasing parameters and various costs in the purchasing processes are listed as follows:

Purchasing Parameter	**Warehouse**	**Steel Mill**
Lead Time	shorter	longer
Minimum Order Amount	lower	higher
Metal Properties Variation	wider	narrower
Material Price	higher	lower

Cost	**Warehouse**	**Steel Mill**
Order Cost	lower each time	higher each time
	higher order frequency	higher order frequency
Transportation Cost	none	higher
Slitting Cost	lower	higher

Holding Cost	lower	higher
Out-of-Stock Cost	less likely	more likely

Due to the complexity of the purchasing operation, more detailed comparison for the economic selection of the material supplier can be done by means of a computer simulation to model the purchasing process in order to calculate various incurred costs over a certain period of time. We can, in the end, obtain the overall cost of the purchasing operation.

CHAPTER 6

AN ANALTIC APPROACH FOR DETERMINING OPTIMUM RAW MATERIAL QUALITY LEVEL

For a general problem, an analytical approach can usually provide generalized solutions and the results from such an approach often have the advantage of ease of use. In this chapter, we use an analytical method to calculate the expected cost impact of raw material characteristic(s) on its application process, and at the same time, to identify the optimal raw material quality level. This approach, though limited in its practical applications, provides an effective tool to resolve some of the simple problems. For more complicated industrial problems, computer simulation methods may be more appropriate.

6. 1. INTRODUCTION

In most industrial situations there are several alternative raw materials that may be chosen for any particular application. It is therefore of interest to manufacturers to be able to decide which raw material is the most technically and economically suitable for the desired level of product quality.

Once a suitable quality level is selected, great cost savings and improvements in manufacturing process efficiency may be achieved by appropriate selection of the raw material. To make a cost effective choice, one should have a clear understanding of how raw material quality characteristics affect its application process. The cost impact assessment should be based solely on the effect of raw material quality characteristics. This approach is assumed that the relationship between the material characteristic and the material impact on its application process is known. Based on that, some analytical solutions which may be used to assist manufacturers in determining the economic alternatives and optimum level of raw material quality characteristics are formulated.

6. 2. APPROACH

We assume that the relationship between a raw material property or properties and their effect on the affected manufacturing costs is known. We also assume that the statistical distribution for the raw material quality characteristic is known (see Figure 6.1).

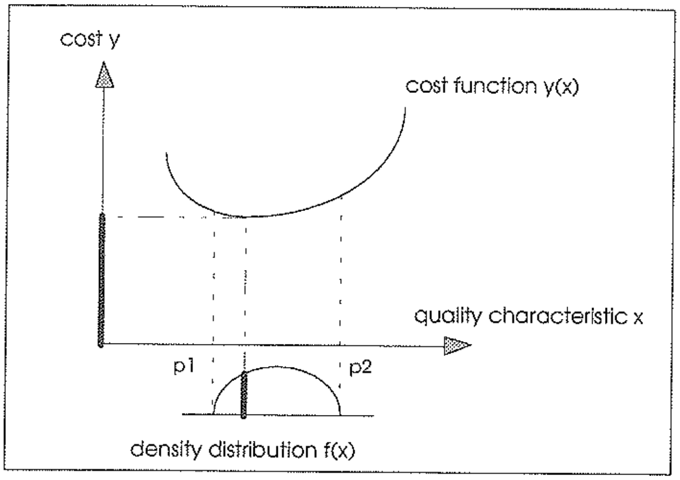


Figure 6. 1 Illustration of A General Problem

Hence, the expected cost effect for the particular raw material can be expressed as:

$$E = \int_{p1}^{p2} y(x)f(x)dx \tag{6.1}$$

Since, in reality, the function y(x) and f(x) can take on a wide variety of forms, it is impossible for us to obtain the E value as well as the optimum quality level (usually, mean value) in an analytical form. Fortunately, we can always use a series of piece-wise linear functions to represent any form of the cost function y(x) within a desired accuracy. For the present, we choose two statistical distributions for f(x) in the above formulation: a uniform distribution and a normal distribution (see Figure 6.2).

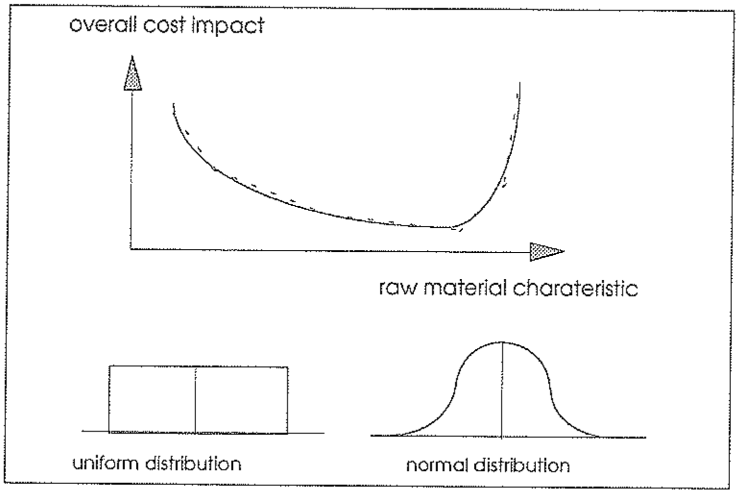


Figure 6.2 Problem Illustration for further Analysis

6. 3. FORMULATION USING A UNIFORM DISTRIBUTION FOR THE QUALITY CHARACTERISTIC

Assume that the raw material quality characteristic of interest follows a uniform distribution with an average value of u and width of 2σ; the density function for this quality characteristic is then 1/2σ in the range of (u-σ, u+σ). Within this range of the quality characteristic, the cost function can be represented by several different piece-wise approximations.

Case 1. Cost Function Represented by a Two-Piece Linear Function.

This condition is illustrated in Figure 6.3.

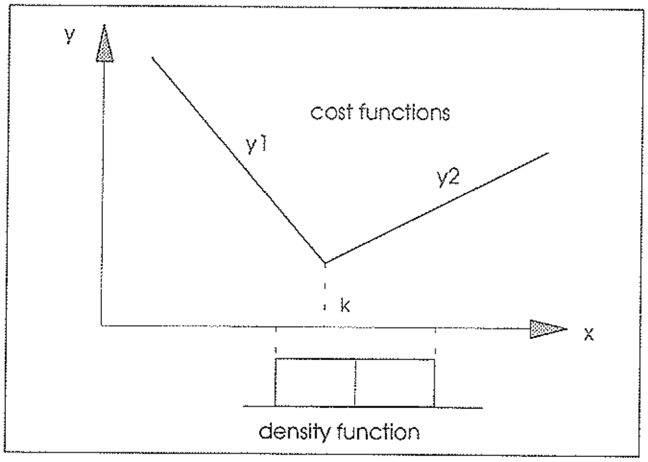


Figure 6. 3 Two Piece-Wise Linear Function With Uniform Distribution

The two piece-wise cost functions are defined as: $y_1=a_1+b_1x$ and $y_2=a_2+b_2x$. The expected cost function E(u) can be defined as:

$$E(u) = \int_{u-\sigma}^{k}(a_1 + b_1x)\frac{1}{2\sigma})dx + \int_{k}^{u+\sigma}(a_2 + b_2x)\frac{1}{2\sigma}dx \qquad (6.2)$$

then:

$$E(u) = \frac{1}{2\sigma}\{a_1k + \frac{b_1k^2}{2} - a_2k - \frac{b_2k^2}{2} - a_1(u-\sigma) - \frac{b_1(u-\sigma)^2}{2} +$$

$$+a_2(u+\sigma) + \frac{b_2(u+\sigma)^2}{2}\} \qquad (6.3)$$

Since the k point corresponds to the intersection point of line 1 and line 2, then,

$$k = \frac{a1 - a2}{b2 - b1} \qquad (6.4)$$

Equation (6.3) can be used to compare the expected cost effect of different raw material quality characteristics on the overall manufacturing cost. To determine the optimum quality level u for a raw material, we need to do some further analysis. We have:

$$\frac{dE(u)}{du} = \frac{1}{2\sigma}\{-a_1 + b_1\sigma + a_2 + b_2\sigma - b_1u + b_2u\} = 0$$

$$\text{then, } u = \frac{a_1 - a_2 - b_1\sigma - b_2\sigma}{b_2 - b_1} \qquad (6.5)$$

$$\frac{d^2E(u)}{du^2} = \frac{1}{2\sigma}\{b_2 - b_1\}$$

Since $b_1<0$ and $b_2>0$ (see Figure 2), $\frac{d^2E(u)}{du^2} > 0$.

From the above analysis, we can see that the average value u in equation (6.5) corresponds to the minimum total cost value E(u) in equation (6.3). Equation (6.5) also can be written in following form:

$$u = \frac{a_1 - a_2}{b_2 - b_1} - \frac{(b_1 + b_2)\sigma}{b_2 - b_1} = k - \frac{(b_1 + b_2)\sigma}{b_2 - b_1} \tag{6.6}$$

If $b_2 > - b_1$, then $u < k = \frac{a_1 - a_2}{b_2 - b_1}$

If $b_2 < - b_1$, then $u > k = \frac{a_1 - a_2}{b_2 - b_1}$

Case 2. Cost Function Represented by a Three-Piece Linear Function.

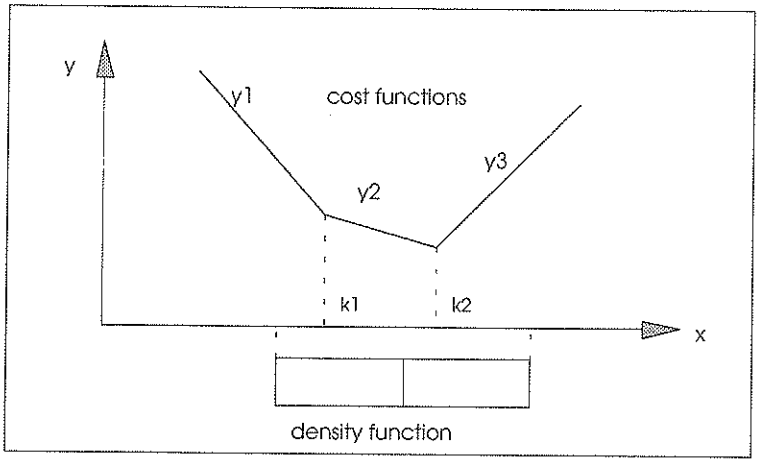


Figure 6. 4 Three Piece-Wise Linear Functions With Uniform Distribution

The three piece-wise cost functions are defined similarly as: $y_1=a_1+b_1x$, $y_2=a_2+b_2x$ and $y_3=a_3+b_3x$.

The expected cost function E(u) can thus be given by:

$$E(u) = \int_{u-\sigma}^{k_1} (a_1 + b_1x)\frac{1}{2\sigma}dx + \int_{k_1}^{k_2} (a_2 + b_2x)\frac{1}{2\sigma}dx +$$

$$+\int_{k_2}^{u+\sigma} (a_3 + b_3x)\frac{1}{2\sigma}dx \tag{6.7}$$

(6.7) yields,

$$E(u) = \frac{1}{2\sigma}\{a_1k_1 + \frac{b_1k_1^2}{2} + a_2k_2 + \frac{b_2k_2^2}{2} - a_2k_1 - \frac{b_2k_1^2}{2} - a_3k_2 - \frac{b_3k_2^2}{2}$$

$$-a_1(u-\sigma) - \frac{b_1(u-\sigma)^2}{2} + a_3(u-\sigma) + \frac{b_3(u+\sigma)^2}{2}\} \tag{6.8}$$

From (6.8), we have:

$$\frac{dE(u)}{du} = \tfrac{1}{2\sigma}\{-a_1 - b_1(u-\sigma) + a_3 + b_3(u+\sigma)\} = 0$$

which yields: $u = \dfrac{a_1 - a_3 - b_1\sigma - b_3\sigma}{b_3 - b_1}$ (6.9)

and:

$$\frac{d^2E(u)}{du^2} = \frac{1}{2\sigma}\{b_3 - b_1\} \tag{6.10}$$

Since $b_1<0$ and $b_3>0$, then $\dfrac{d^2E(u)}{du^2} > 0$.

From this analysis, we can see that the average value u in (6.9) corresponds to the minimum total cost value E(u) in (6.8). (6.9) also tells us that the optimum point is related to the linear functions at starting and ending edges only (here, at y_1 and y_3).

Case 3. Cost Function Represented by an N-Piece Linear Function.

The n piece-wise cost functions are defined as:

$y_1=a_1+b_1x$, $y_2=a_2+b_2x$, ... and $y_n=a_n+b_nx$.

The expected cost function E(u) can thus is given by:

$$E(u) = \int_{u-\sigma}^{k_1} (a_1 + b_1 x)\frac{1}{2\sigma} dx + \int_{k_1}^{k_2} (a_2 + b_2 x)\frac{1}{2\sigma} dx +$$

$$+ \ldots + \int_{k_{n-1}}^{u+\sigma} (a_n + b_n x)\frac{1}{2\sigma} dx \qquad (6.11)$$

which yield:

$$E(u) = \frac{1}{2\sigma}\{a_1 k_1 + \frac{b_1 k_1^2}{2} + a_2 k_2 + \frac{b_2 k_2^2}{2} + \ldots + a_{n-1} k_{n-1} + \frac{b_{n-1} k_{n-1}^2}{2}$$

$$-a_2 k_1 - \frac{b_2 k_1^2}{2} - a_3 k_2 - \frac{b_3 k_2^2}{2} - \ldots - a_n k_{n-1} - \frac{b_n k_{n-1}^2}{2}$$

$$-a_1 (u-\sigma) - \frac{b_1 (u-\sigma)^2}{2} + a_n (u-\sigma) + \frac{b_n (u+\sigma)^2}{2}\} \qquad (6.12)$$

Further, we have:

$$\frac{dE(u)}{du} = \frac{1}{2\sigma}\{-a_1 - b_1 (u-\sigma) + a_n + b_n (u+\sigma)\} = 0$$

The optimum quality level u can thus be described as:

$$u = \frac{a_1 - a_n - b_1\sigma - b_n\sigma}{b_n - b_1} \qquad (6.13)$$

6. 4. FORMULATION USING A NORMAL DISTRIBUTION FOR THE QUALITY CHARACTERISTIC

Assume that the raw material quality characteristic follows a normal distribution with an average value of u and standard deviation σ. The density function for the quality characteristic can then be described as: $f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-u)^2}{2\sigma^2}}$.

Case 1. Cost Function Represented by a Two-Piece Linear Function.

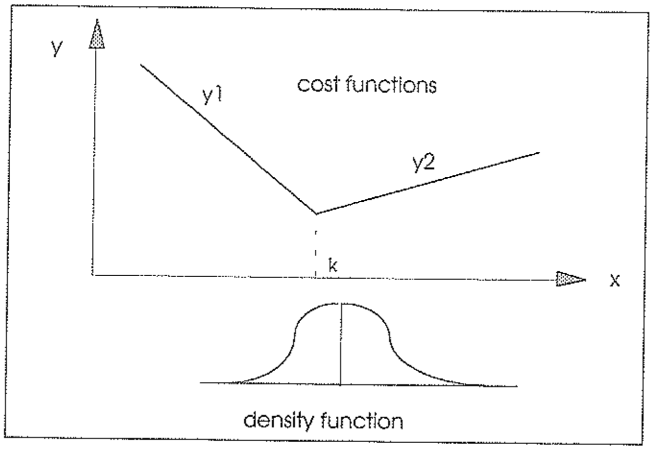


Figure 6. 5 Two Piece-Wise Linear Functions With Normal Distribution

The two piece-wise cost functions are defined as: $y_1=a_1+b_1x$ and $y_2=a_2+b_2x$. The expected cost function E(u) can be given by:

$$E(u) = \int_{-\infty}^{k}(a_1 + b_1x)f(x)dx + \int_{k}^{\infty}(a_2 + b_2x)f(x)dx \tag{6.15}$$

(6.15) yields,

$$E(u) = \int_{-\infty}^{k} a_1f(x)dx + \int_{-\infty}^{k} b_1xf(x)dx + \int_{k}^{\infty} a_2f(x)dx + \int_{k}^{\infty} b_2xf(x)dx \tag{6.16}$$

For the sake of simplification, the (6.16) is defined as $E(u) = I_1 + I_2 + I_3 + I_4$ correspondingly.

The standard normal distribution can be written as: $\varphi(x) = \frac{1}{\sqrt{2\pi}}e^{-\frac{x^2}{2}}$, and we also have that: $\Phi(x) = \int_{-\infty}^{x}\varphi(x)dx$.

In (6.16), assuming $z = \frac{x-u}{\sigma}$, with $dz = \frac{1}{\sigma}dx$ and $dx=\sigma dz$, we have:

$$I_1 = \int_{-\infty}^{k} a_1 f(x)dx = a_1 \int_{-\infty}^{\frac{k-u}{\sigma}} \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz = a_1 \Phi(\frac{k-u}{\sigma})$$

$$I_2 = \int_{-\infty}^{k} b_1 x f(x)dx = b_1 \int_{-\infty}^{\frac{k-u}{\sigma}} (u + z\sigma) \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz$$

$$= b_1 \int_{-\infty}^{\frac{k-u}{\sigma}} u \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz + b_1 \int_{-\infty}^{\frac{k-u}{\sigma}} z\sigma \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz$$

$$= b_1 u \Phi(\frac{k-u}{\sigma}) - b_1 \sigma \varphi(\frac{u-k}{\sigma})$$

$$I_3 = \int_{k}^{\infty} a_2 f(x)dx = a_2 \int_{\frac{k-u}{\sigma}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz = a_2[1 - \Phi(\frac{k-u}{\sigma})]$$

and:

$$I_4 = \int_{k}^{\infty} b_2 x f(x)dx = b_2 \int_{\frac{k-u}{\sigma}}^{\infty} (u + z\sigma) \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz$$

$$= b_2 u\{1 - \Phi(\frac{k-u}{\sigma})\} - b_2 \sigma \{1 + \varphi(\frac{u-k}{\sigma})\}$$

After above mathematic transformation, we obtained:

$$E(u) = a_2 + b_2 u + b_2 \sigma + \Phi(\frac{k-u}{\sigma})(a_1 - a_2 + b_1 u - b_2 u)$$

$$-\varphi(\frac{u-k}{\sigma})(b_1 \sigma - b_2 \sigma) \qquad (6.17)$$

Equation (6.17) can be used to compare the expected cost effects of different raw material quality characteristics.

To find out the optimum quality level u for a raw material, we again need to do some further analysis:

$$\frac{d\Phi(\frac{k-u}{\sigma})}{du} = \frac{d}{du}\int_{-\infty}^{\frac{k-u}{\sigma}} \varphi(x)dx = -\frac{1}{\sigma}\varphi(\frac{k-u}{\sigma}), \qquad \text{and}$$

$$\frac{d\varphi(\frac{k-u}{\sigma})}{du} = \frac{d}{du}[\frac{1}{\sqrt{2\pi}}e^{-\frac{z^2}{2}}]\Big|_{z=\frac{k-u}{\sigma}}$$

$$= \varphi(\frac{k-u}{\sigma})(-z)(\frac{-1}{\sigma}) = \frac{k-u}{\sigma^2}\varphi(\frac{k-u}{\sigma})$$

Then, from (6.17), we can obtain:

$$\frac{dE(u)}{du} = b_2 + \Phi(\frac{k-u}{\sigma})(b_1 - b_2) - \frac{1}{\sigma}\varphi(\frac{k-u}{\sigma})(a_1 - a_2 + b_1u - b_2u)$$

$$-\frac{k-u}{\sigma^2}\varphi(\frac{u-k}{\sigma})(b_1\sigma - b_2\sigma)$$

Since $\varphi(\frac{k-u}{\sigma}) = \varphi(\frac{u-k}{\sigma})$, we obtain:

$$\frac{dE(u)}{du} = b_2 + \Phi(\frac{k-u}{\sigma})(b_1 - b_2) - \varphi(\frac{k-u}{\sigma})(\frac{a_1 - a_2 + b_1k - b_2k}{\sigma}) \qquad (6.18)$$

When $\frac{dE(u)}{du} = 0$, at point u, the value of E(u) reaches a extreme point, resulting in:

$$b_2 + \Phi(\frac{k-u}{\sigma})(b_1 - b_2) - \varphi(\frac{k-u}{\sigma})(\frac{a_1 - a_2 + b_1k - b_2k}{\sigma}) = 0 \qquad (6.19)$$

Since we are unable to obtain an analytic solution for the value of u from equation (6.19), a numerical search method is required to find the optimum value of u and E(u). An optimal search method and a case example is shown in the next "Examples" section.

Case 2. Cost Function Represented by a Three-Piece Linear Function.

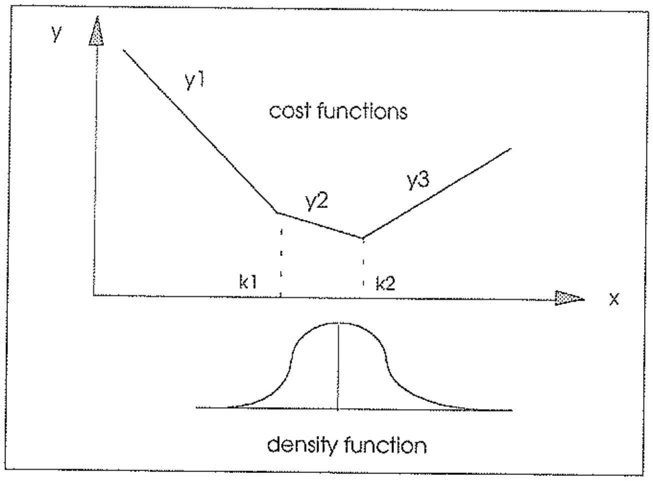


Figure 6.6 Three Piece-Wise Linear Functions With Normal Distribution

The three piece-wise cost functions are defined as: $y_1=a_1+b_1x$, $y_2=a_2+b_2x$ and $y_3=a_3+b_3x$. We have:

$$E(u)=\int_{-\infty}^{k_1}(a_1+b_1x)f(x)dx+\int_{k_1}^{k_2}(a_2+b_2x)f(x)dx+\int_{k_2}^{\infty}(a_3+b_3x)f(x)dx \tag{6.20}$$

(6.20) yields,

$$E(u)=\int_{-\infty}^{k_1}a_1f(x)dx+\int_{-\infty}^{k_1}b_1xf(x)dx+\int_{k_1}^{k_2}a_2f(x)dx+\int_{k_1}^{k_2}b_2xf(x)dx+$$

$$+\int_{k_2}^{\infty}a_3f(x)dx+\int_{k_2}^{\infty}b_3xf(x)dx$$

Similar to the last section, we can obtain following format:

$$E(u)=a_3+b_3u+b_3\sigma+\Phi(\frac{k_1-u}{\sigma})(a_1-a_2+b_1u-b_2u)$$

$$+\Phi(\frac{k_2-u}{\sigma})(a_2-a_3+b_2u-b_3u)-\varphi(\frac{u-k_1}{\sigma})(b_1\sigma-b_2\sigma)$$

$$-\varphi(\frac{u-k_2}{\sigma})(b_2\sigma-b_3\sigma) \tag{6.21}$$

Case 3. Cost Function Represented by an N-Piece Linear Function.

The n piece-wise cost functions are defined as: $y_1=a_1+b_1x$, $y_2=a_2+b_2x$, ... and $y_n=a_n+b_nx$.

As before, we have:

$$E(u)=\int_{-\infty}^{k_1}(a_1+b_1x)f(x)dx+\int_{k_1}^{k_2}(a_2+b_2x)f(x)dx+\int_{k_2}^{k_3}(a_3+b_3x)f(x)dx+$$

$$+\ldots+\int_{k_{n-1}}^{\infty}(a_n+b_nx)f(x)dx \qquad (6.22)$$

Then, we obtain:

$$E(u)=a_n+b_nu+b_n\sigma+\Phi(\frac{k_1-u}{\sigma})(a_1-a_2+b_1u-b_2u)+$$

$$+\Phi(\frac{k_2-u}{\sigma})(a_2-a_3+b_2u-b_3u)+$$

$$+\ldots+\Phi(\frac{k_{n-1}-u}{\sigma})(a_{n-1}-a_n+b_{n-1}u-b_nu)$$

$$-\varphi(\frac{u-k_1}{\sigma})(b_1\sigma-b_2\sigma)-\varphi(\frac{u-k_2}{\sigma})(b_2\sigma-b_3\sigma)$$

$$-\ldots-\varphi(\frac{u-k_{n-1}}{\sigma})(b_{n-1}\sigma-b_n\sigma) \qquad (6.23)$$

6. 5. EXAMPLE

In all following examples, we assume - for simplicity - that the cost function can be represented by means of two piece-wise linear functions: $y_1=6-x$ and $y_2=3+0.5x$. The intersection point of these two lines lies at x=2. We have the following parameters: $a_1=6$, $b_1=-1$, $a_2=3$, $b_2=0.5$ and k=2 in line with our analysis format.

The above V-shape curve can be easily illustrated by the following simple industrial example: For a sheet metal product manufacturer, the sheet thickness selection is important. If the sheet used is too thin, then due to the lack of rigidity during product handling and installation, the chance that it may be rejected by customers will increase, making the overall cost to increase; If the sheet used is too thick, then due to the material weight increase, the material cost will increase. The sheet thickness may follow a certain statistical distribution. Then, selecting a suitable mean sheet thickness may involve a trade-off of the above two factors to reduce the overall cost.

Case 1. Example of a quality characteristic following a uniform distribution

a) Comparison of the cost impact of two candidate raw materials

Material 1: uniformly distributed in the range of (1.2, 3.2)

Material 2: uniformly distributed in the range of (1.9, 3.1)

Using equation (6.3), we can obtain the expected overall cost impact of the above two materials.

For the case of material 1, since u=2.2 and σ=1.0, the expected cost is found to be 4.34;

For the case of material 2, since u=2.5 and σ=0.6, the expected cost turns out to be 4.26.

Hence, the selection of material 2 for the application of interest, results in a lower cost than the selection of material 1.

b) Identifying the optimum raw material quality level

If we are interested in determining the optimum mean value of a characteristic within a range defined by $2\sigma=2.0$, we find this optimum level of the average value u to be 2.33 by using equation(6.5).

Also, if we know the material property to lie in the range of $2\sigma=1.2$, the optimum level of the average value u can be determined to be 2.2.

Case 2. Example of a quality characteristic following a normal distribution

a) Comparison of the cost impact of two candidate raw materials

Material 1: the quality parameter follows a normal distribution (2.2, 0.5).

Material 2: the quality parameter follows a normal distribution (2.5, 0.3).

For material 1, where $u=2.2$ and $\sigma=0.5$,

$$\Phi(\frac{k-u}{\sigma}) = \Phi(\frac{2-2.2}{0.5}) = 0.345, \text{ and } \varphi(\frac{u-k}{\sigma}) = \varphi(\frac{2.2-2}{0.5}) = 0.368$$

Using equation (6.17), we obtain the expected overall cost of the above material 1 to be 4.52.

For material 2, where $u=2.5$ and $\sigma=0.3$.

$$\Phi(\frac{k-u}{\sigma}) = \Phi(\frac{2-2.5}{0.3}) = 0.049, \text{ and } \varphi(\frac{u-k}{\sigma}) = \varphi(\frac{2.5-2}{0.3}) = 0.101$$

Using equation (6.17), we obtain the expected overall cost of material 2 to be 4.41.

Hence, the use of material 2 is less costly than that of material 1 for the particular case considered.

b) Identifying the optimum raw material quality level

The problem is to find the optimum raw material quality level u assuming that we know that the material follows a normal distribution with a standard deviation of 0.3.

Since u can not be expressed in analytical format when the quality characteristic follows a normal distribution, we use the equation (6.17) to search for the optimum value u corresponding to the lowest expected cost. Since the cost function in this case consists of only a two piece-wise linear function, only one extreme point exists the expected cost impact function. We use the "Golden Section Search Method" [103] for this one dimensional searching problem. In the cases where the cost function is represented by more than three piece-wise linear functions, there is a possibility of multiple-extreme points. After a series of searches for local optima, a comparison of these results is necessary to identify a global optimum solution.

For our case, the starting range is set in the range of (0, 5) since the intersection point in the x-axis of the two straight cost function lines lies at x = 2. For each iteration, the search points and $\Phi(\frac{k-u}{\sigma})$, $\varphi(\frac{u-k}{\sigma})$ values are calculated before putting them into equation (6.17). The search points and the results are listed in Table 1 and in Figure 7.

iteration	search range	search points	search results
1	a=0.00, b=5.00	x1=3.09, x2=1.91	E1=4.70, E2=4.36
2	a=0.00, b=3.09	x1=1.91, x2=1.18	E1=4.70, E2=4.97
3	a=1.18, b=3.09	x1=2.36, x2=1.91	E1=4.36, E2=4.70
4	a=1.91, b=3.09	x1=2.64, x2=2.36	E1=4.47, E2=4.36
5	a=1.91, b=2.64	x1=2.36, x2=2.19	E1=4.36, E2=4.32
6	a=1.91, b=2.36	x1=2.19, x2=2.08	E1=4.32, E2=4.31
7	a=1.91, b=2.19	x1=2.08, x2=2.02	E1=4.31, E2=4.32

Table 6.1 Optimum Search Points and Cost Results

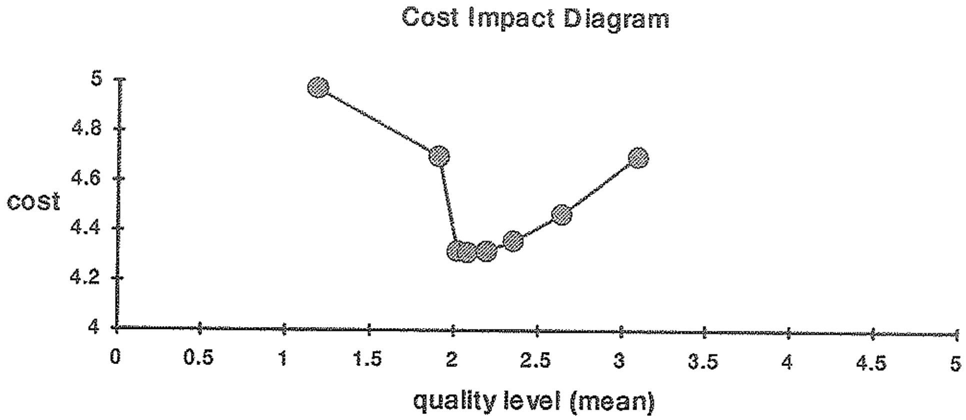


Figure 6. 7 Cost Results Using the "Golden Section Search" Method

The optimum point is reached by the 7th iteration. The optimum level of the raw material characteristic mean value turns out to be 2.08, with an expected cost of 4.31.

6. 6. POSSIBLE EXTENSION AND LIMITATIONS

Although in the above formulations, we have considered raw material to have only one quality characteristic, our approach is not limited to this condition.

Case 1: Each Quality Characteristic Is Independent and Works Independently

If indeed, there are several quality characteristics for each raw material of interest, with each characteristic independent and independently affecting the cost functions, and, if the quality characteristics follow either uniform or normal distributions, the cost calculation equations presented above are also applicable. The optimum values individually obtained for each characteristic in this manner also turn out to be the "overall" optimum levels of the raw material quality characteristics.

Case 2: Each Quality Characteristic Is Independent and Works Interactively

For the case of several raw material characteristics that may be interactively affecting the cost functions, we assume that the interaction between the various quality characteristics is linear within the applied range, which means that the "mixed characteristic" is a linear combination of each quality characteristic.

Assuming x_i (i=1, 2, ..., n) represents one of the characteristics, and assuming x represents the "mixed characteristic", then the following relationships exists between them.

$$x = k_1x_1 + k_2x_2 + ... + k_nx_n \tag{6.24}$$

This x is directly related to the cost function y(x) or a combination of a series of linear functions y1(x), y(2), ... y(n).

If x_i follows a uniform distribution, then x will no longer follow a uniform distribution. So our formulation for the uniform distribution situation is no longer applicable to this "mixed characteristic" x case. The expected cost function should be formulated by a new combined density function.

If x_i follows a normal distribution (μ_i, σ_i^2), we know that the combined quality characteristic x also follows a normal distribution [38]. The mean for the combined characteristic is then $u_x = \sum k_i u_i$ the and deviation is $\sigma_x = \sum k_i^2 \sigma_i^2$. So we can take the "mixed characteristic" x as one quality characteristic to use in our previous equation (6.23) for the calculation of the expected cost.

From equation (6.23), if we use a one-dimensional search algorithm, we also can identify the optimum x for the particular application as long as the cost function used is the only one existing for the material application. Then x_i can be decided by any means as long as the optimum x value is satisfied. If one or more quality characteristics x_i are related to the material cost, it may be possible to select the x_i with a low cost and also satisfying the optimum x value to reduce the overall cost.

If some x_i individually correspond to a certain cost function, the optimum value for each quality characteristic x_i should consider all cost functions in the application, since the trade-offs among the quality characteristics need to be balanced. So, we can calculate the expected cost effect of each x_i as well as the combined x, as well as all cost together. The total cost function can be used to compare the cost effectiveness of different raw materials. By using a multi-dimensional optimum search algorithm, the "overall" optimum values for all quality characteristics $x_1, x_2, \dots, x_n$ can also be identified without much difficulty.

Case 3: Each Quality Characteristic Is Dependent and Works Interactively

For the case of several raw material characteristics that are dependent and that may be interactively affecting the cost functions, we also assume that the interaction between the various quality characteristics is linear within the applied range, which means that the "mixed characteristic" is a linear combination of each quality characteristic. As before, we assume x_i ($i=1, 2, \dots, n$) represents one of the quality characteristics and following a normal distribution $n(\mu_i, \sigma_i^2)$, and that x represents the "mixed characteristic". Then $x = k_1x_1 + k_2x_2 + \dots + k_nx_n$. This x is directly related to the cost function y(x).

From statistical analysis [38], we know that the combined quality characteristic x has the mean value $u_x = \sum k_i u_i$, and deviation $\sigma_x = \sum k_i^2 \sigma_i^2 + 2\sum k_i k_j \sigma_i \sigma_j \rho_{ij}$. The ρ_{ij} is the correlation coefficient value between the quality characteristics x_i and x_j. The combined quality characteristic x may however no longer follow the normal distribution. Previous formulae for normal distribution cannot be applied in this case.

In real industrial applications, more complicated cases exist. The distribution of quality characteristics treated may be neither uniform nor normal and the quality characteristics may not be linearly interrelated. Considering the case of a sheet metal bending operation as an example, the thickness of the sheet and the yield strength of the metal (two quality characteristics) act together to affect the bendability of the metal. The relationship between the bendability and the thickness (x1) and yield strength (x2) is $x = \frac{kM}{x_1^2 x_2}$, i.e. not a linear relationship. This formability, of course, directly influences the product quality or the production cost function, but the previous formulae cannot be applied.

In these cases, a Monte-Carlo simulation approach would be a suitable and effective tool to handle such complicated problems.

6. 7. CONCLUSION

An analytical approach for determining the cost impact of raw material quality characteristics is given. The solutions formulated can be used to select cost-effective raw materials when the quality characteristic follows a uniform or a normal distribution. For uniformly distributed quality characteristics, an optimum (mean) quality level is presented in a simple analytic format. For the case when the desired quality characteristics following a normal distribution, the application of an optimum search algorithm is illustrated for the identification of the optimum point. For more complicated industrial problems, a computer simulation method is suggested to be used for identification of the most suitable material properties for a particular application. This is discussed in the following Chapters.

CHAPTER 7

OPTIMUM RAW MATERIAL IDENTIFICATION USING COMPUTER SIMULATION AND OPTIMIZATION

Before making an economic raw material selection, one needs to understand the real raw material properties requirements for a particular application. These requirements may originate from three possible sources: the material properties themselves, the manufacturing processes, and the product quality. Due to the uniqueness of material properties requirements of different processes, some fine cost trade-off needs to be performed to reach the overall lowest cost. This chapter concentrates on the method of combining a computer simulation model with some optimization techniques in searching for the most suitable raw material properties for the particular case discussed in Chapter 4 and Chapter 5.

In our analysis, the cost impact of raw material specifications, extra manufacturing cost and product quality cost are considered in the model to analyze the cost effect of raw material properties. SLAMSYSTEM^{TM} [75,76] is used for the construction of the simulation model. Two optimum seeking techniques: a modified Hooke and Jeeves algorithm [39] and the Response Surface Method [63], are used for the identification of the optimum material properties.

7. 1 INTRODUCTION

The identification of the most suitable raw material from a range of competing materials with similar properties is a continuous challenge for manufacturers. This is because material properties and their behavior have great impact on the manufacturing processes used to transform them into finished products. This fact is specially true in some cases where the production processes are very sensitive to the changes in raw material properties. Sometimes, this problem may become critical when the material properties interactively affect each other or affect the production processes themselves. In these cases, it is difficult to have a clear understanding of the real requirements for the raw material properties. In this chapter, a computer simulation combined with two optimization techniques is introduced to search for the optimum combination of material properties. The simulation and optimization results can help the manufacturer select the most suitable material from a wide variety of similar materials for their specific manufacturing process requirements and product quality requirements.

In Chapter 3, after a detailed analysis of the possible effect of the use of a specific raw material on the whole manufacturing process and resulting product quality, we formulated an economic model for raw material selection. In that model, a "process by process, parameter by parameter" approach was suggested in order to analyze the extra manufacturing and quality costs, and to use them to determine the economic raw material choice.

The present chapter uses a computer simulation method combined with two optimal search techniques to find the optimum material properties combination for a particular situation. The computer simulation model analyzes various costs incurred in the use of a specific raw material during the manufacturing process as well as costs due to resulting product quality. The objective is to identify the raw material resulting in the lowest overall cost. A modified HJ (Hooke and Jeeves) optimum search algorithm [39] and a Surface Response Method [63] are used to search for this optimum. Some comparison comments about the use of these two search algorithms are made based on our applied experience.

7. 2. CASE STUDY USED

The example used here to illustrate our method is based on a practical situation (discussed in Chapter 4 and Chapter 5) in a local manufacturing firm that produces heating and ventilating hardware. The actual situation chosen is the production of the "outside cone" of a square ceiling air diffuser. The raw material used for the outside cone is steel sheet metal.

The processes influenced by the steel sheet properties are: shape pressing, neck forming, final inspection and packaging operations. Other operations such as painting and final assembly were assumed (for this illustration only) not to be impacted by varying raw material properties and thus are not considered in this analysis. The above manufacturing processes are mainly affected by the following three raw material properties: steel yield strength, steel thickness and steel ductility.

The details of the above data are shown in Chapter 4, Chapter 5 and Appendix F.

Our objective is to determine the optimum set of raw material properties (thickness, yield strength and total elongation) which results in the lowest overall total cost for the particular application.

7.3. THE SIMULATION MODEL

SLAMSYSTEM™ [75,76] is used here to simulate the various costs incurred in the actual process of using the material (steel sheet). SLAMSYSTEM™ is a simulation software widely used for the analysis of industrial processes [4,32,35,69]. It offers an excellent tool for discrete event, continuous event, as well as mixed event modeling. A great advantage of SLAMSYSTEM™ is that it provides a friendly environment for inserting user-defined FORTRAN subroutines which are the important part of our application.

The SLAMSYSTEM™ approach employed in this project uses regular SLAM network modeling augmented by user-written inserts. This network system is only used for cost modeling (see Figure 7. 1).

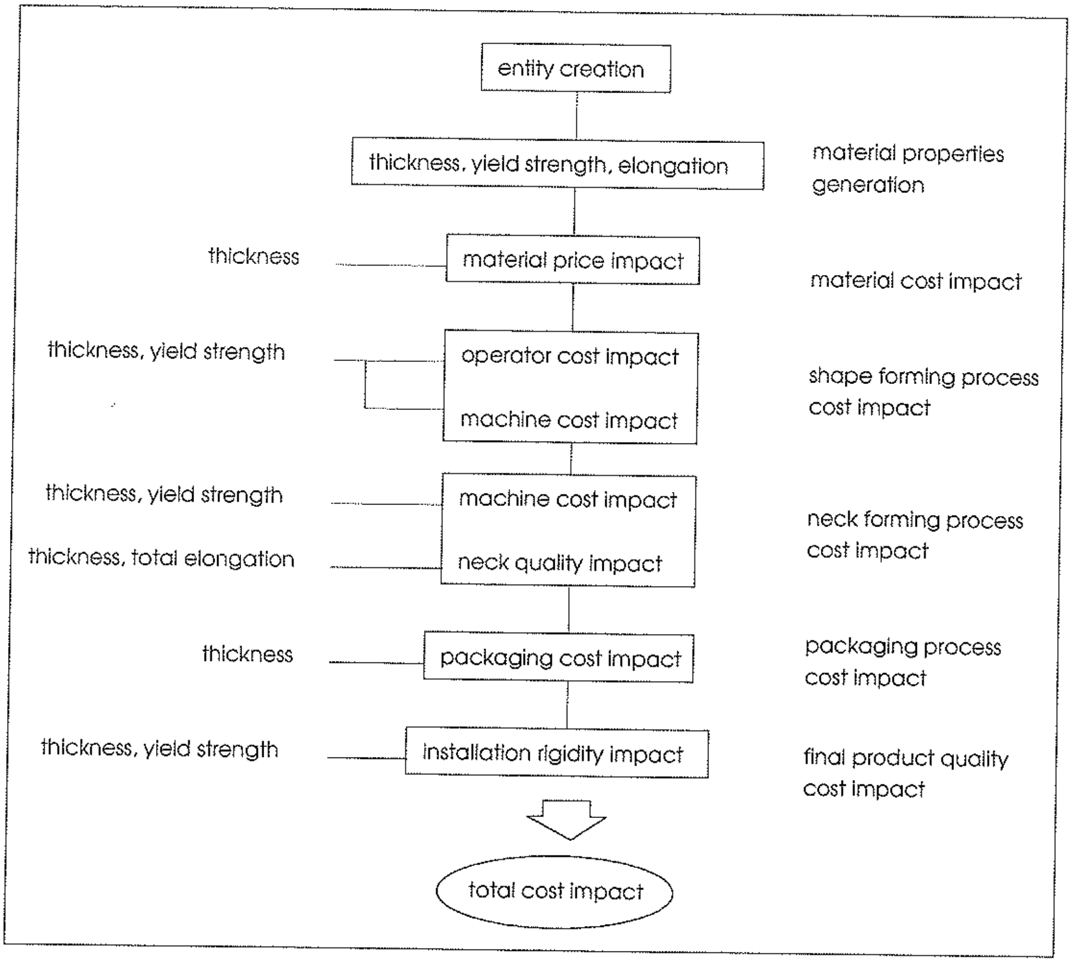


Figure 7. 1 The Structure of the Cost Simulation Model

At first, the computer generates mechanical parts and then assigns certain material properties - taken from a data file - to these parts, Afterwards, it executes a series of "extra cost" calculations that may be incurred during the actual use of the material in the production process. These cost calculations are based on the relationship between the raw material properties and various extra costs that occur due to the use of that particular material (see Chapter 4). Several event nodes are used in the network system for the calculation of the cost impact of the raw material in its application.

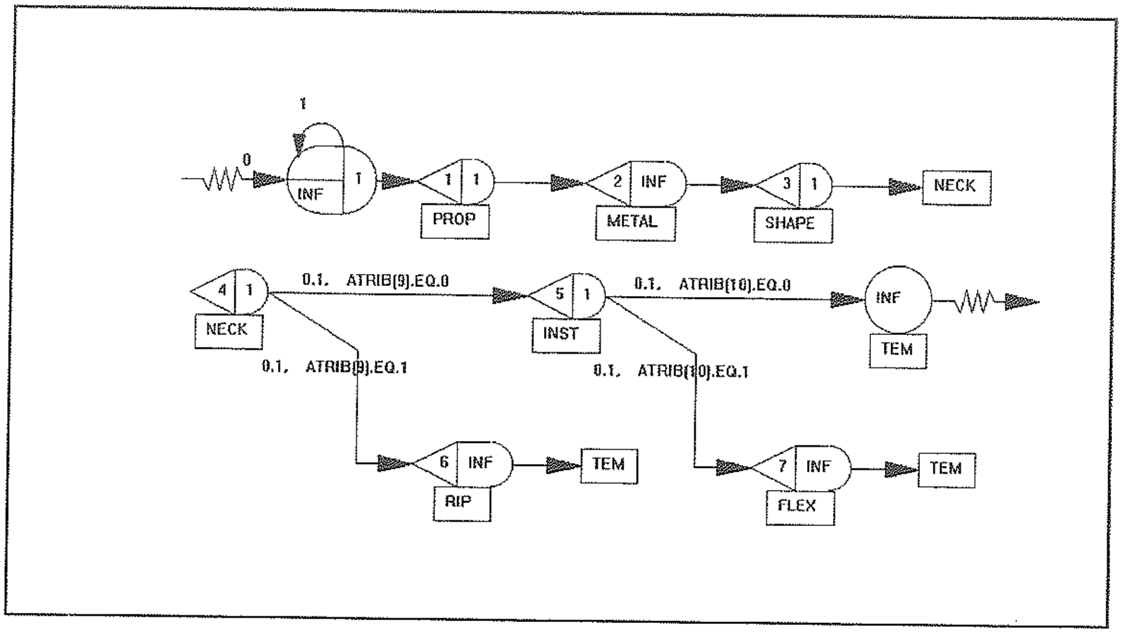


Figure 7.2 Network System for Cost Calculation

The functions of these event nodes in the above network are programmed using FORTRAN subroutines. The detail function of each event node can be explained as follows:

1. The first event node is for material property assignment to a part (the material property is the decision variable at this point).

2. The second node is for the extra material (steel) cost calculation (due to thickness of the sheet steel).

3. The third event node is for the calculation of extra operator and extra machine wear costs during the shape forming operation (due to improper material properties).

4. The fourth event node is for the calculation of the extra machine wear costs during the neck forming operation (due to the improper mix of material properties) and the neck quality judgment in the neck forming operation.

5. The fifth event node is for the calculation of the extra packaging cost and final product quality judgment in the final product.

6. The sixth event node is for the calculation of quality cost because of the lack of enough stretchability of the steel sheet.

7. The seventh event node is for the calculation of the extra product quality cost because of it being too flexible for correct installation of the product.

7.4. OPTIMIZATION USING A MODIFIED H-J SEARCH ALGORITHM

7.4.1. THE HJ ALGORITHM [39] AND ITS MODIFICATION

The HJ algorithm [39] is a widely used search procedure [30,71] to optimize a function and to identify the corresponding levels of the variables that affect it. The method performs two types of search routines cyclically: an exploratory search and a pattern search. The exploratory search is conducted along individual coordinate directions in the neighborhood of a reference point. The pattern search proceeds along the direction defined by the starting and ending points of the exploratory search. Some modifications have to be introduced to the Hook and Jeeves search algorithm in order to allow us to use it for determining the optimum raw material properties. These modifications are needed for our simulation procedure because the normal HJ procedure requires a deterministic evaluation of the function being optimized.

The modification consists of two parts:

1. The statistical aspects of the simulation;
2. The variable constraints.

Simulation models usually have random variables. Hence, in our case, the optimized function would not be a fixed, constant value for a particular set of random data. Means and target value variations are determined from a series of ten simulation runs and are compared to the value of the base reference point. An improvement is only accepted after a statistical confirmation. In our example here, our target value is the overall total cost by the use of various raw materials. When the overall total cost in certain combination of raw material properties is statistically lower than that in a previous reference point, the new combination of raw material properties then can be considered to be better than the previous one.

Since actual material properties values exist only in certain ranges, the search area is limited in that pre-defined range. In our example here, the search range of thickness is between 20 to 36 thou, the search range of yield strength is between 20 to 36 ksi and the ductility range is accordingly deduced by the range of steel yield strength.

The principle of the modified HJ search algorithm is shown in Figure 7. 3.

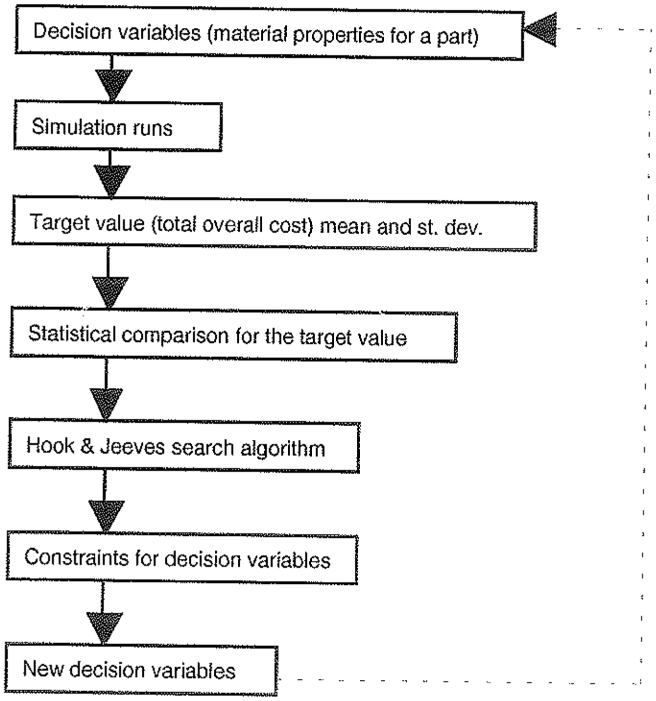


Figure 7. 3 The Principle of the Modified HJ Search Algorithm

7.4.2. THE COMBINATION OF SIMULATION AND H-J OPTIMUM SEEKING

The simulation model combined with the HJ search techniques is used to seek the optimum material properties combination in terms of steel thickness and steel yield strength (ductility can be deduced from yield strength). The SLAM network system works interactively together with our user-inserts (FORTRAN subroutines) as well as user-provided data (material properties data as well as the relationships between material properties and various extra costs). There are three FORTRAN user-insert subroutines used to integrate the simulation and optimization system. They are: subroutine "Intlc", subroutine "Event" and subroutine "Otput". These three subroutines are individually executed before, during and after each simulation run. The functions of each subroutine are as follows:

Subroutine "Intlc":

1. Reading material properties data for simulation testing.
2. Reading the data defining the relationship between material properties and various costs.

Subroutine "Event":

1. Calculating the manufacturing "extra" cost.
2. Calculating of the final product quality cost.
2. Collecting the cost data sets for ten simulation runs.

Subroutine "Otput":

1. Calculating the cost means and standard deviations.
2. Statistical testing of the behavior of the raw material in terms of the new overall cost (the target value).
3. Searching (using the HJ algorithm) for a new point (new material properties) offering the possibility to improve (reduce) the overall total cost.

4. Generating a new point (new combination of properties) for further simulation tests.
5. Outputting the tested material properties and the overall total cost obtained.

We set up three data files for this simulation model. One file is set aside for the material properties data. The material property data in this file are always overwritten after each simulation run by the set of new data. The second file is for the relationship data between material properties and various extra costs. The third file is for the tested output. All data files are located in the user-data directory.

The structure of the simulation and optimization model is shown in Figure 7. 4.

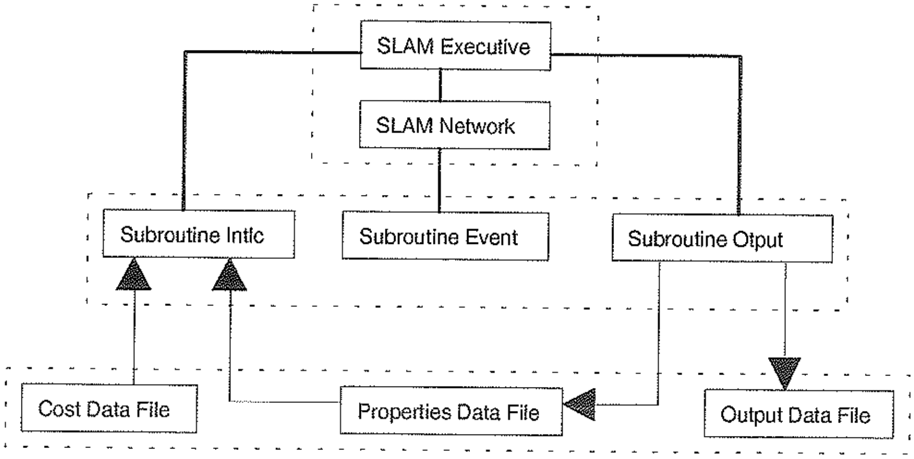


Figure 7. 4 The Structure of the Simulation and Optimization Model

The FORTRAN subroutines of the simulation and optimization are shown in Appendix D - D1.

7.4.3. RESULTS AND ANALYSIS

SLAMSYSTEM™ compiles and links our FORTRAN subroutines to our SLAM network system. The computer simulation and optimization model continuously simulates the costs and uses the HJ algorithm to search for new sets of material properties with the lowest overall total cost for that material.

We select 4 thou as the initial search step-size for material thickness and 4 ksi as the initial search step-size for yield strength. The practical reason for selecting the relatively "big" step sizes is to try to distinguish the real cost difference from the random change of the cost results. The search begins from point 1 (yield strength = 28, thickness = 28) and by simulation, achieves an average target cost value of $15.87. The initial point could represent the raw material presently in use or any other candidate raw material. The points and route followed by the computer in this application are shown in Table 7. 1 and Figure 7. 5.

Run No.	Thickness	Yield strength	Extra Cost
1	28	28	3.04
2	30	28	3.15
3	26	28	2.93
4	26	30	2.93
5	26	26	2.93
6	24	24	2.85
7	26	24	2.94
8	22	24	5.03
9	24	26	2.88
10	24	22	3.86
11	25	24	2.90
12	23	24	3.19
13	24	25	2.87
14	24	23	2.86

Table 7. 1 Results of the Simulation and Optimization Runs

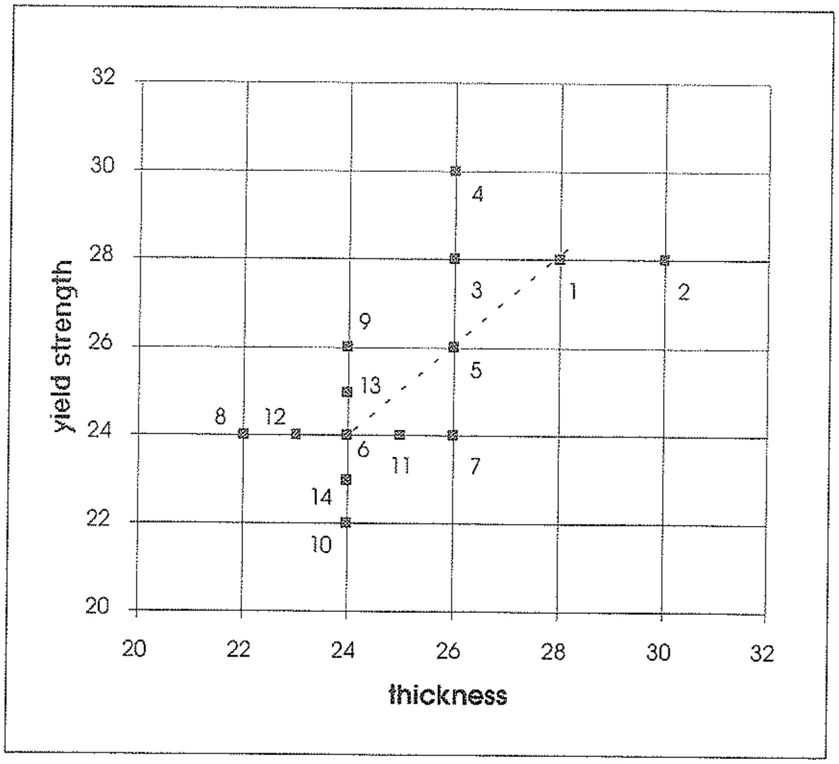


Figure 7. 5 Computer Search Points Diagram

The computer searches from point 1 to point 14 automatically. The target value (average overall total cost) in point 6 is $2.85. No surrounding points (material properties) can result in a lower target value than point 6. As mentioned above, the lowest overall cost means that the material with those properties is the optimum one for this application. We performed several optimum searches from different starting points (see Appendix C). Our results indicate that the overall total cost indicated by point 6 is actually the global optimum in our searching range (thickness = 20 to 36 thou and yield strength = 20 to 36 ksi). The material properties corresponding to this point are: thickness of 24 thou and yield strength of 24 ksi (the average total elongation is 45.81%). A three dimensional presentation of the computer simulation and optimization results is shown in Figure 7. 6.

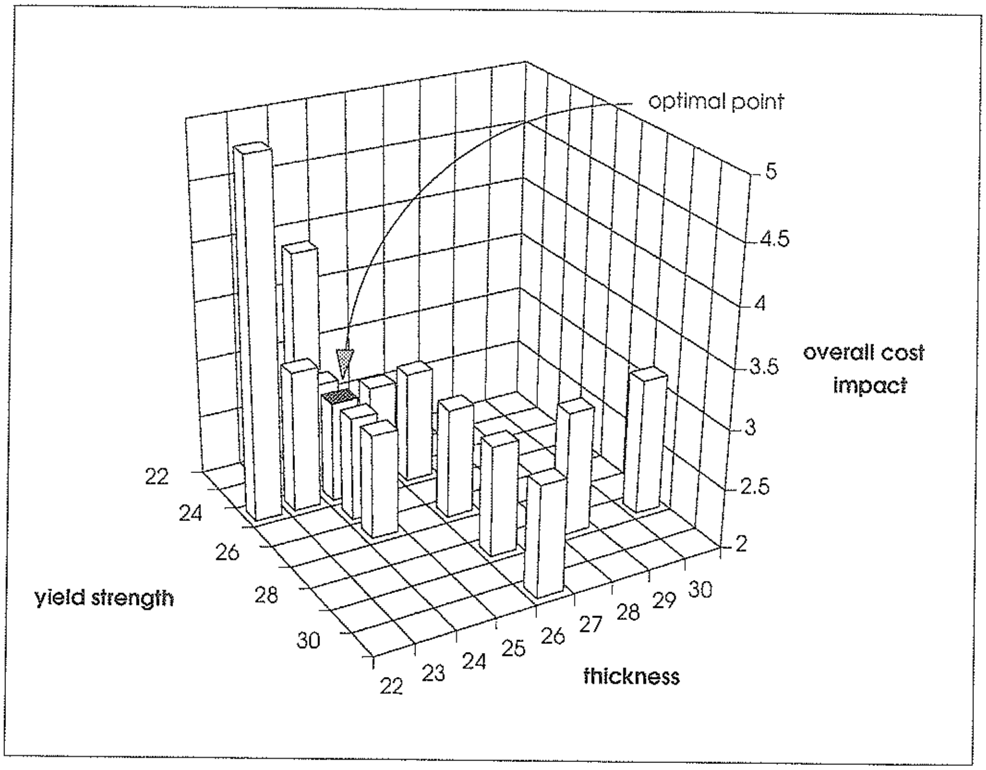


Figure 7. 6 Three Dimensional Presentation of the Search Results

This analysis can be extended further if we know the statistical history of the raw material properties from a material supplier a priori. In these cases, we can substitute the deterministic raw material properties by the given random raw material properties with their specified standard deviations into the simulation and optimization model. Then we can follow with our usual approach to find the means for the optimum raw material properties with those known deviations.

7. 5. OPTIMIZATION USING RESPONSE SURFACE METHOD

7.5.1 THE RESPONSE SURFACE METHOD (RSM)

The response surface method, or RSM [63], is a collection of mathematical and statistical techniques. It is useful for analyzing problems where several independent variables influence a dependent variable or response, and the goal is to optimize this response.

RSM [63] is a sequential procedure. Often when we are at a point on the response surface that is remote from the optimum there is little curvature in the system and the first order model will be appropriate. Our objective here is to rapidly and efficiently lead the experimenter to the general vicinity of the optimum. Once the region of the optimum has been found, a more elaborate model such as the second order response surface may be employed, and an analysis may be performed to locate the optimum.

Now, we introduce some details about the RSM. Frequently, the initial estimate of the optimum operating conditions for the system will be far from the actual optimum. In such circumstances, the experimenter's objective is to move rapidly to the general vicinity of the optimum. He may wish to use a simple and economically efficient experimental procedure. When we are remote from the optimum we usually assume that a first-order model is an adequate approximation to the true surface in a small region of the x's.

The method of steepest ascent is a procedure for moving sequentially along the path of steepest ascent, that is, the direction of maximum increase in response. Of course, if minimization is desired, then we are talking about the method of steepest descent. The fitted first-order model is:

$$\hat{y} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i \tag{7.1}$$

and the first-order response surface, that is, the contours of $\hat{y}$, is a series of parallel lines. The direction of steepest ascent is the direction in which $\hat{y}$ increase most rapidly. We usually take the path of the steepest ascent the line through the center of the region of interest and which is normal to the fitted surface. The experiments are conducted along the path of steepest ascent until no further increase in response is observed. Then a new first-order model may be fit, a new path of steepest ascent determined, and the procedure continued. Eventually, the experimenter will arrive in the vicinity of the optimum. This is usually indicated by lack of fit of a first order model.

When the experiment is relatively close to the optimum, a model of degree 2 or higher is usually required to approximate the response because of curvature in the true surface. In most cases, the second-order model:

$$\hat{y} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i=1}^{k} \hat{\beta}_{ii} x_i^2 + \sum_{i} \sum_{j(>i)} \hat{\beta}_{ij} x_i x_j \qquad (7.2)$$

is a adequent approximation. The analysis of the fitted second-order response surface is often called the canonical analysis [63].

Suppose we wish to find the level of $x_1, x_2, \ldots x_n$ that maximizes the predicted response. This maximum point, if it exists, will be the set of $x_1, x_2, \ldots x_n$ such as that the partial derivatives $\partial \hat{y} / \partial x_1 = \partial \hat{y} / \partial x_2 = \ldots = \partial \hat{y} / \partial x_n = 0$. This point, say $x_{1,0}, x_{2,0}, \ldots x_{n,0}$ is called the stationary point. The stationary point could represent a maximum response, minimum response or a saddle response.

For the first order experiment design, we use a unique class of design (orthogonal first order design [63]) that minimizes the variance of the regression coefficients. The most widely used design for fitting a second-order model is the central composite design. These design consists of a 2^k factorial or fractional factorial augment by 2k axial points $(+/-\alpha, 00, ..0)$, $(0, +/-\alpha, 0, .. 0)$, .. $(0, 0, \ldots +/-\alpha)$ and n_o center points $(0, 0, \ldots 0)$.

7.5.2 APPLICATION OF RSM AND ANALYSIS OF RESULTS

The initial point of this search starts from a thickness equal to 28 thou and a yield strength equal of 28 ksi. If ξ_1 denotes the natural variable thickness and ξ_2 denotes the natural variable yield strength. The coded variables become: $x_1 = \frac{\varepsilon_1 - 28}{\Delta_1}$ and $x_2 = \frac{\varepsilon_2 - 28}{\Delta_2}$. The Δ_1 and the Δ_2 are the designed experiemental step sizes for both parameters and they are equal to 1 in this case (see Figure 7.8 on page 96)

The data for fitting the first order model is as in Table 7. 2.

Nature Variables ξ_1	ξ_2	Coded Variables x_1	x_2	Simulated Response y
28.00	28.00	0	0	3.040
27.00	27.00	-1	-1	2.984
27.00	29.00	-1	1	2.988
29.00	27.00	1	-1	3.093
29.00	29.00	1	1	3.097

Table 7.2. Data for Fitting The First-Order Model - 1

Using SAS (UNIX) program for the first-order fitting, the analysis of variance for the first-order model is shown in Table 7. 3.

Source of error	Sum of squares	Degrees of freedom	Mean square	F_0
Regression	0.011897	2	0.005950	380.14[a]
Error	0.000094	6	0.000016	
Total	0.01199	8		

a: Significant at 0.01 percent.

Table 7.3. Analysis of Variance for First-Order Model - 1

The following model of the coded variable is obtained:

$$\hat{y} = 3.039 + 0.0545x_1 + 0.002x_2$$

To move away from the design center ($x_1=0$, $x_2=0$) along the path of steepest descent, we would move 1 unit in the x_1 direction for every 0.04 units (can be neglected) in the x_2 direction.

The steepest ascent experiment can be arranged as follows:

	Nature Variables		Coded Variables		Simulated Response
	ξ_1	ξ_2	x_1	x_2	y
Origin	28.00	28.00	0	0	3.040
Origin - Δ	27.00	28.00	1	0	2.986
Origin -2Δ	26.00	28.00	2	0	2.932
Origin -3Δ	25.00	28.00	3	0	2.878
Origin -4Δ	24.00	28.00	4	0	2.962

Table 7.4. Steepest Descent Experiment

Decreases in response are observed through the third step; however, the fourth step produces an increase in the result. Therefore, another first order model must be fitted in the general vicinity of the point ($\xi_1=25.00$; $\xi_2=28.00$).

The coded variables are: $x_1 = \frac{\varepsilon_1 - 25}{\Delta_1}$ and $x_2 = \frac{\varepsilon_2 - 28}{\Delta_2}$. The Δ_1 and the Δ_2 are also equal to 1.

The data for fitting the first order model is as Table 7.5.

Nature Variables		Coded Variables		Simulated Response
ξ_1	ξ_2	x_1	x_2	y
25.00	28.00	0	0	2.878
24.00	27.00	-1	-1	2.976
24.00	29.00	-1	1	3.180
26.00	27.00	1	-1	2.930
26.00	29.00	1	1	2.933

Table 7.5 Data For Fitting The First-Order Model - 2

Using SAS program for the first-order fitting, we obtained following results:

Source of error	Sum of squares	Degrees of freedom	Mean square	F_0
Regression	0.032174	2	0.016087	2.21[a]
Error	0.045802	6	0.007634	
Total	0.077976	8		

a: Significant at 20.27 percent.

Table 7. 6 Analysis of Variance Data for First Order Model - 2

The following model of the coded variable is obtained:

$$\hat{y} = 2.9343 - 0.07325x_1 + 0.05175x_2$$

The test statistics shows that the lack of fit is significant, so we conclude that the first-order model is not an adequate approximation. Then, the curvature in the true surface may indicate that we are near the optimum [63]. Thus, we use a second-order model to locate the optimum point.

Selecting the $\alpha = 0.5$, then data for fitting the second-order model is as Table 7.7.

Nature Variables ξ_1	 ξ_2	Coded Variables x_1	 x_2	Simulated Response y
25.00	28.00	0	0	2.878
24.00	27.00	-1	-1	2.976
24.00	29.00	-1	1	3.180
26.00	27.00	1	-1	2.930
26.00	29.00	1	1	2.933
24.50	28.00	-0.5	0	2.906
25.50	28.00	0.5	0	2.904
25.00	27.50	0	-0.5	2.880
25.00	28.50	0	0.5	2.878

Table 7. 7 Data For Fitting Second-Order Model

The experiment design can be shown in Figure 7. 8.

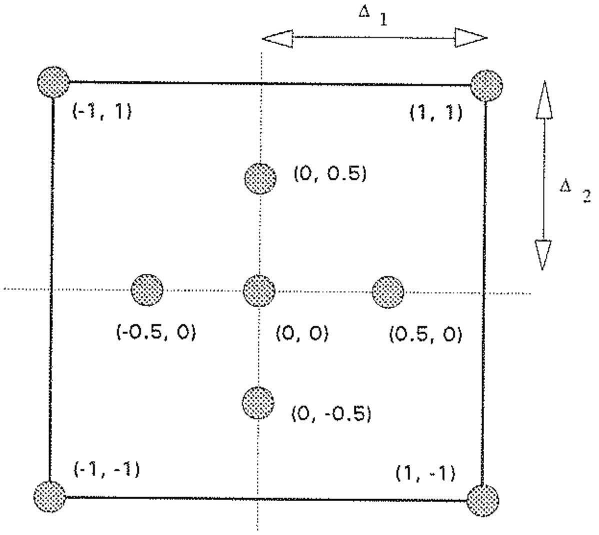


Figure 7. 8 Experiment Design for Fitting Second-Order Model

Using the SAS program for second-order fitting, we obtained following results:

Source of error	Sum of squares	Degrees of freedom	Mean square	F_0
Regression	0.08007	3	0.9576	31.59[a]
Error	0.00355	6	0.000507	
Total	0.08362	5		

a: Significant at 0.01 percent.

Table 7.8 Data of Variance Analysis for the Second-Order Model

The following model of the coded variable is thus obtained:

$$\hat{y} = 2.8772 - 0.0653x_1 + 0.0458x_2 + 0.1157x_1x_1 - 0.05025x_1x_2 + 0.0117x_2x_2$$

The optimum value (the overall cost impact) is 2.828 at coded point $x_1 = -0.267$ and $x_2 = -2.529$. The optimal natural variables are thus thickness = 24.73 thou and yield strength = 25.47 ksi.

The optimum point obtained here is very close to the optimum point (thickness = 24 thou and yield strength = 24 ksi) obtained from H-J search algorithm. The optimum point and optimum value is not exactly the same since as in our H-J optimum search result because in it, the optimal position is constrained by the step sizes (step-size for each of variables is 1 in the last search loop). Then, the optimum raw material specifications can be defined as thickness of 24 to 25 thou and yield strength of 24 to 26 ksi with total elongation of 40% to 45%.

7. 6. COMMENTS ON THE TWO OPTIMIZATION METHODS

From our limited experience, the following comments on using these two search methods can be made.

In terms of programming effort, the H-J algorithm needs considerable FORTRAN programming time, especially when the number of dependent variables increases. The RSM does not need much programming, but it requires the knowledge of the SAS software package. In general, applying the H-J algorithm [39] is much more time consuming than applying RSM [63].

In terms of effectiveness of the optimum search, applying RSM requires the response data to fit a certain model (first-order or second-order) for further procedures. Sometimes, there may be some better points around the design center, but the data or response may not fit a model (first-order or second order) very well. This characteristic may limit the success of an optimum search. On the other hand, the H-J algorithm does not need data to fit a model for further processing, since as long as there are any better points around the original one, the search will continue until one finds the point that there is no better points around it. This point becomes the optimum point.

It is possible that the optimum point obtained may be a local optimum instead of a global one with both of the above methods [39,63]. Several techniques may be used to help in identifying the global optimum point:

1. Run several initial points (distributed in the searching area) for the optimum search.
2. Select a more "suitable" step size.
3. Choose different experiment design (RSM).

In many cases, experience or "trial and error" may help in a search of the globe optimum point.

7. 7. COMPUTER EXPERIMENTS AND DISCUSSION

We have obtained the optimal raw material specifications (thickness of 24 to 25 thou and yield strength of 24 to 26 ksi with total elongation of 40% to 45%) for this particular application from the above computer simulation and optimization analysis. In practical applications, knowing only the optimal answer is not adequate enough. In order to provide a clear picture of what raw material is suitable for only particular application, we also need to understand the cost effects of various raw materials with characteristics around the optimal specifications. For this purpose, we designed a series of computer experiments to calculate the overall cost effect of the raw materials on their application process. To do so, we do not need to seek optimality, we only need to run the simulation (cost modeling) to obtain the cost data (see Appendix D - D2). The results of these experiments are shown as follows:

		thickness						
		20	22	24	26	28	30	32
yield strength	20	10.37	8.32	6.16	4.34	3.04	3.13	3.29
	22	9.29	6.66	3.86	2.95	3.03	3.14	3.29
	24	8.77	5.22	2.86	2.94	3.03	3.14	3.30
	26	8.68	4.65	2.90	2.93	3.04	3.15	3.30
	28	8.91	4.98	3.06	2.93	3.04	3.15	3.31
	30	9.67	4.99	3.43	2.93	3.04	3.15	3.31
	32	10.02	5.69	3.97	2.94	3.05	3.16	3.32
	34	10.59	6.43	4.06	2.94	3.05	3.16	3.32
	36	11.05	7.82	4.56	2.96	3.06	3.17	3.33

Table 7.9 Incremental Added Cost as a Function of Thickness and Yield Strength (Elongation)

When there are a plenty of choices (yield strength) for raw materials, ordering relatively thin metal (24 thou) is thus a better option. When there are limited choices, ordering medium thickness (26 or 28 thou) metal can thus reduce the risk of quality problems and at the same time, without increasing extra cost significantly. Thick metal (32 thou or 34 thou) is not a good choice.

NOTE: Cost Structure in the Simulation Results

To show how the material properties affect the manufacturing processes and product quality in the simulation runs, we take the 16 combinations of material properties as examples to show the simulated results. The simulated cost impacts of material properties on the material price, manufacturing process and product quality are shown in Appendix H.

7. 7. CONCLUSION

A combination of the simulation model with two optimization algorithm has been developed using SLAMSYSTEM, and a modified HJ search algorithm/Surface Response method for the determination of optimum raw material properties including their effect on the production process itself. The results obtained show that the integration of the simulation and optimum seeking techniques is very effective for searching out the optimal combination of raw material properties. When compared to a full factorial experiment design using only simulation, our approach using simulation coupled with an optimization search technique provides good results and can reduce testing and evaluation times significantly.

CHAPTER 8

ECONOMIC RAW MATERIAL SELECTION USING COMPUTER SIMULATION

After a delicate balancing among various costs incurred during the material applied processes using a computer simulation and optimization method (Chapter 7), one achieves a much better understanding about the material requirements for the particular application. Based on these understandings, one can start the economic material selection from a wide variety of materials available (from various suppliers). In this chapter, we use two computer modeling and simulation languages: STELLA II [79,81] (system dynamic modeling) and SLAMSYSTEM [75,76] (general simulation), to assist with the practical economic raw material selection in order to reach the optimum result - the lowest overall cost. The total cost for the economic selection of candidate raw materials includes the actual raw material cost, the extra manufacturing cost and the final product quality cost. These costs are systematically simulated for three typical areas of interest: for the purchasing operation, for the manufacturing procedure and product quality inspection.

8.1 INTRODUCTION

As we mentioned before, raw materials have a considerable influence on the cost of engineering products. It not only affects the material cost, but also affects the manufacturing processes and the final product quality. Using less costly material might not be the answer if it is more difficult and more expensive to process. Using expensive material sometimes may just mean spending too much money on unnecessary material properties. The goal is to select, from a wide variety of materials available, the material with the lowest overall cost, while still fulfilling the required product functions and maintaining or achieving the desired quality levels.

Our analysis is based on our proposed economic model (presented in Chapter 3) for the selection of raw materials. The model considers the raw material application and its impact on the manufacturing process and the resulting costs. We suggested a "process by process, parameter by parameter" approach to analyze the "extra manufacturing cost" incurred by the selection of any particular raw materials.

In this Chapter, we use a simulation method based on the same model to illustrate the usability of this approach in realistic, practical industrial situations. From the systematic modeling of the use of the candidate raw materials (with certain properties) in the purchasing process, production process, and the consideration of the various types of costs incurred, we can determine the total overall cost incurred due to the selection of specified raw materials. It is believed that this kind of simulation procedure can be of real assistance to manufacturers in making more cost effective decisions for the selection of raw material.

8.2 CASE AND APPROACH

We choose again the Outside Cone of a Ceiling Diffuser as our case to evaluate the raw materials and their impact on the manufacturing process and customer acceptance. An illustration of the cone and of its manufacturing process is shown in Figure 4.2 (see Chapter 4). The example is based on a real situation with a local manufacturer.

The raw material used for the outside cone is coiled steel sheet. Two typical steel sheet suppliers are chosen for the analysis. They are: local steel sheet warehouses and steel sheet producers. As we discussed in Chapter 5, the local warehouse can provide the sheet metal material at a relatively higher price, with a shorter lead time, smaller minimum order size but with usually wider material specification ranges. In contrast, the coil producer can provide similar material at a usually lower price, with longer lead time, requiring larger minimum order size but, with narrower material specification tolerances.

As stated before, in order to make an economic selection of raw materials, we need to analyze the whole range of costs incurred in all affected processes where the specific raw material is used. The costs generated by any particular raw material can be divided into three parts: "Raw material cost" (including sheet metal price and all associated handling costs), "Extra manufacturing cost" (including extra operation time, extra machine wear and extra quality cost due to the properties of that particular material) and "Product quality cost" (due to rejection of final defects).

The "Raw material cost" can be obtained from the analysis of the sheet metal purchasing operation. The "Extra manufacturing cost and Final product quality cost" can be obtained from the analysis of the impact of the raw material properties on the manufacturing processes and product quality. From a detailed analysis of the above three components, we can determine the total cost associated with the selection of raw materials from different suppliers. Of course, the raw material with the lowest overall total cost is the best selection.

The first method for the analysis of these costs is carried out by means of a system modeling approach [3,66,80]. The simulation software chosen is "STELLA II", a Systems Dynamics language written for use on Macintosh (Apple) computers. The use of the systems dynamics approach permits relatively easy modeling of the somewhat imprecise relationships between the parameters and processes of interests. The structure of STELLA II is especially convenient to display causal relationships in a very clear, on-screen, graphic manner. Other important benefits of STELLA II are its user-friendly features and its underlying principles that are easily understandable to the analyzer and to the eventual decision maker.

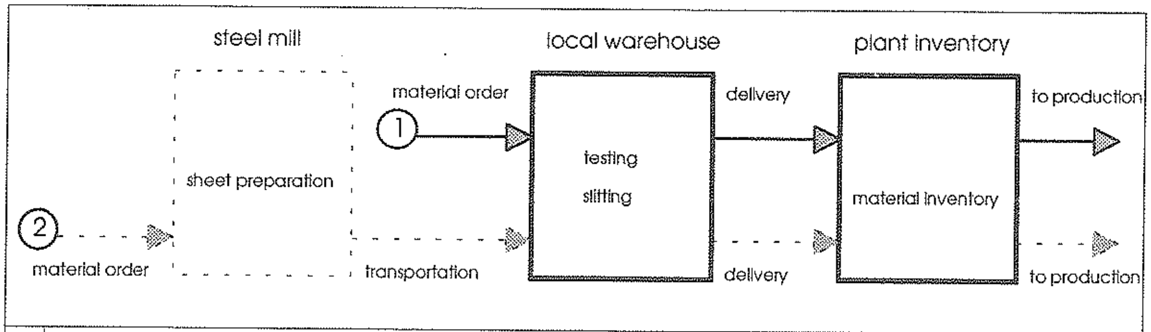
The second method for the analysis of these costs is carried out by a general computer simulation method. The simulation language chosen is SLAMSYSTEM™

[75,76], a sophisticated common simulation language for the modeling of any continuous, discrete or combined variables [4,32,35,69]. It also offers easy insertion of FORTRAN subroutines for complicated mathematical calculations. The structure of SLAMSYSTEM is also convenient for the user due to its on-screen, graphic programming.

8. 3 ANALYSIS OF THE PURCHASING OPERATION

In order to provide practical results for the decision makers, the structure of the simulated purchasing operation should follow real purchasing practice as closely as possible. The use of modeling or simulation methods allow us to recreate reality by modeling it in a manner familiar to and very similar to that used by the decision maker or planner.

The detailed raw material purchasing systems for both types of suppliers are shown in Chapter 5. There are two types of material suppliers available and the purchasing processes are different for each other (see Figure 8.1). One type of suppliers is local warehouses, the other is steel mills.



1			order cost	material price slitting and delivery cost * inspection cost	holding cost out-of-stock cost damage cost
2	order cost	material price transportation cost		slitting and delivery cost * inspection cost	holding cost out-of-stock cost damage cost

Figure 8.1 Diagram of Two Typical Purchasing Processes and Related Costs

From the simulation of the raw material purchasing operation, we may obtain various costs of interest, such as: material price, ordering cost, transportation cost, slitting cost, delivery cost, inspection cost (optional), out of stock cost and holding cost. The "total material cost" is then the sum of all of the above costs.

The simulation model for the purchasing systems using STELLA II, is shown below (Figure 8.2):

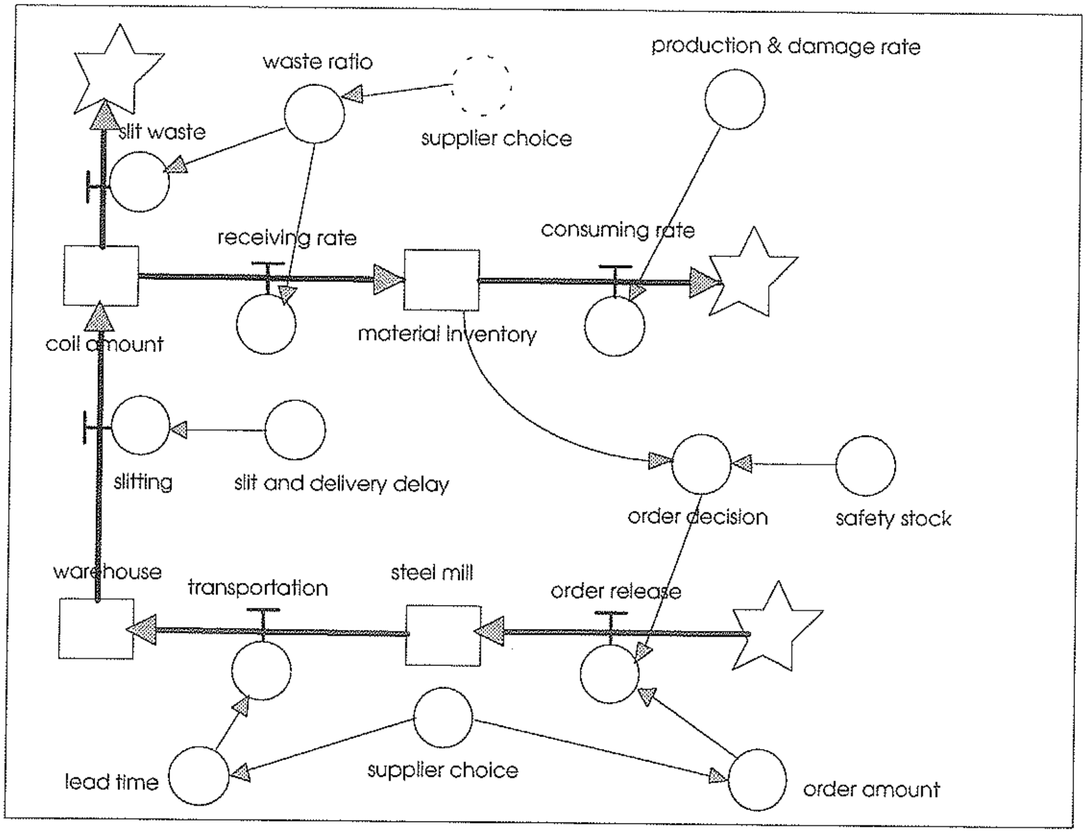


Figure 8.2 STELLA Modeling Structure for Purchasing Operation Analysis

The "order decision" is made when the level of "material inventory" is lower than a certain pre-defined level. The order amount depends on variables such as the supplier's minimum order amount and the company's permitted safety stock. When the material inventory is lower than the permitted safety stock, a material order may be sent to a supplier. If the material is ordered from the steel mill, the material (steel sheet) must be produced and then transported to a local warehouse for slitting into the desired widths (some of the material may be wasted during the sheet slitting process). If the order is directly to a material warehouse, the warehouse will search for the suitable material for the in-plant slitting process. During the material slitting process in the warehouse, there is an option for material inspection. As a result, some of material may be rejected because of some non-conforming properties; the rest is accepted and delivered to the manufacturer's raw material inventory. While most of this material is consumed in the production process, some of it may be damaged or destroyed during stocking or during handling.

The simulation model using SLAMSYSTEM network for purchasing operation is shown below (Figure 8.3): This network can be divided into three sections: the section dealing with demand and total cost calculation; the section dealing with inventory and receiving detect nodes, and the section dealing with the purchasing operation network.

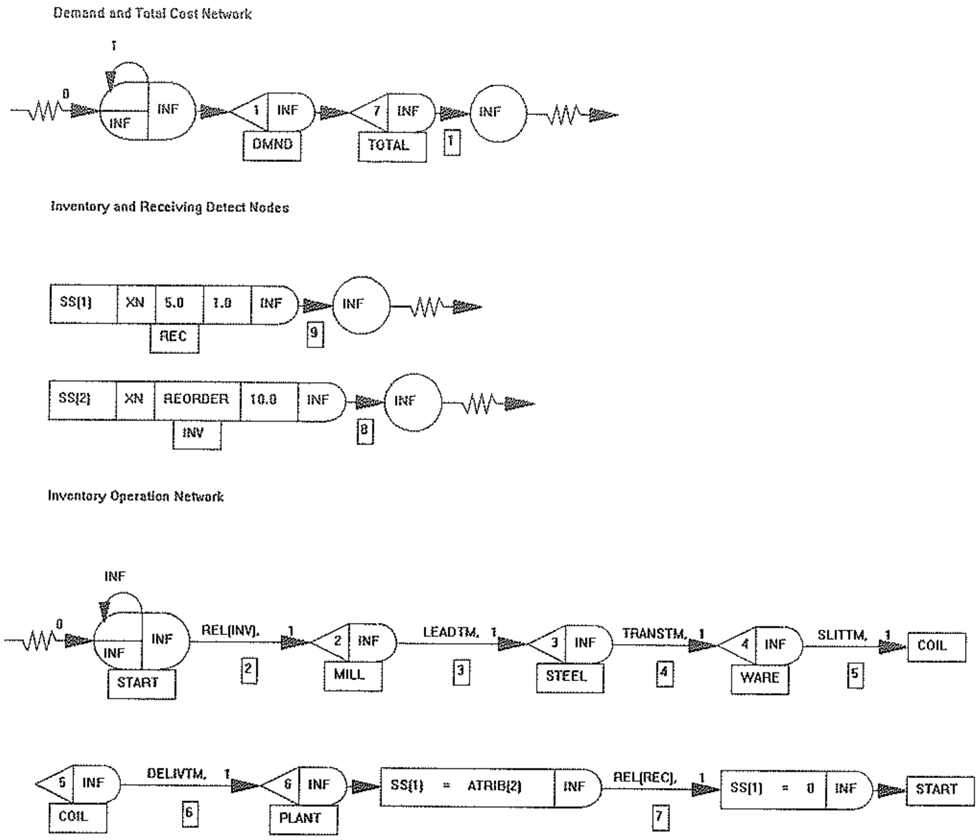


Figure 8.3 SLAMSYSTEM Network Model for Analysis of Purchasing Operations

In the model, the material demand "DMND" changes along with time (normal and seasonal variation of the product). The total cost "TOTAL" is calculated every day to provide up-to-date cost information.

The material (sheet metal) inventory "INV" in the manufacturing plant is checked continuously to send the information "REL(INV)" for material orders.

The material order information "REL(INV)" is made when the level of material inventory "SS(2)" is lower than a certain pre-defined "REORDER" level. The order amount depends on variables such as the supplier's minimum order amount and the company's permitted safety stock. When the material order is sent to the material supplier "MILL", a "LEADTM" period is needed for the actual preparation of the material (if not in stock). Afterwards, the material "STEEL" is transported (TRANTM) to a local steel sheet warehouse "WARE" for slitting into certain desired "COIL" widths. If the material order is directly sent to a warehouse, the material slitting can be proceeded after a suitable material is located in the warehouse. In the mean time, some inspection can be done during material slitting, some of material with non-conforming properties may be rejected; the rest is slit and delivered to the manufacturing "PLANT". The raw material received "REC" is in the material inventory "INV" to satisfy the production requirements. While most of this material is consumed in the production process, some of it may be damaged or destroyed during stocking or during handling.

When ordering from the steel mill or the local warehouse, the simulation network structure is same, the only difference is the input data (such as: order amount, reorder point, transportation time, lead time etc.) in the FORTRAN subroutines.

The FORTRAN subroutines for the network structure of the purchasing operation analysis are shown in Appendix D - D3. We selected a five-year period as the total simulation time. All costs are to be accumulated during this period. The "material cost per unit" can be obtained by dividing the "total material cost" by the number of "units produced" during this period.

8. 4 ANALYSIS OF THE MANUFACTURING PROCESS AND FINAL PRODUCT QUALITY PROBLEM

As we stated in Chapter 3, in order to reduce manufacturing information requirements to a minimum, our cost information analysis only includes the "relative cost" or "extra cost" which is incurred when the "non-ideal" conditions created by the use of the particular raw material exist. This approach means that when the properties of the material are ideal, the manufacturing extra cost is zero or at a standard level. Information costs can thus be reduced significantly since our interest is only in the extra costs caused by the use of that specific material. As mentioned before, we classified extra manufacturing costs into three types: operator extra cost; machine extra cost, and quality extra cost. Based on the understanding of the effect of raw material properties on the production process, the extra manufacturing cost can be simulated by a "process by process and parameter by parameter" manner. This requires the analyst to have access to accurate cost information regarding raw material properties and a thorough understanding of their impact on the manufacturing operations (see Chapter 4 and Appendix F). For simplification, we assume that work-in-process is inspected after each process. We also assume that the quality criterion or standard of the manufacturer regarding the product is the same as that of its customers.

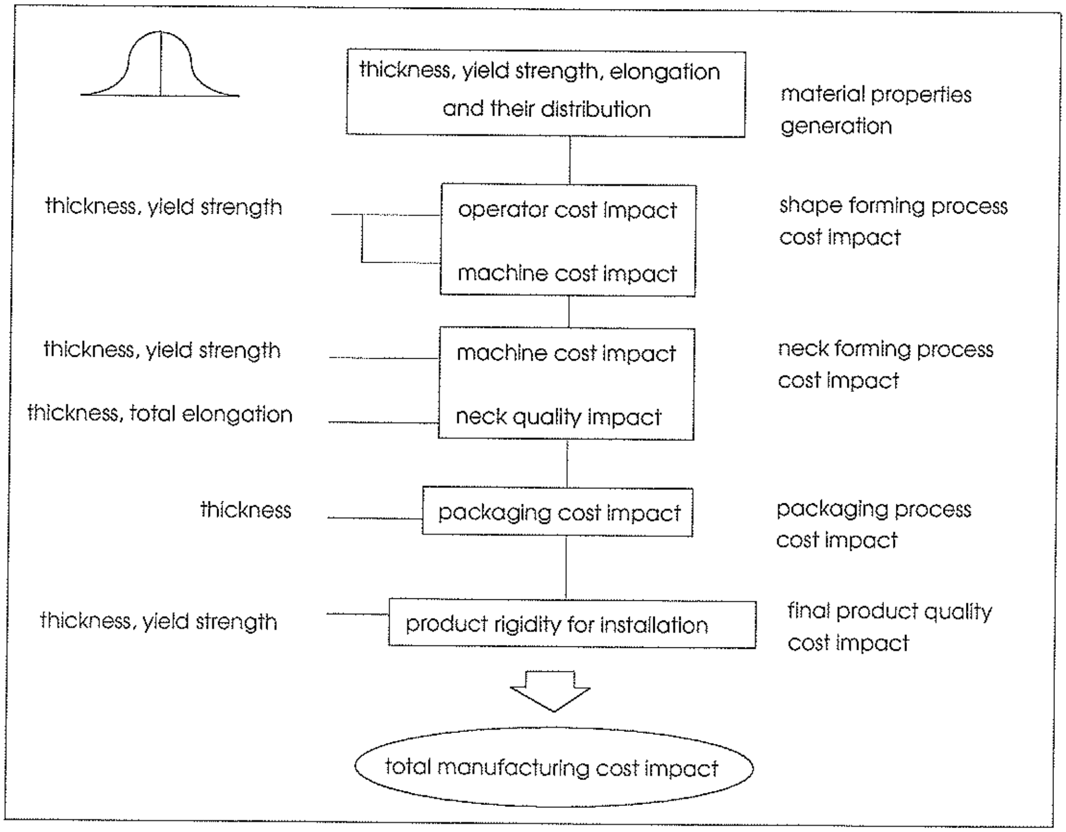


Figure 8.4 Extra Manufacturing and Product Quality Cost Calculation Diagram

The diagram 1 in Chapter 4 shows that the manufacturing processes related to the steel sheet properties are the shape pressing, the neck forming, the final inspection and the packaging operations. Other operations, such as painting and the final assembly, are not considered in this analysis since their manufacturing costs are (in this example only) assumed not to be influenced by the raw material (steel sheet) properties.

According to the properties of the raw material provided by suppliers, the density function distributions of raw material properties such as "metal thickness", "metal yield strength" and "metal total elongation" can be formulated and the property data for each product case are randomly generated. This is done by means of three separate random generators (one for each property). The "metal total elongation" is deduced from "metal yield strength" randomly and two types of "mixed index" are derived using the "metal thickness" and "metal yield strength" values since they usually work together to affect the manufacturing process costs.

The computer then calculates the extra manufacturing costs due to the improper material properties, process by process. At each process, the extra manufacturing cost includes the extra operator cost, extra machine wear cost and extra quality cost. Each cost is affected by some of the raw material parameters or mixed parameters. Based on the relationship between material properties and the manufacturing processes, the extra manufacturing costs in terms of extra operator cost, machine wear cost, and process quality cost at each process can be calculated and accumulated by the computer program. We need to mention that the cost content and the calculation method may change according to the exact effect of raw material properties on the manufacturing operations.

The simulation model for the manufacturing process and the final quality analysis using STELLA is shown below:

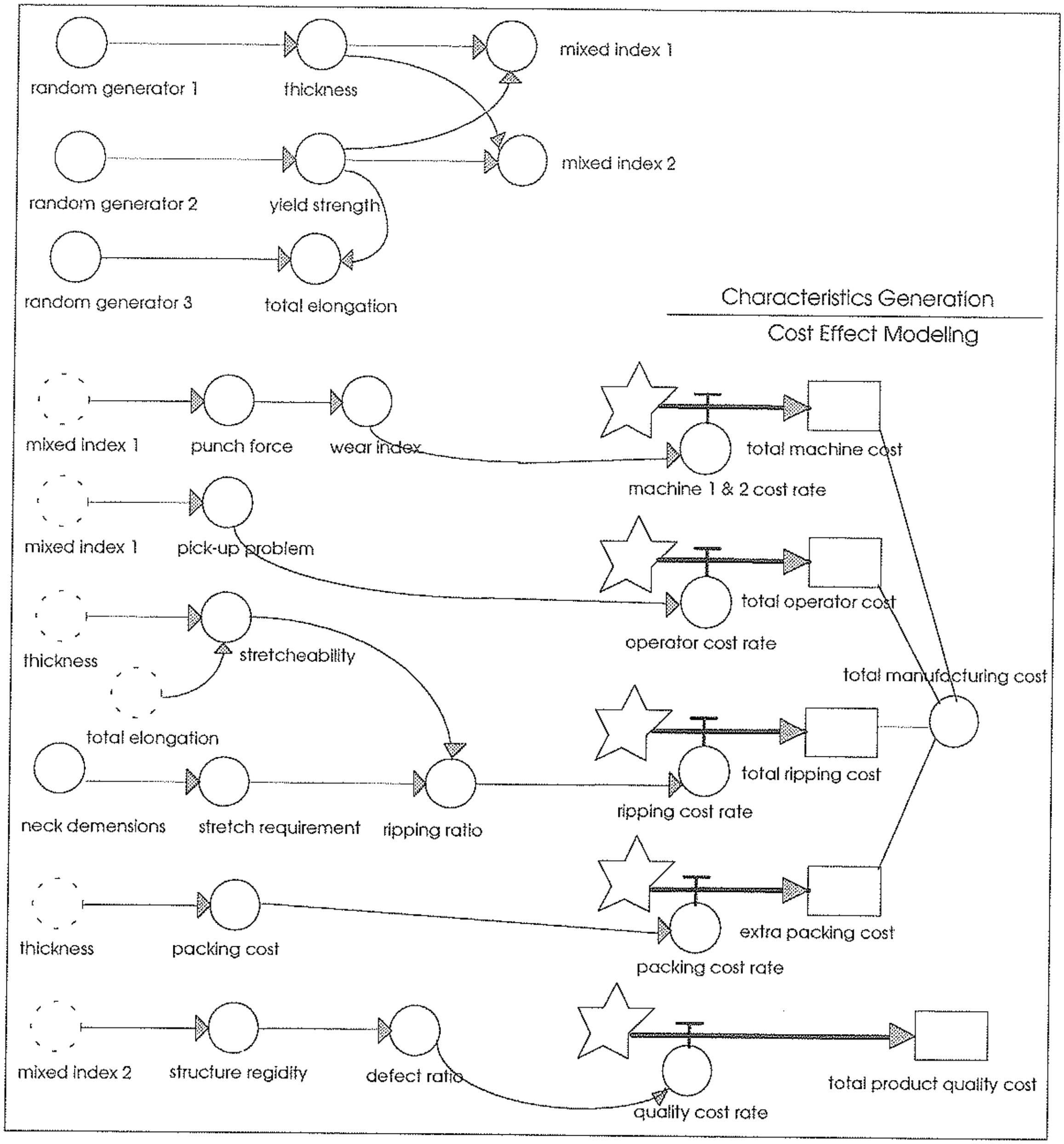


Figure 8.5 STELLA Modeling Structure for Manufacturing Process and Quality Problem Analysis

The above STELLA modeling structure is very easy to understand since the causal relationships between material properties and the related cost impacts are presented in pictorial style and are familiar to the decision maker.

The simulation model for the manufacturing processes and product quality analysis using SLAMSYSTEM is shown below:

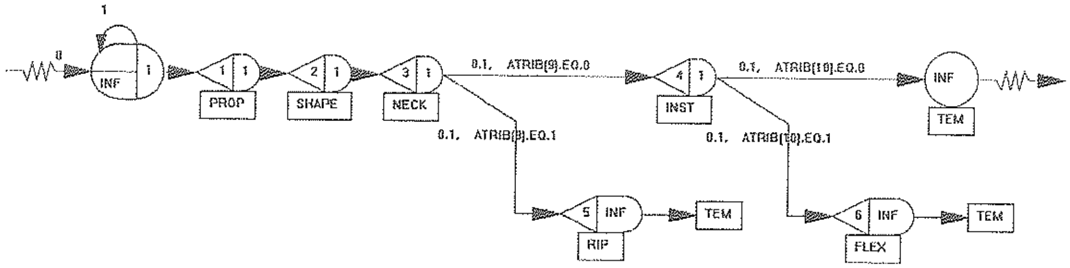


Figure 8.6 SLAMSYSTEM Network for Manufacturing and Final Product Cost Simulation

The SLAMSYSTEM network is shown in Figure 8.6. The simulation network consists of several event nodes which are coded (using FORTRAN subroutines), a series of quality criteria judgments, and cost calculations, as discussed above.

We set up a production run of 1000 units with randomly varying material properties to model the manufacturing extra cost. The "total manufacturing cost" and "product quality cost" are the accumulation of all the above costs. The "extra manufacturing and product quality cost per unit" can then be obtained by dividing the "total extra manufacturing and final product cost" by the number of "units produced" (defined as 1000 units).

NOTE: Generations of Experimental "Simulated" Data

To show the material properties data generation process and their corresponding cost modeling on the manufacturing processes and product quality, we take the following data as an example: sheet thickness follows a normal distribution with an average value of 24 thou and a standard deviation of 2 thou, and sheet yield strength follows a normal distribution with an average value of 28 ksi and a standard deviation of 2 ksi. The material properties generated and their corresponding cost impacts are showing in Appendix G. This data set of simulated properties serves as a simulated experimental input into our proposed solutions of approaches.

8.6 RESULTS AND DISCUSSION

After the two simulation or modeling approaches, the cost results and the comparisons are shown below:

- Purchasing Operations (5 years of simulated data based on the data in Chapter 5)

ORDER POLICY:

	A Steel Mill	A Local Warehouse
Order Amount Assumed	300,000 lb.	30,000 lb.
Safety Stock Assumed	250,000 lb.	25,000 lb.

COST RESULTS:

	Purchasing from a steel mill		Purchasing from a local warehouse	
	SLAMSYSTEM	STELLA II	SLAMSYSTEM	STELLA II
Order Cost ($)	3,000	3,000	12,000	12,000
Steel Cost ($)	864,000	864,000	1,224,000	1,224,000
Transit Cost ($)	90,000	90,000	0	0
Slitting Cost ($)	222,480	222,480	165,672	165,672
Holding Cost ($)	41,893	39,690	3,121	2,739
Out-of-Order Cost ($)	0	0	0	54
Total Cost ($)	1,221,373	1,219,170	1,404,793	1,404,519
Total Production (units)	657,774	656,770	657,710	656,770
Material Cost ($) / Unit	1.86	1.86	2.14	2.14

Table 8.1 Cost Results for Purchasing Operation by Computer Simulation

- Manufacturing Process and Product Acceptance (1000 units simulated)

METAL PROPERTIES:

	A Steel Mill	A Local Warehouse
Thickness Assumed (thou)	Normal(24, 1)	Normal(24, 2)
Yield Strength Assumed (ksi)	Normal(24, 2)	Normal(28, 2)

COST RESULTS:

	Material from a steel mill		Material from a local warehouse	
	SLAMSYSTEM	STELLA II	SLAMSYSTEM	STELLA II
Operator Cost ($)	31.55	30.92	16.71	16.17
Machine Cost 1 ($)	22.33	20.32	23.83	23.81
Machine Cost 2 ($)	13.33	13.33	15.63	15.62
Neck Qaulity Cost ($)	200.00	190.00	1000.00	960.00
Packing Cost ($)	345.57	352.17	306.00	352.06
Product Quality Cost ($)	466.00	408.78	29.22	21.48
Total Cost ($)	1076.79	1015.53	1392.10	1389.14
M & P Cost ($) / Unit	1.08	1.02	1.39	1.40

Table 8.2 Cost Results for Manufacturing Processes & Product Quality by Computer Simulation

From the above data, we can see that we have obtained similar cost results by SLAMSYSTEM simulation and STELLA II modeling, and the cost differences between the two methods are solely due to the randomness of the data generated in the programs.

From the above data, the final comparison results obtained from our computer simulations are shown in Table 8.3.

	Material from A Steel Mill		Material from A Local Warehouse	
	SLAMSYSTEM	STELLA II	SLAMSYSTEM	STELLA II
Raw Material Cost ($) / Unit	1.86	1.86	2.14	2.14
Extra Manufacturing and Final Product Cost ($)/ Unit	1.08	1.02	1.39	1.40
Total Overall Cost ($) / Unit	2.94	2.88	3.53	3.54

Table 8. 3 Cost Comparison for Raw Materials from Two Suppliers

Since the raw material obtained from the steel mill gives the manufacturer a lower total overall cost, it is thus a better choice for this particular example.

8. 7. COMMENTS AND CONCLUSION

Based on our experience in the application of STELLA II [79,81] and SLAMSYSTEM [75,76] to the practical situation, the following comments can be made.

1. From an ease of programming and understanding point of view, and for this type of problem, we believe the system dynamic modeling approach by STELLA is better for the simulation. Using STELLA software, we program the model using icons instead of by text writing. It is simple, and easily understood. It especially fits causal relationship analysis and feedback systems. In contrast, SLAMSYSTEM needs to use FORTRAN programming for the mathematical calculation, logic judgment and many other programming skills.
2. From the point of flexibility, the SLAMSYSTEM is a better language for complex systems. It can be used for discrete events as well as continuous variables. Although FORTRAN programming increases the work effort, it, as subroutine inserts, can increase the flexibility of the simulation approach for complex systems.

In general, for a simple problem or a rough analysis of a problem, we recommend STELLA II. For a detailed analysis of a complicated problem, we believe SLAMSYSTEM is a more flexible or more accurate approach for system modeling.

In this chapter, two systematic analysis methods based on computer simulation for economic raw material selection are presented using a realistic example. The results seem to indicate that such an approach may provide a very effective way to determine costs (material and process) associated with the selection of specific raw materials. These methods should eventually be compared to historical "real company information" if such information becomes available.

The result of the application of our analytic approach should assist managers to make cost effective choices from a wide variety of alternatives or strategies.

CHAPTER 9

ABDUCTIVE NETWORK APPROACH TO IDENTIFY SUITABLE RAW MATERIALS

In this chapter, we use the Abductive Network Method - a knowledge-based method [2,64] for our raw material selection analysis. The advantage of this method is that, even if we do not have a quantitative understanding (due to limited knowledge, limited time etc.) about how the raw material properties affect the manufacturing processes, we can use this method to transfer the experience of "experts" regarding this problem into a systematic network system to effectively identify the suitable raw material range for a particular application. In this approach, we assume that we do not have detailed cost data about the impact of the raw materials on the manufacturing processes. Instead, we do have some "qualitative" general information from "experts". This type of problems exist widely in many industrial situations. This method can be considered as a "quasi-expert-system" (knowledge-based) approach.

9. 1 INTRODUCTION

In a manufacturing environment, many problems cannot be analyzed explicitly due to their complexity. However, for better quality and higher productivity, we need to understand more about the relationships between various variables and the expected output(s). For certain problems, we can define certain variable(s) as output(s) and various variable(s) as input(s). In order to have a better control of the problem, we may need to know which variables influence the output and how they influence it. The practical reason for the existence of unresolved problems is usually the limitation of our knowledge or the actual time and cost constraints for a detailed analysis. Manufacturers are likely to use personal "experience" or "trial and error" approaches to deal with problems in their daily productions. Obviously, a single person's experience to approach some problem in a complex system may be inconsistent and not reliable.

From a network point of view, we may treat some unknown problems or relationships as a system (see Figure 9. 1).

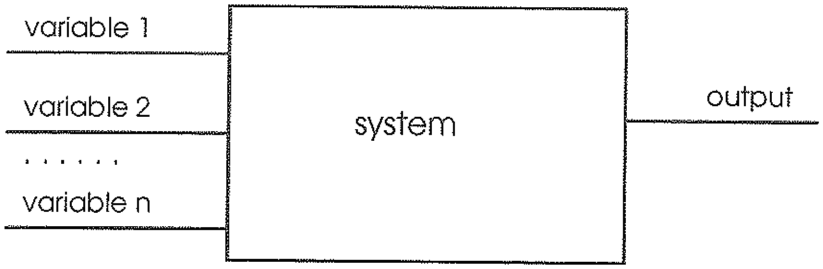


Figure 9. 1 A System Approach to a Manufacturing Problem

Certain variables can be treated as inputs and our interested result may be treated as an output. The question is how to determine the relationship between the output and inputs for a better control of the output result. Based on personal experience, a manufacturer may only roughly know the problem. When the complexity of the problem or time and cost constrains inhibits the use of an analytical approach to resolve the problem, we may find nowhere for us to go to deal with it if we only think of traditional analytical methodologies. Can we transfer valuable personal experience to a systematical approach to certain problems? How do we integrate and synthesize the knowledge of our experts who deal daily with the problems? The answer is positive, and one of the possible solutions is due to the recent development [2,64] of the combination of neural network technology and modern statistical methods, called the abductive network approach. An abductive network system can approach these problems and overcome many of the limitations associated with many conventional expert systems, qualitative reasoning, and statistical diagnostic methods. Even if a problem is described in a "fuzzy" manner by experts, it can also be transformed to a sound knowledge database. Using the abductive network approach, a systematic solution can be obtained for a practical control of the problem.

It is quit rare to find applications of abductive network techniques in the literature [19,20]. This paper uses a realistic example to describe this approach. First, we will give a brief introduction to abductive network techniques; then, a practical problem; followed by the abductive network approach; and finally, the result and discussion.

9. 2. ABDUCTIVE NETWORK TECHNIQUES

As we mentioned, we use an abductive network system to approach a practical problem. The software used is called AIM™ [2]. AIM is the abbreviation of Abductive Induction Mechanism. As the software developer declared, the abductive network technique is a result of almost three decades of neural network and statistical modeling research. AIM is an advanced machine learning tool that automatically discovers network solutions to complex decision, prediction, control, and classification problems. Given a database as an example, AIM synthesizes abductive networks and encodes them into the application software. The database can consist of observed, historical, simulated, or expert generated data. Figure 9. 2. illustrates the AIM synthesis process.

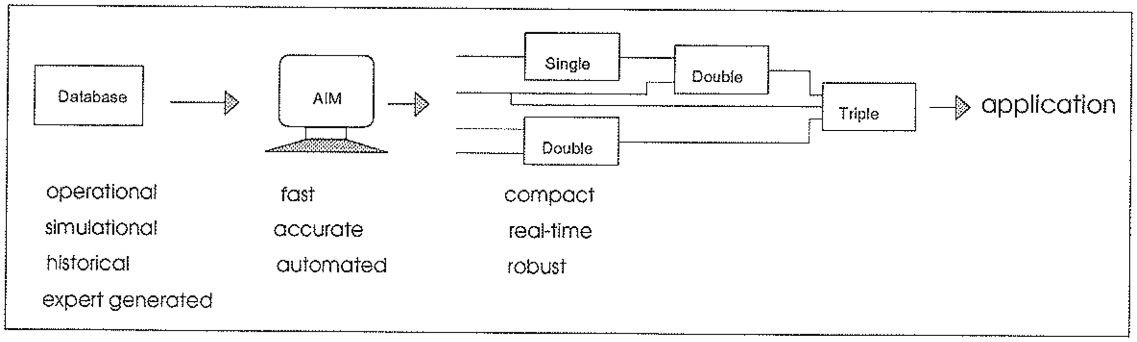


Figure 9. 2 Abductive Network Approach Using the AIM Software Package

Currently AIM [2] has the following types of nodes: normalizers, white elements, singles, doubles, triples, wire elements, and utilizers . Normalizers transform the original input variables into a relatively common region. The white element consists of the linear weighted sums of all the outputs of the previous layer. This element combines more variables than other types, allowing for simple and unique multi-variable configurations.

Singles, doubles, and triples are elements whose names are based on the number of input variables [2].

Solving a problem with AIM [2] has four major steps:

1. create a database
2. build an AIM model
3. evaluate model performance
4. implement the model

9. 3 PROBLEM ANALYSIS

The problem we deal with here is to identify a suitable material range for a particular application in a local manufacturing company. The product being analyzed is the Outer Cone of a Ceiling Diffuser. The material used is low carbon sheet steel. Although this general problem has been discussed before, we present it again due to the different requirements of the analysis method suggested. The application process can be described as follows (see Figure 9. 3): the sheet material is purchased in a local warehouse, then it is pressed into a general shape and a neck is formed in the center for connecting purposes; afterwards, it is painted and assembled with other parts; finally, the product is delivered to the customer for installation.

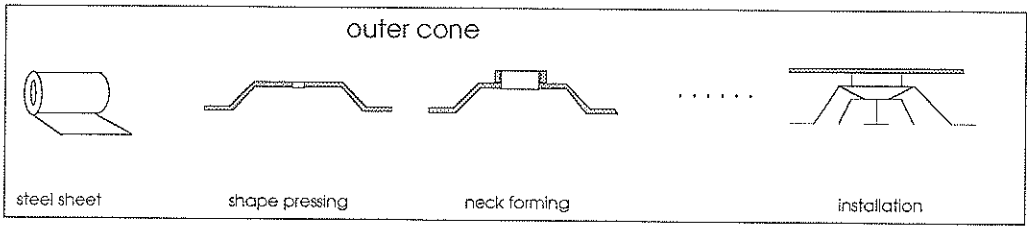


Figure 9. 3 Material Transformation Process for the Case Analysis

Since the manufacturer does not have the adequent material testing facilities (they cannot afford to have them), the engineers or workers do not have a clear idea about the material properties they are using. However, the manufacturing process (pressing and forming operations) and the product quality are directly affected by the material properties. Like many industrial problems, the manufacturers do not have an integrated knowledge about how raw materials affect the manufacturing processes and, in the end, product quality. To reduce manufacturing cost and stabilize product quality, the manufacturer would like to know the suitable range of material properties in "their language" for this product to minimize the negative impact of the use of improper materials.

The sheet metal being used is cold rolled draw quality low carbon steel. There are certain parameters that can be employed to assess the material in this case, e.g.: sheet thickness and metal hardness (the mechanical properties and other forming properties of the sheet metal is not included here since the company does not have the appropriate testing facilities). Each of the various thickness available to the manufacturer is itself variable. As we know, thicker materials usually cost more money since the material price is based on weight. There are also choices regarding material thickness and hardness when ordering materials from local warehouses. In other words, if the company understands the material requirements for any particular application, certain choices have to be made in order to select the suitable one.

The raw material selection needs to be technically and economically sound. Technically, the material should be easy to use, easy to be machined, and should have sufficient properties to result in quality goods. Economically, the overall negative impact of a material (material expenses, producibility, machinability and quality) should be minimized. Because of the complexity of the relationship between the materials properties and its application, the manufacturer does not usually have a clear idea about how the material properties affect their overall application.

To make the problem simpler for analysis, we divide the negative impact of the material into several aspects: material cost impact, operator impact (extra time needed to do the job), machine impact (extra machine wear and maintenance), quality impact (rip or crack of the neck edge) and customer acceptance (rigidity for installation). The effect of material properties on the above aspects can be described in a "fuzzy" manner by the manufacturer as follows:

Material Cost Impact: A thick sheet costs more money than a thin one (after considering a lower packing cost for a thick metal).

Operator's Impact: A combination of thin and soft material may stick to the die or press after the pressing operation, thus reducing the production rate and affecting the part shape.

Machine Maintenance Impact: A combination of thick and hard material may accelerate die wear and increase machine maintenance cost.

Neck Quality Impact: Hard metal and thin metal usually have lower stretchability. The edge of the neck may crack or rip to create a defect during the neck forming process.

Final Quality Impact: The final product using thin and soft sheet metal may be not rigid enough to withstand the transportation and installation process, and may be claimed as a defect by the customer and user.

To each problem, the seriousness of each impact is different and depends on the extremes of the material properties. Although people working with production processes do have a good sense in a "fuzzy" way to describe these effects within their special section (usually from experience), they usually do not have an explicit idea or formula to describe exactly how the material properties affect the processes unless we design a system to utilize their talents to describe these quantitatively.

9. 3 APPROACH USING ABDUCTIVE NETWORK TECHNIQUES

In our case, the input variables are the material properties, i.e., the thickness and hardness. The output variable is the overall negative impact of the material on the material application process.

In order to approach this problem, we scale the material properties into several levels. We do the same for the negative impact of the material on its application process. Each problem is also assessed for the seriousness of the effects based on the manufacturing experience (see Table 9. 1).

material properties	thickness	very thick	thick	normal	thin	very thin
	hardness	very hard	hard	normal	soft	very soft
	rank	1	2	3	4	5
negative impact evaluation	evaluation	ok	little	some	serious	very serious
	rank	0	1	2	3	4
assessment of seriousness	importance	not at all ------------------------- total importance value				
	rank	0.0 ------------------------------------- 1.0				

Table 9. 1 Table Used for Problem Assessment

Since detailed cost impact data is very difficult to obtain, it is difficult to use analytical tools to find the most cost effective material range for an application. Valuable information can be obtained by using description from "experts" using their own terminology. The negative impacts of materials on the five aspects listed above are individually evaluated and four different importance assessments (seriousness levels) for the above five aspects are indicated in Table 9. 2.

material		negative impact evaluation				
thickness	hardness	material cost	operator cost	machine cost	ripping cost	rigid cost
very thick	very hard	very serious	ok	very serious	ok	ok
very thick	hard	very serious	ok	very serious	ok	ok
very thick	normal	very serious	ok	serious	ok	ok
very thick	soft	very serious	ok	some	ok	ok
very thick	very soft	very serious	ok	little	ok	ok
thick	very hard	serious	ok	serious	little	ok
thick	hard	serious	ok	some	little	ok
thick	normal	serious	ok	little	ok	ok
thick	soft	serious	ok	ok	ok	ok
thick	very soft	serious	ok	ok	ok	ok
normal	very hard	some	ok	little	some	ok
normal	hard	some	ok	little	little	ok
normal	normal	some	ok	ok	little	ok
normal	soft	some	little	ok	ok	ok
normal	very soft	some	some	ok	ok	little
thin	very hard	little	ok	ok	serious	little
thin	hard	little	ok	ok	some	ok
thin	normal	little	little	ok	little	ok
thin	soft	little	some	ok	ok	little
thin	very soft	little	serious	ok	ok	some
very thin	very hard	ok	little	ok	very serious	ok
very thin	hard	ok	little	ok	serious	little
very thin	normal	ok	some	ok	some	some
very thin	soft	ok	serious	ok	little	serious
very thin	very soft	ok	very serious	ok	little	very serious
importance assessment 1		0.25	0.05	0.2	0.25	0.25
importance assessment 2		0.25	0.1	0.25	0.2	0.2
importance assessment 3		0.3	0.05	0.2	0.25	0.2
importance assessment 4		0.25	0.05	0.25	0.25	0.2

Table 9.2 Impact Assessment Result Using Local Expert Comments

By transferring the information from Table 9.2, we obtain the evaluation data and an overall evaluation as shown in Appendix B.1 and Appendix B.2 of the Appendices.

The input data considers the combination of 5 thickness levels and 5 hardness levels, to develop related average overall impact evaluations. Hence, 25 observations include in our database. In order to best utilize the data sources, the above 25 observations mentioned are used as the training database as well as the evaluation database for our model.

We use AIM with the above expert-generated data to develop a systematic network representation shown in Figure 9. 4 and described as follows:

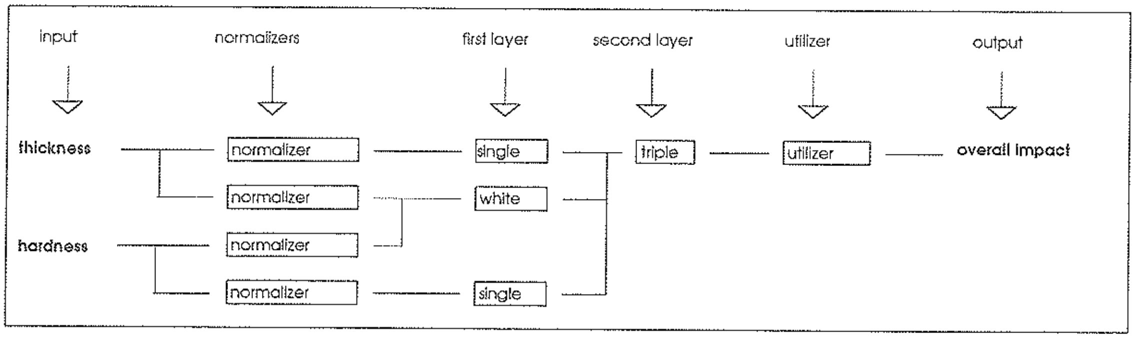


Figure 9. 4 Synthesized Network of The Material Selection Problem

Normalizers: $-2.08+0.693X_1$

Single 1: $-0.649-0.77X_1+0.676X_1^2+0.127X_1^3$

White: $-0.562X_1-0.356X_2$

Single 2: $-0.221-0.656X_1+0.231X_1^2+0.184X_1^3$

Triple: $-0.194-0.562X_1+0.841X_2+0.972X_3-1.24X_1^2+0.475X_2^2$
$-0.642X_3^2+1.07X_1X_2-0.628X_1X_3+0.951X_2X_3-0.834X_1X_2X_3$
$+1.16X_1^3-0.427X_2^3-0.335X_3^3$

Utilizer: $1.11+0.409X_1$

The evaluation of the network performance shows that this synthesized network models the situation reasonably well. Some of the evaluation data is shown below:

average absolute error: 0.030

error standard deviation: 0.0015

root of predicted squared error: 0.0689

predicted squared error: 0.0047

9. 4 RESULT AND DISCUSSION

After the network synthesis and performance evaluation, we obtain the output shown in Table 9. 3 and Figure 9.5, by using AIM's query function.

impact evaluation	very hard	hard	normal	soft	very soft
very thick	1.9	1.9	1.8	1.5	1.3
thick	1.7	1.4	1	0.79	0.87
normal	1.3	1	0.7	0.58	0.81
thin	0.91	0.75	0.58	0.61	0.89
very thin	1	1	0.97	1.1	1.3

Table 9. 3 Material Impact Result by Abductive Network Approach

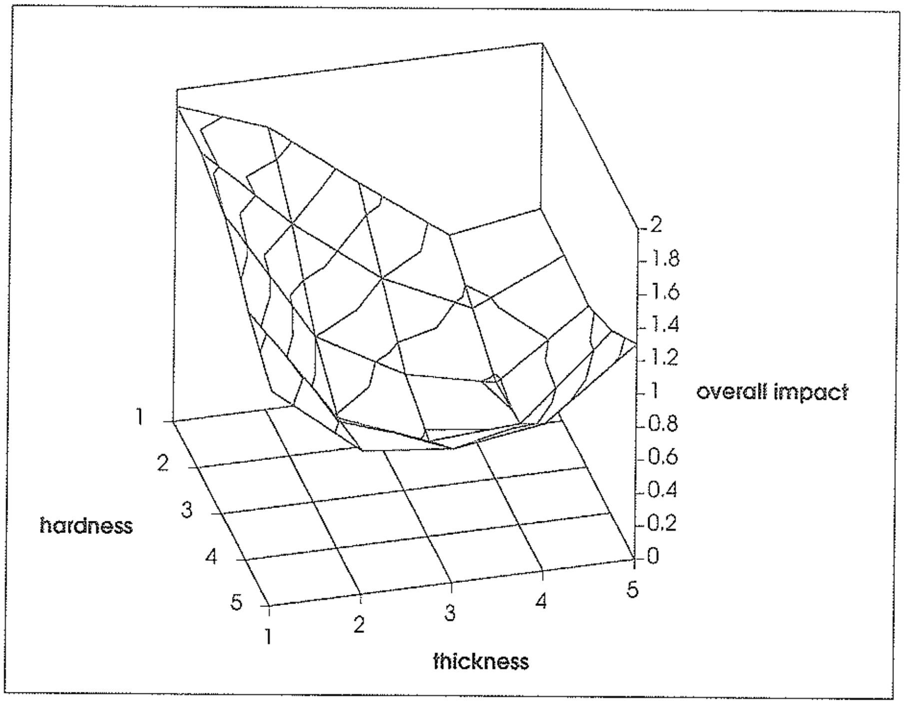


Figure 9. 5 The Overall Impact Results by Material Properties

As we defined before (in section 9.3), the smaller the impact value, the more suitable the material properties are for the application. From the above table and diagram, we can conclude that the following combinations of metal properties are in the most suitable range:

1. thick metal (2) combined with soft metal (4) properties;
2. normal thickness metal (3) with normal or soft hardness (3 or 4);
3. thin metal combined with hard, normal or soft hardness (2, 3, or 4).

Obviously, very thick metal and very hard metal are not good choices for this particular application.

Since one orders material according to some "perceived normal thickness" of, say, 0.028 inches, this "normal thickness" effectively is assumed to be 0.028 inches. From our investigation, the thickness could vary from as thin as 0.024 inch and as thick as 0.032 inch from coil to coil even though the order thickness is 0.028 inch. So "very thick" metal may be around 0.032 inch, "thick" metal is around 0.030 inch, "thin" metal is about 0.026 inch, and "very thin" metal is around 0.024 inch. We also know that the hardness of the material lies in the range of 34 to 50 ksi. From our analysis of this application, the most suitable metal thickness would be around 0.026 inch since it offers the widest choice for metal hardness and offers the lowest negative impact on its application in this particular case. Since the company concerned has thickness and hardness measuring apparatus, further control of these material properties becomes possible as a means to reduce the negative impact of raw materials. Such an approach could provide a valuable tool to the manufacturers in deciding on the most appropriate raw material to use for any specific production process and product.

9.5 Conclusion

The abductive network technique is a very powerful tool for handling some practical industrial problems which can not be explicitly analyzed, or have their analysis constrained by certain limitations. By using data available from operational history, or from experts' assessment, we can thus effectively approach these problems to reach a better control of the overall system.

CHAPTER 10

CONCLUSIONS AND CONTRIBUTIONS OF THIS RESEARCH

In the present chapter, we first state the nature of this research. Subsequently, we state our conclusions and contributions of this research.

10. 1. NATURE OF THIS RESEARCH

This research can be categorized as applied research work. Our effort can be divided into two categories: one is the investigation of problem, the other, the problem solving. Before starting our research, we have familiarized ourselves with the whole production system of the case being analyzed and with the raw material impact for ceiling diffuser products, although, we pick up only the outside cone for our thesis analysis (due to our time and effort limitations). We spent an enormous time and effort in identifying the important variables and their relationship between material variables and production variables in a manufacturing environment. Much time has been spent on information gathering for this problem. From the information gathered, we have then formulated our approach strategy and set up the raw material selection model. We have utilized various advanced techniques such as mathematical formulation, computer simulation, the combination of simulation and optimum seeking techniques, abductive network method etc. to systematically approach this realistic and important industrial problem. This research is also committed to make an effort to close the gap between university academic research and the practical industrial applications.

10. 2. CONCLUSIONS

In this dissertation, the problem of economic raw material selection is extensively investigated. This problem is selected as our research topic because it is a common and important problem in industry. It affects the manufacturer's daily production and it can also significantly affect the manufacturing costs. This research is also of significant interest to E. H. Price Ltd. - a local manufacturing company.

In the literature review in chapter 2, we found that there are no effective and systematic methods available to be used for raw material selection.

In chapter 3, a raw material selection criterion is proposed based on concepts of previous researchers and practitioners. A method is developed for the calculation of the cost impact in the manufacturing process. It is found that the "Process by Process, Parameter by Parameter" strategy is an effective way to analyze the impact of raw material properties to the manufacturing processes.

In Chapter 4 and Chapter 5, we introduced a realistic example from two aspects. We analyzed in detail the relationship between the material properties and their cost impacts to the manufacturing and the final product quality cost. Then, we introduced the purchasing processes and the related costs from two typical suppliers. The investigation of the problem is the first step to combine our research work with the real practical case.

In Chapter 6, an analytical method is used to approach the optimal raw material selection problem. A series of equations are developed to be used for the calculation of the expected raw material cost impacts on its application and for the identification of the optimal material quality level. As mentioned in the chapter, due to the complexity of formulae and some strict assumptions, this method cannot be effectively used for complicated industrial problems.

In Chapter 7, the combination of a computer simulation model with two optimization techniques is applied to the identification of optimal raw material properties for the particular applications. SLAMSYSTEM is used to construct the simulation model, and the two search algorithms: the Hooke and Jeeves algorithm (Using FORTRAN subroutines to program the search strategy) and the Response Surface Method are used to identify the optimum point. From the effective integration of the simulation and optimum search algorithms, we have effectively balanced various costs incurred in the material application processes and thus identified the optimal raw material characteristics. The comparison comments about the application of these two optimization methods are also provided.

In Chapter 8, we use both simulation by SLAMSYSTEM and system dynamic (STELLA II) methods to model the raw material impact on the material application processes; purchasing operation, manufacturing operation as well as product final quality. We obtained the overall total cost impacts (including: raw material cost, extra manufacturing cost as well as product quality cost) by different raw materials from different suppliers. Even with different approaches, the two methods provide us with similar results. We conclude that these systematical approaches may be used to assist the manufacturer to make certain economical choices from a wide variety of materials and suppliers.

In Chapter 9, a knowledge-based approach - abductive network method is applied for the analysis of the economic raw material selection problem. From a synthesis of the experience of "experts" about the impact of raw materials on their application processes, we obtained a suitable range of material characteristics, which have the lowest negative impacts on the material application processes. The application of this technique provides a useful case example for future manufacturing applications of this method.

10. 3 CONTRIBUTIONS

The contributions of this research are twofold. One is that this research has systematically approached this complicated industrial problem. The proposed new economic model and approach (in Chapter 3) comes naturally from the investigation of the problem and is more general and more applicable than previous models. The analytical approach (in Chapter 6) is also more general and explicit than previous models discussed in the reviewed literature and a series of useful equations within this approach can be applied in some industrial problems. The computer simulation and the optimum seeking techniques used (in Chapter 7) have successfully identified optimal raw material requirements. The two system simulation models (in Chapter 8) which represent a realistic case can be used for the practical raw material selection exercise. These techniques and the type of systematic approach for the raw material selection application are not available in literature. We have successfully applied the abductive network method to the raw material selection problem (in Chapter 9). It is very rare to apply this technique in industrial situations and none has been found in material selection research and practice. In general, it can be concluded that our work has significantly pushed forward research with respect to material selection. Another aspect, even more worthwhile to mention here, is that we have used a real industrial problem as an example to show the applicability of our research work. The uniqueness of this aspect can be derived from the following points:

1. In a complicated industrial problem, we have determined the significant variables (important material properties, manufacturing processes impacts) and their interrelationships. Without them, applied research is not possible.
2. We have created several systematic models (analytical, simulation, abductive) which can demonstrate the real relationships and can effectively represent the problem.

3. We have identified the most suitable materials by using the correct information. For this optimization practice, we first identified what to optimize; then we effectively used various advanced methods to optimize them.

4. This type of research is useful and applicable directly to industry. It has effectively combined advanced manufacturing techniques with some realistic industrial situations.

It is believed that the proposed systematic approach, the effective application of various advanced techniques, and the combination of this unique approach with the realistic industrial problem are our significant contributions to the field of economic selection of raw material theory and practice.

BIBLIOGRAPHY

1 Adamczyk, R. D., Dickinson, D. W. and Krupitzer, R. P., 1983, The Edge Formability of High-Strength Cold-Rolled Steel, **SAE Technical Paper Series** 83023

2 **AIM^{TM} User's Manual**, AIM-PC version 1.0, Abtech Corporation, 700 Harris Street, Charlottesville, VA 22901, 1990

3 Backus, G. and Amlim, J., 1985, Comprehensive Corporate Policy Planning Using Large Scale Simulation on Microcomputers, **Proceedings of the 1985 Summer Computer Simulation Conference** (SCSC), pp. 556-561

4 Bandy, B., 1988, Fox River Locks SLAM Simulation Model, **Proceedings of the 1988 Winter Simulation Conference**, pp. 815-820

5 Barker, E., 1975, Why Plan Your Inspection, **Quality Progress**, July, pp. 22-27

6 Barker, T., 1986, Quality Engineering By Design: Taguchi's Philosophy, **Quality Progress**, December, pp. 32-42

7 Beadle, J. D., 1971, **Metal Forming, Production Engineering Series**, Macmillan Engineering Evaluations, The Macmillan Press Limited

8 Bettes, D. C., 1962, Finding An Optimal Target Value in Relation to A Fixed Lower Limit and an Arbitrary Upper Limit, **Applied Statistics**, 11, pp. 202-210

9 Bhuyan, S. K., 1982, Cost of Quality as a Customer Perception, **Annual Quality Congress Transactions**, American Society for Quality Control, pp. 459-464

10 Bisgaard, S., Hunter, W. and Pallesen, L., 1984, Economic Selection of Quality of Manufacturing Product, **Technometrics**, Vol. 26, No. 1, pp. 9-18

11 Burr, I. W., 1967, Specifying the Desired Distribution Rather than Maximum and Minimum Limits, **Industrial Quality Control**, August, pp. 94-101

12 Buzacott, J. A. and Cheng, D. W. H., 1984, Quality Modeling of Assembly Systems, **Proceedings of the 1984 Winter Simulation Conference**, Sheppard, S., Pooch, U., Pegden, D., (eds.), pp. 361-371

13 Carlsson, O., 1984, Determine the Most Profitable Process Level for a Production Process Under Different Sales Conditions, **Journal of Quality Technology**, Vol. 16, No. 1, pp. 44-49

14 Chen, R, Strong, D. and Hawaleshka, O, 1993, Techniques and Case Analysis for Economic Raw Material Selection, **Proceedings 14th Canadian Congress of Applied Mechanics**, pp. 39-40

15 Chen, R., Hawaleshka, O., Strong, D., 1992, **Computer Simulation for Optimal Raw Material Identification**, Unpublished Paper

16 Chen, R., Strong, D., Hawaleshka, O., 1992, An Economic Model for Raw Material Selection, **International Journal of Production Research**, Vol. 31, No. 10, pp. 2275-2285

17 Chiu, W. and Wetherill, G., 1974, A Simplified Scheme for the Economic Design of X-Charts, **Journal of Quality Technology**, Vol. 6, No. 2, pp. 63-69

18 Dalal, J., 1978, Evaluation of a Coiling Temperature-Control Procedure for a Hot Strip Mill, **Journal of Quality Technology**, Vol. 10, No. 1, pp. 31-39

19 Davis, J., Punch, W., and Hess, I., 1987, **Expert System Approach to Diagnosis of Product Quality Deviations**, American Institute of Chemical Engineers, National Meeting Publication by AICHE, New York, NY

20 Davis, J., Punch, W., and Shum., S., 1985, **Application of Knowledge-Based Systems for the Diagnosis of Operating Problems**, American Institute of Chemical Engineers, National Meeting Publication by AICHE, New York, NY

21 Edosomwan, J., 1991, Implementing Customer-Driven Quality Improvement Projects, **The Quality Observer**, Nov., pp. 4-5

22 Farag, M. M., 1979, **Materials and Process Selection in Engineering**, Applied Science Publishers Ltd., London

23 Fredericks, A., 1986, Performance Analysis Modeling For Manufacturing Systems, **AT & T Technical Journal**, Vol. 65, 4

24 From the conversations (1992 - 1993) between the author and the engineering/ management staff on the site of the manufacturing plant (E. H. Price Ltd.)

25 From the conversations (1993) between the author and the account representative in a local sheet steel warehouse

26 From our best educated estimation with our current understanding

27 From our best judgment, with our limited information available

28 Gately, M. P., 1978, Decision Optimization Module for the GASP IV Simulation Language, **MSE thesis**, Department of Industrial & System Engineering, University of Alabama, Huntsville, Alabama

29 Gibra, I., 1975, Recent Developments in Control Chart Techniques, **Journal of Quality Technology**, Vol. 7, No. 4, pp. 183-192

30 Haddock J., Bengu, G., 1987, Application of a Simulation Optimization System for A Continuos Review Inventory Model, **Proceedings of the 1987 Winter Simulation Conference**, pp. 382-390

31 Hassan, M. and Knowles, T., 1979, An Optimal Quality Control Design for a Single-Product Serial Manufacturing System, **Journal of Quality Technology**, Vol. 11, No. 1, pp. 20-11

32 Healy, B., Shaw, W. and Letko, J., 1992, A Modely Perspective for Meteor Burst Communication, **Proceedings of the 1992 Winter Simulation Conference**, pp. 1022 - 1031

33 Hecker, S., 1975, Simple Technique for Determining Forming Limit Curves, **Sheet Metal Industries**, Volume 52, No. 11, pp. 671-676

34 Hecker, S., 1977, Experimental Studies of Sheet Stretchability, **Formability Analysis, Modeling, and Experimentation** (edited by Hecker, Ghosh and Gegel), pp. 150-182

35 Hegde, G. and Kekre, S., 1988, Capacity Choice, Work in Process Inventory and Through Put: a Simulation Study, **Proceedings of the 1988 Winter Simulation Conference**, pp. 662-666

36 Heller, E. D., 1971, **Value Management**, Addison Wesley Publishing Company, Don Mills, Ontario

37 Hindelang, T., 1973, QC Optimization Through Goal Programming, **Quality Progress**, December, pp. 20-22

38 Hogg, R. V. and Craig, A. T., 1972, **Introduction To Mathematical Statistics**, Second Edition, The Macmillan Company, New York

39 Hooke, R., and Jeeves, T., 1961, Direct Search Solution of Numerical and Statistical Problems, **Journal of the Association of Computer Machines**, Vol. 8, pp. 212-229

40 Hunter, J. S., 1985, Statistical Design Applied to Product Design, **Journal of Quality Technology**, Vol. 17, No. 4, pp. 210-221

41 Hunter, W. and Kartha, C., 1977, Determining the Most Profitable Target Value for a Production Process, **Journal of Quality Technology**, Vol. 9, No. 4, pp. 176-181

42 Juran, J. M., 1951, **Quality Control Handbook**, McGraw-Hill, New York, NY

43 Kackar, R., 1985, Off-Line Quality Control, Parameter Design, and the Taguchi Method, **Journal of Quality Technology**, Vol. 17, No. 4, pp. 176-188

44 Kackar, R., 1986, Taguchi's Quality Philosophy: Analysis and Commentary - An introduction to and interpretation of Taguchi ideas, **Quality Progress**, December, pp. 21-30

45 Kackar, R. and Shoemaker, A., Robust Design: A Cost-Effective Method For Improving Manufacturing Progresses, **AT & T Technical Journal**, Vol. 65, 3, pp. 39-50

46 Keeler, S. P., 1985, Statistical Deformation Control For SPQC Monitoring of Sheet Metal Forming, **SAE Technical Paper Series**, 850278

47 Keeler, S. P., 1968, Understanding Sheet Metal Formability, Part 2 - Visible Strain Pattern, **Machinery**, Vol. 74, No. 7, pp. 94-101

48 Keeler, S. P., 1968, Understanding Sheet Metal Formability, Part 3 - Properties Related to Forming, **Machinery**, Vol. 74, No. 8, pp. 94-103

49 Keeler, S. P., 1968, Understanding Sheet Metal Formability, Part 4 - Predicting Forming Limits, **Machinery**, Vol. 74, No. 9, pp. 92-99

50 Keeler, S. P., 1968, Understanding Sheet Metal Formability, Part 5 - Die Design and Lubrication, **Machinery**, Vol. 74, No. 10, pp. 98-104

51 Keeler, S. P., 1968, Understanding Sheet Metal Formability, Part 6 - Practical Application, **Machinery**, Vol. 74, No. 11, pp. 78-83

52 King, J. R., 1967, Vendor Evaluation-A New Approach, **Industrial Quality Control**, December, pp. 300-305

53 Lee, H. and Rosenblatt, M., 1988, Economic Design and Control of Monitoring Mechanisms in Automated Production Systems, **IIE Transaction**, Vol. 20, No. 2, pp. 201-208

54 Lester, R. H., Enrich, N. L. and Mottley, H. E., 1977, **Quality Control For Profit**, Industrial Press Inc., New York

55 Liu, L., Nazaret W. and Beale, R., 1990, Computer-Aided Design For Quality (CADQ), **AT & T Technical Journal**, 3, pp. 46-60

56 Mantz, E., Haddock, J. and Mittenthal, J., 1989, Optimization of An Automated Manufacturing System Simulation Model Using Simulated Annealing, **Proceedings of the 1989 Winter Simulation Conference**,

pp. 390-395

57 McCallum, C., 1986, Operations Research in Manufacturing, **AT & T Technical Journal**, Vol. 65, 4, pp. 4-16

58 **Metals Handbook**, 1990, 9th edition, Volume 1: Properties and Selection: Irons and Steels, American Society for Metals

59 **Metals Handbook**, 1990, 9th edition, Volume 14: Forming and Forging, American Society for Metals

60 Miles L. D., 1972, **Techniques of Value Analysis and Engineering** (second edition), Mcgraw-Hill Book Company, New York

61 Mohanty, R. and Dahanayka, N., 1989, Process Improvement Evaluation of Method, **Quality Progress**, September, pp. 45-48

62 Montgomery, D., 1980, The Economic Design of Control Charts: A Review and Literature Survey, **Journal of Quality Technology**, Vol. 12, No. 2, pp. 75-87

63 Montgomery, D., 1984, **Design and Analysis of Experiments**, John Wiley & Sons, New York

64 Montgomery, G., Gerard, J. and Hwang, J., 1990, Abductive Neural Networks Applied tc Electric Combat, **Proceedings of SPIE - The International Society of Optical Engineering**, Published by International Society for Optical Engineering, Bellingham, WA, USA

65 Nandkeolyar, U. and Christy, D. 1989, Using Computer Simulation to Optimize Flexible Manufacturing System Design, **Proceeding of the 1989 Winter Simulation Conference**, pp. 396-405

66 Narchal, R., 1988, A Simulation Model for Corporate Planning in a Steel Plant, **European Journal of Operational Research**, Vol. 34, pp. 282-296

67 Nelson, L., 1978, Best Target Value for a Production Process, **Journal of Quality Technology**, Vol. 10, No. 2, pp. 88-89

68 Nelson, L., 1979, Nomograph for Setting Process to Minimize Scrap Cost, **Journal of Quality Technology**, 11, pp. 48-49

69 O'Reilly, J. and Ryan N., 1992, Introduction to SLAM II and SLAMSYSTEM, **Proceedings of the 1992 Winter Simulation Conference**, pp. 352-356

70 Palaniswami, S. and Hassan, M. Z., 1988, Simulation the Design and Analysis of Quality Control System In Manufacturing, **Engineering costs and Production Economics**, Vol. 14, No. 3, pp. 217-227

71 Pegden, C., Gately, M., 1980, A Decision-Optimization Module for SLAM, **Simulation**, January, pp. 18-25

72 Peters, M. and Williams, W., 1984, Location of Quality Inspection Stations: An Experimental Assessment of Five Normative Heuristics, **Decision Science**, Vol. 15, pp. 389-405

73 Pettit, R. E., 1984, Vendor Evaluation Made Simple, **Quality Progress**, March, pp. 19-22

74 Phadke, M., 1986, Design Optimization Case Studies, **AT & T Technical Journal**, Vol. 65, 2 pp. 51-68

75 Pritsker, A. A., 1986, **Introduction to Simulation and SLAM II**, Systems Publishing Corporation, West Lafayette, Indiana

76 Pritsker Corporation, **SLAMSYSTEM User's Guide**, Version 2.1, windows

77 Raven, A. D., 1971, Profit Improvement by Value Analysis, **Value Engineering and Purchase Price Analysis**, The Camelot Press Ltd., London

78 Raz, Tzvi, 1986, A Survey of Models for Allocating Inspection Effort in Multistage Production Systems, **Journal of Quality Technology**, Vol. 18, No. 4, pp. 239-247

79 Richmond, B., Vescuso, P. and Peterson, S., 1987, **An Academic User's Guide to STELLA™**, High Performance System, Inc., Lyme, NH

80 Roberts, E., Abrams, D. and Weil, H., 1968, A System Study of Policy Formulation in A Vertically-Integrated Firm, **Management Science**, Vol. 14, No. 12, pp. B674-694

81 Roberts, N., Andersen, D., Deal, R., Garet, M. and Shaffer, W., 1983, **Introduction to Computer Simulation - A System Dynamics Modeling Approach**, Addison-Wesley Publishing Company, California, CA

82 Roslund, J., 1989, Evaluating Management Objectives With the Quality Loss Function, **Quality Progress**, August, pp. 45-49

83 **SAE Handbook**, 1992, Volume 1: Materials, Cooperative Engineering Program, Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096-0001

84 Saniga, E. and Shirland, L., 1977, Quality Control in Practice - A Survey, **Quality Progress**, May, pp. 30-33

85 Saxena, S., Chang, C. M., Chow, H. B., Lee, J., 1990, Evaluation of Heuristics for Inspection Station Allocation In serial Production Systems, **Proceedings of the 1990 Winter Simulation Conference**, Balci, O., Sadowski, R. and Nance, R. (eds.), pp. 919-922

86 Schey, J. A., 1970, **Metal Deformation Process: Friction and Lubrication**, New York, M. Dekker

87 Sengupta, S., 1981, Goal Programming Approach to A Type of Quality Control Problem, **Operational Research Society**, Vol. 32, pp. 207-211

88 Sharp, H. J., 1966, **Engineering Materials: Selection and Value Analysis**, American Elsevier Publishing Company Inc., London

89 Show, J. J., 1982, Quality-The Customer View, Annual Quality Congress Transactions, **American Society of Quality Control**, pp. 519-526

90 **Source Book On Forming Of Steel Sheet**, 1976, American Society for Metals, Metal Park, Ohio 44073

91 Springer C. H., 1951, A Method of Determining the Most Economic Position of a Process Mean, **Industrial Quality Control**, 8, pp. 36-39

92 Sprow, E. E., 1992, What hath Taguchi Wrought, **Manufacturing Engineering**, April, pp. 57-60

93 Sullivan, L., 1986, The Seven Stages in Company-Wide Quality Control, **Quality Progress**, May, pp. 77-83

94 Swaton, L., and Weaver, W.,1966, Five Steps To Supplier Quality Control, **Industrial Quality Control**, 5, pp. 611-616.

95 Taguchi, G., 1984, **Quality Evaluation for Quality Assurance**, American Supplier Institute, Romulus, MI

96 Tang, K., 1988, An Economic Model for Vendor Selection, **Journal of Quality Technology**, Vol. 20, No. 2, April, pp. 81-89

97 Tang, K. and Schneider, H., 1988, Selection of the Optimal Inspection Precision Level for Complete Inspection Plan, **Journal of Quality Technology**, Vol. 20, No. 3, pp. 153-156

98 Tang, K., 1988, Economic Design of Product Specification for A Complete Inspection Plan, **International Journal of Production Research**, Vol. 26, No. 2, pp. 203-217

99 The American Society of Tool and Manufacturing Engineers (ASTME) , 1967 **Value Engineering in Manufacturing**, Prentice-Hall, Inc. Englewood Cliffs, New Jersey

100 Thuesen, G. J. and Fabrycky, W. J., 1984, **Engineering Economy**, Prentice-Hall Inc., Englewood Cliffs, New Jersey

101 Timoshenko, S. and Gere, J., 1972, **Mechanics of Materials**, Van Nostrand Reinhold Company, New York

102 Tomsen, E. G., Yang, C. T., and Kobayashi, S., 1965, **Mechanics of Plastic Deformation In Metal Processing**, The Macmillan Company, New York

103 Wilde, D. J., 1964, **Optimal Seeking Method**, Prentice-Hall, Inc. Englewood Cliffs, New Jersey

APPENDICES

APPENDIX A PROPERTIES DATA FOR VARIOUS LOW CARBON STEELS

Steel Sheet	Processing	Yield Strength		Total Elongation
		(MPa)	(ksi)	(%)
1A	CQ Rimmed Annealed Last	174.3	25.62	44.3
1B	CQ Rimmed Annealed Last	217.4	31.96	44.3
2A	DQ AK Annealed Last	156.0	22.93	46.7
2B	DQ AK Annealed Last	167.4	24.61	45.3
P2A	DQ AK Annealed Last	178.0	26.17	44.1
5	DQ AK Annealed Last	174.5	25.65	44.8
E5	DQ AK	170.9	25.12	43.7
E1	CQ Rimmed Temper Rolled	210.4	30.93	45.6
E2	DQ Rimmed Temper Rolled	213.4	31.37	44.2
10	CQ Rimmed Hot-dip Galvanized	318.8	46.86	28.0
12	DQ Rimmed Hot-dip Galvanized	246.3	36.21	40.0
14	DQ AK Hot-dip Galvanized	225.1	33.09	40.0
E28	DQ AK Fe-Zn Coated	255.2	37.51	32.3
E32	DQ Rimmed Fe-Zn Coated	272.5	40.06	35.3
31	Rimmed 40 ksi min. yield	261.8	38.48	35.9
IF	Interstitial free (Armco Steel)	159.2	23.40	43.4
GIF	Interstitial free (Armco) Hot-dip Galvanized	151.9	22.33	45.0

APPENDIX B DATA FOR ABDUCTIVE NETWORK APPROACH

B. 1. IMPACT EVALUATION DATA

thickness	hardness	material	operator	machine	cracking	rigid
1.00	1.00	4	0	4	0	0
1.00	2.00	4	0	4	0	0
1.00	3.00	4	0	3	0	0
1.00	4.00	4	0	2	0	0
1.00	5.00	4	0	1	0	0
2.00	1.00	3	0	3	1	0
2.00	2.00	3	0	2	1	0
2.00	3.00	3	0	1	0	0
2.00	4.00	3	0	0	0	0
2.00	5.00	3	0	0	0	0
3.00	1.00	2	0	1	2	0
3.00	2.00	2	0	1	1	0
3.00	3.00	2	0	0	1	0
3.00	4.00	2	1	0	0	0
3.00	5.00	2	2	0	0	1
4.00	1.00	1	0	0	3	0
4.00	2.00	1	0	0	2	0
4.00	3.00	1	1	0	1	0
4.00	4.00	1	2	0	0	1
4.00	5.00	1	3	0	0	2
5.00	1.00	0	1	0	4	0
5.00	2.00	0	1	0	3	1
5.00	3.00	0	2	0	2	2
5.00	4.00	0	3	0	1	3
5.00	5.00	0	4	0	1	4
assessment 1		0.25	0.05	0.2	0.25	0.25
assessment 2		0.25	0.1	0.25	0.2	0.2
assessment 3		0.3	0.05	0.2	0.25	0.2
assessment 4		0.25	0.05	0.25	0.25	0.2

Table b.1 The Impact Evaluation of Material Properties on Various Influenced Processes

B. 2 OVERALL EVALUATION TABLE

thickness	hardness	evaluation 1	evaluation 2	evaluation 3	evaluation 4	average
1.00	1.00	1.8	2	2	2	1.95
1.00	2.00	1.8	2	2	2	1.95
1.00	3.00	1.6	1.75	1.8	1.75	1.73
1.00	4.00	1.4	1.5	1.6	1.5	1.50
1.00	5.00	1.2	1.25	1.4	1.25	1.28
2.00	1.00	1.6	1.7	1.75	1.75	1.70
2.00	2.00	1.4	1.45	1.55	1.5	1.48
2.00	3.00	0.95	1	1.1	1	1.01
2.00	4.00	0.75	0.75	0.9	0.75	0.79
2.00	5.00	0.75	0.75	0.9	0.75	0.79
3.00	1.00	1.2	1.15	1.3	1.25	1.23
3.00	2.00	0.95	0.95	1.05	1	0.99
3.00	3.00	0.75	0.7	0.85	0.75	0.76
3.00	4.00	0.55	0.6	0.65	0.55	0.59
3.00	5.00	0.85	0.9	0.9	0.8	0.86
4.00	1.00	1	0.85	1.05	1	0.98
4.00	2.00	0.75	0.65	0.8	0.75	0.74
4.00	3.00	0.55	0.55	0.6	0.55	0.56
4.00	4.00	0.6	0.65	0.6	0.55	0.60
4.00	5.00	0.9	0.95	0.85	0.8	0.88
5.00	1.00	1.05	0.9	1.05	1.05	1.01
5.00	2.00	1.05	0.9	1	1	0.99
5.00	3.00	1.1	1	1	1	1.03
5.00	4.00	1.15	1.1	1	1	1.06
5.00	5.00	1.45	1.4	1.25	1.25	1.34

Table b.2 Overall Evaluation Data by four people

APPENDIX C DIFFERENT SEARCH STRATEGIES AND RESULTS

C.1 SEARCH STARTS FROM A THICKNESS OF 24 THOU AND A YIELD STRENGTH OF 24 KSI (CONDITION 2)

Point No.	Thickness	Yield strength	Extra cost impact
1	24	24	2.86
2	26	24	2.94
3	22	24	5.31
4	24	26	2.91
5	24	22	3.86
6	25	24	2.90
7	23	24	3.17
8	24	25	2.88
9	24	23	2.86

Table c.1 Search Points and Results Under Condition 2

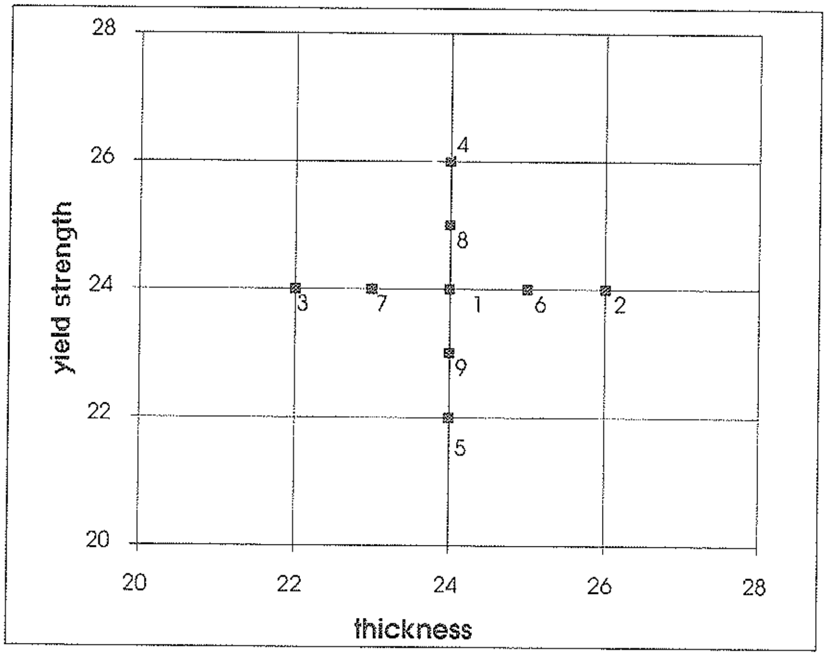


Figure c.1 Search Strategy and Range Under Condition 2

C.2 SEARCH START A FROM THICKNESS OF 32 THOU AND A YIELD STRENGTH OF 32 KSI (CONDITION 3)

Point No.	Thickness	Yield strength	Extra cost impact
1	32	32	3.32
2	34	32	3.53
3	30	32	3.16
4	30	34	3.16
5	30	30	3.15
6	28	28	3.04
7	30	28	3.15
8	26	28	2.93
9	26	30	2.93
10	26	26	2.93
11	22	22	6.66
12	24	22	3.86
13	24	24	2.85
14	26	24	2.94
15	22	24	5.27
16	24	26	2.88
17	25	24	2.90
18	23	24	3.21
19	24	25	2.87
20	24	23	2.86

Table c.2 Search Points and Results Under Condition 3

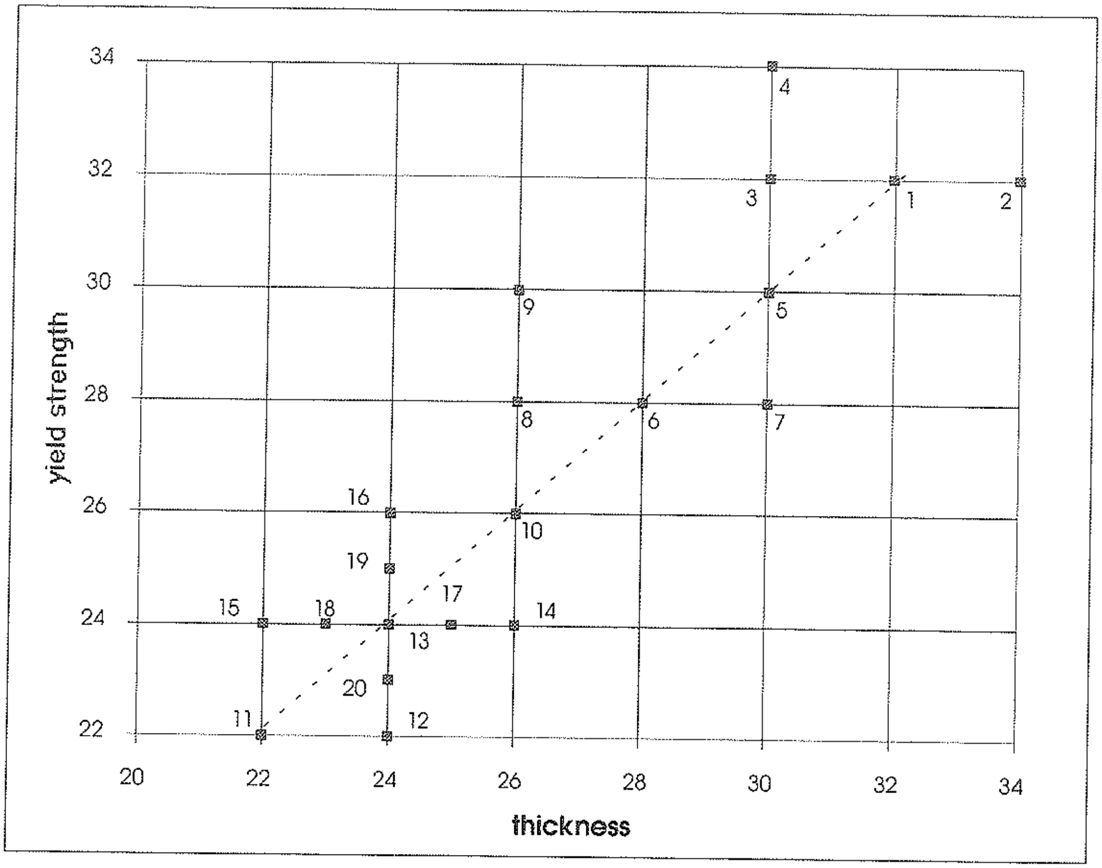


Figure c.2 Search Strategy and Range Under Condition 3

C.3 SEARCH STARTS FROM A THICKNESS OF 24 THOU AND A YIELD STRENGTH OF 32 KSI (CONDITION 4)

Point No.	Thickness	Yield strength	Extra cost impact
1	24	32	3.73
2	26	32	2.94
3	26	34	2.94
4	26	30	2.93
5	28	28	3.04
6	30	28	3.15
7	26	28	2.93
8	26	26	2.93
9	26	22	2.95
10	28	22	3.03
11	24	22	3.86
12	26	24	2.94
13	28	26	3.04
14	24	26	2.87
15	24	28	2.96
16	24	24	2.87
17	22	22	6.71
18	22	24	5.19
19	25	24	2.90
20	23	24	3.24
21	24	25	2.88
22	24	23	2.87

Table c.3 Search Points and Results Under Condition 4

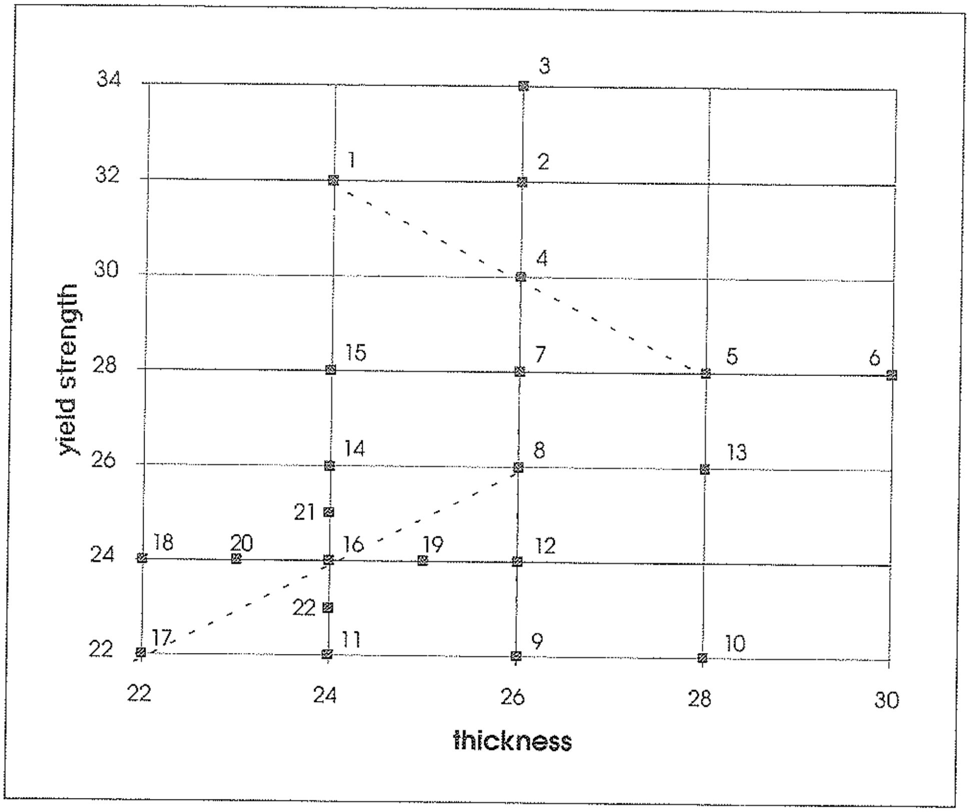


Figure c.3 Search Strategy and Range Under Condition 4

C.4 SEARCH STARTS FROM A THICKNESS OF 32 THOU AND A YIELD STRENGTH OF 24 KSI (CONDITION 5)

Point No.	Thickness	Yield strength	Extra cost impact
1	32	24	3.30
2	34	24	3.51
3	30	24	3.14
4	30	26	3.15
5	30	22	3.14
6	28	20	3.04
7	30	20	3.13
8	26	20	4.34
9	28	22	3.03
10	26	22	2.95
11	24	22	3.86
12	26	24	2.94
13	24	26	2.88
14	26	26	2.93
15	22	26	4.59
16	24	28	2.96
17	24	24	2.87
18	22	24	5.27
19	25	24	2.90
20	23	24	3.24
21	24	25	2.88
22	24	23	2.87

Table c.4 Search Points and Results Under Condition 5

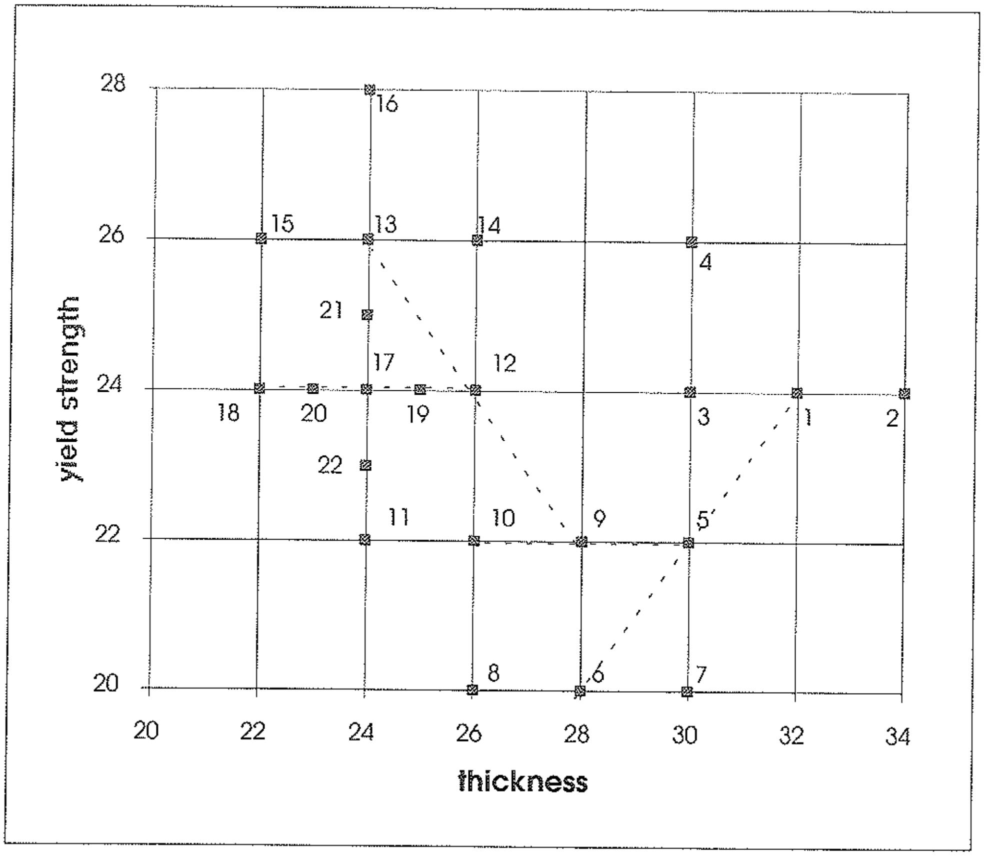


Figure c.4 Search Strategy and Range Under Condition 5

APPENDIX D: FORTRAN SUBROUTINES FOR COMPUTER SIMULATION

D.1 SLAMSYSTEM NETWORK FORTRAN SUBROUTINE FOR THE COMBINATION OF COMPUTER SIMULATION AND OPTIMUM SEARCH

```
c
c clear initial cost data and input structure data
c
      subroutine intlc
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
      common/ucom1/chan(6),duct(6),e(10),d(10),cone,cmat,oper1,wear1
     1,wear2,rip2,pack,flex,cost
      open(23,file='seek.dat')
      read(23,11) xx(1),xx(2)
      close(23,status='delete')
c     thickness xx(1), xx(2) hardness
      open(33,file='manuf.dat')
      read(33,13) cmat,oper1,wear1,wear2,rip2,pack,flex,cost
      do 10 i=1,6
      read(33,12) chan(i)
   10 continue
      do 20 i=1,6
      read(33,12) duct(i)
   20 continue
      close(33,status='keep')
      return
   11 format(2f6.2)
   12 format(f6.2)
   13 format(8f6.2)
      end
c
c     parameter generation, cost calculation and periodically collection
c
      subroutine event(i)
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
      common/ucom1/chan(6),duct(6),e(10),d(10),cone
     1,cmat,oper1,wear1,wear2,rip2,pack,flex,cost
c
      goto(1,2,3,4,5,6,7),i
    1 atrib(1)=xx(1)
```

```
      atrib(2)=xx(2)
      elong=61.89-0.67*atrib(2)
      atrib(3)=elong+rnorm(0.0,2.0,4)
      atrib(4)=atrib(1)*atrib(1)*atrib(2)/21952
      atrib(5)=atrib(1)*atrib(2)/784
      return
c     atrib(1) -- thickness(thou); input normal range (20 to 36 thou)
c     atrib(2) -- yield strength(ksi); input normal range (20 to 36 ksi)
c     atrib(3) -- total elongation (%);  atrib(4) -- bending index
c     atrib(5) -- flexability index
    2 cmat=cmat+atrib(1)*6.357*0.38/24
      return
c
    3 if (atrib(4).gt.0.8) then
      oper1=oper1+0.0
      else
      if (atrib(4).lt.0.6) then
      oper1=oper1+0.041
      else
      oper1=oper1+((0.8-atrib(4))/0.2)*0.041
      endif
      endif
c
      wear1=wear1+atrib(4)*0.032
      return
c     oper1 -- operator cost; wear1 -- machine cost
    4 wear2=wear2+atrib(4)*0.021
c
      strreq=dprob(chan,duct,6,7)
      strpra=atrib(3)+3.6*(atrib(1)-28)
      if (strpra.gt.strreq) then
      atrib(9)=0
      else
      atrib(9)=1
      endif
c     wear2 -- machine cost
c     strreq - stretch requirement
c     strpra - stretch ability of the metal
      return
c     rip2 -- quality cost
    5 if (atrib(1).gt.31) then
      pack=pack+0.0
      else
      pack=pack+(31-atrib(1))*0.5*0.38*(6.357/24)
      endif
```

```
c
      if (atrib(5).gt.0.7) then
      atrib(10)=0
      else
      atrib(10)=1
      endif
      return
c     pack -- packing cost
c     atrib(5)=0.7, ratio=0.0
c     atrib(5)=0.5, ratio=0.5
c     flex -- installation cost
    6 rip2=rip2+10.0
      return
    7 flex=flex+(2.5*(0.7-atrib(5)))*15.0
      return
      end
c
c total cost output, cost average & standard deviration
c
      subroutine otput
      dimension p(30),r(30,2),b(30,2),com(15)
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
      common/ucom1/chan(6),duct(6),e(10),d(10),cone,cmat,oper1,wear1
     1,wear2,rip2,pack,flex,cost
      cost=cmat+oper1+wear1+wear2+rip2+pack+flex
c
      if (nnrun.eq.1) then
       it=0
       is=0
       ref1=0
       b(0,1)=xx(1)
       b(0,2)=xx(2)
       j=0
       else
      endif
      open(15,file='output.dat',status='unknown')
      write(15,22) nnrun,it,is
      write(15,23) b(j,1),b(j,2),com(j)
      write(15,23) xx(1),xx(2),cost
   22 format(3i10)
   23 format(3f10.2)
      i=nnrun
      p(i)=cost
       if (i.eq.1) then
```

```
        r(0,1)=xx(1)
        r(0,2)=xx(2)
        b(1,1)=xx(1)
        b(1,2)=xx(2)
       step1=2
       step2=2
        k=1
        j=1
        it=0
        com(1)=p(1)
       else
        if (p(i).le.ref1) then
          is=1
        else
          is=0
        endif
      endif
     if (k.eq.1) then
      ref1=p(i)
      r(i,1)=r(i-1,1)+step1
      r(i,2)=r(i-1,2)
      it=1
      k=0
      goto 100
     else
      if(it.eq.1) then
        if(is.eq.1) then
          r(i,1)=r(i-1,1)
          r(i,2)=r(i-1,2)+step2
          it=3
          k=0
          ref1=p(i)
          goto 100
        else
          r(i,1)=r(i-1,1)-2*step1
          r(i,2)=r(i-1,2)
          it=2
          k=0
          goto 100
        endif
      elseif(it.eq.3) then
        if(is.eq.1) then
          goto 40
c
        else
```

```
      r(i,1)=r(i-1,1)
      r(i,2)=r(i-1,2)-2*step2
      it=4
      k=0
      goto 100
    endif
  elseif(it.eq.2) then
    if(is.eq.1) then
      r(i,1)=r(i-1,1)
      r(i,2)=r(i-1,2)+step2
      it=5
      k=0
      ref1=p(i)
      goto 100
    else
      r(i,1)=r(i-1,1)+step1
      r(i,2)=r(i-1,2)+step2
      it=7
      k=0
      goto 100
    endif
  elseif(it.eq.4) then
    if(is.eq.1) then
      goto 40
    else
    r(i-1,1)=r(i-1,1)
    r(i-1,2)=r(i-1,2)+step2
    goto 50
    endif
  elseif(it.eq.5) then
    if(is.eq.1) then
      goto 40
    else
      r(i,1)=r(i-1,1)
      r(i,2)=r(i-1,2)-2*step2
      it=6
      k=0
      goto 100
    endif
  elseif(it.eq.7) then
    if(is.eq.1) then
      goto 40
    else
      r(i,1)=r(i-1,1)
      r(i,2)=r(i-1,2)-2*step2
```

```
          it=8
          k=0
          goto 100
        endif
      elseif(it.eq.6) then
        if(is.eq.1) then
        goto 40
      else
        r(i,1)=r(i-1,1)
        r(i,2)=r(i-1,2)+step2
        goto 50
      endif
    else
      if(is.eq.1) then
        goto 40
      else
        b(j,1)=r(i-1,1)
        b(j,2)=r(i-1,2)+step2
        step1=step1/2
        step2=step2/2
        if (step1.lt.1.or.step2.lt.1) then
          stop
        else
         r(i,1)=b(j,1)+step1
         r(i,2)=b(j,2)
         it=1
         k=0
         go to 100
       endif
      endif
    endif
    endif
c
  40 r(i,1)=r(i-1,1)
    r(i,2)=r(i-1,2)
    ref1=p(i)
  50  k=1
     j=j+1
     if (ref1.le.com(j-1)) then
        com(j)=ref1
        b(j,1)=r(i,1)
        b(j,2)=r(i,2)
        r(i,1)=2*b(j,1)-b(j-1,1)
        r(i,2)=2*b(j,2)-b(j-1,2)
     else
```

```
          com(j)=com(j-1)
          b(j,1)=b(j-1,1)
          b(j,2)=b(j-1,2)
          r(i,1)=b(j,1)
          r(i,2)=b(j,2)
       endif
  100 if (r(i,1).gt.36) then
        r(i,1)=36
        else
      endif
      if (r(i,1).lt.20) then
        r(i,1)=20
        else
      endif
      if (r(i,2).gt.36) then
        r(i,2)=36
        else
      endif
      if (r(i,2).lt.20) then
        r(i,2)=20
      else
      endif
  200  open(20,file='seek.dat',status='unknown')
        write(20,10) r(i,1),r(i,2)
        close (20,status='keep')
c
      return
  19 format(2f8.3)
  10 format(2f6.2)
      end
```

D.2 SLAMSYSTEM NETWORK FORTRAN SUBROUTINE FOR THE SIMULATION EXPERIEMENTS

```
c
c clear initial cost data and input structure data
c
      subroutine intlc
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
      common/ucom1/chan(6),duct(6),e(10),d(10),cone,cmat,oper1,wear1
     1,wear2,rip2,pack,flex,cost
      open(23,file='test.dat')
      read(23,11) xx(1),xx(2)
c     thickness xx(1), xx(2) hardness
      open(33,file='manuf.dat')
      read(33,13) cmat,oper1,wear1,wear2,rip2,pack,flex,cost
      do 10 i=1,6
      read(33,12) chan(i)
   10 continue
      do 20 i=1,6
      read(33,12) duct(i)
   20 continue
      close(33,status='keep')
      return
   11 format(2f6.2)
   12 format(f6.2)
   13 format(8f6.2)
      end
c
c     parameter generation, cost calculation and periodically collection
c
      subroutine event(i)
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
      common/ucom1/chan(6),duct(6),e(10),d(10),cone
     1,cmat,oper1,wear1,wear2,rip2,pack,flex,cost
c
      goto(1,2,3,4,5,6),i
    1 atrib(1)=xx(1)
      atrib(2)=xx(2)
      elong=61.89-0.67*atrib(2)
      atrib(3)=elong+rnorm(0.0,2.0,4)
      atrib(4)=atrib(1)*atrib(1)*atrib(2)/21952
```

```
      atrib(5)=atrib(1)*atrib(2)/784
c     atrib(1) -- thickness(thou); input normal range (20 to 36 thou)
c     atrib(2) -- yield strength(ksi); input normal range (20 to 36 ksi)
c     atrib(3) -- total elongation (%);  atrib(4) -- bending index
c     atrib(5) -- flexability index
      cmat=cmat+atrib(1)*6.357*0.38/24
      return
c
    2 if (atrib(4).gt.0.8) then
      oper1=oper1+0.0
      else
      if (atrib(4).lt.0.6) then
      oper1=oper1+0.041
      else
      oper1=oper1+((0.8-atrib(4))/0.2)*0.041
      endif
      endif
c
      wear1=wear1+atrib(4)*0.032
      return
c     oper1 -- operator cost; wear1 -- machine cost
    3 wear2=wear2+atrib(4)*0.021
c
      strreq=dprob(chan,duct,6,7)
      strpra=atrib(3)+3.6*(atrib(1)-26)
      if (strpra.gt.strreq) then
      atrib(9)=0
      else
      atrib(9)=1
      endif
c     wear2 -- machine cost
c     strreq - stretch requirement
c     strpra - stretch ability of the metal
      return
c     rip2 -- quality cost
    4 if (atrib(1).gt.31) then
      pack=pack+0.0
      else
      pack=pack+(31-atrib(1))*0.5*0.38*(6.357/24)
      endif
c
      if (atrib(5).gt.0.7) then
      atrib(10)=0
      else
      atrib(10)=1
```

```
      endif
      return
c     pack -- packing cost
c     atrib(5)=0.7, ratio=0.0
c     atrib(5)=0.5, ratio=0.5
c     flex -- installation cost
    5 rip2=rip2+10.0
      return
    6 flex=flex+(2.5*(0.7-atrib(5)))*15.0
      return
      end
c
c total cost output, cost average & standard deviration
c
      subroutine otput
      dimension p(30),r(30,2),b(30,2),com(15)
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
      common/ucom1/chan(6),duct(6),e(10),d(10),cone,cmat,oper1,wear1
     1,wear2,rip2,pack,flex,cost
      cost=cmat+oper1+wear1+wear2+rip2+pack+flex
      open(15,file='output.dat',status='unknown')
c     write(15,*) 'test results'
c     write(15,21) cmat,oper1,wear1,wear2
c     write(15,22) rip2,pack,flex
      write(15,22) xx(1),xx(2),cost
c     write(15,*)
      return
   21 format(4f8.2)
   22 format(2f6.2,1f9.2)
      end
```

D.3 SLAMSYSTEM NETWORK FORTRAN SUBROUTINE FOR PURCHASING OPERATIONS ANALYSIS

```
      subroutine intlc
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
c.....Input Order Amount xx(10) and Reorder Point xx(11)
      open(15,file='c:\projects\invent\data.dat',status='unknown')
      read(15,20) xx(10),xx(11)
      close(15)
      return
   20 format(2f10.2)
      end
c
c
c
      subroutine state
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
      common/ucom1/medium,small
c
c*****If No Order Is Being Receiving
c
      if (ss(1).le.0.0) then
        rerat=0.0
      endif
c
c*****If A Order Is Being Receiving
c
      if (ss(1).gt.0.0) then
        rerat=30000.0
      endif
c
c*****Material Consumed (medium=6.357 lb/item, small=1.355 lb/item)
c
      demand=medium*6.357+small*1.355
c
c
c*****ss(1)-Material Receiving Simulates;ss(2)-Inventory Level Simulates
c
      ss(1)=ssl(1)-dtnow*rerat
      ss(2)=ssl(2)+dtnow*(rerat-demand)
      return
```

```
      end
c
c
c
      subroutine event(i)
      common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
     1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
      common/ucom1/medium,small
      common/scom2/leadtm,transtm,slittm,delivtm
      go to (1,2,3,4,5,6,7),i
c
c*****Demand From Production (units produced per day)
c
    1 medium=rnorm(297.0,10.0,1)
      small=rnorm(63.0,5.0,2)
      xx(10)=xx(10)+medium+small
      return
c
c*****Order Amount-atrib(1)
c*****Order Cost xx(1) ($200/order)*
c
    2 atrib(1)=xx(10)
      xx(1)=xx(1)+200.0
      return
c
c*****Material Cost xx(2) (from steel mill)*
c
    3 xx(2)=xx(2)+atrib(1)*0.24
      return
c
c*****Transportation Cost (by means of truck or train)*
c
    4 xx(3)=xx(3)+atrib(1)*0.025
      return
c
c*****Slitting & Delivery Cost xx(4) ($90 setup,$3/min processing with 22min/ton)*
c*****Sliting Waste Recovery Cost xx(5) (half price recovery)
c
    5 xx(2)=xx(2)+0.0
      atrib(2)=atrib(1)*0.95
      xx(4)=xx(4)+(90+0.01*atrib(1))*3*2.0
      xx(5)=xx(5)+(atrib(1)*0.05)*0.24*0.5
      return
c
c*****Interest Cost In Ordering Process xx(8) (mill-trans-slit-deliv)
```

```
c
   6 proctm=delivtm+transtm+leadtm
     xx(8)=xx(8)+0.0
     return
c
c*****Holding Cost xx(6) (interest of 10% for 365 days)
c*****Out-Of-Stock Cost xx(7) ($1/medium unit, $0.5/small unit for price discount)
c
   7 if (ss(2).gt.0.0) then
     xx(6)=xx(6)+(ss(2)*0.24)*0.000274
     endif
     if (ss(2).le.0.0) then
     xx(7)=xx(7)-1*(ss(2)*0.825)/6.357-0.5*(ss(2)*0.175)/1.355
     endif
c    Total Cost xx(9)
     xx(9)=xx(1)+xx(2)+xx(3)+xx(4)-xx(5)+xx(6)+xx(7)
     return
     end
c
c
     subroutine otput
     common/scom1/atrib(100),dd(100),ddl(100),dtnow,ii,mfa,mstop,nclnr
    1,ncrdr,nprnt,nnrun,nnset,ntape,ss(100),ssl(100),tnext,tnow,xx(100)
     open(10,file='c:\projects\invent\stelco.dat',status='unknown')
     write(10,30) xx(1)
     write(10,35) xx(2)
     write(10,40) xx(3)
     write(10,45) xx(4)
     write(10,50) xx(5)
     write(10,55) xx(6)
     write(10,60) xx(7)
     write(10,70) xx(9)
     write(10,75) xx(10)
     write(10,80) xx(9)/xx(10)
  30 format(1x,'Order Cost = ',f8.1)
  35 format(1x,'Steel Cost = ',f12.1)
  40 format(1x,'Transit Cost = ',f8.1)
  45 format(1x,'Slitting Cost = ',f8.1)
  50 format(1x,'Slitting Recovery = ',f8.1)
  55 format(1x,'Holding Cost = ',f8.1)
  60 format(1x,'Out-of-Stock Cost = ',f8.1)
  70 format(1x,'Total Cost = ',f12.1)
  75 format(1x,'Total Production= ',f8.1)
  80 format(1x,'Cost per Item = ',f8.2)
     end
```

APPENDIX E STELLA MODELS FOR RAW MATERIAL SELECTION

E.1 STELLA MODEL FOR PURCHSING OPERATION ANALYSIS

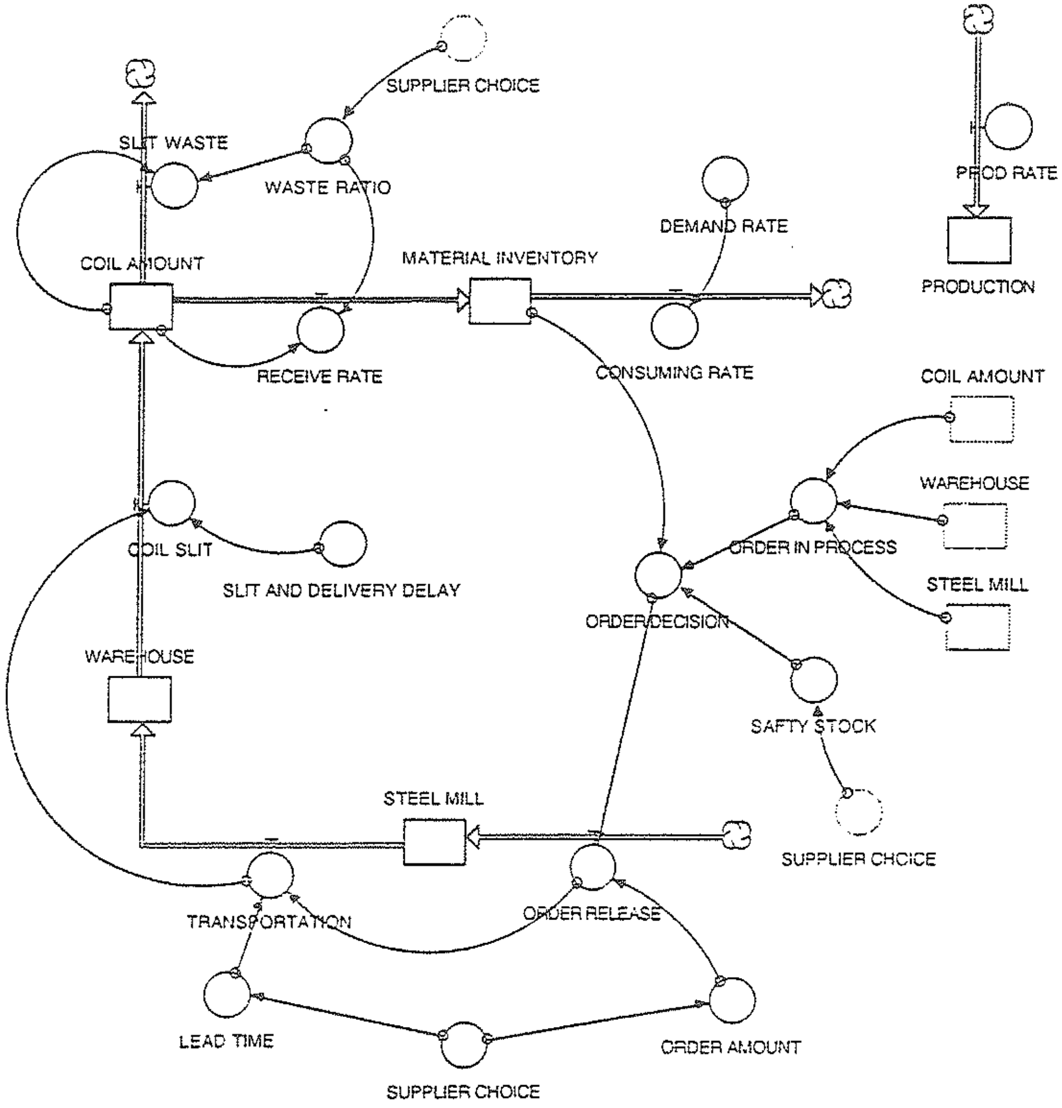


Figure e.1 STELLA Model for Purchasing Operation Analysis (continue ...)

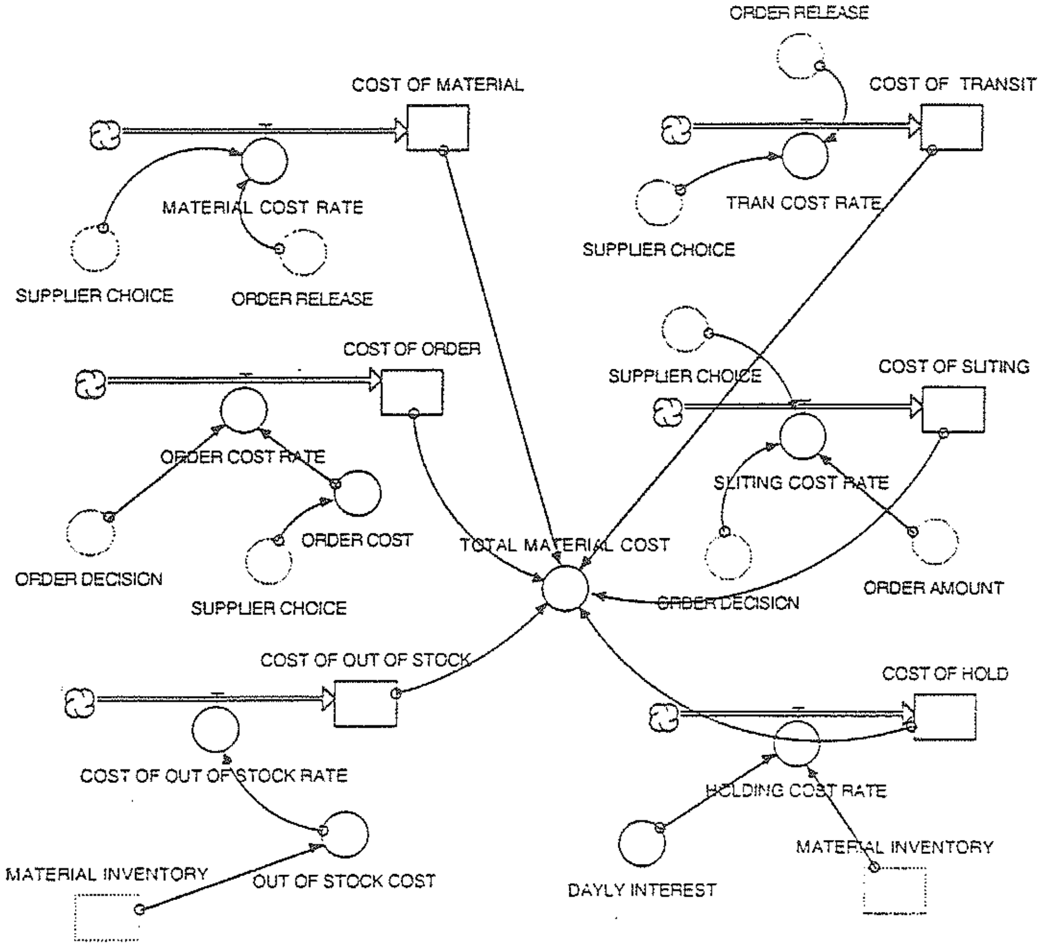


Figure e.1 STELLA Model for Purchasing Operation Analysis

E.2 STELLA MODEL FOR MANUFACTURING PROCESS AND PRODUCT QUALITY ANALYSIS

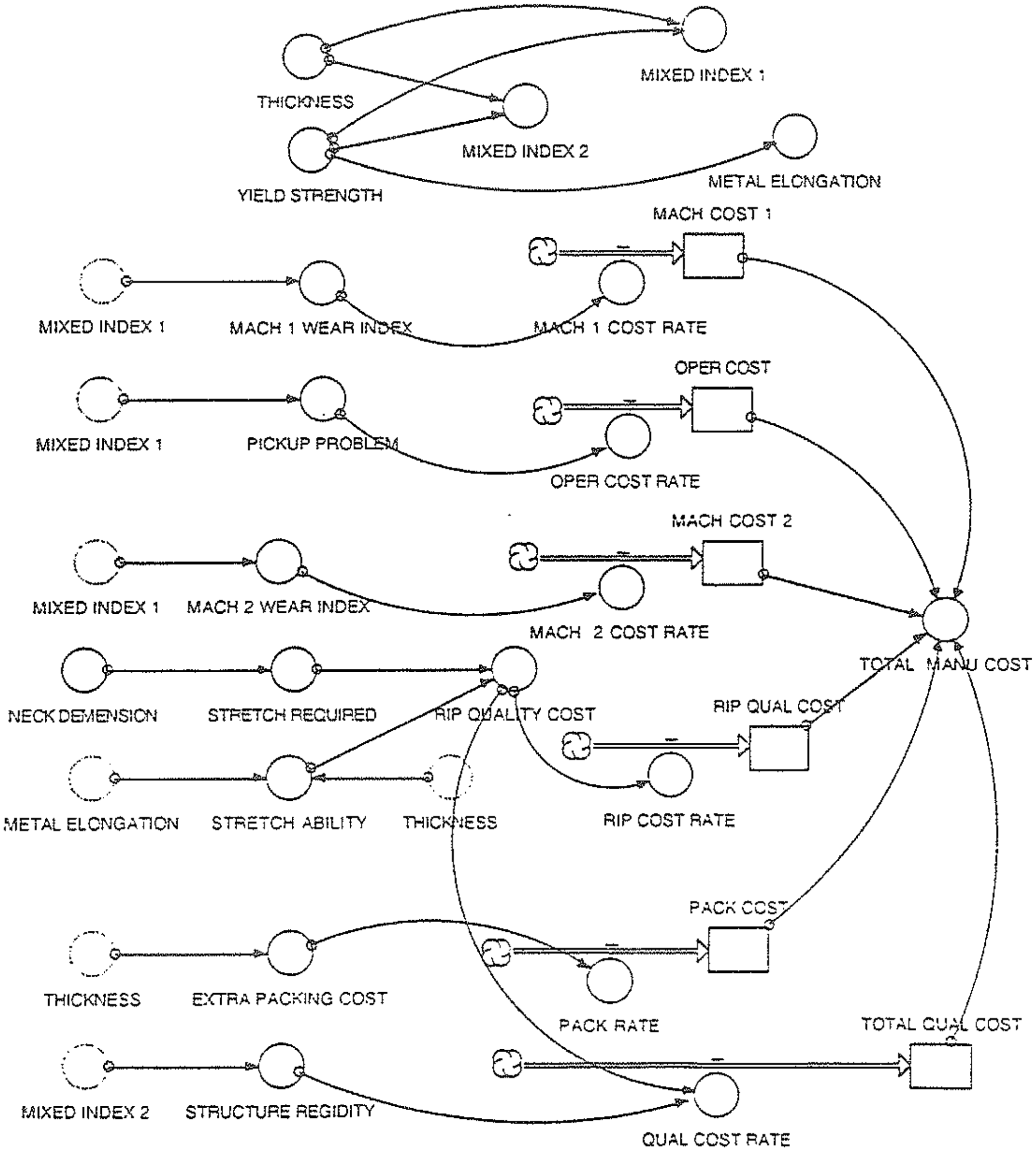


Figure e.2. STELLA Model for Manufacturing Process and Product Quality Analysis

APPENDIX F COST IMPACT ANALYSIS OF MATERIAL PROPERTIES ON THE MANUFACTURING PROCESS AND PRODUCT QUALITY

Since the data needed for this analysis are not directly available, and due to the time limitation of the study and the scope of the thesis, the detailed relationship analysis regarding the cost impact of the raw material properties on the manufacturing processes and product quality is investigated and gathered from three types of sources: 1. Literature on the related topics; 2. Conversations with the manufacturer; and 3. Our best estimations with our current understanding.

The following problems are individually investigated here:

- Part pickup problem (affecting operator cost);
- Metal bendability (affecting machine cost);
- Shape springback (affecting quality cost in the shape pressing operation);
- Metal stretchability (affecting quality cost in the neck forming operation);
- Packaging (packing cost); and
- Part flexibility (affecting final product quality).

F.1 Operator Cost - The Pickup Problem:

The part pickup problem affects the operator cost in the shape pressing operation.

The severity of the pickup problem depends on the rigidity of the sheet metal [24,27]. The sheet rigidity depends on the combination of metal thickness and yield strength [101]. A mixed index kT^2Y [101] (T: thickness; Y: yield strength; k: used as a factor which relates the metal stiffness, so that the mixed index equals 1 for the standard condition of T=28 thou and Y=28 ksi) is used to assess the severity of the pickup problem.

Costs related to the pickup problem include [24]:

- extra time to remove the part being stuck;
- time to adjust the machine setup;
- time for coil replacement in a more serious condition.

Since the cost per hour for a production worker is assumed to be $15.00 [24,26], the operator cost per extra time (second) is $0.0041/second. If a pickup problem exists, the average time spent on a single part is assumed to be 10 seconds [24,26]. The cost for having a pickup problem per part is assumed to be $0.041.

In our cost analysis, we assume that [26]:

- if the mixed index is 0.8 or over, the chance of having a pickup problem is 0;
- if the mixed index is 0.6 or below, the chance of having a pickup problem is 100%;
- if the mixed index is between 0.6 to 0.8, the chance of having a pickup problem has a linear relationship with the mixed index.

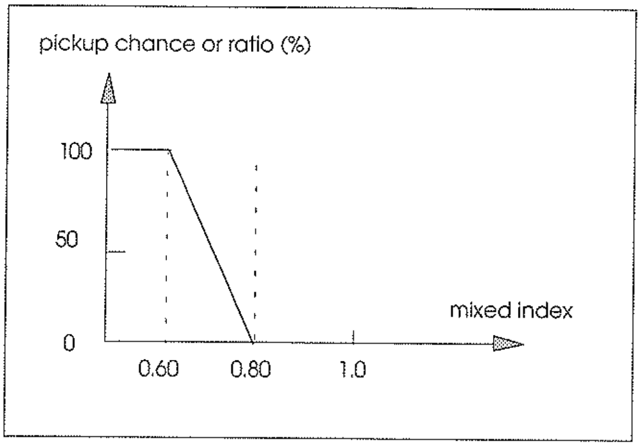


Figure f.1 Mixed Index and Pickup Problem

F.2 Metal Bendability - Machine Wear:

As we mentioned before, the machine cost is affected by the metal bendability. For certain bend shapes, the bending force [90,101] is related to the yield strength, sheet thickness, as well as the length of the bend (see Figure f.2).

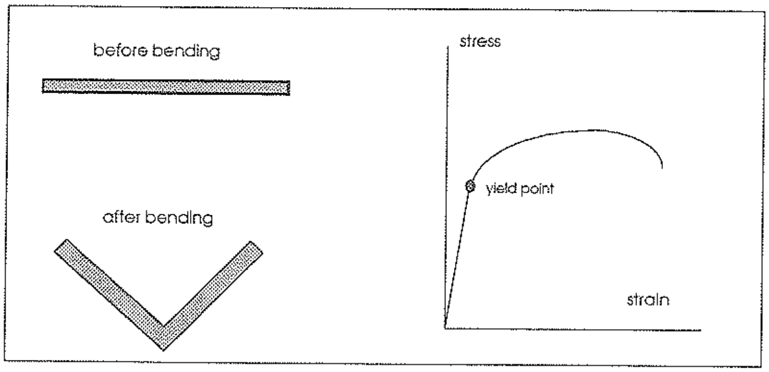


Figure f.2 Diagram for bending force analysis

For effective bending, the bending moment [101] can be expressed as:

$$M = kF \tag{f.1}$$

where,

F: bending force;

k: die open factor.

The stress on the surface in the bending cross section can be written as:

$$\sigma = \frac{My}{I} \tag{f.2}$$

where,

y: distances away from the center neutral axis

I: the moment of inertia, where the moment of inertia for a rectangular cross-section shape is: $I = \frac{bh^3}{12}$;

h: thickness of the plate;

b: length of the bend.

So we have: $\sigma = \frac{kFy}{I} = \frac{12kF}{bh^2}$ (f.3)

In order to have effective bending, the stress on the sheet metal should fulfill the following conditions:

$$\sigma \geq \sigma_y \qquad \text{(f.4)}$$

where,

σ: stress on the part;

σ_y: yield stress of the sheet metal.

Then, we have:

$$F \geq \frac{bh^2\sigma_y}{12k} = k'h^2\sigma_y \qquad \text{(f.5)}$$

If the bending length and die opening are the same, the bending force will be directly related to the mixed index - the product of square of the metal thickness and the material yield strength.

Similar formulae can also be found from a formula used in industrial practice [90]:

$$F \approx k\frac{bh^2\sigma_t}{d} \qquad \text{(f.6)}$$

where,

F: press load (in tons of force);

h: material thickness (in inches);

b: length of bend (in inches);

σ_t: tensile strength (in tons per square inch);

d: width of die opening (in inches);

k: die-opening factor:

In an actual case, the larger the bending force (the thicker and the higher yield strength of the metal), the more severe the machine or die wear and the more maintenance cost is needed. In our analysis, the machine wear index (an index is defined to assess the seriousness of a machine wear) is assumed to be linearly related to the bending force [27]. In a standard condition (material thickness is 28 thou and yield strength is 28 ksi), the force is at a certain value. This value can be taken as normal wear, say 1. When the thickness and tensile strength increase, the bending force increases, the wear index, of course, will be increased. The relationships between the wear index (unit) and bending force can be expressed in Figure f. 3.

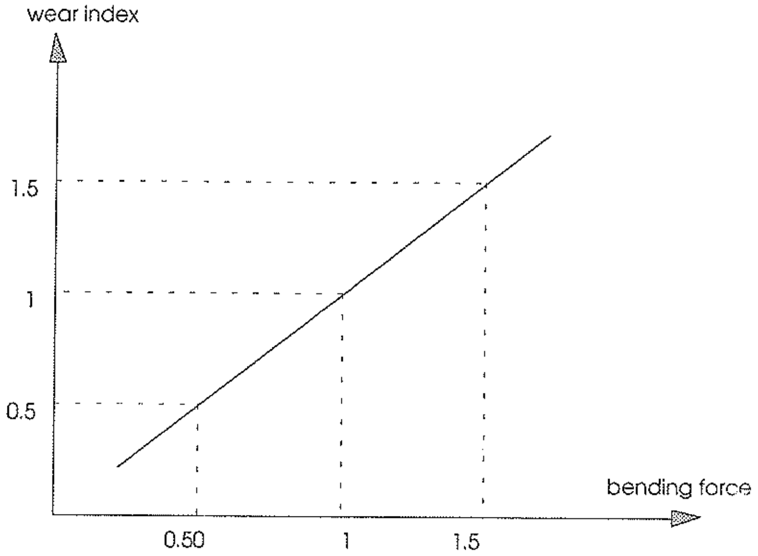


Figure f.3 Bending Force and Machine Wear Index

The wear index 1 indicates that the wear and maintenance cost for die and pressing equipment is in a assumed standard condition.

For the shape pressing operation, we estimate at $10,000.00 for the die sharping and press maintenance cost per year [26]. The press generally experiences 1000 punches each day [24], so the cost in the normal condition is $0.021/punch;

For the neck forming operation, a cost of $15,000.00 is estimated for the die sharping and press maintenance per year [26]. The press generally experiences 1000 punches each day [24], so the cost in the normal condition is $0.032/punch;

When the bending force is 50% higher than the normal condition, the wear index is 50% higher than the normal condition and the maintenance cost will be 50% higher than for the normal condition.

F.3 Shape Quality - Springback Problem:

Our concern is that the final shape of the product may be affected by severe springback. For a certain bend angle, the springback is related to the yield strength, material thickness as well as the tension enforced while bending [90].

Springback is a common problem in metal bending processes [24] and sometimes the control of springback is of great importance.

We explain: When bending occurs, the stress and strain is across the sheet thickness, and the bending strain varies linearly across the section. After removal of the load, in the vicinity of the neutral axis, i.e. on either side of where the material is neither compressed nor stretched by the process, there will be material under stress below the elastic limit. This will give the material a tendency to springback [7,83,102]. Hence, a simple forming operation may result in a complex system of stresses and a superficial mathematical analysis is only of a limited value.

Practically, effective reduction of this elastic portion to the plastic portion will help to eliminate the problem. Often, in stretch forming, the tool does not apply a pure bending moment as assumed above. Rather, tension is applied simultaneously with bending. With increasing tension forces, this tension may be sufficient to remove the neutral plane completely out of the sheet so that the entire cross section may yield in this tension. With a work-hardened material, springback does not vanish with applied tension, but can be greatly reduced.

A bending case with tension is given in Figure f.4.:

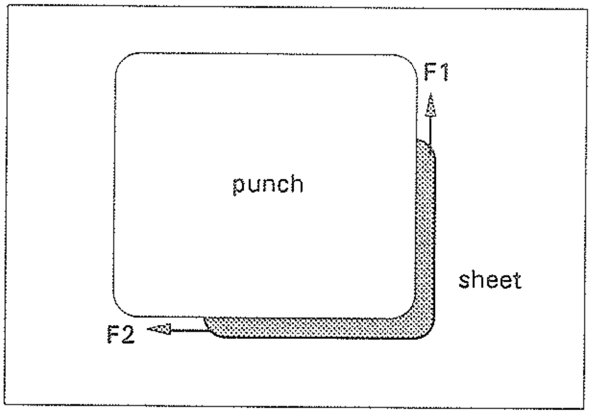


Figure f.4 Illustration of A Case of Bending with Tension

The prediction of the springback angle, or the degree of over bending required, depends on the yield stress of the material, on the radius of the bend and on the bottom force in the die. A practical equation [90] for estimating springback angle, θ, for a bend angle, α, around a radius R, is:

$$\theta \approx \alpha \frac{R}{T} \frac{S}{70000} N \qquad (f.7)$$

where,

S: yield strength of the material (MPa);

N: a constant, depends on die opening;

R: bending radius (mm)

T: thickness of the sheet (mm);

α: bend angle.

Actually, springback has little effect in the bending of low-carbon steel. The springback angle ordinarily ranges from 0.5 to 1.5 ° and can be controlled by overbending or by striking the bend area. It is considered only when very close dimensional control is needed. In our case, springback is not considered as a serious quality problem [90].

F.4 Metal Stretchability - Neck Ripping:

The limitation of material stretch is one of the manufacturing concern in the neck forming process of the outside cone (see Figure f.5). In the forming operation, the sheet metal may rip or crack due to extreme stretching on the neck area. In the above forming process, we can treat the forming as stretching flanging. So the approximate state of stress at a small squared area (an element) can be simplified as in Figure f.5. For certain shape and stretch requirements, the stretchability is related to sheet ductility, thickness, as well as to other mechanical properties.

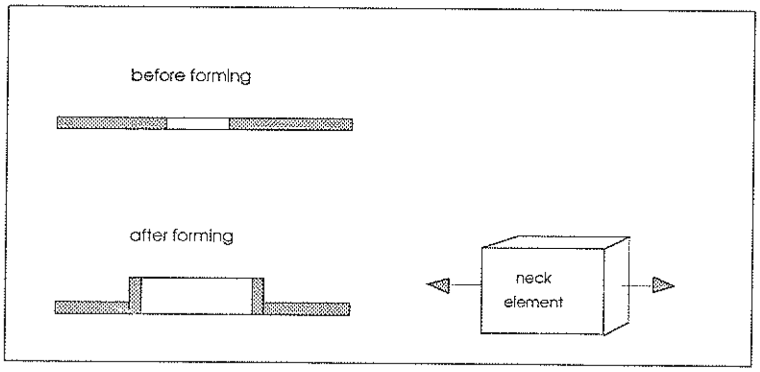


Figure f.5 Diagram for sheet stretch analysis

In order to analyze the neck ripping problem, we need to discuss both the stretch requirement for certain products and the stretch limit for certain metal properties.

Stretch Requirement:

The distribution of the strain in the neck area is shown in Figure f.6.

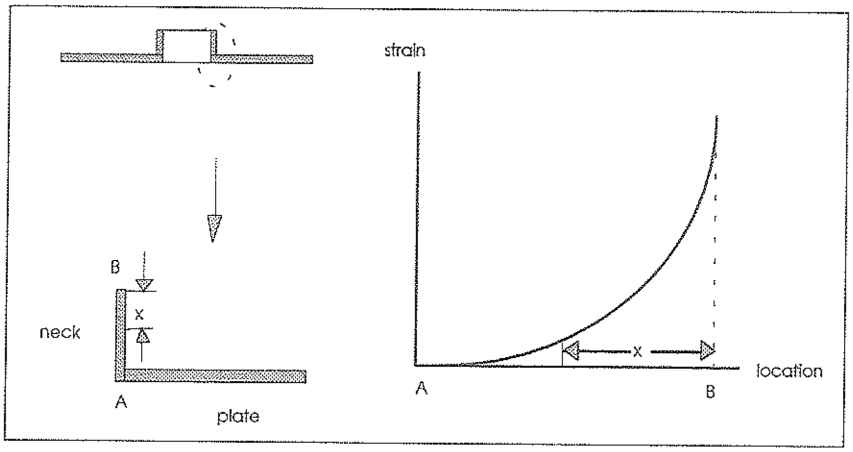


Figure f.6 The distribution of strain in the neck area

The strain at point x (x is also the distance between point B and point x):

= [R-(r+x)] / (r+x) = R/(r+x) - 1 (f.8)

where,

R: neck radius (after necking);

r: hole radius before necking;

At point A, since the r+x = R, the strain = 0

At point B, since the r+x = r, the strain = R/r - 1. The top circle (point B indicated) is the most stretched region on the part.

In actual cases, where R equals 3", 4", 5", 6", 7" and 7.5", which are half the neck diameters. The heights of various corresponding necks are 0.75", 0.75", 1", 1", 1" and 1". So, the r values (radius before necking), are 2.25", 3.25", 4", 5", 6" and 6.5". From the above formula (f. 8), the maximum strains for the different neck sizes are: 33.3%, 23.1%, 25.0%, 20%, 16.7% and 11.5%.

Stretch Limit (Stretchability):

The stretching limit relates primarily to the exhaustion of ductility. There are several ways to assess the stretching limit for sheet metals. They are: uniform elongation;

plastic strain ratio r; the work hardening exponent n; FLC, various cup-drawing tools and procedures such as the Olsen, Erichsen, Swift and Fukui tests [33,34,49,59].

The Rockwell Hardness and the Ball Punch Deformation Tests have historically been the primary mechanical tests to indicate formability [59]. These tests are easily and quickly made, and require a minimum quantity of material. Unfortunately, they are not good measures of stretchability [59]. To our special hole expansion problem, correlating elongation to metal stretchability is an easy and effective way to identify the right sheet material. We know that the total elongation is a direct measure of ductility and represents an important consideration in evaluating formability. Steels with a higher percent elongation will stretch further before failure. The elongation can be easily decided by one dimensional tensile test. There are some other elongation measures which can also be obtained from a simple tensile test: uniform elongation and yield point elongation. For sheet metals that fail by local necking, uniform elongation may not give a true estimate of formability, and estimates based on total elongation are often considered more reliable.

The general range of total elongation of sheet metal is shown [90] here:

quality	commercial quality	draw quality	draw quality special killed
total	30 - 44%	33 - 46 %	38 - 46 %

(Note: test condition: thickness 0.03 to 0.06 in. or 0.76 to 1.52 mm , width 50 mm)

When using different sample widths, sample thickness and other conditions, the total elongation data will be different. Test data by previous researchers tells us that increasing sample width generates a lower total elongation and increasing thickness generates a higher total elongation.

As a matter of fact, thickness is a very important factor that contributes to the stretch limit of sheet metal. Previous test data [90] shows that for the same material (with same strain hardening exponent), if the thickness increases by 0.01", the stretchability increases 3.6%.

As we mentioned, the stretch limit of a metal is affected by the total elongation and the thickness [59]. For certain metal thicknesses, the larger the total elongation, the more stretchability the metal has; for certain metal ductility, the thicker the sheet metal, the more stretchability the metal has [59]. If the value of total elongation (in the standard condition) of a metal is very close to the stretch limit of the metal when the thickness is 26 thou (approximately), then the following formula may be used as an approximation of the calculation of the stretchability of a sheet metal [27]:

stretch limit = total elongation + 3.6 x (thickness - 26)

Neck Ripping Problem:

For our analysis, we assume that [27,90]:

if the stretch limit ≥ stretch requirement, the rip size on the neck is acceptable;

if the stretch limit < stretch requirement, the rip size on the neck is not acceptable.

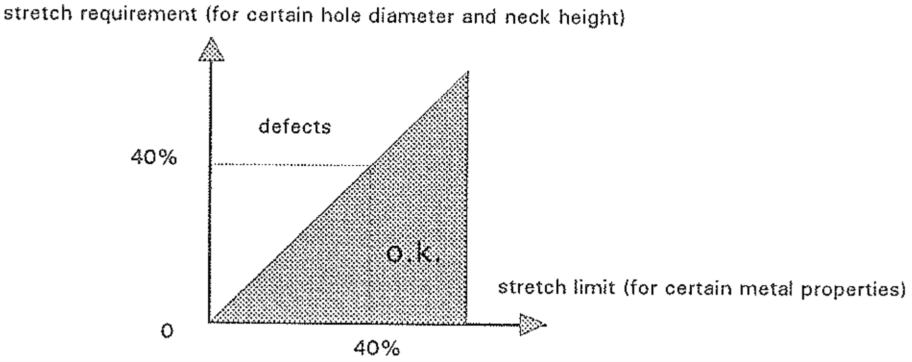


Figure f.7 Stretch Limit and Stretch Requirement

The costs related to neck ripping include [24]:

- cost of non-conforming products;

- cost of removal, return and shipment of the non-conforming coil;
- delay in production;
- lack of work.

We assume all neck defects can be sorted out before the products are shipped to the customers. The cost per neck defect is assumed to be $10.00/part [24,26].

In practice, sheet metal stretch limits are affected by many other factors [1]. Strain uniformity is also a very important factor. Sometimes, it even overpowers the effect of material properties. Strain uniformity is governed by three types of variables: 1. design variables (e. g., shape, curvature), 2. process variables (e. g., die alignment, hold-down pressure, lubrication, etc.), and 3. intristic properties of the sheet material.

If the metal is too thick, die clearance may become too small. This may produce a burr on the blank edge which may cause problems. The surface roughness of the material and the die is important too. Dull tools have a similar effect on a small clearance and produce a burr on the blank edge [1].

Previous research [1,59] also tells us that the tendency to edge cracking is greatly aggravated if shearing has left a burred edge. Therefore, sharp and aligned tools decrease the problem. Lubrication always acts to improve strain uniformity during stretching and its effect often overshadows material differences. Good lubrication ensures that the thickness strain is more evenly distributed over the punch surface [1,86]. Poor lubrication or no lubrication causes localized thinning, which eventually leads to fracturing relatively early in the test. Some lubrication also can effectively prevent pickup and scoring.

F.5 Product Quality Inspection - Part Flexibility:

The structure flexibility is the major quality concern for the effective product shipment and installation. The product should be easily installed without damaging the shape. The extreme condition is that, when a person holds the piece by one of the corners of the diffuser, the diffuser should not bend.

For a very rough estimation, the above case can be simplified for analysis (see Figure f.8).

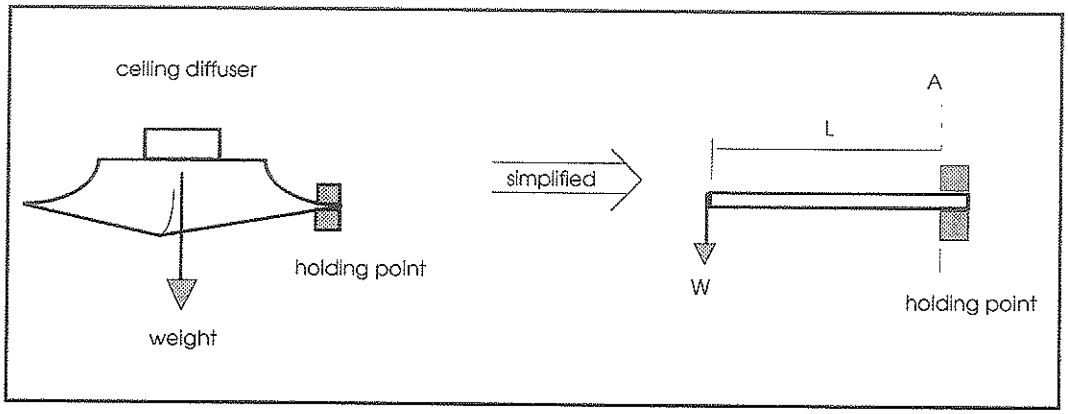


Figure f. 8 Part Flexibility Analysis

In order to avoid bending, the maximum stress on the sheet metal (roughly assumed as a beam) should fulfill the following condition:

$$\sigma_{\max} \leq \sigma_y \qquad \text{(f.9)}$$

where,

$\sigma_{\max}$: maximum stress on the part;

σ_y: yield stress of the sheet metal;

From Figure f.8, we can see that the maximum bending moment is in the cross section A and its value equals [101]:

$$M = WL \qquad \text{(f.10)}$$

where,

W: weight of the whole ceiling diffuser;

L: distance between the center of the ceiling diffuser and the holding point.

The stress of the surface in the cross section A can be written as:

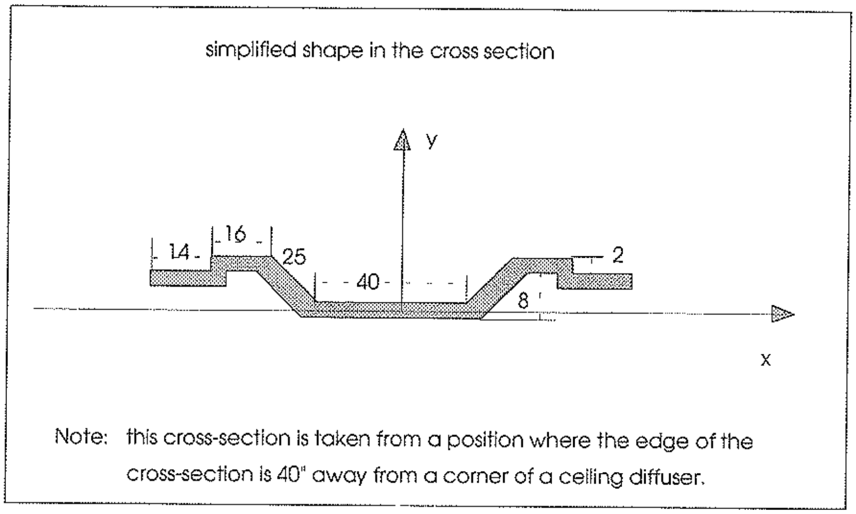
$$\sigma = \frac{My}{I} \qquad \text{(f.11)}$$

where,

y: distances away from the center neutral axis;

I: the moment of inertia.

For the rigidity requirement (company's quality standard), if one holds a certain position of a ceiling diffuser (say, 40" away from the corner), the ceiling diffuser shouldn't bent [27]. We take above assumed requirement for a rough analysis to see how the material properties affect the product rigidity (see Figure f.9).



simplified shape in the cross section

Note: this cross-section is taken from a position where the edge of the cross-section is 40" away from a corner of a ceiling diffuser.

Figure f. 9 Simplified shape in Cross Section

The centroid of the composite area in y axis:

$$\bar{x} = 0 \text{ mm}, \quad \bar{y} = \frac{2(14h * 6 + 16h * 8 + 25h * 5)}{(14h + 16h + 25h) * 2 + 40h} = 4.50 \text{ mm}$$

The moment of inertia for a rectangular shape is: $I = \frac{bh^3}{12}$. We use several formulae: Parallel Axis Theorem, Product of Inertia and Rotation of Axes [101] for the calculation of the moment of inertia of x_c. We obtained:

$$I_{x_c} = 2[\frac{14h^3}{12} + 14h(6-4.5)^2 + \frac{16h^3}{12} + 16h(8-4.5)^2] + \frac{40h^3}{12} + 40h(4.5)^2 +$$

$$+[\frac{\frac{25h^3}{12} + \frac{h*25^3}{12}}{2} + 0 - 0 + 25h(5-4.5)^2]*2$$

Finally, $I_{x_c} = 10.41h^3 + 132958h$

The position of the maximum stress σ_{max} lies in the upper or lower surface of the beam (sheet), and given by:

$$\sigma_{max} = \frac{My}{I} = \frac{WLy}{10.41h^3 + 132958h} \qquad \text{(f.12)}$$

Where, the W (weight of a ceiling diffuser) = 3.12 kg, L (distance from corner to the center of a ceiling diffuser) =355 mm, h (thickness of the metal) = 0.61 mm (0.024").

We also have:

On the top surface, y = (8-4.5)+h/2 = 3.81,

On the bottom surface, y = 4.5+h/2 = 4.81 (the maximum y value in this case).

The equation (f.12) yields:

$$\sigma_{max} = \frac{WL(4.5+\frac{h}{2})}{10.41h^3 + 132958h} \qquad \text{(f.13)}$$

$= 6.41\ kg/mm^2 = 641\ kg/cm^2 = 23.14$ ksi

The general range of yield strength σ_y of low carbon steel is between 25 ksi to 34 ksi, so that the above maximum stress is a little bit higher than the yield point.

Although, for an accurate calculation, the above formulae are far too simple (more accurate results may need more accurate diffuser shape definition and use of Finite Element Analysis methods), the above analysis suggests some of the very important principles. From formulae (f.13), we see that the part flexibility is related to material yield stress, metal thickness and more importantly, the product shape design. Selecting a metal with higher yield stress, with greater thickness and reducing the overall weight will benefit the part flexibility.

In Formula (f.13), 1329.58h is much bigger than $10.41h^3$, and 4.5 is much bigger than h/2, then, we have $\sigma_{max} \propto \frac{WL4.5}{132958h} = k\frac{WL}{h}$. In order to keep the part from being easily bent, we should have: $\sigma_{max} < \sigma_y$. Then following formula may be used for the selection of sheet metal properties.

$$\sigma_y h > kWL \qquad \text{(f.14)}$$

where,

WL: bending moment;
σ_y: yield strength;
h: sheet thickness;
k: a constant.

We can see from equation (f.14) that the yield strength and thickness are important factors for the rigidity of ceiling diffuser product. The mixed index of the material properties is defined as the product of yield strength and material thickness.

From above rigidity problem analysis, we assume that [24,27]:

- if the mixed index is 0.7 or over, the defect ratio (rigidity quality) is 0%;
- if the mixed index is 0.5 or below, the defects ratio is 50%;
- if the mixed index is below 0.7, the defects ratio has a linear relationship with the mixed index.

The relationship [27] between the mixed index and the defects ratio can be assumed as follows (Figure f.10).

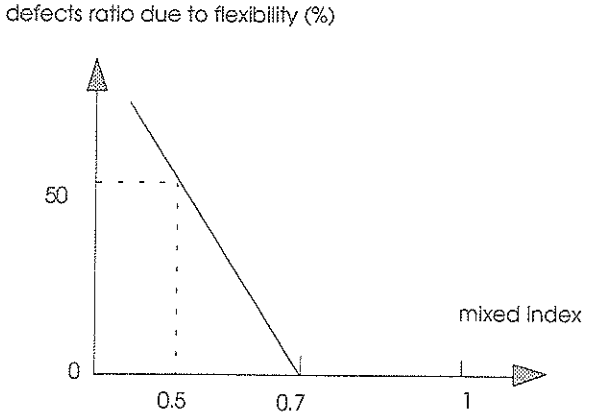


Figure f.10 Mixed Index and Defects Ratio due to Flexibility

The cost for each defect in this stage is assumed to be \$15.00 [27].

Discussion:

If there are rigid requirements for the flat surface in the far corner of the outer cone, the cross-section would be a rectangular shape. Using same principle as above analysis, we have the following Figure f. 11.:

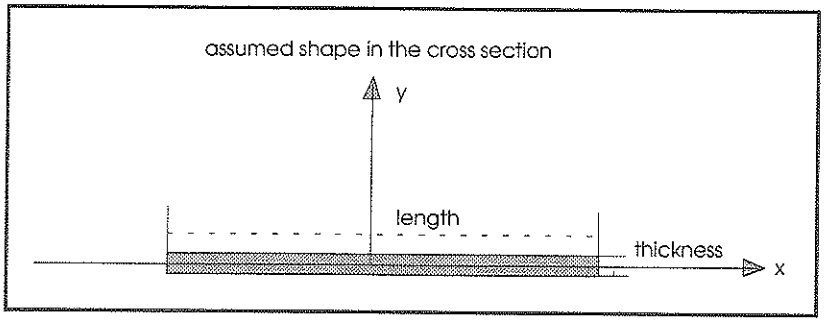


Figure f. 11 Edge Shape of The Outer Cone

Now, we have: $I_{x_c} = \frac{bh^3}{12}$, and y=h/2

and, $\sigma_{max} = \frac{Mh}{2I} = \frac{6WL}{bh^2} = k\frac{WL}{h^2}$

In order to maintain required rigidity, we have:

$$\sigma_y h^2 > kWL$$

Then, the mixed index would be the product of the yield strength and the square of the thickness (instead of the product of the yield strength and the thickness).

F.6 Packaging Cost

The packaging design is the company's decision. Increasing the complexity of the packaging will increase the overall product cost.

If the metal is too thin, extra packaging material and effort is necessary to prevent part bending in shipment and in the handling processes.

The cost related to packaging includes [24]:

- extra packing material;
- extra packing effort;
- extra transportation cost due to packing change

One realistic example for the packing cost change [24] is that, when the sheet metal thickness changed from 31 thou to 26 thou, the packing cost increased. The value of packaging cost increase is as half of the material saving due to the thickness decreases.

For the cost analysis, we assume [27]:

- if the metal is thicker than 31 thou, the packing cost is same as for 31 thou;
- if metal is thinner than 31 thou, the packing cost has linear relationship with the thickness and the changing ratio is the same as for the example given.

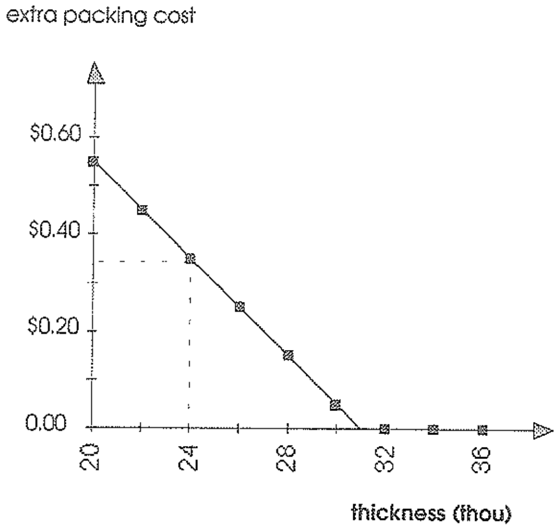


Figure f.12 Metal Thickness and the Extra Packing Cost

APPENDIX G SIMULATED RESULTS OF THE IMPACT OF RAW MATERIALS ON MANUFACTURING PROCESSES AND PRODUCT QUALITY

The purpose of this simulation is to create a set of realistic experiemental data sets for use in our proposed methods of solution.

In this simulation, material properties assumed to be as follows:

The metal thickness (T) follows a normal distribution with a mean value of 24 thou and a standard deviation of 2 thou;

The metal yield strength (Y) follows a normal distribution with a mean value of 28 ksi and a standard deviation of 2 ksi;

The total elongation (E) of the metal has the following relationship with the yield strength: E (%) = 61.89 - 0.67 Y with a variation (+/- 5.27) (see page 42 in Chapter 4).

The raw material properties randomly generated by computer are shown below (only showing the first 100 data):

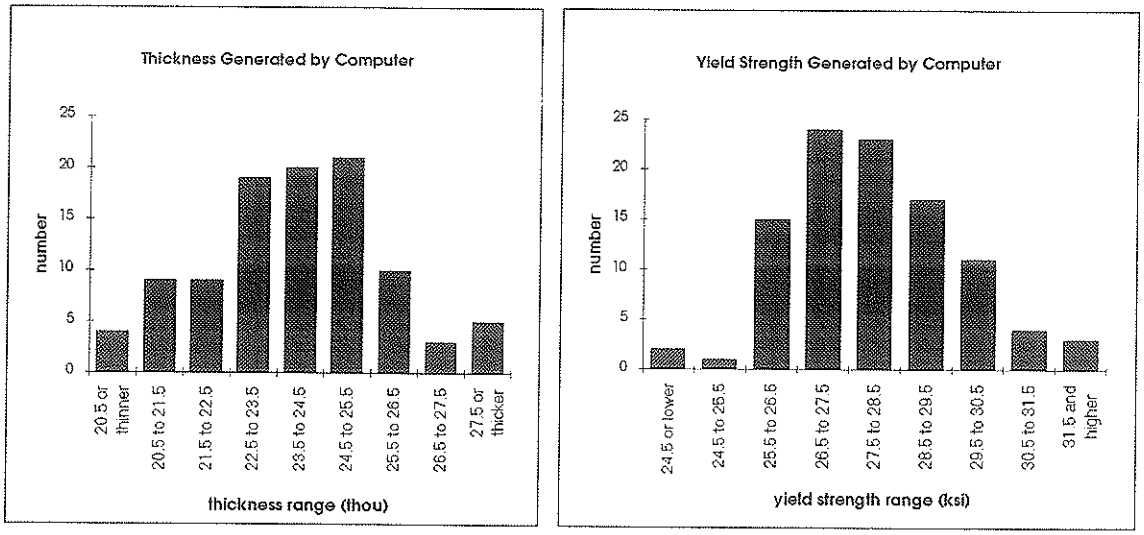


Figure g.1 Raw Material Properties Generated by Computer in the Simulation Program

If we change the random "seed" number (in the computer simulation program), the material properties generated will change accordingly, but the data will still follow the general normal distribution shape within the ranges chosen.

By means of computer simulation (using SLAMSYSTEM software), the material properties generated and their cost impacts on the manufacturing process and product quality are shown below (only showing the first 100 data sets):

Thickness (thou)	Yield Strength (ksi)	Average Total Elongation (%)	Manufacturing Process / Product Quality Cost Impact ($)
21.52	27.02	43.79	2.36
23.21	26.44	44.18	0.92
20.01	25.70	44.67	6.43
27.96	26.81	43.93	0.20
22.40	27.40	43.53	2.05
24.09	26.95	43.83	0.50
21.13	26.00	44.47	2.92
24.26	29.23	42.30	0.38
26.23	26.46	44.16	0.28
24.46	26.79	43.94	0.47
20.87	25.57	44.76	3.55
21.43	30.86	41.22	3.90
20.28	26.46	44.16	5.67
25.77	28.75	42.63	0.31
22.97	28.13	43.04	1.84
22.47	27.15	43.70	1.96
26.23	26.83	43.91	0.28
25.79	26.70	44.00	0.31
25.26	26.25	44.30	0.34
24.08	27.99	43.14	0.4
25.65	30.93	41.17	0.32
25.40	30.48	41.47	0.33
25.00	31.44	40.82	0.44
23.27	27.86	43.22	1.09
23.72	25.85	44.57	0.43
23.32	33.56	39.40	1.99
26.30	27.96	43.16	0.28
25.34	28.75	42.63	0.33

(continued ......)

22.85	27.28	43.61	1.57
26.63	27.18	43.68	0.27
21.95	27.91	43.19	3.07
24.69	27.94	43.17	0.36
27.35	29.22	42.31	0.24
21.21	29.67	42.01	4.64
23.65	25.57	44.76	0.71
23.10	26.63	44.05	1.47
25.34	30.08	41.74	0.33
25.71	30.65	41.35	0.32
27.94	31.76	40.61	0.21
27.87	28.59	42.74	0.21
25.46	27.65	43.37	0.32
22.55	29.62	42.05	2.40
22.25	30.46	41.48	3.05
25.84	29.80	41.93	0.31
23.41	28.94	42.50	0.99
23.75	27.70	43.33	0.70
25.14	28.36	42.89	0.34
23.51	27.41	43.52	1.26
23.67	27.63	43.38	1.25
23.01	28.19	43.00	1.83
24.81	27.35	43.57	0.36
22.63	28.87	42.55	1.94
23.22	26.71	43.99	0.73
24.78	27.21	43.66	0.45
20.59	27.91	43.19	6.10
25.04	27.68	43.35	0.34
25.41	28.66	42.69	0.33
23.68	26.45	44.17	0.61
22.69	26.36	44.23	2.04
23.54	24.38	45.55	0.63
22.96	24.80	45.27	1.21
23.65	28.33	42.91	0.97
23.58	29.46	42.15	1.07
28.14	29.60	42.06	0.20
22.96	27.15	43.70	1.75
22.64	27.44	43.50	1.58

(continued ......)

21.15	28.81	42.59	3.56
25.40	27.60	43.40	0.33
18.90	27.49	43.47	8.47
23.77	27.93	43.17	0.60
24.65	28.30	42.93	0.36
23.87	28.20	42.99	0.78
21.06	26.82	43.92	3.56
23.71	29.52	42.11	1.06
21.72	29.05	42.42	3.71
25.96	29.38	42.20	0.30
24.59	27.83	43.24	0.37
20.83	29.23	42.31	4.65
24.48	27.71	43.33	0.38
27.61	26.33	44.25	0.22
23.84	30.07	41.74	0.87
19.32	27.33	43.58	7.50
24.74	27.20	43.66	0.36
24.51	29.64	42.03	0.55
23.02	28.39	42.87	2.38
23.19	29.17	42.35	1.46
21.48	27.76	43.29	2.91
24.91	29.55	42.09	0.44
25.01	28.95	42.49	0.35
26.93	29.05	42.43	0.26
25.41	26.20	44.34	0.33
24.23	23.42	46.20	0.41
23.63	27.64	43.37	0.43
			Average Cost Impact (for the above 100 data) = $2.41

Table g.1 Simulated Results of the Impact of Raw Materials on Manufacturing Process and Product Quality

Above simulated cost impact data sets of the raw materials on manufacturing process and product quality does not consider the cost impact of the actual materials on the material price and related purchasing handling cost, which are simulated separately in another purchasing process model.

APPENDIX H DETAILED SIMULATED COSTS IN OUR SIMULATION MODEL

The purpose of this Appendix is to show the detailed cost impact of raw materials on material price, manufacturing process costs and product quality costs by setting a series of arbitrary combinations of material properties.

We take the 16 arbitrary combinations of material properties as examples to give an idea how the process works. The general cost relationships between the material properties and various cost impacts are discussed in Chapter 4, Chapter 5 and Appendix F. The detailed material property combinations and the simulated cost impacts from our model are shown in Table h.1. Below is an explanation of the table:

In the Table h.1, the following combination of material thickness is assumed:

- The sheet thickness varies from 20 thou to 32 thou in increment of 4 thou;
- The yield strength varies from 20 ksi to 32 ksi in increment of 4 ksi;
- The total elongation is derived from the yield strength with certain variations (+/- 5.27%) [see Chapter 4], and the average total elongation varies from about 49% for 20 ksi yield strength to about 40% for 32 ksi yield strength.

The various cost impacts (see Table h.1) of the material properties on various affected process steps are obtained from our simulation runs. They are explained as follows:

- Sheet Metal Price Per Unit

In this simulation model (in Chapter 7), we assume that the metal price per unit has a linear relationship with the sheet thickness since the manufacturer pays for the sheet metal by weight [24]. The formulae used to calculate the unit price [27] is:

Material price per unit (\$) = 0.1007 x thickness

This equation is only for commercial quality steels. Not shown in the price column is a switch that can change the material quality levels (commercial quality, draw quality, and draw quality special killed) and related prices.

- Cost Due to Pickup Problem

The pickup problem only occurs in the shape pressing operation (see Chapter 5). When the metal sheet is thin and the yield strength is low, the parts have more tendency to stick on the die or press after pressing which increases operation time and the operator cost. The detailed relationship used is discussed in the section F.1 of the Appendix F.

The worst case shown on the table is \$0.04/unit.

- Machine #1 Extra Wear Cost and Machine #2 Extra Wear Cost

Thicker and higher yield strength metal requires a higher pressing force to bend the sheet to the right shape, which increases the machine wear and maintenance cost (see Table h.1). The detailed relationship is discussed in the section F.2 of the Appendix F.

The cost calculation formulae for machine extra wear are:

Machine #1 extra wear cost (\$) = 0.032 x $(\text{thickness})^2$ x yield strength / 21952

Machine #2 extra wear cost (\$) = 0.021 x $(\text{thickness})^2$ x yield strength / 21952

The formulae show that the problem builds quickly as the thickness increases. The machine extra wear cost varies from \$0.01 to \$0.05 per unit. This formulae may not suit extreme thickness and yield strength conditions.

- Cost Due to Neck Ripping

The metal with a higher total elongation and great thickness tends to have higher stretchability to reduce the possibility of the neck ripping in the neck forming operation. The ripped neck is causing rejects and causes extra quality cost in this operation (see Table h.1). Different neck sizes also have different metal stretch requirement and the part with a smaller neck size has a greater possibility to become a defect. The worst condition is the very thin metal with a low elongation such as the thickness of 20 thou with elongation of 40.45% shown in the Table h.1. The detailed relationship is discussed in the section F.4 of the Appendix F.

- Cost Due to Product Rigidity

To reduce the chance of part being too flexible in handling and installation, the part needs minimum rigidity. The metal with a thinner and lower yield strength will tend to be too flexible to handle. For the model, we assume that the part is tested for flexibility just before the final assembly rather than having the customer return the product. The worst case regarding the cost due to product rigidity is the combination of thickness of 20 thou with yield strength of 20 ksi. The cost relationship is discussed in the section F.5 of the Appendix F.

- Cost Due to Extra Packing

Thinner metal requires more sophisticated packing to avoid part bending during the transportation process, however, more packing material and effort increases the packing cost, with the 20 thou thickness indicating the worst case (see Table h.1). The detailed relationship is discussed in section F.6 of the Appendix F.

Note that the packing cost varies even if the thickness is a constant value. The 20 thou case is most prominent. The reason is that when the metal has very unsuitable properties (very thin or very low yield strength), many parts may be rejected through the production process. The rejected parts, here in neck forming and rigidity testing operations, are not packed for shipment. So the extra packing costs for these rejected parts are not counted in the packing operation.

- Overall Total Cost

The overall total cost is the combination of the various costs discussed above. The data (shown in the Table h.1) indicate that many parts made from very thin metal cannot become quality products. However, if the metal is too thick, the material price and the manufacturing cost will increase accordingly. The best combination would be: on one hand, the metal satisfying the quality requirements; on the other hand, with the lowest possible material price and manufacturing expenses. In the Table h.1, the metal with the thickness of 24 thou and the yield strength of 24 ksi shows the best cost balance - the lowest overall cost among the 16 combinations of metal properties.

The above simulated costs could be adjusted to be closer to the real situations as more test information becomes available. Also, if other operations are found to be affected by the material properties, they could be easily added to the model. The model could also provide other types of outputs such as defects ratio if more accurate data and related information become available.

sheet thickness (thou)	yield strength (ksi)	average total elongation (%)	sheet metal price per unit ($)	cost due to pickup problem ($)	machine #1 extra wear cost ($)	machine #2 extra wear cost ($)	cost due to neck ripping ($)	cost due to product rigidity ($)	cost due to extra packaging ($)	overall total cost impact ($)
20	20	48.49	2.03	0.04	0.01	0.01	2.47	5.39	0.42	10.37
20	24	45.81	2.03	0.04	0.01	0.01	4.47	1.84	0.31	8.70
20	28	43.13	2.03	0.04	0.02	0.01	6.85	0.00	0.18	9.12
20	32	40.45	2.03	0.04	0.02	0.01	7.89	0.00	0.12	10.11
24	20	48.49	2.44	0.04	0.02	0.01	0.00	3.31	0.35	6.16
24	24	45.81	2.44	0.04	0.02	0.01	0.00	0.00	0.35	2.85
24	28	43.13	2.44	0.01	0.02	0.02	0.17	0.00	0.35	3.00
24	32	40.45	2.44	0.00	0.03	0.02	0.88	0.00	0.32	3.68
28	20	48.49	2.85	0.02	0.02	0.01	0.00	0.00	0.15	3.04
28	24	45.81	2.85	0.00	0.03	0.02	0.00	0.00	0.15	3.03
28	28	43.13	2.85	0.00	0.03	0.02	0.00	0.00	0.15	3.04
28	32	40.45	2.85	0.00	0.04	0.02	0.00	0.00	0.15	3.05
32	20	48.49	3.25	0.00	0.03	0.02	0.00	0.00	0.00	3.29
32	24	45.81	3.25	0.00	0.04	0.02	0.00	0.00	0.00	3.30
32	28	43.13	3.25	0.00	0.04	0.03	0.00	0.00	0.00	3.31
32	32	40.45	3.25	0.00	0.05	0.03	0.00	0.00	0.00	3.32

Table h.1 Detailed Simulated Costs from Our Simulation Model