THE DEVELOPMENT AND IMPLEMENTATION OF MULTIVARIATE COST OF POOR QUALITY LOSS FUNCTIONS

By

LAURA BETH RAIMAN

Bachelor of Science
University of Illinois
Urbana, Illinois
1984

Master of Science
Okahoma State University
Stillwater, Oklahoma
1986

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 1991

ACKNOWLEDGMENTS

I would like to give special recognition to those people whose continued support and interest helped me to successfully complete this dissertation. First, very sincere thanks go to Dr. Ken Case for his role as a mentor, teacher, advisor and friend through my entire graduate education. With his help and example, I have been able to set my goals higher and higher, and continue to reach them. Through realizing and sharing his examples of quality improvement, I have developed my own passion for helping others in the quest for continuous improvement. I hope that I will provide similar inspiration to my own students in the years ahead.

Very special thanks also go to the other members of my committee. Dr. Joe Mize always helped me conceptualize new ideas and develop a stronger understanding of the big picture. His example as both a superb educator and engineer also provided me with inspiration. Thanks also go to Dr. Carl Estes and Dr. Allen Schuermann for being role models as educators and industrial engineers, and to Dr. Barry Moser for expanding my horizons in statistics.

I would also like to give very special thanks to my family, who helped instill into me a strong sense of ambition and values. My mom and dad have always believed in me no matter what road I have taken, (and who have travelled down many roads to see me), my grandmother whose love is always there to support me, and to my fantastic, talented brother, who always keeps me modest.

TABLE OF CONTENTS

Chapter Page

I. BACKGROUND AND RESEARCH OBJECTIVES 1

1.1. Introduction 1
1.2. Developing a Cost of Poor Quality Matrix 2
1.2.1. Current State of Cost of Quality Systems 2
1.2.2. Taguchi's Concept of Loss 3
1.2.3. Quantifying COQ Factors 4
1.2.4. Expanding Cost of Quality 5
1.3. Developing a Multivariate Cost of Poor Quality Loss Function 6
1.3.1. Traditional Univariate Loss Functions 6
1.3.2. Taguchi Loss Function 8
1.3.3. Multivariate Loss Functions 11
1.4. Strategic Uses of a COPQ Loss Function 12
1.4.1. Indicators of Process Performance 13
1.4.2. Using a Loss Function to Make Operations Decisions 14
1.5. Research Objectives 15
1.5.1. Subobjective 1 15
1.5.2. Subobjective 2 16
1.5.3. Subobjective 3 16

II. LITERATURE REVIEW 18

2.1. Defining Cost of Poor Quality 18
2.1.1. Traditional Approaches 18
2.1.2. Taguchi's Loss to Society 19
2.1.3. Other Outlooks on Cost of Quality 20
2.2. Developing a Loss Function 24
2.2.1. The Taguchi Loss Function 25
2.2.2. Multivariate Loss Functions 27
2.3. Strategic Uses of a Loss Function 29

Chapter Page

III. COST OF POOR QUALITY MATRIX DEVELOPMENT 32

3.1. Philosophy Behind the COPQ Matrix 32
3.2. Basic Layout of Matrix 33
3.3. Characteristics of the Matrix 34
3.3.1. Defining Cost of Poor Quality 35
3.3.2. Defining Societal Loss 35
3.3.3. Defining a Relationship Between COPQ and Quality Characteristics 37
3.4. Design of the Matrix 38
3.4.1. Category Description 38
3.4.2. Item Description 40
3.4.3. Societal Effect Description 41

IV. CATEGORY AND ITEM DEFINITIONS 43

4.1. Category and Item Development 43
4.2. Category Defining Items 44
4.2.1. Original Manufacturer 44
4.2.2. Acquisition 46
4.2.3. Operations 48
4.2.4. Maintenance and Reliability 49
4.2.5. Safety 50
4.2.6. Warranty 51
4.2.7. Regulatory and Liability 52
4.2.8. Societal 54
4.3. Summary of COPQ Matrix 55

V. DEVELOPING A MULTIVARIATE COST OF POOR QUALITY LOSS FUNCTION 57

5.1. Quantifying the COPQ Matrix 57
5.2. Identifying Sources of COPQ Information 58
5.2.1. Existing Sources of COPQ Data 58
5.2.2. Additional Sources of COPQ Data 59
5.2.3. Summary of COPQ Data Collection 60
5.3. Modelling Univariate Loss Functions 60
5.4. Modelling a Response Surface Using the COPQ Matrix 64
5.4.1. Estimating Loss for Univariate Functions 64
5.4.2. Modelling Multivariate COPQ 65
5.4.3. Estimating Loss for a Multivariate Function . . . 68
5.5. Remarks Concerning the MVCOPQLF 72

Chapter Page

VI. EXAMPLE OF USING A COPQ MATRIX TO DERIVE A LOSS FUNCTION 74

6.1. Setup of Example 74
6.2. Determining the Experimental Points 75
6.3. Estimating COPQ at the Experimental Points. 76
6.3.1. Quantifying the Original Manufacturer COPQ . . 76
6.3.1.1. Manufacturing Appraisal 79
6.3.1.2. Maintenance and Calibration Labor 79
6.3.1.3. Material Review 79
6.3.1.4. Operations Rework and Repair. . 80
6.3.1.5. Rework 80
6.3.1.6. Repair 80
6.3.1.7. Troubleshooting and/or Failure Analysis 80
6.3.1.8. Extra Operations 80
6.3.1.9. Scrap 80
6.3.1.10. Downgraded or Substandard End Product 81
6.3.1.11. Internal Failure Labor 81
6.3.2. Quantifying the Societal Costs COPQ 81
6.3.2.1. Lost Sales 81
6.3.2.2. Goodwill 83
6.3.2.3. Waste Disposal 83
6.3.2.4. Environmental 83
6.3.2.5. Hazardous Material 83
6.3.2.6. Spillover 83
6.4. Modelling the MVCOPQLF 83
6.4.1. Original Manufacturer COPQ 84
6.4.2. Societal COPQ 86
6.4.3. Overall MVCOPQLF. 92

VII. STRATEGIC USES OF A MVCOPQLF 98

7.1. Overview of Strategic Uses 98
7.2. Transition Loss using a MVCOPQLF 99
7.2.1. Calculating Transition Loss with a Univariate Function 100
7.2.2. Calculating Transition Loss with a MVCOPQLF. 105
7.2.3. Example of Transition Loss Calculation 108
7.3. Scheduling Production Sequences Using Transition 110

Chapter Page

VIII. EXAMPLE OF SCHEDULING USING TRANSITION LOSS 111

8.1. Statement of Problem 111
8.2. Calculating Transition Loss 115
8.2.1. Calculating Pairwise Transition Loss 115
8.2.2. Calculating Total Transition Loss 118

IX. EXTENSIONS OF MVCOPQLF USAGE 120

9.1. General Comments 120
9.2. Process Variation 120
9.3. Grade Transition Paths 122
9.4. Target Identification 122
9.5. Sensitivity Analysis 123
9.6. MVCOPQLF Accuracy 123

X. CONCLUSIONS 125

BIBLIOGRAPHY 128

APPENDIXES 134

APPENDIX A - SAS INPUT FILES 135

APPENDIX B - BASIC PROGRAM FOR CALCULATING PAIRWISE TRANSITION LOSS 138

LIST OF TABLES

Table Page

1. Experimental Point Layout 70

2. Specific Experimental Points 77

3. LE_{1jk} Values for Original Manufacturer Category 78

4. LE_{8jk} Values for Societal Category 82

5. CL_{1n} Values for Original Manufacturer Category 85

6. CL_{8n} Values for Societal Category 91

7. MVCOPQLF Calculations 109

8. Pairwise Transition Times 114

9. Pairwise Transition Loss Values 117

LIST OF FIGURES

Figure		Page
1.	Traditional Loss Function	7
2.	Taguchi Loss Function	10
3.	Example of Loss Function Derivation	26
4.	COPQ Matrix	39
5.	TLF Using One Experimental Point	62
6.	TLF Using Three Experimental Points	63
7.	Example of Bivariate TLF	67
8.	SAS Results from Original Manufacturer Category	87
9.	Number of Parameters vs. C(p) for Original Manufacturer Category	90
10.	SAS Results from Societal Category	93
11.	Number of Parameters vs. C(p) for Societal Category	96
12.	Univariate LFs for Three Plastic Grades	102
13.	Pairwise Transition Loss Curves	103
14.	MVCOPQLFs for Two Plastic Grades	106
15.	Contour Plots for Four MVCOPQLFs	113

NOMENCLATURE

C	Number of quality characteristics used in a multivariate loss function
CL_{in}	Total COPQ Loss in Category i, at experimental point n
COPQ	Cost of Poor Quality
COPQLF	Cost of Poor Quality Loss Function
COQ	Cost of Quality
D	Density
i	COPQ Matrix Category; i=1,2,...,8
Iij	Specific Item number, i is a one digit Category number (i=1,2,...,8), and j is a two digit Item number (j=01,02,...,11)
j	COPQ Matrix Item; j=1,2,...,i_m
k	COPQ Matrix Societal Effect; k=1,2,3,4
l(x)	Taguchi Loss Function
L_n	Value of COPQ Loss at experimental point n
$LE_{ijk}(n)$	An element of the COPQ Matrix at experimental point n, for Category i, Item j, and Societal Effect k
$LF_i(X_1,X_2)$	Multivariate COPQ Loss Function for Category i which is a function of two quality characteristics, X_1 and X_2
m_i	number of items in Category i
MI	Melt Index
MVCOPQ	Multivariate Cost of Poor Quality
MVCOPQLF	Multivariate Cost of Poor Quality Loss Function

$MVCOPQLF_g$	Multivariate Cost of Poor Quality Loss Function for a specific grade, g
n	specific experimental point
N	total number of experimental points used to estimate a MVCOPQLF
s	increment number when calculating a pairwise transition loss
S	total number of increments taken to calculate a pairwise transition loss
x	a generic quality characteristic
X_c	general reference to quality characteristic c
$x_c(s)$	a specific value of quality characteristic c, at increment number s, used when calculating total transition loss
$X_c$step	step size taken on quality characteristic c when calculating a pairwise transition loss
δt	time increment taken when calculating a pairwise transition loss
T	Target for the Taguchi Loss Function
TLF	Taguchi Loss Function
TT	Total Time for a pairwise transition
TTL_{AB}	Total Transition Loss from Grade A product to Grade B product
(Tg_{1g}, Tg_{2g})	Value of two quality characteristics, X_1 and X_2, at the Target for grade g

CHAPTER I

BACKGROUND AND RESEARCH OBJECTIVES

1.1. Introduction

Companies which are determined to stay in business are increasingly using high quality and low cost as their competitive strategy. These companies search for ways to continuously and incessantly improve quality and reduce the manufacturing cost of their products. The Taguchi Methods of quality improvement include an important measurement model for supporting such a strategy of continuous improvement.

This research expands upon the under-developed areas of the Taguchi Loss Function in order to (1) develop a Cost of Poor Quality Matrix which will guide a user in enumerating and quantifying significant factors required to upgrade the current definition of cost of poor quality, (2) determine how the Matrix may be quantified and then used to model a loss function, and (3) provide direction concerning the strategic uses of the resulting loss function to evaluate production run sequences in the chemical industries.

1.2. Developing a Cost of Poor Quality Matrix

Quality cost systems were created to highlight the cost of poor performance, the cost of doing things wrong. These systems have never reached their full potential. It has been estimated that less than 15% of the opportunities for quality cost application in manufacturing companies in the U.S. are actually being pursued in a profitable manner. [29] In fact, this failure to develop and use quality cost to effectively support quality management programs has damaged the credibility of the concept as it is currently understood. This research is an attempt to use experience and new developments to redesign quality cost methodology in order that it be used to its full potential.

1.2.1. Current State of Cost of Quality Systems

The term "Cost of Quality" (COQ) denotes a complex and multifaceted concept, just like quality itself. There is, in fact, no one definition which encompasses all possible aspects of quality cost to everyone's satisfaction. The importance of a particular aspect of COQ also changes with the nature of the product or service, and the needs of the customer. More often than not, in order to quantify COQ into dollars, industry uses dollars spent as a result of nonconformance to specifications as a definition of quality cost.

John Hagan has superbly documented the good and bad aspects of the current COQ system used by many companies. [29] After making observations concerning current use, he documents some ideas for improvements to the current system. He notes that any attempt at a new concept of quality cost should:

1) Be clearly limited in application to costs associated with the conformance quality of manufactured product,

2) Focus on failure costs as a prime target for reduction,

3) Eliminate prevention cost as an element of quality cost, thereby allowing total quality cost to become a target for total reduction.

Hagan also states that there is an underlying need for any new quality cost system to become untangled from other cost control or improvement systems with which they often become intermingled, such as manufacturing cost control, inventory controls and formal cost reduction programs. COQ needs to stand alone and be easily recognized by management as an entity with obvious merit. One of the most valuable contributions to move forward COQ thinking in recent years is Genichi Taguchi's outlook on quality and quality improvement.

1.2.2. Taguchi's Concept of Loss to Society

Taguchi purports that quality is "the loss imparted to the society from the time a product is shipped." [73] In this statement, Taguchi associates quality loss with every product that reaches the consumer's hand. Among other things, conceptually, Taguchi's definition includes failure to meet the customer's requirements of fitness for use, added warranty cost to the producer, harmful side effects caused by a product, and loss resulting from a company's bad reputation and lost market shares in the long run.

Taguchi's definition demonstrates a customer oriented emphasis. This is in sharp contrast to the producer oriented definition of quality inherent in COQ systems by most companies, in which costs of scrap, rework, and possibly warranty repair are the chief measures of quality performance. In contrast to the typical COQ system, Taguchi realizes that the value of quality may ultimately be more important than the cost of quality.

Investments in quality improvement projects appear much more attractive when one takes a long-term view that considers net savings to society and customers' good will. Deming pointedly states that the cost of poor quality may be infinite when it causes customers to look elsewhere for products that better meet their expectations [28]. Taguchi's definition attempts to capture this important dimension of the quality of a manufactured product; the total loss generated by a product to society. Since most COQ programs do not concern themselves with such a long-range perspective, Taguchi's definition of quality is a first step towards making the realization that product quality is determined by many factors outside of the manufacturing plant. This provides a new way of thinking about investments in quality improvement projects. An investment in a project is justified provided the resulting loss savings to customers, and the company are more than the cost of improvements.

1.2.3. Quantifying COQ Factors

Merely recognizing and defining the many facets of quality loss accomplishes nothing, however, unless there is a way to convert the losses associated with a product into dollars to quantify the problem. Taguchi claims that in order to quantify "loss to society", it must be viewed in the equivalent terms "long term losses to a company". Applications of this adjusted definition have resulted in models which do not go much further than catching the traditional COQ components such as scrap, rework and sometimes warranty costs. This does not come close to estimating the long-term losses to the company, when the broader perspective of loss to society is intended.

Today's consumer is sophisticated, educated and demanding, and there are indications that societal wants in the coming years will stem from a desire to improve the "quality of life", including the quality of production. Even Taguchi's definition falls short under this realization. The raw materials, energy and labor used in producing unusable product are all societal losses. The toxic chemicals produced during manufacturing can also cause losses to society. Taguchi's definition needs to be expanded to include all the societal losses which occur during manufacturing. New definitions of quality cost categories are necessary in order to generate information which will improve both producer and consumer decisions, and lead toward a better understanding of product quality and consumer preference.

1.2.4. Expanding Cost of Quality

It should be clear that the ultimate value of quality cost systems will not be achieved without some changes in the current concepts. This research expands the current thought into laying out the characteristics of quality which are crucial to the definition of cost of poor quality when viewed in terms of societal loss. Particularly, which aspects can be, and should be, included for their contribution to cost of poor quality so that they may be used strategically by management.

Taguchi's definition is perceptive, but applications to date fall short of expressing quality in terms of the entire system in which the product is manufactured and used.

Cost of quality systems are growing, but in most cases the data generated is not being used to the fullest extent possible. This research takes the best parts of two outlooks on quality costs - a COQ system and Taguchi's definition - and combines them with some independent observations and improvements in order to define a COPQ Matrix which can be used to quantify a quality loss function to be used in guiding plant operations, and turn focus on cost of poor quality into a competitive opportunity.

1.3. Developing a Multivariate Cost of Poor Quality Loss Function

The Taguchi Loss Function is an economic model for quantifying quality loss. The model completely redefines the traditional go/no-go gaging into target or best-value analysis. This change effectively redirects the quality effort to reducing variability. Given a quantifiable loss function, it becomes possible to evaluate the impact of different quality strategies, quantify the effects of different patterns of variation on long-term economic performance, and suggest economic opportunities that might be realized by continuous improvement in the way products meet customers' needs.

1.3.1. Traditional Univariate Loss Functions

Figure 1 shows the traditional method of quantifying quality. The target, T, represents the ideal level of the quality characteristic being considered. The solid vertical lines on either side represent the point of decision (often arbitrary) between

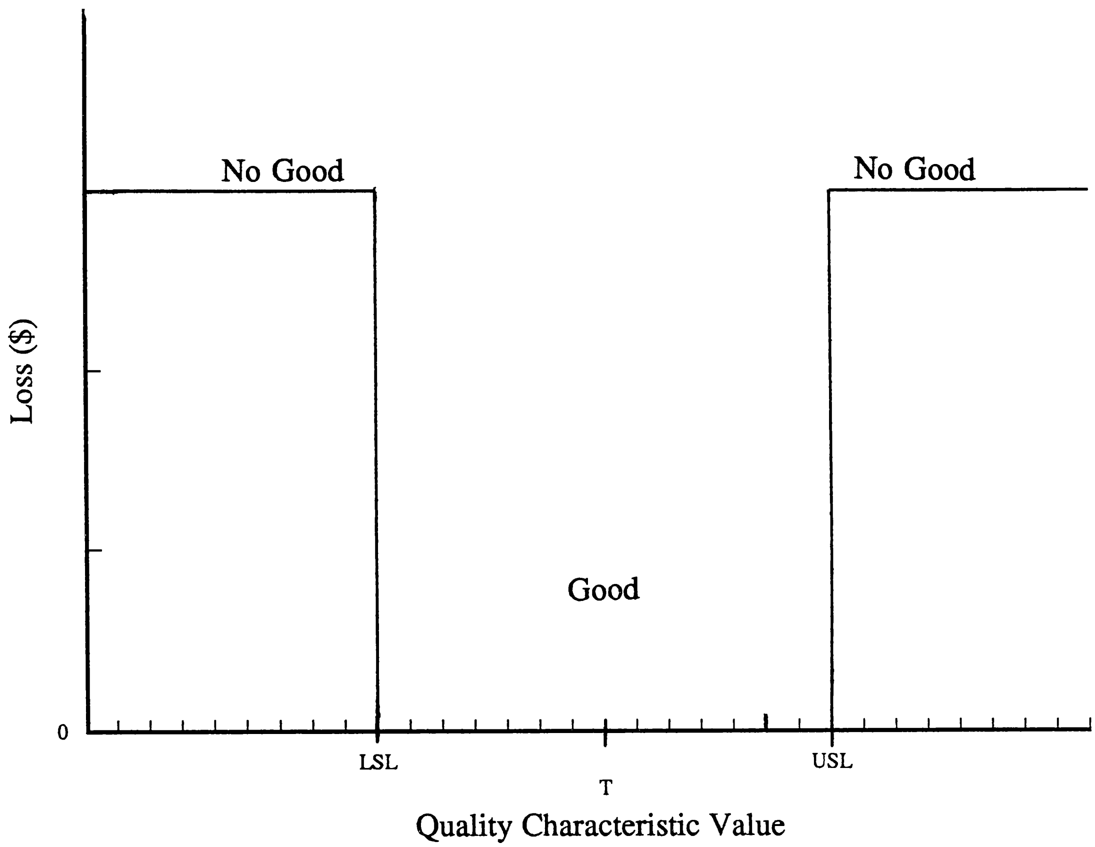

Figure 1. Traditional Loss Function

acceptable and non-acceptable quality products; these are usually depicted as the specifications. The vertical axis represents dollar loss per unit to the producer (or by Taguchi's definition, loss to society). If the product is within spec, everything is fine and no cost is incurred. As soon as the value being measured ranges out of spec, the product cannot be sold, or must be sold at a reduced price, and therefore some set cost of defective is incurred, and the product must be scrapped or repaired.

This idea has been the traditional, and comfortingly clear, basis for decision-making on quality characteristics. The problem with this view of quality is that it is unrealistic. In many situations this seemingly black and white picture becomes a discussion of shades of gray. The functional distinctions between parts just on either side of a spec limit can be very small. Similarly, a comparison of parts within the acceptable region shows some performing better than others.

1.3.2. Taguchi Loss Function

Taguchi realized that in the eyes of a customer, there is no abrupt change from perfect to useless as some arbitrary boundary is crossed. Actually, product performance gradually deteriorates as a quality characteristic deviates further and further from the specified target. The deterioration continues as the product characteristic moves beyond a spec limit. As perceived by the customer, or society, it is the variation from the targeted value that causes the reduction in the quality of the product.

Taguchi also notes that quality is best when product characteristics are at target values, and that as they deviate from target values quality decreases and customer dissatisfaction and loss increase. The Taguchi Loss Function (TLF) quantifies this idea, as shown in Figure 2. The TLF assesses quality loss due to deviation of a quality characteristic from its target value and expresses this loss in monetary terms.

As before, the horizontal axis is the value of some quality characteristic, the target value of which is denoted by T. The specifications are shown as USL and LSL. The vertical axis is loss per unit, measured in dollars. Rather than the step-function depicted previously, the TLF utilizes a quadratic relationship that takes the form of a parabola. In other words, the loss is minimum at the target T, and increases quadratically as the deviation of the quality characteristic from the target increases. In mathematical notation, the TLF can be denoted as $l(x) = k(x-T)^2$, where $l(x)$ denotes a Taguchi Loss Function which is a function of a quality characteristic, x, and where T is the target value, and k is a constant.

The TLF implies an important philosophical departure from traditional thinking in that it defines loss continuously over the entire range of variation, and there is loss associated with any deviation from target in the quality characteristic. With the TLF, the engineer can provide economic justification in dollars for trying to keep quality characteristics right on target, rather than merely within specifications. The TLF provides an economic perspective that redefines the traditional cost control guidelines which most companies use to operate. The loss function can be used to quantify the dollar impact of deviation from customer requirements. Lower losses provide the drive to try to meet customer requirements more consistently.

In order to use the TLF to actually evaluate performance it is necessary to determine the value of the constant k. In words, this is a simple matter of finding a

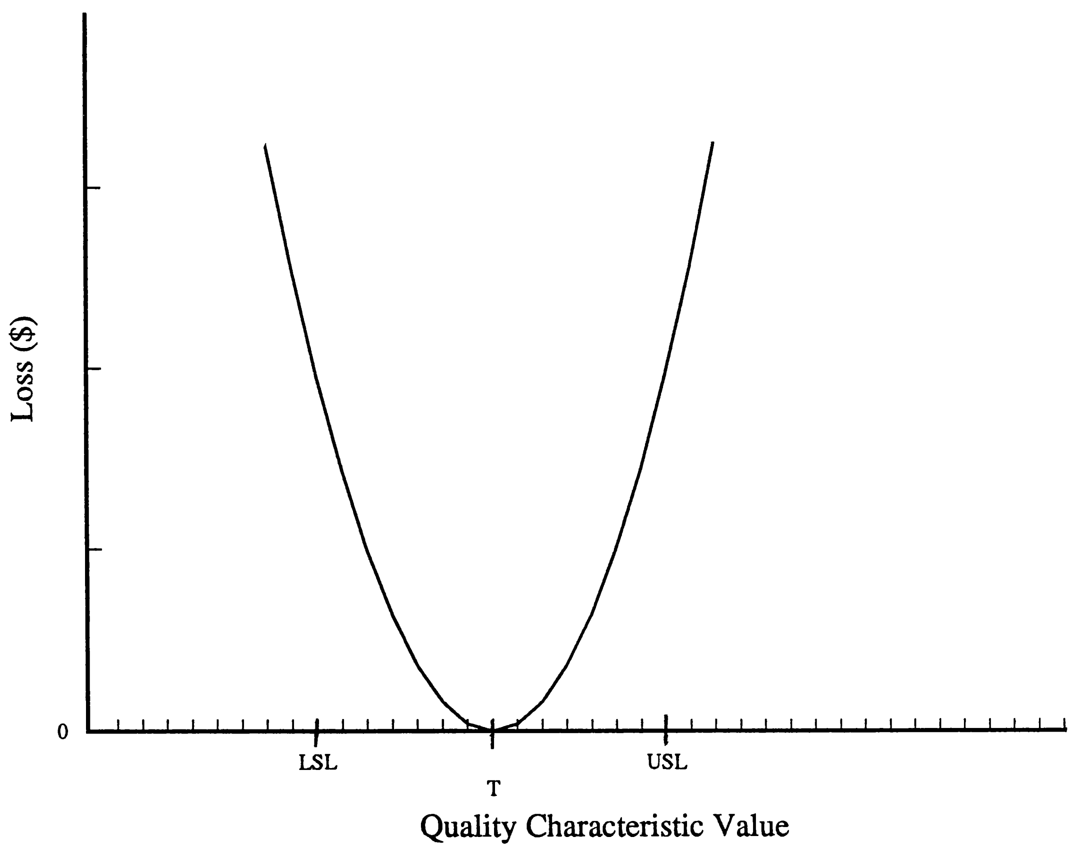

Figure 2. Taguchi Loss Function

value of x (the quality characteristic) for which the loss in dollars is known. By substituting the known loss, and the corresponding value of x into the TLF, the equation can be solved for the constant k. Once k is known, the loss associated with any deviation from target can be calculated. Although this sounds like a simple task, the matter of solving for k presents one of the largest inconsistencies in the TLF.

In virtually every referenced case of application of the TLF, solving for the unknown k is done by estimating the loss at either the lower or upper specification. This loss is estimated simply as a repair cost, or a warranty cost, thereby leaving out all of the other aspects of loss to society. In industry application, it has also been found that severe discrepancies can be created when simply using a "mark-down" cost to tie down the loss function. This decreases the ability of the loss function to be used in a strategic manner.

1.3.3. Expanding into a Multivariate Loss Function

Another discrepancy revealed by industrial application is the univariate nature of the TLF. To date, all published examples of the Taguchi Loss Function have dealt with a single quality characteristic. This is most likely because Taguchi uses the loss function primarily to support the other aspect of the Taguchi Methodology, that of robust design. This research builds upon the realization that the TLF can be used by itself as a powerful decision tool, with some revisions and expansions.

When one does try to apply the TLF in industry, it is soon clear that decision makers are faced with not just one, but a multiplicity of quality measures which must be simultaneously measured, monitored and controlled in order to make business decisions. Quality is the composite of a family of properties which are often interrelated and nearly always measured in a variety of units. Quality to the ultimate consumer is the combination of these properties, the overall performance to which each property contributes, but which no single property defines to the exclusion of the others. Even when the quality factors are precisely measurable, a serious problem exists in systematically combining the individual measurements into one equally precise index representing the total comparison. The TLF, as it currently exists, fails to adequately address this issue.

This research shows that a loss function, based upon the same ideas as the TLF, can be developed. Rather than being one-dimensional, for only one quality characteristic, this function is multi-dimensional. This allows different quality characteristics of the same product to be evaluated simultaneously in terms of loss to society. In effect, a multivariate loss function, represented by a response surface, defines the cost of poor quality. The COPQ Matrix defined in the previous section is used to numerically define the surface. Using the Matrix to define quality loss in conjunction with a multivariate loss function, a new, and very necessary, model is presented which has strategic applications for guiding quality improvements in manufacturing.

1.4. Strategic Uses of a COPQ Loss Function

The crucial importance of the loss function to the management of continuous improvement has not yet been realized. Most firms do not quantify the cost and reliability advantage of moving toward the target, and as a result very often they establish barriers to improvements past specification limits. As more companies are agreeing with the new definition of loss, they are searching for ways to use the loss function to revise and guide the directions of their business. The measurement model developed through this research brings about new ways to guide process improvements, and new ways to choose and manage projects that enhance an organization's capabilities.

1.4.1. Indicators of Process Performance

Based on conformance to specifications, the traditional U.S. definition of quality, performance measures such as process capability indices (Cpk) and process performance indices (Ppk) have been used to monitor process performance. These indices do little to encourage improvement where part characteristics are within predetermined specifications. Another drawback of these indices is that there is no apparent immediate basis for specifying the optimal value of an index. They are also poor measures of quality levels because there is no direct way to quantify in dollars, the results of improvements gained as the index changes from one value to another.

COQ systems have also been used to monitor loss incurred by process performance. A common complaint about quality cost systems is that they often demonstrate high cost numbers but do not signal a direction for improvement, and therefore present no real opportunity to reduce loss. [47] Another problem with quality costs systems can be seen when one considers using warranty costs to estimate losses. Warranty cost is not received until after products are released to customers. At that point, the information is relatively useless for making changes to production processes because of time lag, and the problem of getting enough dependable data to use in decision making is present.

A measurement model like the TLF allows one to quantify annual cost savings as product characteristics improve toward target value, even when they are within specifications. This puts a whole new economic perspective on quality and encourages continual improvement as a method to reduce costs. It allows managers to lay out corporate resources toward the investigation of specific high cost areas while documenting and quantifying progress.

1.4.2. Using a Loss Function to Make Operations Decisions

There are some strategic uses of loss functions that Taguchi has discussed, one of which is setting tolerances. As traditionally established, tolerances do not ensure quality. Instead, they dictate the limits of product functionality as specified by the engineer. Two products can both function adequately, but one can still be better than the other in terms of functionality and in the eyes of the customer. The TLF provides a method for establishing economically justifiable tolerances.

By using a multivariate loss function as in this research, the possibilities for strategic use can be taken much further. For example, a plant in the chemical industries can use one form of a multi-dimensional loss function to monitor the cost of grade changes from product to product. Grade changes can be ranked in difficulty using the results of the loss function. The concept can then be extended greatly, using the loss function to estimate the cost of various product run sequences, and thereby determine the more efficient sequences.

In an even broader sense, a loss function can be used as a strategic long-range planning tool to determine provision of adequate resources, and thereby guide quality improvement efforts. A firm's strategic plan is an ideal device to force changes and a loss function is a way to guide and support this. In this manner, quality improvement efforts receive the management visibility that is often lacking when "quality" is set forth as a business objective. In 1983, a vice-president of Ford stated that "Our new quality thinking should be reduced process variability around the nominal as an operating process philosophy for never-ending quality improvement." [71] This research builds upon Taguchi's definition of quality and the TLF, to expand current COQ thinking in order to create a Cost of Poor Quality Matrix which can serve strategically to support an operating philosophy of continuous improvement.

1.5. Research Objectives

The primary objective of this research is to develop a useful method for defining quality loss, determine a way to use the definition to model a multidimensional loss function, and to show how the resulting loss function can be used in industrial applications to evaluate production run sequences in terms of quality loss. Achieving this objective will entail three subobjectives.

1.5.1. Subobjective 1

Propose a logical, distinguishable set of Categories which may be used to define Cost of Poor Quality. The factors should include the costs incurred through the well-known "loss due to scrap" thinking, and further extend through a "loss to society" orientation. The steps in achieving this subobjective are to:

1) Determine the aspects of quality loss which justify inclusion in a COPQ definition;

2) Define the dimensions of the quality loss categories in order to achieve a Matrix definition for COPQ which allows for inclusion of data available from existing quality cost system records; and

3) Propose new types of quality costs to address, in order that the COPQ Matrix may achieve a new, long-term, loss to society perspective on COPQ.

1.5.2. Subobjective 2

Determine the multidimensional form of a loss function associated with the COPQ Matrix, and show how a user can take the information from a COPQ Matrix and use it to model a multivariate COPQ loss function. This procedure will:

1) Demonstrate how to quantify the different elements of the COPQ Matrix;

2) Determine how, once quantified, the COPQ Matrix may be used to arrive at data suitable for modelling a response surface; and

3) Provide the methodology for taking a COPQ Matrix and transforming it into a MVCOPQ loss function.

1.5.3. Subobjective 3

Develop and illustrate, using typical industrial data, a procedure for the practical use of the MVCOPQLF in the sequential production of a multi-product slate. This procedure will:

1) Develop a procedure to explicitly consider the loss associated with product to product transitions in a chemical industry;

2) Use the results from 1) in order to determine a method for ranking the overall performance of product to product transitions with regard to quality loss;

3) Compare the rankings generated by the loss function to existing performance rankings in order to evaluate results; and

4) Determine how to use the above information to generate low cost production run sequences for a chemical plant.

CHAPTER II

LITERATURE REVIEW

2.1. Defining Cost of Poor Quality

Quality cost systems were created many years ago to highlight the cost of achieving quality. There are currently a wide range of approaches used to collect and identify quality cost information. Many of these quality cost systems have been written about extensively. [3,4,5,6,56,62]

2.1.1. Traditional Approaches

The most common approach used today is documented in an ASQC publication, Quality Costs - What and How. [2] The method identifies four main areas of cost breakdown needed to evaluate cost performance. The areas are:

1. PREVENTION COSTS: Costs associated with personnel engaged in designing, implementing and maintaining the quality system, including auditing the system.

2. APPRAISAL COSTS: Costs associated with measuring, evaluating or auditing products, components and purchased materials to assure conformance with quality standards and performance requirements.

3. INTERNAL FAILURE COSTS: Costs associated with defective products, components and materials that fail to meet quality requirements and cause manufacturing losses before they reach the customer.

4. EXTERNAL FAILURE COSTS: Costs generated by defective products being shipped to customers.

The basic relationship among the four cost areas is that dollar investments in prevention and appraisal can reduce costs in both failure areas.

In recent years, some quality professionals have started to realize that the traditional approach to determining quality costs may have limitations. The most common complaint is that COQ systems always deal with visible costs, and fail to capture intangible costs. This causes the traditional method of cost allocation to create prejudices in the ways that executives view and compute the costs of their decisions. Often even business decisions that are intended to produce intangible benefits are treated, for purposes of cost computations, as if they involved only tangible factors. The most important costs are sometimes omitted altogether as a result.

There are also complaints that often numbers generated by such a system look acceptable on paper, but waste and rework are being generated on the side at high levels. [47] Though the numbers may not be reflected on the company books, poor quality does result in an increased price to the customer, which in turn makes the producer uncompetitive with its rivals. This indicates that there are other aspects of quality which should be included in a model.

2.1.2. Taguchi's Loss to Society

Taguchi's definition of quality - "the loss imparted to society from the time a product is shipped" [73] is quoted in numerous articles which deal with the Taguchi Methods of Quality Engineering. The essence of his definition is that the societal loss generated by a product, starting from the time a product is shipped to the customer, determines its desirability. The smaller the loss, the more desirable the product.

Although Taguchi's definition captures in words a very important aspect of quality losses, problems arise when one attempts to use the definition to actually quantify loss to society. This problem, of quantifying long term losses to a customer, has been addressed in words to some extent. In an article discussing the Taguchi Loss Function, Jessup [36] states that for a decision model to be effective, it must use a broadly inclusive measure of loss. This must include both near and long-term effects, taking the perspective of the organization as a whole ("the long-term best interest of the firm"), and is usually expressed in monetary terms. The problem is, finding reasonable measures of these aspects of quality which can be quantified for use in an economic loss function model.

2.1.3. Other Outlooks on Cost of Quality

A 1987 ASQC publication [4] indicates that the losses incurred by reduced quality are of two types, direct and indirect. Furthermore, direct losses come from the customer's dissatisfaction and increased service costs. Indirect costs are loss of market share, and the increased sales and marketing effort needed to promote and sell a poor quality product. It goes on to discuss three types of hidden quality costs: those incurred by the supplier in-plant, those incurred by the buyer in solving problems at the supplier's plant, and those which usually are not allocated to suppliers, but are incurred by the buyer as a result of potential or actual supplier problems.

In talking about suppliers, there are supplier related quality costs which are apparent and perhaps more easy to identify by the buyer. These are referred to as visible costs [3]. They fall primarily into the appraisal and failure categories and include such things as receiving or incoming inspection, measuring equipment calibration, source inspection and control programs, purchased material reject disposition and replacement, and scrap or rework of supplier-caused rejects.

Juran's definition of quality is fitness for customer use [5]. When quality is defined this way, the cost of quality certainly encompasses both quality of design and quality of conformance, and programs for quality improvement must encompass all phases of product life, from design through use by the customer.

Gunter [28] makes reference to inefficiencies which are caused by variation. His list includes costs of increased maintenance, downtime due to equipment breakdown, and excess inventory. He also states that quality should be defined in terms of the whole system in which a product is manufactured and used, not just in terms of the accounting practices at particular points in the system. Finally, the worst costs of all, but hardest to capture, are the costs to customers incurred because of degraded product performance, reliability and durability.

An article in American Machinist [23] states that cost has to include design, engineering and all of the elements that go in before a product goes to the floor. Also, it has to consider what happens beyond the factory floor. It has to consider the channels of distribution used, marketing costs, and must focus all of these together as product costs in order to use them in a strategic manner.

An article in Electronic Design [19] describes how "cost of ownership" should be considered for IC procurement decisions. The "cost of ownership" includes the purchase price and costs for screening, rework, inventory, and warranty repair, all of which are a result of ICs with less than perfect quality and reliability. The author presents an example of a customer who evaluated four digital product families from a number of different suppliers. The product from suppliers with the worst reliability had a cost of ownership that ranged from 3 to 14 times greater than for suppliers with the best reliability.

Hartford Insurance, a service company, measures "escape costs" in dollars. [69] This is the cost of money lost because defects were never caught. Billing mistakes are used as an example. If a company makes a mistake in its own favor on a bill, the customer is likely to complain. But if the mistake is made in the customer's favor, the company may never hear about it. These losses can be especially important in a service industry since there are many direct customers.

Celanese Fibers Operations includes expenses that are "in our ability to control if we follow effective operating practices" into the basic cost of quality. They realize however, that the operating procedures themselves do not provide the whole picture since a certain amount of other loss may be designed into a process. They therefore created an "opportunity for quality" category [69] which accounts for design losses. The "opportunity for quality" totals might allow a company to move the process technology closer to perfection.

Crosby uses Price of Nonconformance (PONC) as the measurement of quality. All costs incurred because things were not done right the first time go into the PONC, this being the cost of waste. Typical PONC expenses include reprocessing, expediting, unplanned service, downtime, rework and returns. All costs incurred to make certain things are done right the first time go into the Price of Conformance (POC). Typical

POC expenses include preventive maintenance, product testing, procedure verification, and auditing. Crosby also includes a third category called Error-free costs, which are all expenses incurred for operating processes as they were designed, assuming no planned waste, rework, or nonconformance was part of the design. [68]

In recent years, the field of cost accounting has also started to address the issue of quantifying costs of manufacturing. Robert S. Kaplan [41] makes the point that today's management accounting systems provide a misleading target for managerial attention. They fail to provide the relevant set of measures that appropriately reflect the technology, product, processes, and competitive environment in which an organization operates. Kaplan has been one of the leading advocates of changing the system to reflect manufacturing costs more accurately.

Probably the most comprehensive and widely supported response to addressing this problem is a cost management system being developed by Computer Aided Manufacturing- International (CAM-I). Their research to date has resulted in the following realizations [23]:

> Cost has to include design, it has to include engineering, it has to include all of the elements that go in before the product gets to the floor. It also has to consider what happens beyond the factory floor. It has to consider the channels of distribution we use. It has to consider marketing costs, and to be able to focus all of these together as product costs is a very powerful help to management in looking strategically at its business. We need to look at things that are not only quantitative in the financial sense but are quantitative in the non-financial sense, like process yield, quality, cycle time, and schedule attainment. And, for certain products and markets, some factors are more important than others.

In 1984, David Garvin took a slightly different approach to this problem of defining quality, or lack thereof [24]. Garvin developed eight "dimensions of quality" which provide a comprehensive framework for organizing quality characteristics. These dimensions are Performance, Features, Reliability, Conformance, Durability, Serviceability, Aesthetics, and Perceived Quality. Garvin believes that by identifying and defining the most important dimensions of quality, a company can achieve competitive advantage, while focusing its downstream quality and cost reduction efforts on a few key objectives.

In terms of creating a hierarchical definition of quality, Johnson and Lo [38] attempted to do something similar in order to define quality determinants. There was some attempt made to quantify some aspects of a global definition of quality through a questionnaire sent to different companies. However, this was not done for all facets of the quality definition, and nothing was done to quantify the definition such as through a loss function.

2.2. Developing a Loss Function

Numerous articles have appeared in Quality Progress [7,13,40,70,71,76], and the Journal of Quality Technology [39,49,61], concerning not only the TLF, but covering the entire arena of the Taguchi Methodology. The majority of the Taguchi literature however, has focused on the methods of robust design, using the loss function only to support this methodology. The literature which discusses the development and uses of the TLF to any extent tends to be very conceptual, and does not provide very complete industry examples.

2.2.1. The Taguchi Loss Function

One of the best discussions of the loss function, and its use in industry, can be found in a recent book by Taguchi, Elsayed and Hsiang [74]. An entire chapter is devoted to the development of the loss function. Later Chapters center in on its use in setting economical tolerances, and some other uses in a manufacturing setting.

Jessup [36] provides a good explanation of the general idea behind the loss function, providing an example which is often used for explanation by Taguchi. Jessup presents the situation of thinking in terms of a customer-acceptance characteristic such as the temperature in a room filled with people. In this case, the lower the temperature, the more people present who are likely to feel too cold. And by the same token, as the temperature rises, there will be an increasing number of people who are likely to consider a given temperature uncomfortable. In each case, the more extreme the condition, the more likely it would prompt a customer complaint. Then, a total complaint rate is the sum of these two individual factors. Between the extremes, the net complaints from the two conditions hits a low point. The results of this example are shown in Figure 3.

Given such a situation, there tends to be a best point at which the loss is a minimum, with performance deteriorating continuously as values move away from the target. Also, it usually appears that while the rate of deterioration may be quite low right around the target, this rate accelerates as one moves farther away from the target.

Taguchi significantly simplifies this situation to make evaluation and subsequent calculation much easier, but without, in his opinion, sacrificing the usability of the model [22]. Taguchi uses only the net curve, and sets the loss at the target equal to

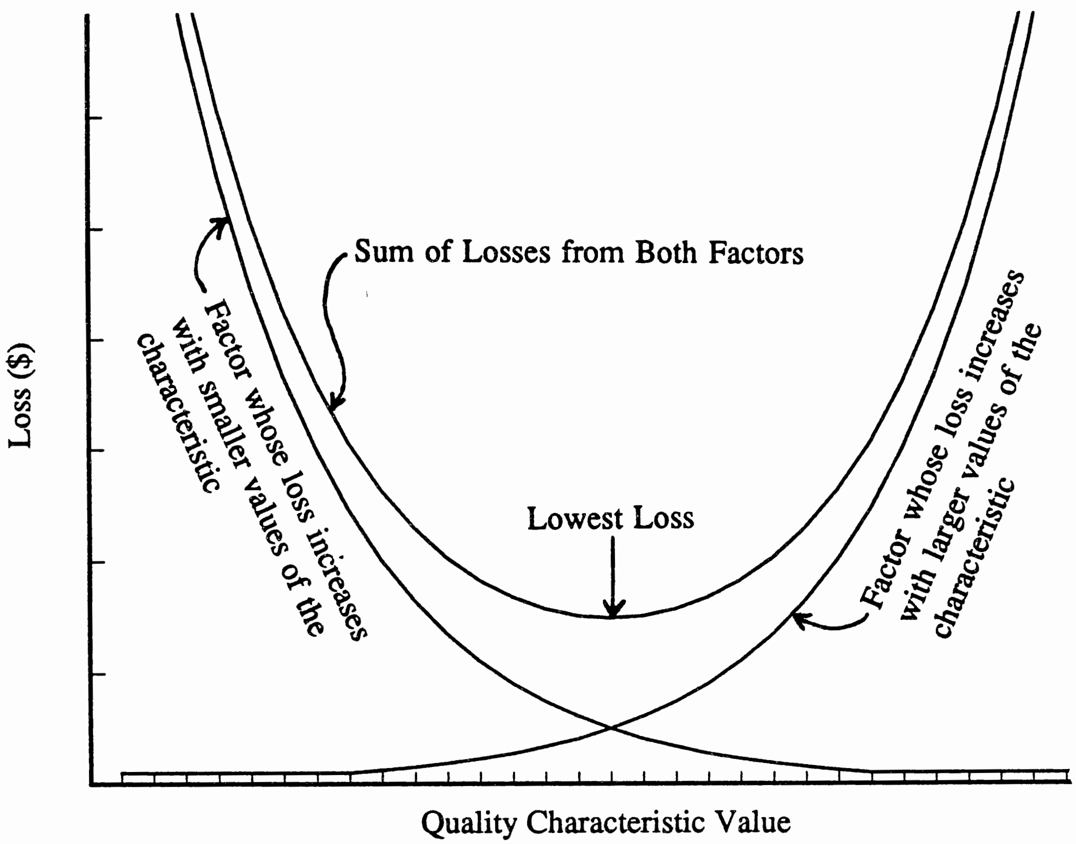

Figure 3. Example of Loss Function Derivation

zero. He has found that a simple quadratic function relationship, that he often proves through a Taylor series expansion [73,75], approximates the behavior of loss in the majority of cases. The equation for this TLF is $l(x)=k(x-T)^2$, where k is some constant, T is the target, and x is a value of the quality characteristic. Taguchi admits that a more analytic loss function can be formed, but only by using more time and resources [72].

Once the form of the loss function is known, there is a way to evaluate incremental dollar loss probabilities in relation to departure from target mean for a given quality characteristic. The target is the point of no incremental loss, since every time a product is produced to its target spec, it reduces the quality liability of the company and the future likelihood of lost good will. If a part is produced off target, according to the loss function, it has just increased the quality liability of the product by an easily tractable amount.

For a nominal-is-best situation, the loss on either side of the target need not be symmetric. In such a case, the TLF becomes piece-wise quadratic. In addition to the nominal-is-best loss function described to this point, Taguchi identifies two other common forms of the loss function [74]. One is a higher-is-better, in which only the right half of a parabola is used. The other is a lower-is-better characteristic, in which only the left half of a parabola is used.

2.2.2. Multivariate Loss Functions

There is very little literature available concerning a multivariate loss function that accomplishes generally the same things as the TLF. Taguchi indicates only that when a product has several measurable function quality characteristics, the total losses caused by deviations can be estimated by simple adding up the individual loss values for each characteristic [74]. In practice, this can only be done if the individual loss functions are independent, which by nature of the problem is virtually impossible. In one industry example, adding the losses results in total loss values which make no sense in the context of the problem. When a product is being evaluated, each of its characteristics are interrelated when it comes to defining the loss. So, if changes are made to one characteristic to reduce its loss, the change is likely to result in the loss for a different characteristic increasing.

In 1965, Edwin Harrington [30] recognized that quality to the ultimate consumer is the combination of quality properties, the over-all performance to which each property contributes, but which no single property defines to the exclusion of the others. His goal was to find a mathematical solution to combine the individual measurements into one equally precise index representing the total comparison. His result, the Desirability Function, permits the treatment of the family of properties which characterize a product by all the statistical methods commonly used to analyze, compare, optimize and control the individual measures of product quality. The Desirability Function accomplishes this by transforming the measured properties into a desirability scale, where d=1.0 represents a completely acceptable level of quality, and d=0.0 represents completely unacceptable performance.

Harrington also recognized that from the manufacturer's standpoint, it is nearly always desirable to stay appreciably within the spec limits, if for no other reason than to avoid substandard quality due to the inherent process variability. Furthermore, because of sampling and testing imprecision, it is quite impossible to separate borderline quality into two unequivocal groups of acceptable and unacceptable product. The desirability function, in effect, smooths the discontinuities of the discrete step function of loss through mathematically transforming the measurement of the property into the desirability function scale. Since the desirability function is in no way tied to dollars, this model still does not attack the problem of getting engineers and management to talk the same language.

In 1989, Chen and Kapur [15] presented some different forms of a univariate loss function, and included a generic multi-variate loss function developed by simply replacing Taguchi's univariate loss function with vectors. The paper did not address the issue of where, or how to get the relevant loss data needed to actually quantify the loss function.

Multiple regression appears to be a desirable technique for describing the loss function response surface which applies to a given set of quality characteristics, for a given definition of loss. There is an abundance of literature on methods of multiple regression, and response surface exploration [9,10,11,16,34,57].

2.3. Strategic Use of a Loss Function

While a loss function provides the means to quantify and measure key quality characteristics, quality improvement necessitates using this information to keep the process or product on target while making ongoing efforts to reduce the measured variability. There are a number of ways in which Taguchi recommends using the loss function in order to make decisions [74].

Jessup [36] gives a good description of using the TLF to establish economic specifications. This is a simple matter of determining the point of indifference between paying dollars to fix a product, and letting the product hit the hands of the consumer. Another way in which it has been greatly used is for evaluating the aggregate expected loss from a process, based on the distribution of actual performance on the characteristic in question. For a nominal-is-best characteristic, this calculation is as follows:

$$\text{Average Loss per Piece} = k(\sigma_x^2 + (\overline{x}\text{-}T)^2)$$

This turns out to be beneficial in that the average loss due to performance variation is a measure of process variation which is independent of the specification limits. This makes it a more reasonable index than the many forms of capability indices which are directly tied to specification limits. It is this fact which prompted the interest in using the loss function to monitor and direct continuing process improvement efforts in a manufacturing situation.

Gunter [28] has discussed how the loss function seems to prove that achieving zero defects may not be good enough. For some companies which are attempting to attain zero defects through inspection, a loss function mentality and quantification would show no value to be gained from this process. For those companies that make honest attempts at zero defects, as the point of zero defects is approached, it becomes harder to quantify any increased costs or benefits as less tangible issues enter the equation [66]. A loss function approach can actually pinpoint the place where this becomes an issue, and get around the problem.

Perhaps intelligent managers in industry are the ones who are beginning to investigate the many possibilities of the loss function to the largest degree [1,32,33,42,58]. It has been recognized by organizations such as ASQC [4] that strategic quality program planning is vital to the continuing profitability of many segments of American industry. The pressures for safer, cleaner, and more reliable products are becoming stronger each year. This pressure presents the need to find ways to meet these increasing demands and still remain competitive. To this point though, there has been no published work suggesting ways to use the loss function in such a global manner.

CHAPTER III

COST OF POOR QUALITY MATRIX DEVELOPMENT

3.1. Philosophy Behind the COPQ Matrix

A product is not at its best until it has been shown to work to the satisfaction of the manufacturer, the customer and society. A manufacturer is usually successful if a profit is made on sales to customers, customers return to buy a second time, and if a third party is not offended. So, while profit making must be dominant in decision making, the extent to which other things are sacrificed determines the character of a company. When products do not meet customer expectations, the manufacturer is too often truly not aware of the scope or magnitude of the situation. In most cases this is because the manufacturer has not established close enough contact with its own customers.

Since estimating or predicting what a product will cost, and then controlling the cost of making that product within the limits of the estimate, is an essential part of any project and therefore any industry, determining quality costs is not confined to any particular industry and it has applications throughout the business world. Any informed producer should know about a product's manufacturing cost, performance figures, regulatory guidelines, maintenance needs, product durability, safety issues and customer good-will issues. It is clear that no product can be ideal with respect to all desirable traits, including low cost. Determining where to "give" is a very difficult decision though, especially when a product failure can involve a consumer's (or society's) health or life. Therefore, identifying and removing unnecessary cost, and thus improving value, must be done with regard to the issues noted above.

3.2. Basic Layout of Matrix

This portion of the research develops a Matrix which can be used to define components of quality costs per unit of production, under the viewpoint of "loss to society". The Matrix is based on the belief that the cost of poor quality must be expanded beyond the traditional internal failure costs thinking. Costs of poor quality are not only incurred by the original manufacturer. In most cases, it is more likely that they are incurred by other manufacturers who incorporate the product into their own products, by consumers who use the final product, and eventually by society at large. All costs of poor quality will eventually affect one or all of the above, and regardless of which of these four pieces it affects, the result is a loss to society. In other words, <u>every</u> societal effect must be considered when determining the dollar amount of COPQ. The COPQ a company should be monitoring is the sum of all COPQ dollars incurred by the original producer, other manufacturers, consumers, and society - all Societal Effects. This viewpoint is much more customer oriented than the traditional COQ viewpoint, and utilizes a necessary expansion of Taguchi's use of "society".

There are eight main components of the Matrix which are referred to as

Categories. Each of the Categories includes a certain number of suggested Items to consider when defining the Category. Each Item can ideally be evaluated with respect to four Societal Effects. The structure supports the idea that quality is a cooperative effort between industry personnel, direct consumers, indirect consumers, and ultimately society. Furthermore, when poor quality exists it affects, in monetary terms, one or all of the above. Only when **all** of the societal effects are measured in dollars, can a good evaluation of total COPQ be calculated.

3.3. Characteristics of the Matrix

There are three main differences between this COPQ Matrix and any other COQ systems currently in existence. These differences are:

1) Emphasis is placed on only including costs associated with poor quality. These are the costs which would completely disappear if the product were made perfectly on target, with regard to all pertinent quality characteristics, every time.

2) Significant importance is placed on not only establishing costs incurred to the producer but, perhaps even more importantly, extending the cost outlook into those experienced by intermediate users (other producers), end users (consumers) and ultimately, society at large.

3) All costs included in the model are associated directly with at least one quality characteristic of a product. This means that COPQ is directly dependent on the ability of a product/process to meet target expectations, and to maintain minimum variation around these targets. This also means that in estimating cost for a production time period, all dollar values for loss are estimated per unit of production.

3.3.1. Defining Cost of Poor Quality

COPQ involves not only whether a product works for the customer, but also includes the cost that is built in if it does not work the first time. Deciding upon what constitutes a part of this cost is the difference between many COQ systems. Virtually all of a company's activities exist to support the production, delivery, and support of products, and they should therefore all be considered relevant costs of some sort. Not all of these activities however, are associated with the cost of poor quality. Only those activities which would disappear if every product were produced exactly on target every time actually contribute to COPQ.

The Matrix presented here deals only with cost categories that are made up of cost of poor quality items. The goal of reduction then holds for every category in the structure, and the resulting measurement model, described in a later chapter, can be used to monitor continuous improvement with regard to dollars associated with COPQ.

Some of the Categories of quality costs included in the structure presented here may seem familiar to users of the traditional COQ system. Some traditional COQ categories still exist in a revised form, where only costs that come about as a result of less than 100% quality levels are considered. There are also a number of Categories that have been added to the old ones. These new Categories attempt to capture costs which are more likely to be incurred in the long-term.

3.3.2. Defining Societal Loss

Past COQ practice has focused considerable attention on the production/ manufacturing aspect of quality costs, with little or no attention placed on the external factors such as the customer and the environment. These COQ systems are generally good at identifying cost of poor quality associated with products prior to release from company hands, and are almost always limited to inspection, failure and rework costs. Most of them are very poor at estimating costs once the product gets into the hands of the user, and beyond. Taguchi's definition of quality was the first step in enlarging the scope to societal losses. Growing problems of air pollution and waste disposal are evidence that society is experiencing just the beginnings of the previous lack of attention placed on more global issues.

In an article in Quality Progress, Lawrence Schrader gives a good explanation of how the global cost of poor quality categories can monetarily affect a company as follows [67]:

> To review how costs escalate, it is best to use a hypothetical case. If an engineering error is found on the drafting board, it costs $1 to correct. If the error is found at checking, it will cost $10 to correct. If that same error is found when the piece parts are produced, it costs $100 to correct. If found in an assembly prior to release it costs $1000 to correct. But if not found until the product is in the hands of the user, the cost is $10,000 to correct. If the error requires field retrofits, it will cost $100,000 to correct. If the engineering error results in a lawsuit, cost is in the area of $1,000,000. If the judgment is against the company, the cost can be even greater.

In some cases, such errors may not immediately affect the firm's tangible fiscal position. Subsequently though, these errors can alter a firm's sales, prices, ability to borrow, labor productivity, ability to attract employees, and degree of government regulation, any one of which can directly affect a firm's profits. The tendency to ignore short-term intangibles when they occur leads managers to overlook the subsequent long-term tangible sacrifices that result from the often-intangible beginnings.

An individual corporation is not only responsible to the owners and/or shareholders. The corporation is also responsible to its employees, its customers, its vendors, to the government and to the general public. All of these responsibilities are important. Careful judgment is required to balance the value of the Categories of cost of poor quality with the overall cost and competitiveness of the product.

3.3.3. Defining a Relationship Between COPQ and Quality Characteristics

This research deviates substantially from previous COQ literature, in proposing that cost of poor quality be associated with carefully chosen quality characteristics, **and** their operating levels. Incessant reduction in the variation of product quality characteristics about their target values is crucial to a good quality improvement program. A product's quality, and therefore its true cost, cannot be substantially improved unless product characteristics which are truly representative of the customer's quality concerns, can be identified and measured. This creates a direct customer-to-manufacturing link regarding variation, and it is through this direct link that more accurate costs can be obtained and utilized.

The effect of variability is that users must try to adjust their process, or operating environment, to accommodate the variability. Even when the incoming, or purchased, goods are within specifications, they almost surely include variation. As a result, the customer and/or the customer's process sees an increase in variation and cost of operation. Under current COQ systems, some managers have learned to accept some level of quality cost as inevitable, and uneconomical to reduce. There is no pressure to change this view so long as the cost of quality, or some other measure of quality performance, is not an operating performance issue in management meetings. The Matrix presented here supports a mindset of tying together variation reduction and dollars in order to make this happen.

3.4. Design of the Matrix

As described previously, the COPQ Matrix has three dimensions. One dimension includes eight Categories of cost of poor quality. Each of these Categories is characterized by a variable number of Items, which represents the second dimension. The Items can each be quantified by considering their Societal Effects, the third dimension. A pictorial representation of the Matrix is shown in Figure 4. In this Figure, the X-axis represents the Societal Effects, the Y-axis represents the Items, and the Z-axis represents the Categories. The number of Categories, and the number of Societal Effects are fixed at eight and four, respectively. The number of Items addressed will vary depending on the category being considered.

3.4.1. Category Description

COPQ arises not only out of the operations people perform on a product, but also from the circumstances under which that product is eventually used. It is often quite difficult to put generic titles on the general ways in which these costs will arise. The eight Categories included in this structure attempt to pull together vital areas that have been addressed under traditional COQ systems, and new areas that create the

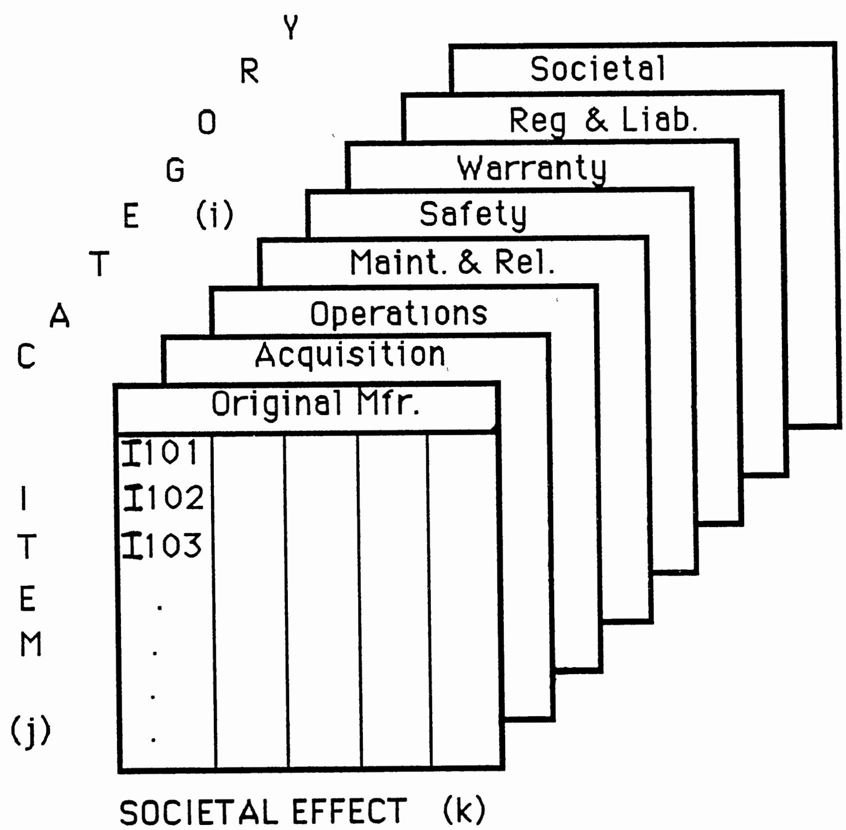

Figure 4. COPQ Matrix

necessary expansion of COQ thinking. The recent COQ literature indicates a realization that quality is some combination of such things as features, performance, functionality, costs, availability and good feelings. A thorough search of the literature provides two main perspectives. It provides enough information to determine which factors that have been used in existing COQ systems would also be required in a structure which concentrates on a societal COPQ. It also provides information as to which aspects of quality costs manufacturers expressed interest in quantifying, but which have never been adequately addressed in existing COQ systems. The eight Categories of COPQ are: Original Manufacturer, Acquisition, Operations, Maintenance and Reliability, Safety, Warranty, Regulatory and Liability, and Societal.

3.4.2. Item Description

Each Category can be characterized by the Items which are included in the Category. Items represent particular costs to consider when attempting to quantify the Category. It is extremely difficult, by no means straightforward, and certainly not practical to create an all-encompassing list of Items to cover all possibilities of COPQ for all companies. There will always be those which are specific to particular situations and industries. The lists of Items included in this paper are meant to be a form of guidance in characterizing the eight Categories. They are meant to give a company an idea of how to set about analyzing its main areas of COPQ, and highlight where quality-related costs are being incurred.

As noted previously, traditional COQ systems have been primarily concerned only with inspection, failure and rework. The Items presented in the COPQ Matrix are meant to lead the user out beyond these limited, traditional costs. A sincere attempt to estimate many of the intangible costs associated with external failures, and to rationally allocate certain elements of cost among the quality loss Categories results in a COPQ outlook that is more accurate than one that omits such costs altogether.

3.4.3. Societal Effect Description

In order to achieve the most accurate account of cost of poor quality, it is not adequate to simply include new loss Categories and Items. It is also necessary to take on a much broader viewpoint than has previously been adopted when considering when and where the costs are incurred. The major importance of considering quality and costs from the customer's vantage point is just getting to be widely accepted. Two, out of seven, entire Examination Categories of the Malcolm Baldrige National Quality Award are devoted to customer concerns. The first one considers "the effectiveness of the company's integration of the customer's quality requirements into its business plans." The second one considers "the effectiveness of the company's systems to determine customer requirements and demonstrated success in meeting them." [50] Methods of achieving this customer focus, and using it as a driver in quality management are still being studied and developed.

The Societal Effects dimension of the COPQ structure presented here is intended to be a driver behind a societal viewpoint. To quantify a COPQ Category, each Item in the Category must be examined to determine whether there is a corresponding COPQ incurred to any, or all, of four possible Societal Effects: Original Manufacturer, Downstream Manufacturers, Individual Consumers, and Society at Large. The user is thereby urged to at least consider all possible societal losses, not merely those that occur in a short-term time frame within a manufacturing plant. The total COPQ for a Category is then determined by summing the costs associated with all of the pertinent Items, across all Societal Effects.

CHAPTER IV

CATEGORY AND ITEM DEFINITIONS

4.1. Category and Item Development

It is imperative that businesses recognize all of the various costs associated with a given product. In addition to the unit price, there are costs the producer and/or the consumer experience resulting from downtime, servicing needs, warranty, process adjustment to accommodate incoming product variability, scrap and rework, administration, and damage to company reputation due to unsatisfactory performance of a product. Lately, there is considerable public attention being focused on production and design defects of products and the related servicing problems. In fact, a report published by the National Academy of Engineering [62] indicates that the quality of production, design and servicing of consumer products stimulate the majority of complaints received by the President's Office of Consumer Affairs.

It is generally not practical or economical to trace out all such effects and adopt measures causing them all to be reflected in a firm's accounts. However, it is reasonable to believe that companies can do, and are being pressured to do, a better job than they have in the past. The eight Categories included in the COPQ Matrix reflect this belief. The Items under each Category are an attempt to define the

Category to such an extent, that any industry could take this model and apply it in their own environment. Recall that all Items included in any of the eight Categories fulfill three requirements; they must:

1) Represent a cost that would disappear if the product were made perfectly on target;

2) Be considered in light of specific Societal Effects; and

3) Be directly associated with one or more measurable quality characteristics.

The eight Categories also follow a product through its life cycle. From the time it is originally manufactured, through the initial receival into a customer's hands, through the product's actual performance in the customer's hands, through the warranty issues that arise for defective products, through the safety and liability issues that arise in service, and eventually through the very broad issue of satisfying society as a whole.

4.2. Category Defining Items

The subsections below contain an explanation of each COPQ Matrix Category, along with a list of defining Items. The Items included are meant to serve as a guide to the user in defining a given Category, but are not intended to be an all-inclusive list. The user may have to adapt and/or extend the Items, given in-depth knowledge concerning a specific application.

4.2.1. Original Manufacturer

Taguchi's original definition only included costs incurred "from the time the product is shipped", which excludes all in-plant losses. The manufacturing plant however, is also part of society. The losses incurred in-plant will also be felt by the "rest of society" since they will be reflected in the purchase price. At most, the traditional in-plant losses reflect the short-term losses that a company will directly feel.

This Category includes any costs being incurred as a result of operations performed inside of the original manufacturer's plant, prior to installation or delivery. This Category contains many of the traditional items companies currently consider in COQ systems. Some of the items found in the Internal Failure Cost category of current COQ systems fit into this Category in the Matrix. In addition, some items labelled as Prevention Costs and Appraisal Costs are also placed in this Category. The Items included in this Category are:

MANUFACTURING APPRAISAL COSTS - Costs incurred for all in-process and final inspection and acceptance tests of manufactured product which are necessary because product is not produced on target.

MAINTENANCE AND CALIBRATION LABOR COSTS- Cost of all inspections, calibration, maintenance, and control of appraisal equipment, instruments, and gages used for the evaluation of support processes, products, or services for conformance to requirements.

MATERIAL REVIEW COSTS - Costs incurred in the review and disposition of product which is not on target.

OPERATIONS REWORK AND REPAIR COSTS - Costs (labor, material, and overhead) of reworking or repairing defective product or service discovered within the operations process.

REWORK COSTS - Costs (material, labor and burden) of all work done to bring off-target product or service back to an acceptable condition.

REPAIR COSTS - Costs (material, labor and burden) of all work done to bring nonconforming product to an acceptable, but still off-target, condition. This reduces, but does not completely eliminate the nonconformance.

TROUBLESHOOTING AND/OR FAILURE ANALYSIS COSTS - Costs of failure analysis (physical, chemical, etc.) conducted by, or obtained from, outside laboratories in support of defect cause identification.

EXTRA OPERATIONS COSTS - costs of extra operations, such as touch-up or trimming, added because the basic operation is not able to achieve conformance to requirements.

SCRAP COSTS - Costs (material, labor, and overhead) of defective product or service that is wasted or disposed of because it cannot be reworked or repaired to conform to requirements.

DOWNGRADED OR SUBSTANDARD END-PRODUCT COSTS - Price differential between normal selling price and reduced selling price due to nonconforming or off-grade end-products or services.

INTERNAL FAILURE LABOR COSTS - Costs due to lost labor time because of nonconforming products. Typical losses occur because of equipment shutdowns and reset-up or line stoppages for quality reasons.

4.2.2. Acquisition

External failure costs are those costs incurred to the original manufacturer when products fail to meet quality requirements after transfer of ownership to the customer. Traditionally, this does not include costs incurred to downstream manufacturers or customers. To quantify external costs to the extent proposed by the COPQ Matrix requires that manufacturer representatives go out and talk to the customer(s). The COPQ Matrix expands the outlook on external costs, so that each component of the life-cycle picture becomes a Category in its own right. Each of the remaining seven Categories could be referred to as a type of external failure cost. While the true costs of the whole downstream impact of these Categories may be difficult to quantify, the dollar amount of these costs can far exceed any potential benefit. Expanding each one individually stresses the importance of these costs when trying to get a real picture of COPQ.

The first of these external failure costs is the COPQ associated with product acquisition. All costs that are associated with acquisition, which arise due to the fact that a product is off-target for at least one quality characteristic, must be rigorously considered. The Category includes any costs that are incurred upon receival of a product, due to the fact that the pertinent quality characteristic(s) are not exactly on target. Although some manufacturers have improved their performance substantially in the past few years, in most cases customers/users must still carry out their own in-house evaluations to determine if additional quality and reliability screens are required. These are costs that downstream users are covering, due to the off-target performance of the manufacturer - they are costs that ideally should not exist. The Items included in this Category are:

DAMAGE IN TRANSIT COSTS - Costs due to damage in transit, as a result of the product being off-target with respect to one or more quality characteristics.

LATE DELIVERY COSTS - Costs associated with late delivery of a product.

CUSTOMER SOURCE INSPECTION COSTS - Costs associated with the customer having to go to the manufacturer's plant to inspect or test product(s).

PRODUCT ACCEPTANCE COSTS - Costs associated with the customer's need for inspections and screening of product when it arrives, due to the fact that it is not all produced right on target.

RETURN OF DAMAGED/POOR QUALITY PRODUCT COSTS - Costs incurred because of having to return product which fails to meet the target for one or more quality characteristics.

INSTALLATION FAILURE COSTS - Costs of all rework and scrap incurred during the customer's installation process, due to the quality characteristic(s) being off target.

REWORK COSTS PRIOR TO USE - Costs the customer, or supplier, incurs to "fix" the product, or make the product work, or perform properly.

4.2.3. Operations

In their book, Engineering Design for Profit, Leech and Turner point out that "assuming that the product [a customer] has bought works, the customer judges it almost entirely by the cost of using and owning it." [46] They also point out that a knowledgeable customer will not merely hope that the designer has considered the costs of use and ownership, but will have written maximum permissible values for these into the design spec. The less sophisticated customers, too, are aware of these costs of use and ownership, and simply buy where they see satisfaction of their standards.

User oriented operations costs represent the cost of maintaining quality over the reasonable life of a product. Many companies make irreversible commitments to customers and/or resalers regarding the performance of their products. The real costs of not meeting these commitments may not be clear for a long period of time, if ever. Companies need to start considering these costs much earlier, rather than waiting until they are felt - which may be too late. The Items included in this Category are:

LOST EFFECTIVENESS COSTS - Costs associated with idle direct labor before and during a shutdown which was due to unsatisfactory performance of a product. Also included are costs of extra defective product made before, during and immediately after such a process shutdown.

EXTRA OPERATING COSTS - Costs due to lower functional output per cycle of operation, or special power and fuels required to run a process, due to the value(s) of the quality characteristics.

FUNCTIONAL DESIGN COSTS - Costs associated with maintaining extra capacity because of expected failures, costs of extra labor to handle failures, costs of extra equipment, parts and materials due to the off-target quality characteristic(s) of a product.

SPECIAL TOOLS COSTS - Costs due to the necessity for special tools and/or equipment needed to make off-target product work in the customer's hands.

COMPLAINT COSTS - Costs of investigating, resolving, and responding to customer or user complaints or inquiries, including necessary field service.

EXTRA INVESTMENT COSTS - Costs associated with special installation and/or running-in requirements due to a product's quality characteristic(s). Similarly, costs associated with special checkout and maintenance equipment.

4.2.4. Maintenance and Reliability

Many companies realize that long-term success of a product is due in large part to its durability, and its functional reliability. In other words, how well the product performs, relative to target, after time zero. This Category considers two types of related costs. Those costs associated with complete product failure (other than those failures covered by warranty) and those costs associated with a product if it does not perform as required (but it is not registered as a failure). Maintenance and reliability tracking can help send signals to managers, through consumer's complaints and product failures, revealing those products/components that require special attention to maintain long run high quality. Many manufacturers understand this cost of poor quality, but because of the difficulties and expense in tracking down and analyzing field failures, do not estimate these costs. The Items included in this Category are:

CUSTOMER LOCATION REPAIR COSTS - Costs of repairs performed on the customer's premises, which are not covered under warranty, and are typically performed by the customer. These include costs of parts and labor to repair.

LOST INCOME COSTS - Profit lost during downtime of a manufacturer's failed product. Any other monetary penalties incurred because of downtime due to a failed item.

REASONABLE LIFE COSTS - Costs associated with maintaining product quality over the reasonable life of a product. These include service, repair and replacement costs not covered under warranty.

SERVICING COSTS - Producer costs of providing servicing (not covered under warranty) for failed or off-target product.

WAITING COSTS - Customer costs of waiting for replacement or repair or service, not covered under warranty. Includes value of customer time expended in having a product failure corrected.

RELIABILITY COSTS - Difference in costs of competitor's product as opposed to manufacturer's in terms of perceived customer reliability.

4.2.5. Safety

Safety is not just a facet of good design, it needs to be integrated throughout the operating structure. Getting precise and definitive data must be a part of this process. Organized methods are needed so that products can be objectively evaluated. A new relationship must be forged, linking product characteristics to the safe performance of a product in the customer's hands. Accidents are costly, and somebody pays for them. Whether the people paying for the accidents are the customers, the distributors, the manufacturers, or the insurance companies, society as a whole suffers. An unreliable product may result in the termination of purchase of that product, or it may result in an accident.

Besides any explicit warranty, the manufacturer is also committed to an implied guarantee of safety to the customer. There is a common, but false, belief that a product designed in accordance with the requirements of a code or standard will be safe. Continuous improvements in standards themselves are proof that inadequacies and unsafe conditions can exist even when all of the requirements of earlier standards are met. Associated with the specifications for every product is the question of how much an increment of safety is worth to the individual consumer and to society as a whole. It is doubtful whether an ordinary consumer, or producer, has the insight necessary to make such a tradeoff. However, if this evidence of safety can be tied into the loss function it becomes a measurable characteristic. This Category accounts for the losses from accidents, not of a legal nature, and the day to day costs of failing to produce a safe product. The Items included in this Category are:

DAMAGE COSTS - Costs associated with injuries to customer personnel due to the off-target quality characteristic(s) of the product.

STANDARDS COSTS - Costs associated with failure to measure up to industry standards.

REMOVAL COSTS - Costs associated with the removal, recovery or salvage of damaged product.

REPLACEMENT COSTS - Costs incurred from having to replace a product which causes some damage.

OBSOLESCENCE COSTS - Costs associated with the new obsolescence of equipment associated with the product which failed.

MEDICAL COSTS - Costs due to medical fees for doctors, nurses, ambulances, and hospital assistance to persons involved in an accident.

4.2.6. Warranty

An explicit warranty is a statement that a product will perform a described function for a stated period of time. If the consumer finds a discrepancy between the claimed and actual performance, the manufacturer agrees to refund, replace or repair the product. A manufacturer can reduce the responsibility by making conservative claims or limiting the period covered by the warranty. However, this may have a negative effect on sales. As a result, manufacturers need to track expenditures associated with explicit warranties in order to correctly weigh the effects. This Category covers the costs of customer complaints, returned goods, field repairs, recalls and claims on faulty product or service all covered under warranty. The Items included in this Category are:

REPAIR COSTS - Costs associated with repairs made during the warranty period.

VALUE LOST COSTS - Costs associated with value of service lost while a product is down for warranty covered repairs.

WARRANTY COSTS - Costs associated with replacement of failed products covered under warranty.

RECALL COSTS - Costs associated with recalls of poor product, which include notification of customers, actual recall costs, and all replacement costs.

INVESTIGATION COSTS - Costs due to complaint investigations at the customer's location arising from off-target values of the quality characteristic(s).

RETURNED GOODS COSTS - Costs due to product which has been returned by the customer due to off-target values of the quality characteristic(s).

4.2.7. Regulatory and Liability

The costs incurred by not meeting constraints imposed by government or regulatory bodies can be very large. The responsibility of a regulatory agency is not just to protect the public from harm. The other responsibility, that is often ignored, is the duty to encourage progress, not just to inhibit action. [14] None of this should be done however, without at least recognizing the economic factors that exist in every decision made by every agency. The safest drug company would be a company that was not allowed to produce drugs - but the benefits are also eliminated.

The direct effect of losing a product liability action is the loss of money paid in compensatory damages and, perhaps, penalty damages. These may only be the tip of the iceberg. Beyond direct costs, companies pay a lesser but significant toll in general and administrative expenses. In a study by McGuire [51], 4 out of 10 company's counsel said that the product liability system had a major impact on their direct costs. They also pointed out that transaction costs of product liability claims and litigation are among the most troublesome burdens the system imposes, and it is not uncommon for a CEO to spend several weeks a year involved with product liability testimony, discussions, and the like. Some of these costs exist whether or not the defense is successful. All companies, small and large, are adversely affected by product liability. Prospective product liability losses should be treated as any other cost of doing business, and this Category includes all costs associated with violating regulatory guidelines, or with product liability cases. Items included in this Category are:

REGULATORY COSTS - Costs imposed by not meeting certain quality characteristic(s) constraints imposed by government, or other regulatory bodies.

LIABILITY STAFF COSTS - Costs associated with staff time necessary to argue claims, court testimony time, etc.

TRANSACTION COSTS - Costs of carrying out product liability claims and litigation, including court costs, attorney fees, expert witness fees, company personnel testimony time.

DIRECT COSTS - Costs of payment of claims, penalties or awards.

PRESSURE COSTS - Production and quality control costs for current production due to product liability pressures.

PRODUCT CHANGE COSTS - Costs involved with having to make changes to product to avoid future product liability cases.

CORRECTIVE ACTION COSTS - Costs of actions required to correct deficiencies which caused the accident, such as recall campaigns, redesign of tooling, replacement of hazardous items.

LOST SALES COSTS - Costs associated with loss of good will, prestige, and sales due to publicity of the product liability cases.

4.2.8. Societal

The final Category arises from an awareness that ultimately, a manufacturer's success and even survival depends on how the quality of the product or service is perceived. Feigenbaum [69] notes that the loss of a customer's goodwill as a result of a quality problem is an intangible quality cost, but is "nevertheless real". He also notes that general awareness of such losses can be of critical importance. McKean [52] addresses such items as "spillover effects", which are uncompensated effects on the costs or receipts of one group of firms caused by the actions of any other set of firms. Ideally, manufacturers should take these spillovers into account when considering their actions.

One of the ever-increasing areas of consumer awareness today is that of the consumer dissatisfaction with the effects of products, and industrial production, on the environment. Pollution of air, water, and soil are sometimes just different versions of saving money by abusing and exploiting the environment. A polluted environment is a source of discomfort and is often harmful to humans and animals. Yet, zero pollution is too heavy a burden for most industries. If the actual cost of a product has to include the cost of all that cleaning up, the price would probably be beyond reach. That does not mean however, that the entire cost should be ignored.

An ugly, noisy or smelly product may damage the environment for others, and consumer protection organizations may put constraints on what the customer will buy. Although the costs of satisfying society may often seem high, the costs of not satisfying society are likely to be much higher. Regulatory agencies are moving slowly because they are unsure of what controls to establish. Incorporating this Category into the Matrix allows companies to start considering these issues directly in their evaluation of COPQ performance. This Category considers the costs associated with not satisfying the global needs of society. The Items included in this Category are:

LOST SALES - Costs of losing customers due to performance of product, such as ugly, noisy or smelly product damaging the environment for others.

GOODWILL COSTS - Costs incurred to customers or users who are not completely satisfied with the quality of delivered product or service. Also included are costs associated with convincing a customer not to leave due to unsatisfactory performance of the quality characteristic(s).

WASTE DISPOSAL - Costs associated with waste disposal in the manufacturer's plant (such as metal shavings, or hazardous chemical by-products)

ENVIRONMENTAL COSTS - Costs associated with pollution of the air, water and/or soil in association with product manufacture, use, or disposal.

HAZARDOUS MATERIAL COSTS - Costs associated with the collection and transportation of hazardous materials/products.

SPILLOVER COSTS - Costs associated with the impact of product quality characteristic(s) on the activities of other parts of society.

4.3. Summary of COPQ Matrix

Future chapters describe how the COPQ Matrix for a product is used to generate loss functions for that product. Although the Matrix was developed primarily for that purpose, it is a valuable idea in itself. A fundamental requirement of a good manufacturing system is to know the product. By spending time collecting cost information, discussing the possible cost ramifications for each Category, and attempting to quantify costs for every box in this COPQ Matrix, a large amount of learning will take place. Once the appreciation for acquiring this hard-to-get information is developed, the process of seeking this information in itself generates a better understanding of the product's abilities and limitations. This process stimulates an awareness of the mindset that manufacturers have an obligation not only to themselves, but also to customers, to their employees, to the government and regulatory agencies, and to society as a whole. Only with an understanding of all the possible Societal Effects can a company truly speak with assurance in defense of its products, or set meaningful standards for its products. Used correctly, the COPQ Matrix helps a manufacturer get closer to being right on these issues, in order to meet the ever-increasing demands of society.

CHAPTER V

DEVELOPING A MULTIVARIATE COST OF POOR QUALITY LOSS FUNCTION

5.1. Quantifying the COPQ Matrix

While defining a COPQ Matrix is a learning experience in itself, in order for the Matrix to be valuable, there must be some way of using information from the Matrix to learn about products and processes. This research combines the COPQ Matrix with an expansion of Taguchi's loss function in order to generate information to help run a business. The first step towards developing a loss function based upon the COPQ Matrix requires the user to quantify the boxes in the Matrix, wherever possible, with realistic numbers. Ideally, every box in the COPQ Matrix can be quantified in terms of dollars. When quantifying the Matrix, this dollar value is expressed in units of production (for example, dollars per pound).

In order to derive a MVCOPQ Loss Function from the Matrix, the user must attempt to quantify each box in the MVCOPQ Matrix in terms of present worth COPQ, at predetermined values of one or more quality characteristics. This is a sequential process in which the user(s) must consider each of the eight Categories, one at a time, filling in loss values for all Items where COPQ can be estimated. Where this information is not readily available, such as in the Societal Loss Category, it may be necessary to develop new systems for collecting some cost information. In some cases, boxes in the Matrix may even remain empty.

5.2. Identifying Sources of COPQ Information

To forecast the monetary effects that result from a quality characteristic being at a specific value requires a thorough knowledge of the product, the customers, and the technology of operations involved. Where information is not already available, new methods of tracking the required data should be investigated. To get data on the cost impact of a product on a downstream manufacturer or end user may require the use of customer surveys, interviews with potential customers, reports from salespeople, and field experiments. Public information of a more general nature can be obtained through independent research organizations, government agencies, and the news media.

5.2.1 Existing Sources of COPQ Data

Some of the quality cost data required to fill in the MVCOPQ Matrix will be readily available from a company's existing cost of quality system. Since most COQ systems do not recognize the multiple dimensions of quality to the extent done here however, the numbers are likely to require some modification. COQ numbers are usually lump sums for an entire period of production, while the numbers in the MVCOPQ Matrix represent dollars per some unit of production, and are directly associated with a discrete value of one or more quality characteristics. Changing the lump sum figures into the required value can sometimes be accomplished as easily as dividing a lump sum by the total production run during a specific time period. For example, consider a plant which reworks an average of 8000 pounds of plastic A per month. If the average cost of rework for plastic A (obtained from accounting records) is $4000/month, then an estimate of the Rework Cost is $0.5/lb. While some data can be estimated in this manner, other data will require the collection or estimation of additional cost information.

5.2.2 Additional Sources of COPQ Data

The reader might also want to consider some methods for quantifying costs that have previously been developed and documented. Work by Gryna [25,26,27] is readily transportable into the COPQ Matrix technique. Gryna develops a present worth model for user failure cost, and comparative user quality cost. Although Gryna's technique lumps all costs together into one value, the basic idea of identifying user costs and quantifying them in terms of present worth is directly applicable. Denton [19] does a good job of describing a method for quantifying the cost of reliability for electronic components. Similarly, Grimm [5] describes a method for predicting warranty costs, given reliability data. Krishnamoorthi [44] shows how regression may be used to predict quality cost changes. In the area of product liability, Vaughn [78] gives a technique for estimating product liability cost, which takes into account the probability of certain types of liability costs occurring.

The Societal Effects in particular require a conscious effort to avoid the traditional approach to cost estimation and to instead consider any and all possible adverse effects that might result from a certain product being off-target. Losses that are generated by a major accident are numerous. Almost all such losses can be evaluated in terms of dollars, directly or indirectly. Loss of public confidence might be estimated by estimating a decrease in sales. Another good source of dollar loss in this Category is an examination of the cost records of similar expenditures in the past.

5.2.3. Summary of COPQ Data Collection

The chief difficulty in computing any particular component of quality cost is the degree of uncertainty attached to it. Using the MVCOPQ Matrix, an error in estimating the magnitude of an Item in any Category is usually is far less serious than overlooking the consequences entirely. It is not all that important that every box in the Matrix be quantified, as long as a concerted effort is made to reasonably estimate costs over all Societal Effects and Categories. With regard to Items, it is reasonable to expect that no two companies will use exactly the same list of Items in quantifying the eight different Categories. Each organization must study its own operations very carefully and determine which Items are applicable to its own operations. Whatever Items are used, it is necessary to provide an operational definition of each class of costs, and inform all potential users and suppliers of quality cost information. In general, the imagination and ingenuity of the team members estimating the costs will determine the degree to which the resulting numbers are valuable.

5.3. Modelling Univariate Loss Functions

In order to define the loss function, the COPQ Matrix must be quantified at "predetermined" values of the quality characteristic(s). Examples of Taguchi's univariate loss function describe how only one value on the loss function is needed in order to define the entire curve. Figure 5 shows the most common form of the Taguchi Loss Function. If the value of loss is \$3.00 at $x = 2.4$, then the constant k in the TLF is calculated as $k=3.00/(2.4-2)^2$ or $k=18.75$. This in turn results in a loss function defined as $l(x) = 18.75\ (x-2.0)^2$.

To make this process even more flexible while still considering only one quality characteristic, additional values on the loss function can be estimated, and then linear regression used to estimate the loss function. In order to estimate a quadratic curve, loss must be estimated for at least three different values of the quality characteristic. In a Taguchi scenario it is most reasonable to estimate loss at the target (at which point loss is defined to be zero), and at two values on either side of the target, perhaps out near the upper and lower specs. Figure 6 depicts a similar loss function, derived from estimating loss at three points instead of one. Using the STEPWISE function in SAS, allowing for the possibility of a quadratic form of the surface, the resulting loss function is: $l(x) = 69.0 - 69.5(x) + 17.5(x)^2$.

In most previous applications of the TLF, a primary difficulty has been with how to actually estimate the value of loss at a specific value of the quality characteristic. Most applications simply use a markdown cost, or a cost of scrap, thereby completely missing the ideology of the TLF. This is precisely where the power of the COPQ Matrix can be utilized.

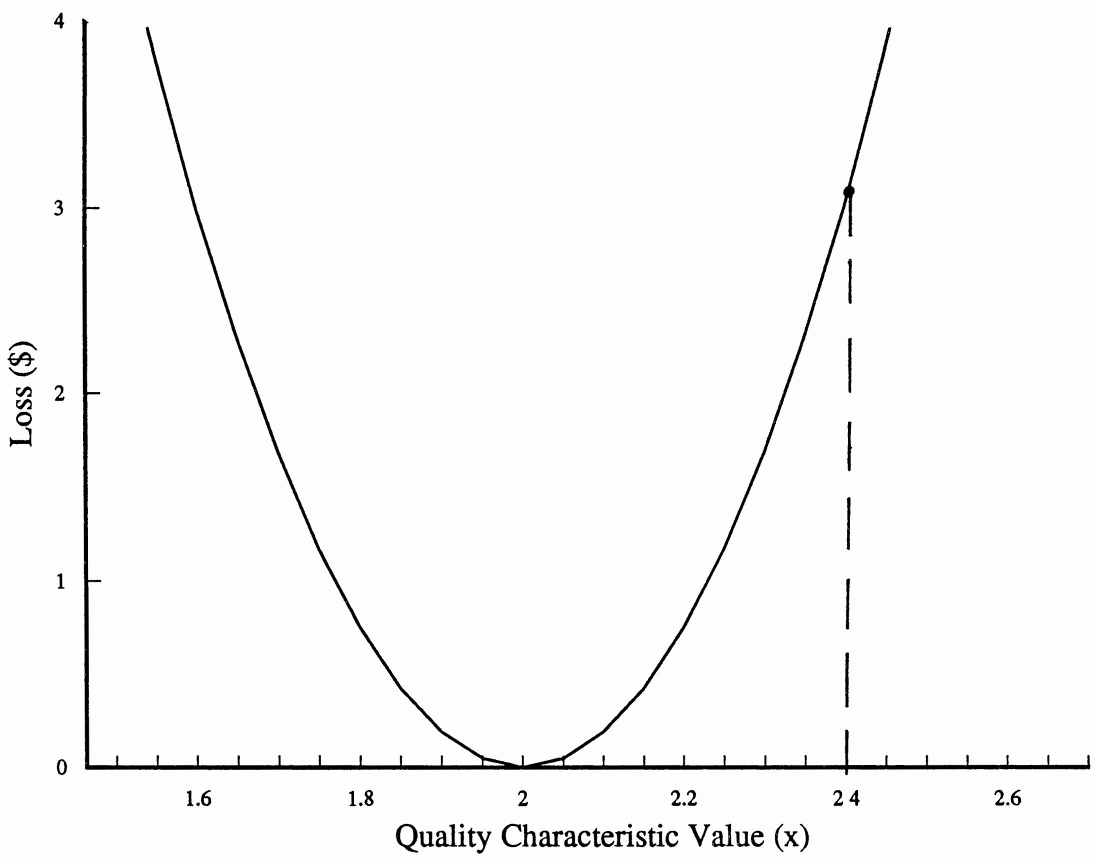

Figure 5. TLF Using One Experimental Point

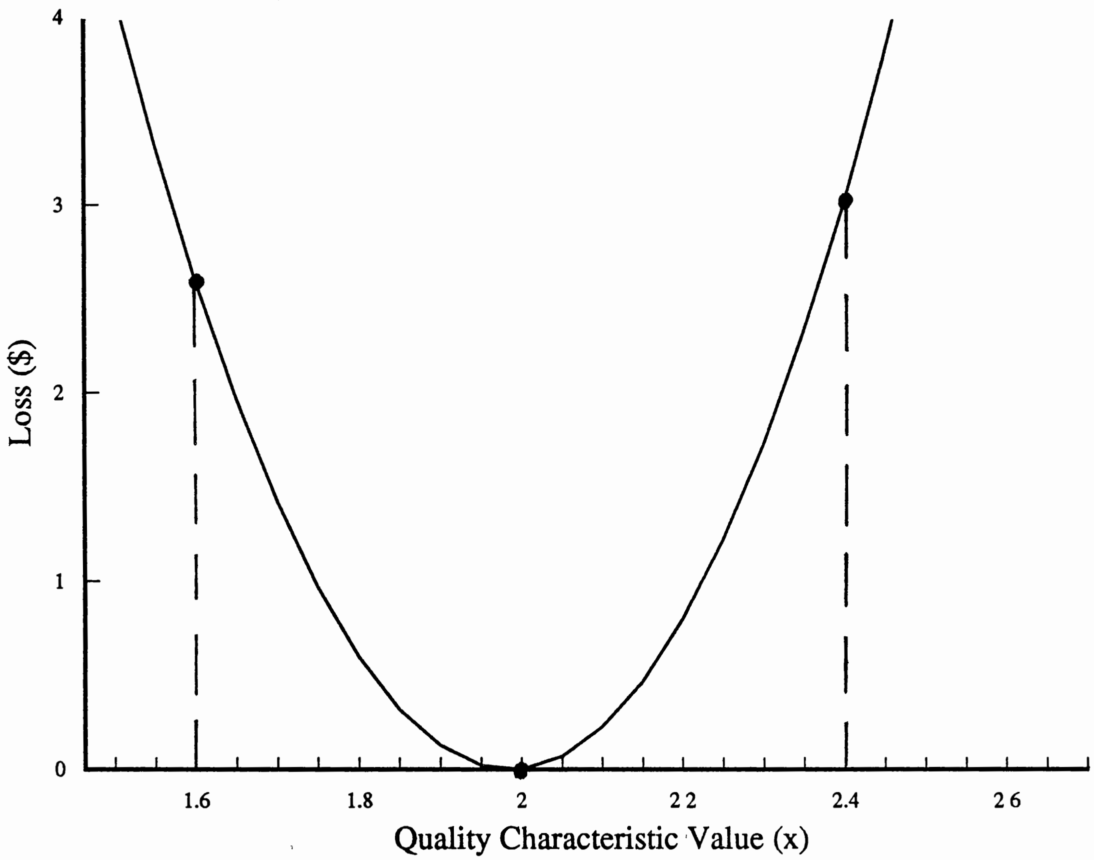

Figure 6. TLF Using Three Experimental Points

5.4. Modelling a Response Surface Using the COPQ Matrix

When the idea of the COPQ Matrix is merged with the idea of using regression to estimate a multivariate response surface for quality loss, the result is the ability to model a Multivariate Cost of Poor Quality Loss Function. The COPQ Matrix provides the means for estimating loss - estimating a point on the response surface - at given values of the quality characteristic(s). Regression techniques provide the ability to model the response surface, given estimates of loss for certain combinations of values of the quality characteristics.

5.4.1. Estimating Loss for Univariate Functions

Conceptually, when considering only one quality characteristic, X_1, an entire COPQ Matrix can be defined at any specific value of the quality characteristic, x_{1n}. To model the corresponding loss function, a COPQ Matrix must be generated for at least three values of the quality characteristic, as explained in Section 5.3. These values are referred to as experimental points and are each denoted by n, where n increments from 1 to the total number of experimental points, N. If loss is being estimated for three values of the quality characteristic (as in the previous example), then N=3. For a given value of n, each box in the COPQ Matrix is **one element** of the total loss at x_{1n}, and is denoted as $LE_{ijk}(n)$. The subscript i indicates the Category, subscript j indicates the Item, and the subscript k indicates the Societal Effect. There are 8 possible Categories, 4 possible Societal Effects, and m_i possible Items since the number of Items is dependent on which Category is being considered. The three axes of the COPQ Matrix are independent of one another, which means that an estimate of the total COPQ loss at an experimental point x_n is defined by Equation (1).

$$L_n = \sum_{i=1}^{8} \sum_{j=1}^{m_i} \sum_{k=1}^{4} LE_{ijk}(n); \qquad n=1,2,...,N \tag{1}$$

For the previous example, there are three unique, quantifiable, COPQ Matrices; one each at x_{11}=1.6, x_{12}=2.0 and x_{13}=2.4. In other words, since there are three experimental points, N = 3, there is a COPQ Matrix associated with all three experimental points, n = 1, 2, and 3. Following Equation (1), the overall COPQ loss at x_{11}, denoted as L_1, is calculated by adding together all the elements in the COPQ Matrix defined for that point. Similarly, L_2 and L_3 can also be calculated using their respective COPQ Matrices. Eventually, the three points, (1.6, L_1), (2.0, L_2), and (2.4, L_3), are used as input data to linear regression techniques, in order to fit the loss function curve.

5.4.2. Modelling Multivariate COPQ

If the above ideas are expanded into consideration of two or more quality characteristics, where the number of quality characteristics is represented by C, the loss function evolves into a multivariate form. The quality loss curve becomes a quality loss response surface. In order to picture this, one might first consider the old "goalpost" idea of loss. That is, any product whose quality characteristic is inside specs is considered good, anything outside of specs is bad. If this model is expanded into three dimensions (C=2) the response surface is represented as a box, with the top flaps each folded outward. Expanding the nominal-is-best TLF into three dimensions results in a loss function surface that resembles a bowl as pictured in Figure 7. In general, there is some relationship - called a Multivariate Cost of Poor Quality Loss Function (MVCOPQLF) - which exists between the response, quality loss, and the C levels of two quantitative quality characteristics. Nothing is assumed about the MVCOPQLF except that within a specified region of immediate interest, in the space of C characteristics, the function can be adequately represented by a polynomial of degree d.

To accurately model such a surface, it is again necessary to observe a response at N experimental points. These are N sets of values of the quality characteristics that correspond to N points in the space of the C characteristics. This means that it is necessary to estimate the value of loss (L_n) at N points, so as to get a good representation of the surface. Each of the N points represents a unique combination ($x_{1n},x_{2n},...,x_{cn}$; n=1,2,...,N) of values of the C quality characteristics. These points are then used as data for multiple regression, in order to estimate the coefficients of the polynomial function.

Knowing something about the general nature of the surface allows some simplification of the problem of what N points to chose. It is known that each characteristic has a target value, and when these target values are taken in combination, the estimated loss will be zero. Beyond that, it is a matter of examining the surface to a sufficient extent on each side of the target. Surfaces of a quadratic nature will dominate the loss functions due to the way quality loss is defined.

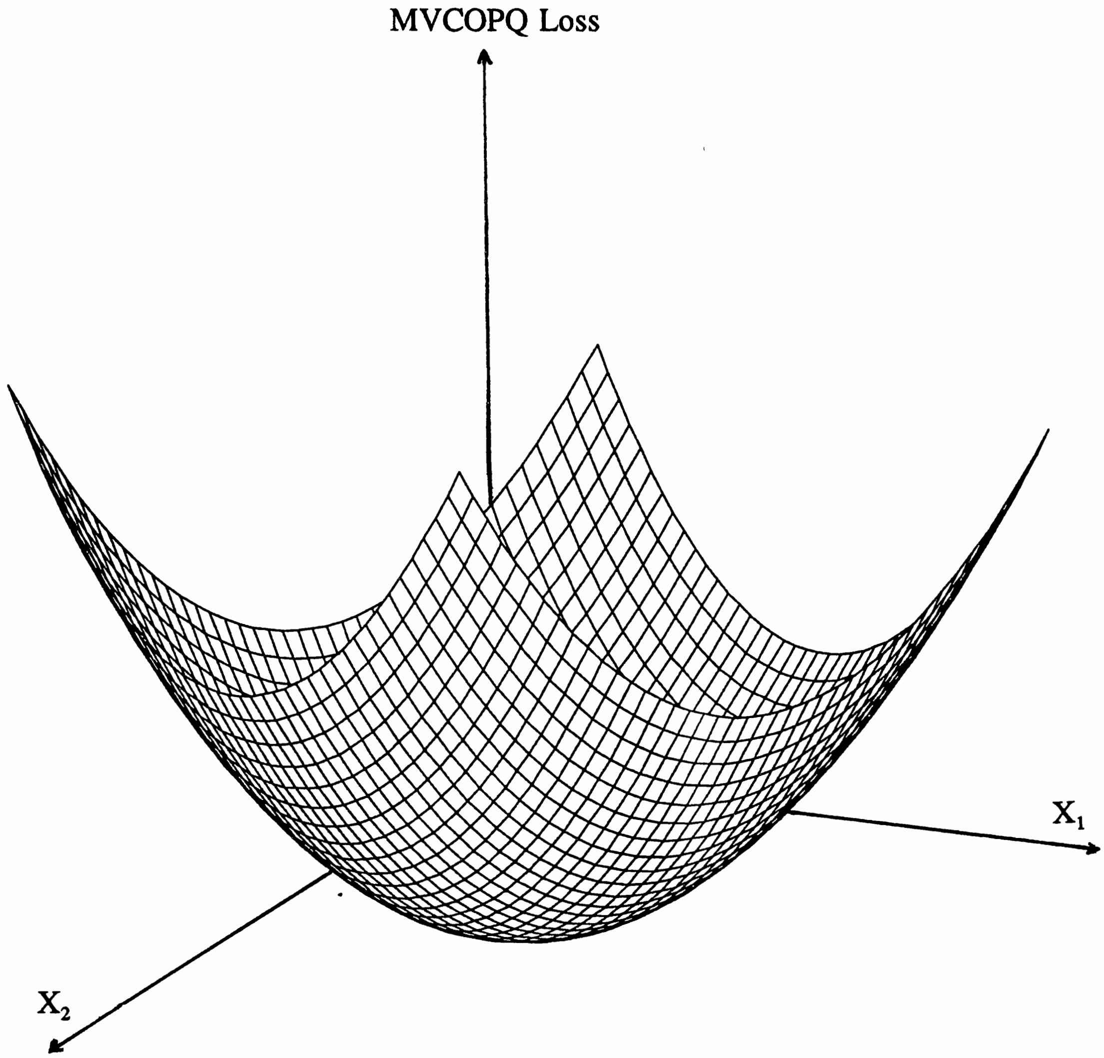

Figure 7. Example of Bivariate TLF

Surfaces of a cubic nature will not be as likely, since costs would not be expected to fall back down after they have been on the increase.

If a quadratic surface is being modelled, and two quality characteristics are being considered, then the value of L_n must be estimated for a minimum of 6 points for statistical purposes. In order to get a better depiction of the surface however, it is suggested that this number be raised to 9 points - three levels of each quality characteristic, taken in all combinations with one another. One of these points should be the point of estimated zero loss, or the experimental point which is made up of the target values for all quality characteristics involved. The other two levels for each characteristic should be taken equi-distant on either side of the target. This provides for adequate coverage of the response surface. Once the loss at these nine points is estimated, regression techniques can be used to estimate a model for the loss function surface.

This research attempts to fit a quadratic form to all functions being modelled. This keeps the function simple enough for an unsophisticated user, without losing accuracy in the majority of situations. In general, if a response variable is measured at different combinations of values of two factor variables, X_1 and X_2, then the quadratic response surface model for the variable is given by Equation (2):

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \qquad (2)$$

5.4.3. Estimating Loss for a Multivariate Function

If more than two quality characteristics are considered, the response surface cannot be drawn, but the technique for modelling the surface is the same as above.

However, the total number of points that must be estimated increases exponentially. The minimum number of points at which loss must be estimated, assuming a quadratic form of the loss function, is calculated as 3^C, where C is the number of quality characteristics being considered.

When considering C quality characteristics, one entire COPQ Matrix can be generated for any specific combination of values of those quality characteristics. Each box in the COPQ Matrix is **one element,** $LE_{ijk}(n)$, of the total loss at experimental point n, which corresponds to the specific values $(x_{1n},x_{2n},...,x_{Cn})$ of the quality characteristics. The total loss at any experimental point n, L_n, is still defined by Equation (1).

Consider a manufacturing situation where two quality characteristics are monitored, X_1 and X_2. There is a desire to model the MVCOPQLF associated with the product. As previously stated, loss (L_n) should be estimated at 9 experimental points (N=9). A specific experimental point is denoted as (x_{1n},x_{2n}), where the n denotes the experimental point. Suppose the experimental points are those shown in Table 1. In accordance with the above statement, the total loss at each of the nine experimental points (L_n, n=1,2,...,9) is estimated using a separate COPQ Matrix. That is, there are N=9 COPQ Matrices, one for each of the experimental points (x_{1n},x_{2n}); n=1,2,...,9. These Matrices are used to estimate the total loss at the respective experimental point. Using Equation (1), the total dollar value of loss at a specific point is given calculated as follows:

$$L_n = \sum_{i=1}^{8} \sum_{j=1}^{m_i} \sum_{k=1}^{4} LE_{ijk}(n); \qquad n=1,2,...,9$$

TABLE 1

EXPERIMENTAL POINT LAYOUT

		Quality Characteristic, X_1		
		Level 1	Level 2	Level 3
Quality Characteristic, X_2	Level 1	(x_{11}, x_{21})	(x_{12}, x_{22})	(x_{13}, x_{23})
	Level 2	(x_{14}, x_{24})	(x_{15}, x_{25})	(x_{16}, x_{26})
	Level 3	(x_{17}, x_{27})	(x_{18}, x_{28})	(x_{19}, x_{29})

There are two options for how to use the COPQ Matrix data to provide input to regression techniques in order to model the MVCOPQLF. The first method is to simply use the nine values of total loss, L_n for n = 1,2,...,9, along with the corresponding (x_{1n},x_{2n}) experimental point as the input data for regression. The best model obtained from this regression is defined as the MVCOPQLF. Using this method the overall total loss is modelled, but the information about the total loss for individual Categories is inherent in the function and not easily retrievable.

An alternate method would be to generate 8 individual multivariate loss functions, $LF_i(X_1,X_2)$, i=1,2,...,8, one for each Category, and then simply add the 8 functions together to arrive at the MVCOPQLF. Using this method, the data in the COPQ Matrix is used one Category at a time. For a given Category, k, the dollar loss at a specific experimental point (x_{1n},x_{2n}) is defined by Equation (3).

$$CL_{in} = \sum_{j=1}^{m_i} \sum_{k=1}^{4} LE_{ijk}(n) \qquad (3)$$

To model a loss function for a specific Category k, all nine CL_{in} values are used, along with their corresponding (x_{1n},x_{2n}) experimental points, as input data to regression techniques in order to model a loss function for the specific Category, $LF_i(X_1,X_2)$. Once this process is completed for all eight Categories, the overall Multivariate COPQ Loss Function is calculated using Equation (4).

$$MVCOPQLF = \sum_{i=1}^{8} LF_i(X_1,X_2) \qquad (4)$$

Conceptually, the resulting TLF is the same for both methods. However, the second method allows for easier use of the individual Category loss functions, if necessary. These may come into play particularly when COPQ loss functions are used for management decision-making as described in later Chapters of this paper.

5.5. Remarks Concerning the MVCOPQLF

A MVCOPQLF as developed in this work is a function which allows for the estimation of cost of poor quality, as a function of actual, measurable quality characteristics, to an extent never before accomplished. Minimizing this COPQ does not necessarily mean maximum profit will result, nor will it imply the point of minimum product cost. A MVCOPQLF is directly tied into a specific product design, and different designs will result in different loss functions just as different products do.

The COPQ does provide an economic common denominator through which managers and line employees can communicate clearly and effectively in business terms. Such information can alert management to the impact of poor quality on financial performance. This can be an effective motivator for action to improve quality. As a result of attention to the MVCOPQLF, greater satisfaction in the use of the product is likely to result, as well as increased competition among producers to meet the consumer's needs most effectively. Using the MVCOPQLF can also lead to improvements in the use of natural resources, reduction in accidents and deaths from the use of unsafe and off-target products, and perhaps even a reduction in pollution. Imagine the day that consumers are informed to the degree that a decision to buy a car is based on an evaluation of the various manufacturer's MVCOPQLFs, and estimated loss values for a specific car.

CHAPTER VI

EXAMPLE OF USING A COPQ MATRIX TO DERIVE A LOSS FUNCTION

6.1. Setup of Example

This example considers a hypothetical, but realistic, process industry plant. The plant uses a continuous process to produce plastic pellets. Once produced, these pellets are sold to a number of different manufacturers, who produce a variety of products. These products range anywhere from very thin plastic garbage bags, to somewhat thicker plastic milk bottles, to very thick injection molded parts. There are four quality characteristics that determine what end use a batch of plastic pellets may be used for: melt index, density, ash content and bulk density.

Due to the variety of end uses, the measured value of the quality characteristics of the pellets sent to each of the downstream manufacturers mentioned above vary anywhere from slightly to substantially. A set of unique values for each of the four quality characteristics defines a grade of plastic. Two of the characteristics, melt index and density, are the characteristics of vital concern. Ash and bulk density are not as important in defining unique grades. Different grades of plastic which are used for similar purposes, have density and melt index values which are relatively close together, and are commonly grouped together into families. The hypothetical plant produces on the order of 80 grades of plastic, some of which may be grouped together into about 8 families.

For purposes of developing a loss function, this example will concern itself only with the two primary quality characteristics - melt index and density. Since these are the main characteristics which define a grade, this is a reasonable example within the interest of the hypothetical chemical plant.

Theoretically, each grade of plastic will have a unique loss function associated with it. In reality, there may not be 80 unique loss functions. In particular it is likely that grades within the same family will have similar loss functions, and possibly even identical ones. Depending on the nature of the quality loss values, it is even possible that different grades will have similar or identical loss functions.

This example demonstrates how to take the loss information from one grade of plastic, and use it to develop a MVCOPQ loss function. The loss values used are hypothetical, but explanations are given for why certain values are used.

6.2. Determining the Experimental Points

The first step in developing the loss function is to define the points at which the COPQ matrix must be enumerated. As previously specified, for a quadratic surface this set of experimental points must include at least three values of each characteristic (taken in combination with the other characteristics). Since this example is concerned with two characteristics, density (X_1) and melt index (X_2), the experimental space will contain nine points. The target for each characteristic will be used as the midpoint, density target is .918 and melt index target is 1.0. The upper and lower spec will then define the points on either side of these targets. The entire experimental matrix is shown in Table 2. Note that the upper and lower spec values are used merely for convenience, and not as a requirement. Any set of equidistant points on either side of the target, where the loss is quantifiable, may be used. For companies which are not yet mature in quantifying quality costs, the specs may be a good place to start this process.

6.3. Estimating COPQ at the Experimental Points

Once the experimental points are defined, a COPQ matrix is used to quantify quality loss at each of these points. In other words, there is a COPQ matrix associated with each one of the nine experimental points. In order to develop the overall MVCOPQLF for a Grade, the user must sequentially consider the total loss values for each Category, from each of the nine COPQ Matrices (CL_{in}; n=1,2,...,9; i=1,2,...,8), and develop eight loss functions, LF_i (one for each category). Then, these eight loss functions are added together to form the overall MVCOPQLF. For purposes of demonstration, this example will develop the loss functions for two categories, Original Manufacturer and Societal, and then show how they would be combined with the other 6 loss functions to form the overall MVCOPQLF.

6.3.1 Quantifying the Original Manufacturer COPQ

As shown previously, there is an entire COPQ Matrix associated with each of the nine experimental points. Table 3 shows the contents of each Matrix cell for the

TABLE 2

SPECIFIC EXPERIMENTAL POINTS

Melt Index, X_2		Density, X_1 .916	.918	.920
	0.8	$x_{11}x_{21}$	$x_{12}x_{22}$	$x_{13}x_{23}$
	1.0	$x_{14}x_{24}$	$x_{15}x_{25}$	$x_{16}x_{26}$
	1.2	$x_{17}x_{27}$	$x_{18}x_{28}$	$x_{19}x_{29}$

TABLE 3

LE_{1jk} VALUES FOR ORIGINAL MANUFACTURER CATEGORY

		DENSITY											
		.916				.918				.920			
MELT INDEX		OM	DM	IC	SL	OM	DM	IC	SL	OM	DM	IC	SL
	I101	0.03				0.03				0.03			
	I102	0.04				0.04				0.04			
	I103	0.06	0.01			0.04				0.06	0.01		
	I104	0.02				0.01				0.02			
	I105	0.05	0.03		0.01	0.04	0.02			0.04	0.03		0.01
0.8	I106												
	I107	0.02				0.02				0.02			
	I108	0.04				0.04				0.04			
	I109	0.05	0.05	0.15		0.04	0.04	0.10		0.10	0.05	0.15	0.02
	I110	0.10				0.10				0.10			
	I111												
	I101	0.03				0	0	0	0	0.03			
	I102	0.04				0	0	0	0	0.04			
	I103	0.04				0	0	0	0	0.04			
	I104	0.01				0	0	0	0	0.01			
	I105	0.04	0.02			0	0	0	0	0.04	0.02		
1.0	I106					0	0	0	0				
	I107	0.02				0	0	0	0	0.02			
	I108	0.04				0	0	0	0	0.04			
	I109	0.04	0.04	0.10		0	0	0	0	0.04	0.04	0.10	0.02
	I110	0.10				0	0	0	0	0.10			
	I111					0	0	0	0				
	I101	0.03				0.03				0.03			
	I102	0.04				0.04				0.04			
	I103	0.06	0.01			0.04				0.06	0.01		
	I104	0.02				0.01				0.02			
	I105	0.05	0.03		0.01	0.04	0.02			0.04	0.03		0.01
1.2	I106												
	I107	0.02				0.02				0.02			
	I108	0.04				0.04				0.04			
	I109	0.05	0.05	0.15		0.04	0.04	0.10		0.10	0.05	0.15	0.02
	I110	0.10				0.10				0.10			
	I111												

NOTE: I101-I111 Correspond to the 11 Items in Category 1
OM: Original Manufacturer
DM: Downstream Manufacturers
IC: Individual Consumers
SL: Society at Large

Original Manufacturer category. As defined, all cell contents for each Category at the target (n=5), where density = .918 and melt index = 1.0, are equal to zero. The contents of the Item costs for the other experimental points are shown. All costs are estimated in dollars per unit of production, which translates to \$/lb for the process industries. The descriptions for all Item costs are given below, where each Item is denoted by a number following the letter I. The first digit of the number represents the Category, and the second two digits represent the Item number within that specific Category.

6.3.1.1. Manufacturing Appraisal (I101). There is a cost of \$.03 shown for all 8 experimental points. This represents the cost of maintaining inspectors for this grade to perform the final inspection of the product. The amount is constant since the cost of inspection is the same, regardless of how far off-target the product is. No other societal affects were quantified for this item.

6.3.1.2. Maintenance and Calibration Labor (I102). This shows a cost of \$.04 at 8 experimental points, which represents the cost of maintaining the equipment required to perform the inspections noted above. This cost is regardless of degree off-target.

6.3.1.3. Material Review (I103). The Material Review Costs for the original manufacturer (OM) depend on what experimental point is being evaluated, or how far off-target the product actually is. The difference between \$.04 and \$.06 represents the degree to which it will cost more to accomplish Material Review for product which is further off target. This is due to the fact that there are more people involved in the process if product is further off-target. A cost of \$.01 to downstream manufacturers also exists for product which is further off target. This cost occurs due to the fact that the downstream manufacturer pays to have this product reviewed in order that it meet stringent process requirements once it enters the downstream plant.

6.3.1.4. Operations Rework and Repair (I104). If the product is identified as slightly off-target during the original production operation, the pellet material can be reblended. For product further off target, more reblending is necessary, which creates the difference between the $.02 cost and the $.01 cost.

6.3.1.5. Rework (I105). Once the material is made into pellet form, it is more expensive to rework the material because it must be entirely reprocessed. This is reflected in the values $.04 and $.05 for rework costs at the original manufacturer. If this off-target product gets to the customer without being noticed, an extra $.03 or $.02 will be incurred upon the downstream manufacturer. For severely off-target product which must be entirely reworked, an additional cost of $.01 to society was identified. This represents an extra cost for unnecessary contamination to the environment due to reprocessing.

6.3.1.6. Repair (I106). These were left zero since the only option for nonconforming product is scrapping, or rework as addressed above.

6.3.1.7. Troubleshooting and/or Failure Analysis (I107). A cost of $.02 represents the cost of having an outside lab test off-target product. This cost is irrespective of how far off the product is.

6.3.1.8. Extra Operations (I108). A cost of $.04 represents the cost of an extra operation which is performed on this grade to refine the texture of the plastic pellets so they will effectively run through the downstream manufacturers production facility.

6.3.1.9. Scrap (I109). The cost of scrapping off-target product in the original plant varied from \$.04 to \$.10, depending on the actual value of the quality characteristics. If this product gets out to a downstream manufacturer, there is a cost incurred upon that manufacturer from processing defective material. If not identified in the downstream processing, and defective material is in fact processed into a final product, there is a cost incurred to the consumer for purchasing a defective product. For product that is on the high end for density, there is also a societal cost since the product must be disposed of and will take longer to decompose in a waste dump.

6.3.1.10. Downgraded or Substandard End Product (I110). The cost of downgrading any material is uniformly \$.10, regardless of degree off-target.

6.3.1.11. Internal Failure Labor (I111). At present, no costs are quantifiable for this item.

6.3.2. Quantifying the Societal Costs Category

This Category is the last of 8 in the entire COPQ Matrix. These cells are quantified just as they were for the OM Category, and again there is a group of Category cells for each of the nine experimental points. Again, all cell contents at the target (n=5), where density = .918 and melt index = 1.0, are equal to zero. All other cell contents are as shown in Table 4. The descriptions for each Item cost are given below, denoted by the same notation used for the Original Manfacturer Category.

6.3.2.1. Lost Sales (I801). Product in the extremes of the target range will cause more pollutants to be emitted during processing and, if locally publicized, has the potential of discouraging customers. This shows up as a cost of \$.05 to the original manufacturer. If the product is used downstream, and such publicity is made, there is

TABLE 4

LE_{8jk} VALUES FOR SOCIETAL CATEGORY

METL INDEX		DENSITY .916 OM	.916 DM	.916 IC	.916 SL	.918 OM	.918 DM	.918 IC	.918 SL	.920 OM	.920 DM	.920 IC	.920 SL
	I801	0.05	0.03							0.05	0.03		
	I802		0.02	0.04			0.01				0.02	0.04	
0.8	I803	0.08			0.02	0.04			0.01	0.08			0.02
	I804				0.03				0.03				0.03
	I805												
	I806				0.04								0.06
	I801					0	0	0	0				
	I802		0.01			0	0	0	0		0.01		
1.0	I803	0.04			0.01	0	0	0	0	0.04			0.01
	I804				0.03	0	0	0	0				0.03
	I805					0	0	0	0				
	I806					0	0	0	0				0.02
	I801	0.05	0.03							0.05	0.03		
	I802		0.02	0.04			0.01				0.02	0.04	
1.2	I803	0.08			0.02	0.04			0.01	0.08			0.02
	I804				0.03				0.03				0.03
	I805												
	I806				0.04								0.06

NOTE: I801-I806 Correspond to the 6 Items in Category 8
OM: Original Manufacturer
DM: Downstream Manufacturers
IC: Individual Consumers
SL: Society at Large

the potential of incurring costs of $.03 to the end-product manufacturer also.

6.3.2.2. Goodwill (I802). These represent an attempt to quantify the customer discontent with product that is not exactly on-target. The $.02 and $.04 represent estimates of the cost of losing a customer should the customer be dissatisfied. This cost is higher if the product is further off-target, since this results in higher discontent.

6.3.2.3. Waste Disposal (I803). There is a direct cost of $.08 or $.04, to the OM to dispose of byproducts from the production process of off-target material. This may also incur a cost upon society, in that the byproducts will be taken to a dump and cause pollution as they decay.

6.3.2.4. Environmental (I804). Due to the processing method for this grade, there is a cost of $.03 associated with the emittants from the production process. This is identified as a societal loss.

6.3.2.5. Hazardous Material (I805). Since none of the quality characteristic combinations lead to generation of hazardous material, this cost is zero.

6.3.2.6. Spillover (I806). For product far off-target, the extra emittants to the air cause the local environmental protection agency to incur a larger cost to monitor these emisions. This is represented by the cost of $.04 or $.06, depending on the value of the quality characteristics.

6.4. Modelling the MVCOPQLF

The overall MVCOPQLF is simply the sum of the eight Category loss functions. From the information in Section 6.3.1 and 6.3.2, cell contents for two Categories of the 9 COPQ Matrices are generated, one for the Original Manufacturer Category (i=1) and one for the Societal Category (i=8). Using this information, two Category loss functions, $LF_1(X_1,X_2)$ and $LF_8(X_1,X_2)$, can now be generated.

6.4.1 Original Manufacturer COPQLF

The estimated loss values, CL_{1n} where n=1,2,...,9, for the OM Category at the 9 experimental points are shown in Table 5. These values are the sum of the individual cell values across each of the 11 Items and 4 Societal Effects in the OM category. Using Equation (3) these values are calculated as follows:

$$CL_{1n} = \sum_{j=1}^{11} \sum_{k=1}^{4} LE_{1jk}(n); \qquad n = 1,2,\ldots,9$$

With this information, it is just a matter of using linear regression techniques to fit a surface which defines $LF_1(X_1,X_2)$, given 9 points on the surface. Each of these 9 data points has a density (x_{1n}), melt index (x_{2n}), and loss estimate (CL_{1n}) associated with it, as previously defined in Table 5.

The 9 data points (x_{1n}, x_{2n} and CL_{1n}; n=1,2,...,9) are now used as input data to SAS, for the stepwise regression procedure, PROC STEPWISE. The actual SAS file used to run the regression is included in Appendix A. Since a quadratic model is being fit, five terms are considered for entry into the model. Denoting X_1 by D and X_2 by MI, these terms are D, D^2, MI, MI^2, and D*MI. These cover a possible of two linear terms, two quadratic terms, and a cross product term. There is also a possible intercept. Whether all of these terms actually appear in the final model is a function of the results of the stepwise regression procedure.

TABLE 5

CL_{1n} VALUES FOR ORIGINAL MANUFACTURER CATEGORY

		Density, X_1		
		.916	.918	.920
Melt Index, X_2	0.8	0.66	0.52	0.72
	1.0	0.52	0.00	0.54
	1.2	0.66	0.52	0.68

The results from the stepwise regression in SAS are shown in Figure 8. The crucial data from this output are the R-square values for each model, the Error Mean Square, and the C(p) value. As long as the R-square value is increasing, and the Error Mean Square value is decreasing, the resultant model is improving with regard to fit. The C(p) value is typically plotted vs. the number of parameters in the model, to get another measure of model fit. The closer the plotted point is to a 45 degree line, the better the fit of the corresponding model. A plot of the C(p) values for the OM data is shown in Figure 9 (note different scaling on x and y axes). From this chart it can be seen that a model with 4 variables, D, D^2, MI^2, D*MI, and an intercept term, results in a point that is very close to the 45 degree line. The fact that the Error Mean Square value increases for the model with 5 parameters indicates that too many parameters were entered into the model. Given all of this information, the best model for the OM loss function, $LF_1(X_1,X_2)$, is:

$$LF_1(X_1,X_2) = 59677.77 - 130024.87\ X_1 + 70832.32\ X_1^2$$

$$6.84\ X_2^2 - 14.93\ X_1X_2$$

6.4.2. Societal COPQLF

The Societal Category loss function, $LF_8(X_1,X_2)$, is developed in precisely the same manner as $LF_1(X_1,X_2)$, however using a different set of estimated loss values. The 9 points representing the characteristic values (x_{1n},x_{2n}) and the corresponding loss estimates (CL_{8n}), for the nine experimental points are shown in Table 6. For each experimental point, these numbers are the summation of the cell values across all 6 Items and all 4 Societal Effects within the Societal Category. Using equation (3), The SAS System

Maximum R-square Improvement for Dependent Variable LOM

Step 1 Variable DSQ Entered R-square = 0.00451849 C(p) = 13.24811822

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.00168731	0.00168731	0.03	0.8636
Error	7	0.37173492	0.05310499		
Total	8	0.37342222			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-3.31306621	21.59129839	0.00125037	0.02	0.8824
DSQ	4.56686838	25.62059871	0.00168731	0.03	0.8636

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2 Variable D Entered R-square = 0.43441422 C(p) = 7.36772273

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.16221992	0.08110996	2.30	0.1809
Error	6	0.21120230	0.03520038		
Total	8	0.37342222			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	59684.79140779	27949.87872628	0.16051473	4.56	0.0766
D	-130039.8033524	60893.13853193	0.16053262	4.56	0.0766
DSQ	70832.31845671	33166.19089826	0.16055326	4.56	0.0766

Bounds on condition number: 2528137, 10112547

The above model is the best 2-variable model found.

Figure 8. SAS Results from Original Manufacturer Category

Step 3 Variable CROSS Entered R-square = 0.43513144 C(p) = 9.35457525

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	3	0.16248775	0.05416258	1.28	0.3755
Error	5	0.21093447	0.04218689		
Total	8	0.37342222			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	59684.79140788	30598.13864857	0.16051473	3.80	0.1086
D	-130039.7669628	66662.78282768	0.16053253	3.81	0.1086
DSQ	70832.31845681	36308.69806227	0.16055326	3.81	0.1086
CROSS	-0.03638981	0.45670923	0.00026783	0.01	0.9396

Bounds on condition number: 2528137, 15168824

The above model is the best 3-variable model found.

Step 4 Variable MSQ Entered R-square = 0.83616848 C(p) = 4.00318676

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	0.31224389	0.07806097	5.10	0.0717
Error	4	0.06117833	0.01529458		
Total	8	0.37342222			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	59677.77139197	18423.62325362	0.16047697	10.49	0.0317
D	-130024.8701108	40138.71593609	0.16049575	10.49	0.0317
DSQ	70832.31850780	21862.04123892	0.16055326	10.50	0.0317
MSQ	6.83771968	2.18518284	0.14975614	9.79	0.0352
CROSS	-14.93333545	4.76866735	0.14998824	9.81	0.0351

Bounds on condition number: 2528137, 20227500

The above model is the best 4-variable model found.

Figure 8. (Continued)

Step 5 Variable M Entered R-square = 0.83634233 C(p) = 6.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	0.31230881	0.06246176	3.07	0.1927
Error	3	0.06111341	0.02037114		
Total	8	0.37342222			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	59668.52589924	21263.10836683	0.16041774	7.87	0.0675
D	-130014.8034575	46323.94295082	0.16046852	7.88	0.0675
M	9.25000247	163.85777617	0.00006492	0.00	0.9585
DSQ	70832.31851543	25230.71363365	0.16055326	7.88	0.0674
MSQ	6.83333334	2.52308944	0.14942222	7.33	0.0733
CROSS	-25.00000270	178.40936527	0.00040000	0.02	0.8974

Bounds on condition number: 2528174, 28444973

The above model is the best 5-variable model found.

No further improvement in R-square is possible.

Figure 8. (Continued)

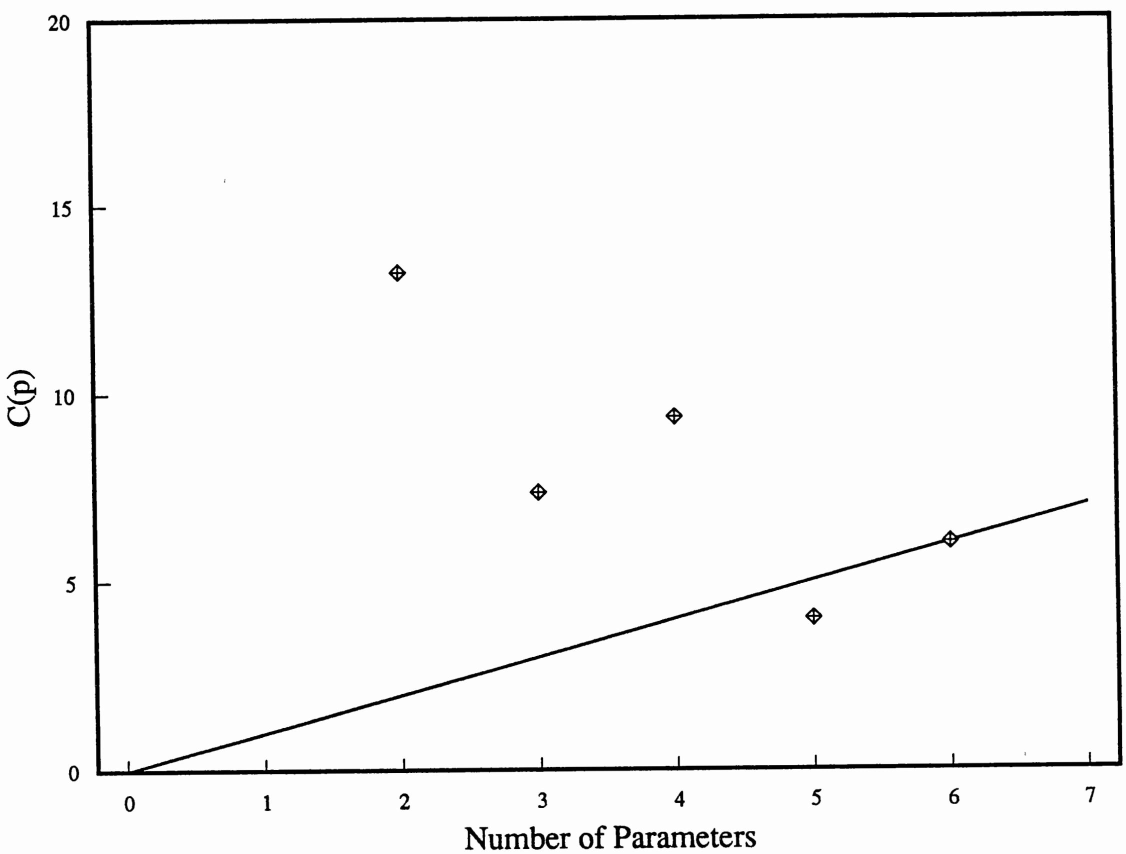

Figure 9. Number of Parameters vs. C(p) for
Original Manufacturer Category

TABLE 6

CL_{8n} VALUES FOR SOCIETAL CATEGORY

		Density, X_1		
		.916	.918	.920
Melt Index, X_2	0.8	0.31	0.09	0.33
	1.0	0.09	0.00	0.11
	1.2	0.31	0.09	0.33

these values are calculated as:

$$CL_{8n} = \sum_{j=1}^{6} \sum_{k=1}^{4} LE_{8jk}(n) \qquad \text{where } n = 1,2,\ldots,9$$

The nine loss estimates, along with their corresponding characteristic values, (x_{1n}, x_{2n}, and CL_{8n}; n = 1,2,...9) are used as input to the SAS stepwise regression procedure, PROC STEPWISE. The actual SAS program is included in Appendix A. Since the surface is again being approximated by a quadratic model, the five variables possible for entry into the model are the same as before; D, D^2, MI, MI^2, and D*M.

The results of performing the stepwise regression in SAS are shown in Figure 10. A plot of C(p) vs. the number of parameters is shown in Figure 11 (again, note different scaling for x and y axes). Evaluating the same measures of model fit as before, it is seen that the 4 variable model (5 parameters) is again the model with the best fit. The Societal Loss Function (k=8) is represented as:

$$LF_8(X_1,X_2) = 39326.32 - 85673.77\, X_1 - 8.83\, X_2 + 46666\, X_1^2 + 4.42 X_2^2$$

6.4.3. Overall MVCOPQLF

The overall MVCOPQLF for a given product was defined in Chapter 5 as the addition of the individual loss functions for each of the 8 categories (LF_i) in the COPQ matrix. If there were only 2 categories, OM and S, then the overall MVCOPQLF for the above example is:

SAS

Maximum R-square Improvement for Dependent Variable LSOC

Step 1 Variable DSQ Entered R-square = 0.00433712 C(p) = 50.75560182

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.00060816	0.00060816	0.03	0.8663
Error	7	0.13961406	0.01994487		
Total	8	0.14022222			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.12611751	13.23203564	0.00051493	0.03	0.8769
DSQ	2.74176912	15.70135658	0.00060816	0.03	0.8663

Bounds on condition number: 1, 1

-The above model is the best 1-variable model found.

Step 2 Variable D Entered R-square = 0.50126071 C(p) = 24.92863928

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.07028789	0.03514395	3.02	0.1241
Error	6	0.06993433	0.01165572		
Total	8	0.14022222			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	39322.02653005	16083.32435971	0.06967217	5.98	0.0501
D	-85673.77239324	35040.01244086	0.06967973	5.98	0.0501
DSQ	46665.99803581	19084.97032193	0.06968789	5.98	0.0501

Bounds on condition number: 2528137, 10112547

-The above model is the best 2-variable model found.

Figure 10. SAS Results from Societal Category

```
Step 3   Variable MSQ Entered       R-square = 0.50273967   C(p) = 26.84581988

                DF        Sum of Squares      Mean Square            F   Prob>F

Regression       3            0.07049527       0.02349842         1.69   0.2843
Error            5            0.06972695       0.01394539
Total            8            0.14022222

                Parameter         Standard          Type II
Variable         Estimate            Error   Sum of Squares            F   Prob>F

INTERCEP    39322.01146547  17592.25696735       0.06967211         5.00   0.0757
D          -85673.77239327  38327.45576703       0.06967973         5.00   0.0757
DSQ         46665.99803582  20875.51644176       0.06968789         5.00   0.0756
MSQ             0.01467331      0.12032534       0.00020738         0.01   0.9077

Bounds on condition number:      2528137,     15168824 -------------------------
-----------------The above model is the best  3-variable model found.


Step 4   Variable M Entered         R-square = 0.94642711   C(p) =  4.00000000

                DF        Sum of Squares      Mean Square            F   Prob>F

Regression       4            0.13271011       0.03317753        17.67   0.0083
Error            4            0.00751211       0.00187803
Total            8            0.14022222

                Parameter         Standard          Type II
Variable         Estimate            Error   Sum of Squares            F   Prob>F

INTERCEP    39326.32544053   6455.90591033       0.06968740        37.11   0.0037
D          -85673.77244028  14065.19055547       0.06967973        37.10   0.0037
M              -8.83333334      1.53471799       0.06221484        33.13   0.0045
DSQ         46665.99806143   7660.77765459       0.06968789        37.11   0.0037
MSQ             4.41666667      0.76608325       0.06242222        33.24   0.0045

Bounds on condition number:      2528137,     20227502 -------------------------
-----------------The above model is the best  4-variable model found.
```

Figure 10. (Continued)

Step 5 Variable CROSS Entered R-square = 0.94642711 C(p) = 6.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	0.13271011	0.02654202	10.60	0.0401
Error	3	0.00751211	0.00250404		
Total	8	0.14022222			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	39326.32543891	7454.85917809	0.06968327	27.83	0.0133
D	-85673.77243851	16241.20355850	0.06967870	27.83	0.0133
M	-8.83333171	57.44863947	0.00005920	0.02	0.8876
DSQ	46665.99806143	8845.90408216	0.06968789	27.83	0.0133
MSQ	4.41666667	0.88459675	0.06242222	24.93	0.0155
CROSS	-0.00000177	62.55043577	0.00000000	0.00	1.0000

Bounds on condition number: 2528174, 28444973 --------------------------
-----------------The above model is the best 5-variable model found.

No further improvement in R-square is possible.

Figure 10. (Continued)

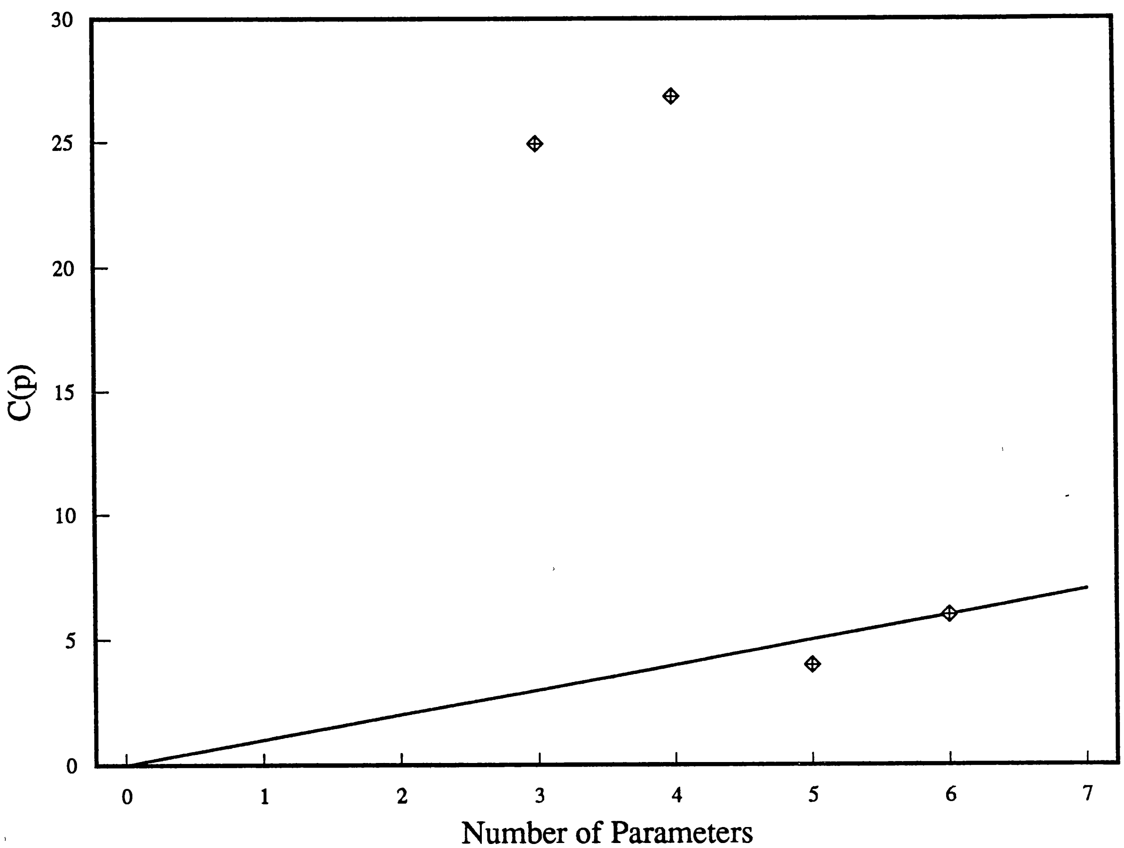

Figure 11. Number of Parameters vs. C(p) for
Societal Category

$$MVCOPQLF = LF_1(X_1,X_2) + LF_8(X_1,X_2)$$

$$= 99004.09 - 215698.64\ X_1 - 8.83\ X_2 + 117498.32\ X_1^2$$

$$+ 11.26\ X_2^2 - 14.93\ X_1X_2$$

If instead, the user develops a COPQ loss function for the other 6 Categories, just as for Original Manufacturer and Societal, then the overall MVCOPQLF is calculated as:

$$MVCOPQLF = \sum_{i=1}^{8} LF_i(X_1,X_2)$$

CHAPTER VII

STRATEGIC USES OF A MVCOPQLF

7.1 Overview of Strategic Uses

The TLF has not yet received the attention it is due as an important measurement model in itself. Once there is a method to get a good estimate of quality loss, the model may be used for may purposes. A MVCOPQLF can be used to demonstrate the financial worth of quality improvement programs, as well as be used in the capital budgeting of quality improvement projects. Raiman and Case [63] show examples of how the TLF can be used as a powerful strategic decision-making tool, to aid in monitoring continuous improvement. Their work shows how the MVCOPQLF may be used to evaluate the relative importance of quality problems, and then provide a guide as to which problems to address first.

A MVCOPQLF can also be used to help evaluate an organization's success in achieving quality objectives. Since dollars can be added to one another, they are more meaningful than other disaggregated quality data, especially to management. The MVCOPQLF is a new and vital form of the basic, univariate model, and becomes even more valuable for strategic planning purposes.

7.2 Estimating Transition Loss using a MVCOPQLF

When considering products one at a time, each one having its own MVCOPQLF, calculating loss associated with the product at any point in time is a simple matter of substituting quality characteristic values into the MVCOPQLF and calculating a loss value. However, continuous process production facilities must deal with another type of loss. While discrete part facilities can stop production of one product, possibly perform some equipment changeover, and then immediately start producing a different product, it is not as easy in a continuous process plant. These plants must deal with intermediate time, and product, resulting from a transition.

When a decision is made to shift production from one grade of plastic to another, the change is not made instantaneously. Instead, the features of the production process are slowly changed, which causes the primary quality characteristics being monitored to also shift, to the target values required for the new grade. The time required for this shift in process parameters depends on how severe the changes in parameters are, and typically may take anywhere from 30 minutes to 12 hours. According to the MVCOPQLF, there is dollar loss associated with the product made during transitions.

Suppose that Grade A is being produced for some period of time, exactly on target. Then, during this period of production there is zero loss associated with Grade A product. Imagine also that Grade A and Grade B each have a unique MVCOPQLF, $MVCOPQLF_A$ and $MVCOPQLF_B$. If the process must next shift to production of Grade B, a transition will occur. During this transition, the quality characteristics will move from the target values associated with Grade A to those associated with Grade B. As this happens, the MVCOPQ loss associated with Grade A will increase over time (since the process is moving away from target values). Over the same period of time, the loss associated with Grade B will decrease (since the process is moving towards Grade B target values).

At some point in time as this transition occurs, the two MVCOPQLFs will intersect, at which point it is less costly, in terms of loss, to consider the product to be Grade B rather Grade A. The total loss incurred over the length of the transition is referred to as transition loss. Extending this concept to multiple Grades, the intent is to minimize the total transition loss incurred over all of the transition paths. The important issue then is how to most effectively schedule the many Grades of product that must be produced, while minimizing transition loss. This provides a new and interesting application of the MVCOPQLF. Initially, the assumption is made throughout that there is no variation during normal Grade production, and therefore the loss at any time other than during transitions is zero. Eliminating this assumption is discussed in Chapter 9.

7.2.1. Calculating Transition Loss with a Univariate Function

For illustration purposes, suppose that density (X_1) is the only quality characteristic being considered, and that there are three grades of plastic that must be scheduled. These three grades have loss functions defined as follows:

$$\text{Grade A: } MVCOPQLF_A = 100(X_1\text{-}1.0)^2$$
$$\text{Grade B: } MVCOPQLF_B = 600(X_1\text{-}2.0)^2$$
$$\text{Grade C: } MVCOPQLF_C = 200(X_1\text{-}1.6)^2$$

These three functions are shown in Figure 12. The functions have already been converted to $/hour, as opposed to $/lb which was the unit for the previous development. Since the loss functions are used in conjunction with transition times, the units must be changed to work in this application. Changing from $/lb to $/hour is simply a matter of multiplying by a constant, expressed in pounds per hour. For this chemical plant, this constant is the number of pounds of plastic generated through the production process per hour.

Transitions are designated to take place in a linear fashion, and the transition times associated with the different grades (transitioning in either direction) are:

A - B	10 hours
B - C	4 hours
A - C	6 hours

The problem at hand is simply to determine in what sequence the three grades of plastic should be produced. Consider first a sequence of Grade A to B to C. The numbers above indicate that the transition from Grade A to Grade B will take 10 hours, and a plot of the loss versus time is shown in Figure 13. The area under this curve is the measure of loss during the transition in units of dollars. Calculating this number entails integrating under the two curves along the transition path. This means breaking the area down into numerous rectangles, and adding up their areas from left to right. The height of each rectangle is expressed in $/hr, and the width is expressed in hours. The width is defined by δt, which represents the transition time length associated with each interval (or specific quality characteristic value). When each area

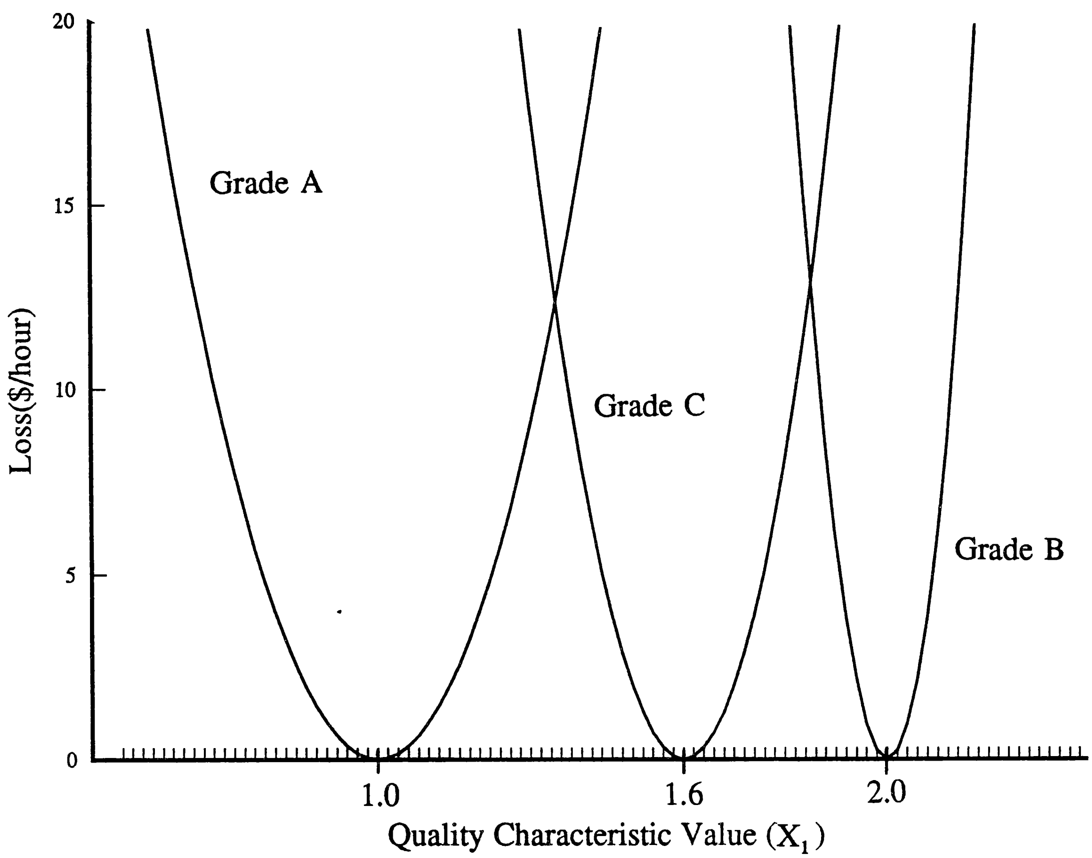

Figure 12. Univariate LFs for Three Plastic Grades

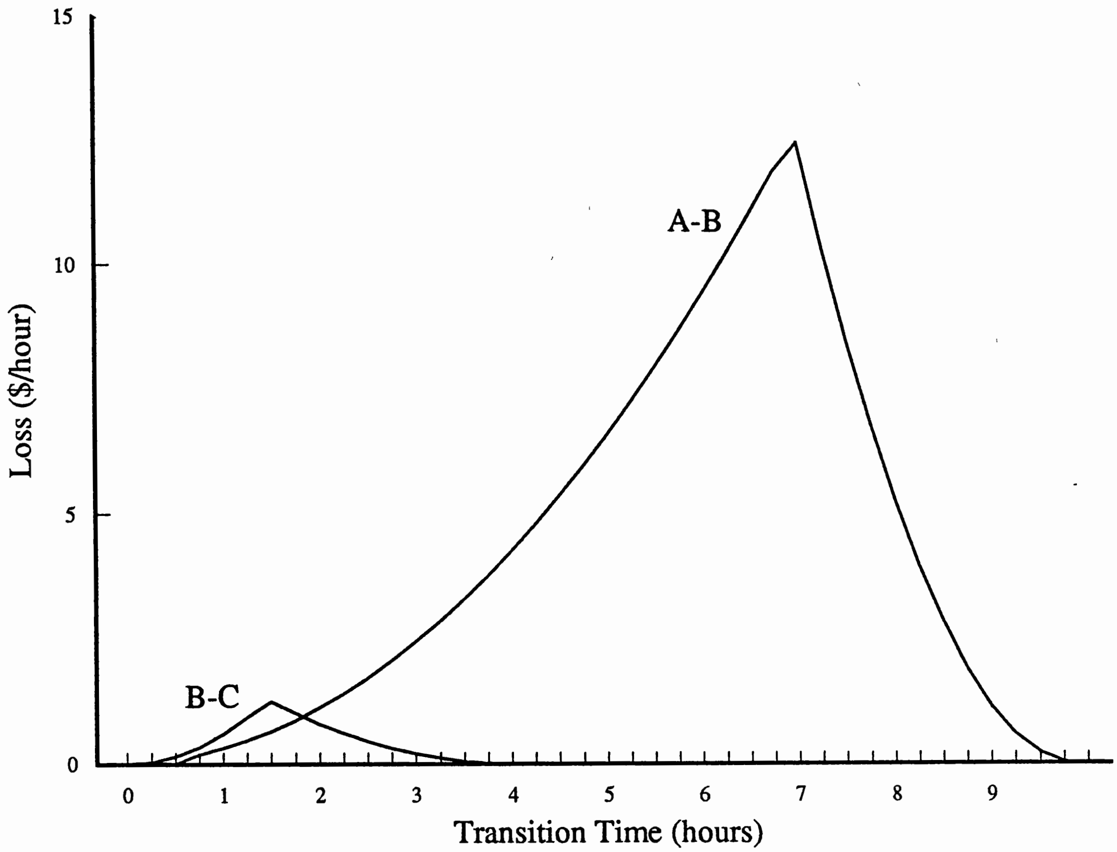

Figure 13. Pairwise Transition Loss Curves

is added up over all of the delta values, the result is the total transition loss, expressed in dollars. In units, this is represented as follows:

$$\sum_{s=0}^{S-1} \$/hr * hrs/x_1(s)$$

For the transition from Grade A to B, this results in a loss of \$168.08. Using the same procedure to calculate the loss for the transition from Grade B to C, also shown in Figure 13, the result is \$17.15. Summing these losses, the total cost of the sequence Grade A to Grade B to Grade C is \$185.23. Transitioning in the opposite direction, from Grade C to Grade B to Grade A also results in a total loss of \$185.23.

In the same manner as above, other sequences can be evaluated. Consider the transition sequence of Grade A to Grade C to Grade B. The loss to transition from A to C is \$24.71, and the loss to transition from C to B is \$17.15. Therefore, the total loss associated with this sequence is \$41.86. Additionally, the loss for the sequence Grade B to Grade C to Grade A is also \$41.86. Using the same technique, the loss for the sequence of Grade B to Grade A to Grade C results in a loss of \$168.08 + 24.71 = \$192.79.

From these calculations, it is clear that the best sequence of grade production when attempting to minimize COPQ transition loss is Grade A to Grade C to Grade B. While the conclusions from this univariate case may appear obvious, it is only because one characteristic is being considered. When the univariate loss function is instead a MVCOPQLF, and multiple quality characteristics are being considered, the situation becomes too complex to solve intuitively.

7.2.2. Calculating Transition Loss with a MVCOPQLF

The multivariate case for calculating transition loss is an extension of the method presented above. To understand this extension consider two simple, hypothetical MVCOPQLFs:

$$\text{Grade A:}\quad MVCOPQLF_A = (X_1\text{-}5)^2 + (X_2\text{-}10)^2$$

$$\text{Grade B:}\quad MVCOPQLF_B = (X_1\text{-}10)^2 + (X_2\text{-}5)^2$$

where X_1 and X_2 are two different quality characteristics. It is clear that one of these functions is centered at (5,10) and the other is centered at (10,5), and both functions take on the value zero at their corresponding center point. A picture of these two functions is shown in Figure 14. In order to transition from Grade 1 to Grade 2, two things must take place. The characteristic represented by X_1 must move from a target of 5 to a target of 10, and the characteristic represented by X_2 must move from a target of 10 to a target of 5. Assume that this transition is made in a linear fashion, and that it takes one hour to complete.

In order to picture what will happen with respect to loss during this transition, consider Figure 14. The transition will force a move from (5,10) to (10,5), in a straight line. Consider a plane dropping down through the two bowl shapes in Figure 14, along the line $X_2 = 15\text{-}X_1$. Once this slice is made, the total area under the two functions along the slicing plane represents the total loss associated with the transition.

To actually calculate this loss, the two loss functions must be known, the time to make the transition must be known, and it must be possible to determine the coordinates of the quality characteristics, X_1 and X_2, at any given point in time during

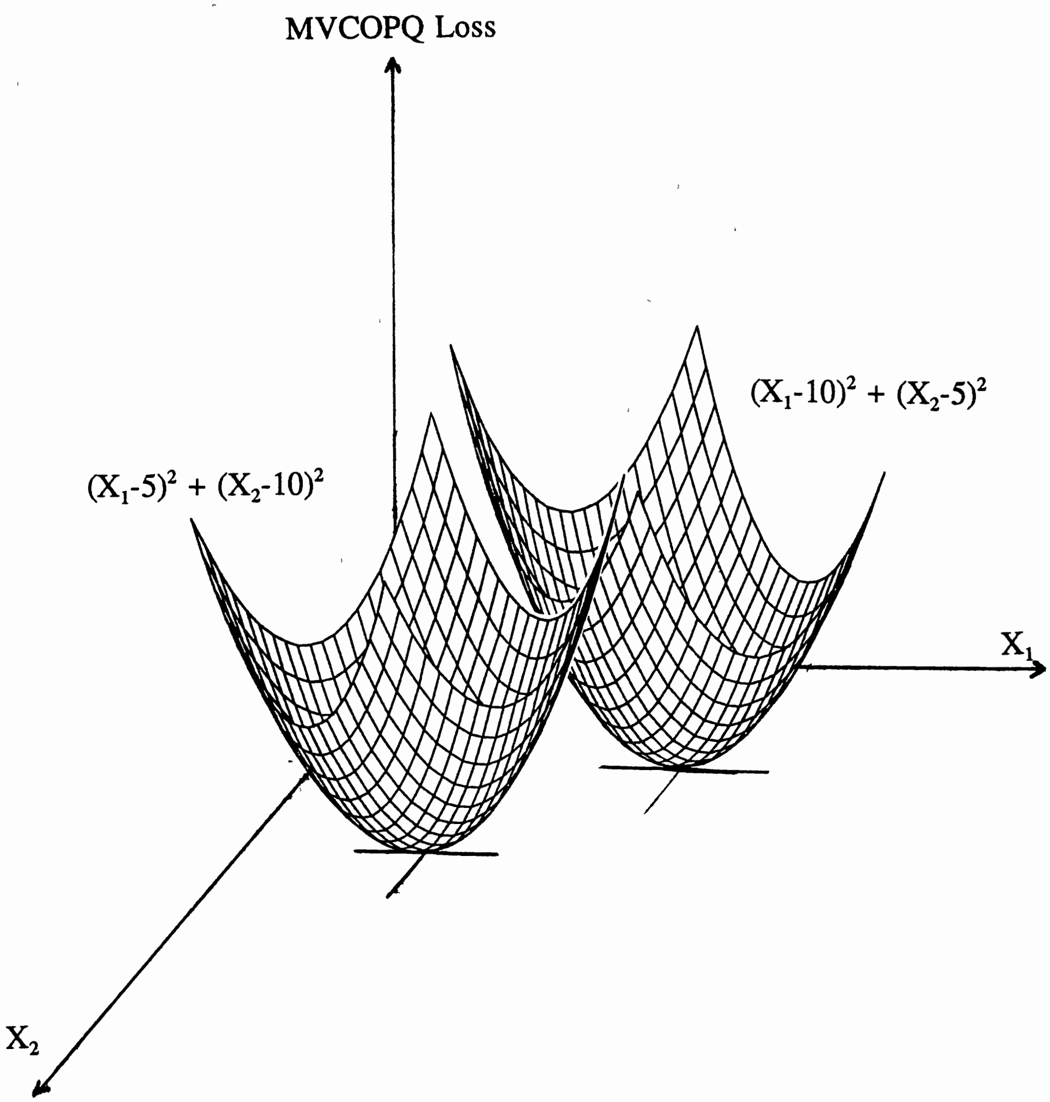

Figure 14. MVCOPQLFs for Two Plastic Grades

the transition. The total time to make the transition above was defined as 1 hour, and is represented as TT. The target associated with the starting grade is represented by (Tg_{1A}, Tg_{2A}), and the target associated with the ending grade is represented by (Tg_{1B}, Tg_{2B}), where the letter represents the Grade associated with that target. In order to calculate loss along the path of the transition, the curve is broken up into S increments of time length δt. Given this information, the step size that each quality characteristic takes through time, as the transition occurs, are calculated from Equations (5) and (6).

$$X_1step = [(Tg_{1B} - Tg_{1A})/(TT/\delta t)] \tag{5}$$

$$X_2step = [(Tg_{2B} - Tg_{2A})/(TT/\delta t)] \tag{6}$$

So, at a given increment number s, the X_1 and X_2 coordinates are determined by Equations (7) and (8).

$$x_1(s) = .5 * X_1step + s*X_1step; \quad s = 0,1,...,S-1 \tag{7}$$

$$x_2(s) = .5 * X_2step + s*X_2step; \quad s = 0,1,...,S-1 \tag{8}$$

The .5 factor at the beginning of the equation is simply a correction factor used so that the function is being calculated at the center of the rectangle.

To calculate the total loss for a complete transition from Grade A to Grade B, denoted by TTL_{AB}, requires summing up the areas over the total number of increments as shown in Equation (9).

$$TTL_{AB} = \sum_{s=0}^{S-1} \min\{MVCOPQLF_A(x_1(s),x_2(s)),MVCOPQLF_B(x_1(s),x_2(s))\} * (\delta t) \tag{9}$$

In terms of units, the transition loss is represented as:

$$\sum_{s=0}^{S-1} \$/hr * hrs/(x_c(s))$$

This results in a TTL_{AB} expressed in dollars per transition.

The minimization function is needed in order to pick up the lower of the two loss function values. When the $(x_1(s),x_2(s))$ coordinates are closer to the (5,10) target, $MVCOPQLF_A$ will typically be the appropriate function to use. As the $(x_1(s),x_2(s))$ coordinates move further away from (5,10), and closer to (10,5) the appropriate function is likely to change over to $MVCOPQLF_B$. At any point during the transition, the $(x_1(s),x_2(s))$ coordinates will have only one loss function which is appropriate to use. The function indicates the Grade of the transition product, in order to incur minimum loss. That appropriate function is always the one which results in the minimum COPQ loss for the given coordinates.

7.2.3. Example of Transition Loss Calculations

Consider the example above, and assume that 10 increments will be used to calculate the transition loss. Recalling that the transition takes 1 hour to complete, δt is equal to 1/10 = .10. X_1step is equal to (10-5)/(1/.10), or .5, and X_2step is equal to (5-10)/(1/.10), or -.5. The resulting loss calculations are shown in Table 7. To complete the calculation of total loss for the transition, it is necessary to sum up the minimum loss values across the 10 steps and multiply by δt. When this process is performed, the resulting total transition loss, TTL_{AB}, is \$4.125. A BASIC program which calculates the total loss associated with a transition between two target values is provided in Appendix B. The program is used to generate all transition loss calculations appearing later in this paper.

TABLE 7

MVCOPQLF CALCULATIONS

s	$x_1(s)$	$x_2(s)$	$MVCOPQLF_A$	$MVCOPQLF_B$	MIN
1	5.25	9.75	.125	45.125	.125
2	5.75	9.25	1.125	36.125	1.125
3	6.25	8.75	3.125	28.125	3.125
4	6.75	8.25	6.125	21.125	6.125
5	7.25	7.75	10.125	15.125	10.125
6	7.75	7.25	15.125	10.125	10.125
7	8.25	6.75	21.125	6.125	6.125
8	8.75	6.25	28.125	3.125	3.125
9	9.25	5.75	36.125	1.125	1.125
10	9.75	5.25	45.125	.125	.125
				Total Loss	=41.250

7.3. Scheduling Production Sequences using Transition Loss

Sequencing a series of more than two grades for production is just a process of evaluating total transition loss for a series of sequences. In the univariate case, the total loss for a sequence from Grade A to Grade B to Grade C is just the summation of the individual transition losses of Grade A to Grade B and Grade B to Grade C. This process remains exactly the same for the multivariate case. However, the method for calculating the loss for each transition becomes somewhat more complicated, since the loss functions depend on more than one quality characteristic.

CHAPTER VIII

EXAMPLE OF SCHEDULING USING TRANSITION LOSS

8.1. Statement of Problem

This example will use assumptions similar to those found in Chapter 6. The situation will again consider a chemical plant which produces numerous grades of plastic. There are two quality characteristics which determine the grade of plastic, density and melt index. The plant is concerned with determining a scheduling sequence for four particular grades of plastic, P11, P12, P15, and P35, with targets for density and melt index as follows:

P11: (.918, 1.0)
P12: (.918, 2.0)
P15: (.930, 1.0)
P35: (.924, 22.0)

The first three grades happen to be in the same family, while P35 comes from a different family. Loss functions, as a function of density (D, or X_1) and melt index (MI, or X_2), in \$/hr have been previously determined for each of these grades as follows:

$$MVCOPQLF_{P11} = 100(D - 0.918)^2 + 60(MI - 1.0)^2$$
$$MVCOPQLF_{P12} = 390(D - 0.918)^2 + 420(MI - 2.0)^2$$
$$MVCOPQLF_{P15} = 500(D - 0.930)^2 + 120(MI - 1.0)^2$$
$$MVCOPQLF_{P35} = 50(D - 0.924)^2 + .05(MI - 22.0)^2$$

Contour plots of these surfaces are shown in Figure 15.

The final piece of information known at the start are transition times for each of the possible transitions, which are shown in Table 8. The bottom half of this table is a mirror image of the top half since a transition from one grade to another takes the same amount of time regardless of which grade is the starting point. The transition times may **not** be viewed proportionally. Just because it takes 4 hours to move from a density of 4 to a density of 8, does not mean that it will take 8 hours to move from a density of 4 to a density of 12. Each transition is an independent transition, and must be viewed as such. The transition times do reflect the fact that in general, it takes longer to make a change in density than it does to make a change in melt index.

With the previous information all known, the problem at hand is to determine in exactly what sequence these four grades should be produced, in order to minimize overall COPQ loss. In this case there are 4! = 24 possible grade sequences that are candidates for use. The actual loss only needs to be calculated for 12 of these sequences, since the loss for a particular sequence is the same whether the sequence is run forward or backward. For example, the loss associated with the transition sequence from grade P11 to P15 to P12 to P35 is exactly the same as the loss associated with the transition sequence from grade P35 to P12 to P15 to P11. The twelve sequences for which transition loss must be calculated are as follows:

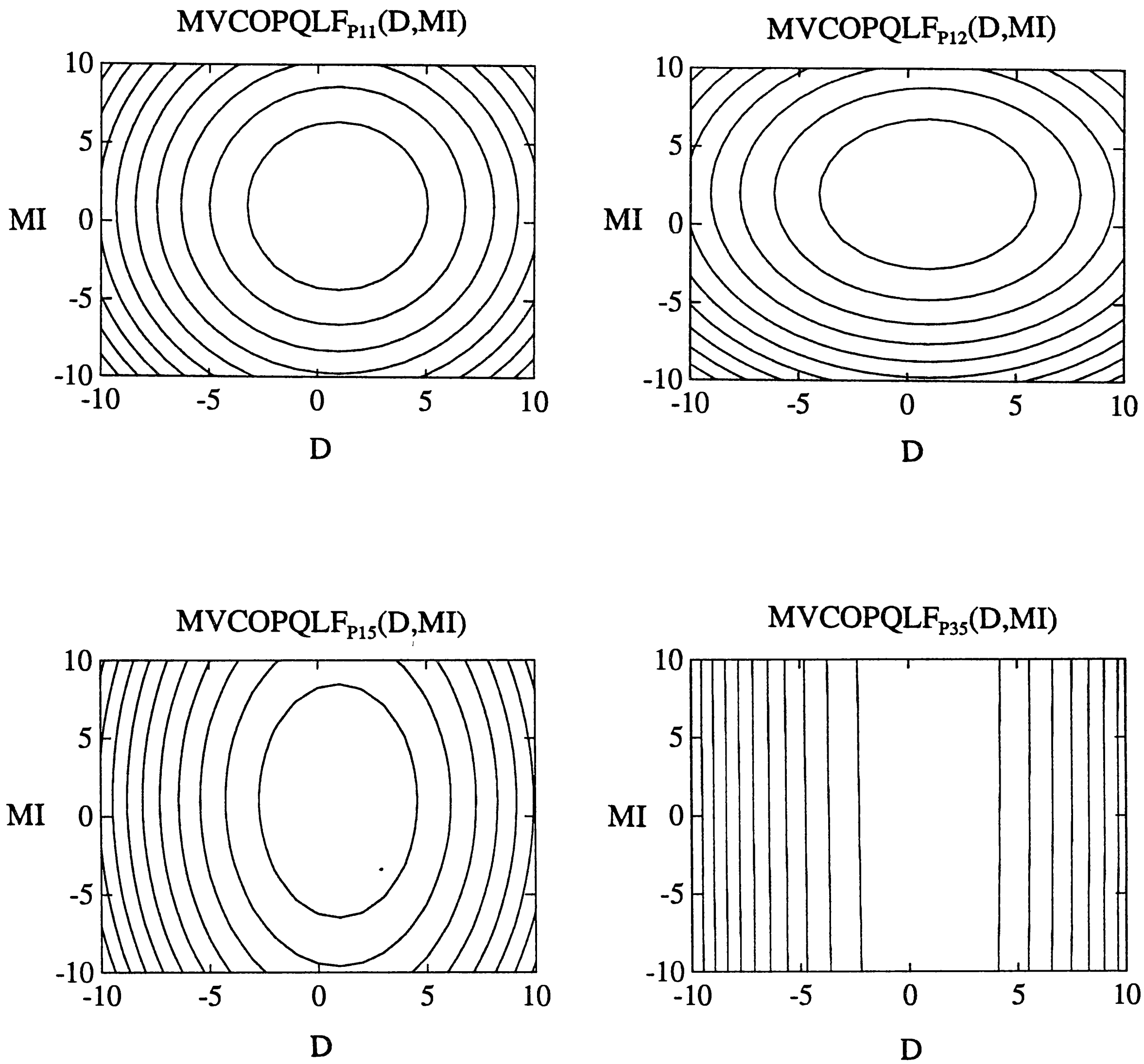

Figure 15. Contour Plots for Four MVCOPQLFs

TABLE 8

PAIRWISE TRANSITION TIMES

	P11	P12	P15	P35
P11	******	3 hours	12 hours	5 hours
P12	3 hours	******	8 hours	3 hours
P15	12 hours	8 hours	******	6 hours
P35	5 hours	3 hours	4 hours	******

P11 - P12 - P35 - P15
P11 - P12 - P15 - P35
P11 - P35 - P15 - P12
P11 - P35 - P12 - P15
P11 - P15 - P35 - P12
P11 - P15 - P12 - P35
P12 - P35 - P11 - P15
P12 - P15 - P11 - P35
P12 - P11 - P15 - P35
P12 - P11 - P35 - P15
P35 - P11 - P12 - P15
P35 - P12 - P11 - P15

8.2. Calculating Transition Loss

In order to calculate the total loss for an individual sequence, the transition must first be broken down into the pairwise transitions which make up the sequence. In this case there are 3 separate pairwise transitions which make up each sequence. For example, the sequence P11 - P12 - P35 - P15 is made up of the pairwise transitions: P11 to P12, P12 to P35, and P35 to P15. Since a MVCOPQLF is known for each of the four grades, the concepts demonstrated in Chapter 7 provide a method for estimating the pairwise transition losses.

8.2.1. Calculating Pairwise Transition Loss

To calculate any particular pairwise transition loss, it is necessary to consider the MVCOPQLFs associated with two grades involved. The transition path and time also must be known. For this example, all transitions assume a linear path. That is, when moving from a target of (.918,1) to (.924,2), the density change from .918 to .924 is performed in a linear fashion, and the melt index change from 1 to 2 is also performed in a linear fashion. This means that if the total transition takes 1 hour, at 30 minutes into the transition the product is being produced to a target of (.921,1.5).

Using the methods described in Chapter 7, and the BASIC program provided in Appendix B, the transition times between each pair of grades are generated using Equation 9. For example, the transition between Grade P11 and P35 is calculated as:

$$\sum_{s=0}^{S-1} \min \left[\{100(x_1(s)-0.918)^2 + 60(x_2(s)-1.0)^2\}, \{50(x_1(s)-0.924)^2 + .05(x_2(s)-22.0)^2\}\right] * \delta t \qquad (9)$$

The results for the pairwise transition losses are shown in Table 9, using a total increment number of S=100. Again, the bottom half of Table 9 is a mirror image of the top half, since loss is the same regardless of which direction the transition happens. Table 9 demonstrates some interesting results with regard to pairwise transition loss values. The highest loss on the table is that which occurs when moving between grades P12 and P15, which are both in the same grade family. In fact, a lower loss even results when moving between P11 and P35, two different families, than between P12 and P15.

Another thing to note is that even though the transition from P11 to P15 takes a substantial amount of time, the loss associated with the transition is noticeably low. So, although it is easier (less time) to move between grades with different melt index values, it is certainly cheaper (in terms of COPQ loss) to move between the two grades with different densities.

TABLE 9

PAIRWISE TRANSITION LOSS VALUES

	P11	P12	P15	P35
P11	*****	$ 38.77	$ 0.03	$35.03
P12	$38.77	*****	$135.95	$19.57
P15	$ 0.03	$135.95	*****	$42.30
P35	$35.03	$ 19.57	$ 42.30	*****

8.2.2. Calculating Total Transition Loss

As noted previously, once the individual transition losses are known, calculating transition loss per sequence is just a matter of summation. The transition loss for the sequence P11 - P12 - P35 - P15 is simply \$38.77 + \$19.57 + \$42.30 = \$100.64. All other sequence transition losses are calculated in exactly the same fashion. The results of calculating transition loss for each of the twelve sequences are shown below.

Transition Sequence	TTL
P11 - P12 - P35 - P15	\$100.64
P11 - P12 - P15 - P35	217.02
P11 - P35 - P15 - P12	213.28
P11 - P35 - P12 - P15	190.55
P11 - P15 - P35 - P12	47.80
P11 - P15 - P12 - P35	155.55
P12 - P35 - P11 - P15	54.63
P12 - P15 - P11 - P35	171.01
P12 - P11 - P15 - P35	81.01
P12 - P11 - P35 - P15	116.10
P35 - P11 - P12 - P15	209.75
P35 - P12 - P11 - P15	58.37

It is clear from looking at these results that the production sequence which minimizes COPQ loss is P11-P15-P35-P12, or equivalently, P12-P35-P15-P11.

This result is in one respect counter-intuitive. Without information on COPQ loss, it is easy to expect the "best" path to be one which produces all grades within a given family, and then proceeds to the next closest family. The result above shows that in fact the lowest transition loss path moves back and forth between the two families. This makes it very clear that if the intent of plant management is to base production sequences on the minimization of COPQ loss, the best path is not likely to be intuitive from the beginning. Nor is the best path derived from sequencing all grades in the direction of the quality characteristic that appears easiest to change, i.e. the minimum time transitions. Clearly, the entire MVCOPQLF must be carefully considered when generating production sequences intended to minimize overall loss.

CHAPTER IX

EXTENSIONS OF MVCOPQLF USAGE

9.1. General Comments

Since the use of loss functions as a measurement tool for business is such uncharted territory, there are a number of possibilities for extensions and enhancements of the methodologies presented in this paper. Proper application of the techniques already presented allows the user to make a sincere attempt at estimating, and including in decision making, the external failure costs which have previously been deemed intangible. This in itself prevents the user from omitting costs due to financially significant consequences of poor quality, and obtaining a distorted outlook on quality costs. Once a user becomes adept at generating COPQ Matrices, and using the MVCOPQLF as a genuine measurement tool, there are some additional aspects of the generation and use of loss functions which may be considered.

9.2. Process Variation

The results presented in the example in Chapter 8 for estimating total transition loss for different production sequences, are based on the premise that no variation occurred in the quality characteristics while a given Grade of plastic was under normal production. Only during transition periods did the values of quality characteristics change, and those changes occurred linearly over prespecified transition paths. For situations where a production process is in a state of statistical control, with very small variation, the methods presented in Chapter 8 are likely to be directly applicable. However, in many cases it is unlikely that a process is able to hit a specified target, at every point in time, without some levels of variation. Sometimes this variation may even be substantial. In such cases it is necessary to include the effect of variation in the formulation of transition loss calculations.

It should not be too difficult to include variation in the calculation of transition loss. One possible method involves using simulation to generate typical production sequences, factoring in different levels of variation. At any point in time, the loss is calculated by substituting the values of the quality characteristics being monitored into the MVCOPQ loss function. This could also be accomplished using actual data from historical production sequences in a given plant.

Including variation will most likely increase the total transition loss over a given sequence of grades. This is especially important for Grades which are commonly hard to produce, and involve large levels of variation. Having the ability to measure loss in such circumstances also opens up the possibility of weighing process variation improvements against the corresponding reduction in transition sequence loss which would occur as a result of the improvement, and doing it all in dollars. This opens up a whole new area of opportunity for using the MVCOPQLF to make trade-off decisions regarding different process and product improvements.

9.3. Grade Transition Paths

Examining Grade transition paths other than those of a linear nature is easily transportable into the techniques presented for transition loss calculation. As long as there is a way to determine the value of each of the quality characteristics at any point in time during a transition, the equations presented for calculating transition loss are identical to those presented in Chapter 7. In some cases chemical companies consider transition paths which ramp up the quality characteristics significantly in the beginning of the sequence, and then level out once the target area is approached. Another method which is sometimes tried is to ramp up significantly until one of the characteristics, such as density, is past the new target value. Then, the quality characteristics are allowed to level out until they reach the new target exactly. In fact, any transition imaginable could be used in conjunction with the MVCOPQLF. This makes the MVCOPQLF a new tool for actually evaluating different transition sequencing paths, with respect to cost of poor quality.

9.4. Target Identification

Another potential use of MVCOPQLFs is for identifying low-loss target values. Often in industry, targets are set using only past knowledge, or worse yet, a general feel for the situation. Once a MVCOPQLF has been developed, it is a simple matter of determining exactly where the low point on the COPQ response surface actually falls. This just requires taking the derivative of the MVCOPQLF with respect to each of the quality characteristics included, and setting each one equal to zero. The equation may then be solved for the minimum value of a given quality characteristic.

Once this low-loss point is determined, decisions having to do with tolerances could also be considered. Taguchi has already demonstrated the use of the TLF for tolerancing applications. The extended power of MVCOPQLFs makes this application even more important.

9.5. Sensitivity Analysis

Traditional methods of sensitivity analysis are easily applicable to a MVCOPQLF. Using classical methods of examining sensitivity, answers might be obtained concerning which quality characteristic out of the two or more being considered have the largest impact on COPQ loss. Such results lead the evaluator to determine which characteristic(s) are most important to control. It also provides direction concerning which characteristic(s) could require further evaluation. The idea of sensitivity analysis could in fact, be combined with tolerancing in order to provide direction for tighter control over variables that are more significant to the corresponding MVCOPQLF, while opening up tolerance levels for variables to which the function is less sensitive.

9.6. MVCOPQLF Accuracy

For those users who choose to become proficient at using the MVCOPQLF to evaluate production scenarios, there are techniques which will allow a better determination of the accuracy of the fitted function. The main thing needed to get this added measure is replication. This means that the loss function estimates, made when filling in the COPQ matrix, must be evaluated more than one time. This would be possible through, for example, the use of different teams to estimate the loss function values. All estimates would be used to fit a loss function, and then ANOVA used to test the lack-of-fit. This entails a good deal more work than simply estimating the matrix once; however much more information results concerning the adequacy of the fitted MVCOPQLF.

CHAPTER X

CONCLUSIONS

The methods and ideas presented in this research provide much improved guidance on the collection, application, and analysis of Cost of Poor Quality (COPQ) information from a societal loss perspective. The Multivariate Cost of Poor Quality Loss Function (MVCOPQLF) raises the role of quality cost information from the level of occasional cost reports to a level that is vital to the performance of a company. In today's arena of world class manufacturing, a company's success depends in large part on how effectively it can shift from measuring and controlling costs to choosing and managing projects that enhance its organizational capabilities. The MVCOPQLF is a new and effective tool for making these changes, realizing that it is not merely cost, but rather societal loss that should be minimized in order to make effective decisions.

The COPQ Matrix is a unique tool which helps eliminate uncertainty about what should be included under the quality cost umbrella by providing a new framework for defining COPQ. It maintains a broad perspective and avoids concentrating on the standard cost of quality techniques. The Matrix forces the user to branch out into new territory, not only by instilling a long-term, customer-oriented perspective, but also by requiring the user to think about new methods for estimating this COPQ data.

The MVCOPQLF takes this new COPQ information, and converts it into a new and necessary tool for effective decision-making. In the absence of MVCOPQLFs, a common method for making manufacturing decisions is to have a meeting, and argue. The MVCOPQLF presents, in no uncertain terms, the dollar value of loss associated with production techniques. It provides a way to give concrete feedback to a manufacturing group concerning its performance, while additionally providing a means of assessing progress and signalling the need for corrective action. Employees who are committed to hitting a target consistently, cast a sharper eye on every aspect of the production environment. When their ingenuity and societal loss consciousness are encouraged, conditions change dramatically, and valuable data is generated which supports better product and process design.

The strategic values of MVCOPQLFs are endless. At a high level, the loss functions allow the user to easily analyze major trends in customer satisfaction, and use this information to provide inputs for setting objectives. This allows management to develop an overall strategic plan which incorporates financial aspects of the quality objectives. While very effective at a high level, MVCOPQLFs also are invaluable as an engineering tool. The ability to develop scheduling sequences is just one example of the value of loss functions to every day decision-making. They provide the ability to factor customer and societal satisfaction into the day-to-day activities of a manufacturing plant. MVCOPQLFs provide this capability in a way which obliges the user to take a much longer and wider viewpoint than that to which people are accustomed.

Once executives are armed with this more reliable and more pertinent COPQ data, they can more accurately decide among a range of strategic options. MVCOPQLFs allow them to do this while maintaining the goal of continuously reducing cost of poor quality (and therefore variation), and thereby creating products which minimize loss to society and ultimately loss to the company. At a less global level, MVCOPQLFs may also help managers to make better decisions about product design, pricing, marketing, and mix, in order to provide high quality at low cost to society.

Intensified global competition and radically new production technologies have made accurate COPQ information crucial to competitive success. Consistently good decisions can not be made by "shooting from the hip." They must come from the application of sound COPQ analysis, based on the best and most relevant quality loss estimates available. Until managerial and technical people in business and industry recognize and accomodate the fundamental changes in concepts and values that cut through all elements of the economy and society, it is not possible to solve the chronic problems. If used correctly, the concept and strategic applications of MVCOPQLFs have the potential to mold the corporate future of America.

BIBLIOGRAPHY

[1] Adams, D.J. (1988), "Management Tools for Guiding and Measuring a Quality Process," Rubber World, 198, 1, 38-41.

[2] ASQC Quality Cost-Cost Effectiveness Technical Committee (1971), Quality Costs - What and How, American Society for Quality Control, Wisconsin.

[3] ASQC Quality Costs Committee (1987), Guide For Managing Supplier Quality Costs, Quality Press, Wisconsin.

[4] ASQC Quality Costs Committee (1987), Guide for Reducing Quality Costs, Quality Press, Wisconsin.

[5] ASQC Quality Costs Committee (1989), Quality Costs: Ideas and Applications, Vol. 1, Quality Press, Wisconsin.

[6] ASQC Quality Costs Committee (1989), Quality Costs: Ideas and Applications, Vol. 2, Quality Press, Wisconsin.

[7] Barker, T. (1986), "Quality Engineering By Design: Taguchi's Philosophy," Quality Progress, 19, 12, 32-42.

[8] Bendell, A., J. Disney and W.A. Pridmore, Editors (1989), Taguchi Methods: Applications in World Industry, Springer-Verlag, New York.

[9] Box, G.E.P. and N.R. Draper (1987), Empirical Model-Building and Response Surfaces, John Wiley & Sons, New York.

[10] Box, G.E.P. and W.G. Hunter (1962), "A Useful Method for Model-Building," Technometrics, 4, 3, 301-318.

[11] Box, G.E.P., W.G. Hunter, and J.S. Hunter (1978), Statistics for Experimenters, John Wiley & Sons, New York.

[12] Burgam, P. (1985), "Design of Experiments - The Taguchi Way," Manufacturing Engineering, 96, 5, 44.

[13] Byrne, D. and S. Taguchi (1987), "The Taguchi Approach to Parameter Design," Quality Progress, 20, 12, 19-26.

[14] Carney, T.P. (1981), False Profits - The Decline of Industrial Creativity, University of Notre Dame Press, Indiana.

[15] Chen, G. and K.C. Kapur (1989), "Quality Evaluation System Using Loss Function," Proceedings of the Institute of Industrial Engineers Conference, 363-368.

[16] Daniel, C. and F.S. Wood (1980), Fitting Equations to Data, John Wiley & Sons, New York.

[17] (1987), "Defining Quality at the Marketing/Development Interface," Quality Progress, 20, 6, 28-36.

[18] Dehnad, K., Editor (1989), Quality Control, Robust Design, and the Taguchi Method, Wadsworth & Brooks/Cole, California.

[19] Denton, D. (1986), "Quality and Reliability Screens Impact the Cost of Owning ICs," Electronic Design, 34, 27, 105-11.

[20] Dhir, K.S. (1987), "Formulating ManagementPolicies for Value Engineering/Value Analysis," IEEE Transactions on Engineering Management, EM-34, 3, 161-171.

[21] Ealey, L.A. (1988), Quality By Design, American Supplier Institute, Wisconsin.

[22] Elmaghraby, S.E., Fathi, Y. and W.G. Ferrell, Jr. (1986), The Taguchi Approach to Quality Control and Enhancement: A Primer, AT&T Technical Report, November.

[23] (1988), "First, find the real costs," American Machinist, 132, 12, 57-59.

[24] Garvin, D.A. (1984), "What Does 'Product Quality' Really Mean?" Sloan Management Review, 26, 1, 25-43.

[25] Gryna, F.M. (1970), User Costs of Poor Product Quality, Ph.D. Dissertation, University of Iowa.

[26] Gryna, F.M. (1972), "User Quality Costs," Quality Progress, 5, 11, 18-21.

[27] Gryna, F.M. (1977), "Quality Costs: User vs. Manufacturer," Quality Progress, 10, 6, 10-13.

[28] Gunter, B. (1987), "A Perspective on the Taguchi Methods," Quality Progress, 20, 6, 44-52.

[29] Hagan, J.T. (1985), "Quality Cost II: The Economics of Quality Improvement," Quality Progress, 18, 10, 48-57.

[30] Harrington, E.C., Jr. (1965), "The Desirability Function," Industrial Quality Control, 21, 10, 494-498.

[31] Harrington, J. (1984), Understanding the Manufacturing Process, Marcel Dekker, Inc, New York.

[32] Hayes, R.H. and R. Jaikumar (1988), "Manufacturing's Crisis: New Technologies, Obsolete Organizations," Harvard Business Review, 66, 5, 77-85.

[33] Hayes, R.H. and S.C. Wheelwright (1984), Restoring Our Competitive Edge, John Wiley & Sons, New York.

[34] Hoaglin, D.C., F. Mosteller and J.W. Tukey, Editors (1985), Exploring Data Tables, Trends and Shapes, John Wiley & Sons, New York.

[35] Jacoby, J. and J.C. Olson, Editors (1985), Perceived Quality, Lexington Books Massachusetts.

[36] Jessup, P.R. (1985), "The Value of Continuing Improvement," Proceedings of the International Communications Conference, "ICC 85", June.

[37] Johnson, H.T. and R.S. Kaplan (1987), "The Rise and Fall of Management Accounting," Management Accounting, 65, 1, 22-30.

[38] Johnson, M.M. and R. Lo (1985), "An Investigation of the Effects of Quality Determinants," Proceedings of the International Industrial Engineering Conference, May, 555-561.

[39] (1985), Journal of Quality Technology, 17, 4, (1985).

[40] Kackar, R. (1986), "Taguchi's Quality Philosophy: Analysis & Commentary," Quality Progress, 19, 12, 21-29.

[41] Kaplan, R.S. (1988), "One Cost System Isn't Enough," Harvard Business Review, 66, 1, 61-66.

[42] Kirkland, C. (1988), "Quality Program Saves Big Bucks For Sheller-Globe," Plastics World, 46, 2, 48.

[43] Kolb, J. and S.S. Ross (1980), Product Safety and Liability, McGraw-Hill, New York.

[44] Krishnamoorthi, K.S. (1989), "Predict Quality Cost Changes Using Regession," Quality Progress, 22, 12, 52-55.

[45] Kume, H. (1988), "Business Loss and Quality Management," Quality Progress, 21, 7, 40-43.

[46] Leech, D.J., Turner, B.T. (1985), Engineering Design for Profit, John Wiley & Sons, New York.

[47] Lenaue, D.M. (1986), "Accounting for the Real Cost of Quality," Quality Progress, 19, 1, 22-27.

[48] Leon, R.V., Shoemaker, A.C. and R.N. Kackar (1987), "Performance Measures Independent of Adjustment," Technometrics, 29, 3, 253-265.

[49] Maghsoodloo, S. (1990), "The Exact Relation of Taguchi's Signal-to-Noise Ratio to His Quality Loss Function," Journal of Quality Technology, 22, 1, 57-67.

[50] Malcolm Baldrige National Quality Award Application Guidelines (1991), United States Department of Commerce, Maryland.

[51] McGuire, E.P. (1988), The Impact of Product Liability, The Conference Board, Inc., New York.

[52] McKean, R.N. (1958), Efficiency in Government Through Systems Analysis, John Wiley & Sons, Inc., New York.

[53] Miller, R. (1988), "Continuing the Taguchi Tradition," Managing Automation, Feb., 34.

[54] Miller, R.E. (1986), "Multiple Regression," Chemical Engineering, 93, 7, 85-91.

[55] Miller, R.E. (1986), "Polynomial Regression," Chemical Engineering, 93, 3, 77-80.

[56] Morse, W.J., H.P. Roth and K.M. Poston (1987), Measuring, Planning, and Controlling Quality Costs, National Association of Accountants, New Jersey.

[57] Neter, J., W. Wasserman, and M.H. Kutner (1983), Applied Linear Regression Models, Richard D. Irwin, Inc., Illinois.

[58] Ohmae, K. (1988), "Getting Back to Strategy," Harvard Business Review, 66, 6, 149-156.

[59] Oxenfeldt, A.R. (1979), Cost-Benefit Analysis for Executive Decision Making, AMCOM, New York.

[60] Phadke, M.S. and K. Dehnad (1987), "Optimization of Product and Process Design for Quality and Cost," ASQC Congress Transactions, May, 330.

[61] Pignatiello, J.J., Jr. and J.S. Ramberg (1985), "Discussion of Off-Line Quality Control, Parameter Design and the Taguchi Method, Journal of Quality Technology, 18, 3, 198-206.

[62] Product Quality, Performance, and Cost (1972), National Academy of Engineering, Washington, D.C.

[63] Raiman, L.B., Case, K.E. (1990), "Monitoring Continuous Improvement Using the Taguchi Loss Function," International Industrial Engineering Conference Proceedings, May, 391-395.

[64] Ryan, N.E. (1987), "Tapping into Taguchi," Manufacturing Engineering, 98, 5, 43.

[65] Ryan, T.P. (1989), Statistical Methods for Quality Improvement, John Wiley & Sons, New York.

[66] Schneiderman, A.M. (1986), "Optimum Quality Costs and Zero Defects: Are They Contradictory Concepts?" Quality Progress, 19, 11, 28-31.

[67] Schrader, L.J. (1986), "An Engineering Organization's Cost of Quality Program," Quality Progress, 19, 1, 29.

[68] (1975), "Special Report: Building the Safe Product," Quality Progress, 8, 2, 16-29.

[69] Sullivan, E. (1983), "Quality Costs: Current Applications," Quality Progress, 16, 4, 34-37.

[70] Sullivan, L.P. (1984), "Reducing Variability: A New Approach to Quality," Quality Progress, 17, 7.

[71] Sullivan, L.P. (1987), "The Power of Taguchi Methods," Quality Progress, 20, 6, 76-79.

[72] (1988), Taguchi Methods: Quality Engineering, Executive Briefing, American Supplier Institute, In c., Michigan.

[73] Taguchi, G. (1986), Introduction to Quality Engineering, UNIPUB, New York.

[74] Taguchi, G., Elsayed, E.A. and T. Hsiang (1989), Quality Engineering in Production Systems, McGraw-Hill, New York.

[75] Taguchi, G. and Y. Wu (1980), Introduction to Off-Line Quality Control, Central Japan Quality Control Association.

[76] Tribus, M. and G. Szonyi (1989), "An Alternative View of the Taguchi Approach," Quality Progress, 22, 5, 46-52.

[77] Turrie, B. and W. Wright (1988), "Application of the Taguchi Loss Function," Exxon Chemical Americas Conference Proceedings, March.

[78] Vaugn, R.C. (1975), "Zubits: regular $18.50 - liability extra," Quality Progress, 8, 2, 16-19.

APPENDIXES

APPENDIX A

SAS INPUT FILES

```
1                      The SAS System
NOTE: Copyright(c) 1989 by SAS Institute Inc., Cary, NC USA.
NOTE: SAS (r) Proprietary Software Release 6.06.01
         Licensed to OKLAHOMA STATE UNIVERSITY, Site 0001354002.

NOTE: Running on VAX Model 6320 Serial Number 0A000005.

 Welcome to the new SAS System, Release 6.06.


1          DATA test;
2              INPUT X LOSS;
3              XSQ = X*X;
4              LIST;
5          CARDS;

RULE:      ----+----1----+----2----+----3----+----4----+----5----+----6----+----7
6          1.6  2.6
7          2.0  0
8          2.4  3.0
NOTE: The data set WORK.TEST has 3 observations and 3 variables.

9          PROC  STEPWISE;
10           MODEL LOSS =  X XSQ/MAXR;

NOTE: 3 observations read.
         3 observations used in computations.
NOTE: The PROCEDURE STEPWISE printed page 1.


NOTE: SAS Institute Inc., SAS Circle, PO Box 8000, Cary, NC 27512-8000
```

Maximum R-square Improvement for Dependent Variable LOSS

Step 1 Variable XSQ Entered R-square = 0.03232107 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.17151717	0.17151717	0.03	0.8849
Error	1	5.13514950	5.13514950		
Total	2	5.30666667			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	1.11627907	4.30930779	0.34457489	0.07	0.8386
XSQ	0.18272425	0.99981338	0.17151717	0.03	0.8849

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2 Variable X Entered R-square = 1.00000000 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	5.30666667	2.65333333	.	.
Error	0	0.00000000	.		
Total	2	5.30666667			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	69.00000000	.	5.28412875	.	.
X	-69.50000000	.	5.13514950	.	.
XSQ	17.50000000	.	5.22666667	.	.

Bounds on condition number: 301, 1204

The above model is the best 2-variable model found.

No further improvement in R-square is possible.

```
NOTE: Copyright(c) 1989 by SAS Institute Inc., Cary, NC USA.
NOTE: SAS (r) Proprietary Software Release 6.06.01
         Licensed to OKLAHOMA STATE UNIVERSITY, Site 0001354002.

NOTE: Running on VAX Model 6320 Serial Number 0A000005.


  Welcome to the new SAS System, Release 6.06.


           DATA SAMPLE;
               INPUT D M LOM LSOC;
               DSQ = D*D;
               MSQ = M*M;
               CROSS = D*M;
               LIST;
           CARDS;

RULE:      ----+----1----+----2----+----3----+----4----+----5----+----6----+----7
           .916  0.8  .66  .31
           .916  1.0  .52  .09
           .916  1.2  .66  .31
           .918  0.8  .52  .09
           .918  1.0   0    0
           .918  1.2  .52  .09
           .920  0.8  .72  .33
           .920  1.0  .54  .11
           .920  1.2  .68  .33
NOTE: The data set WORK.SAMPLE has 9 observations and 7 variables.

           PROC  STEPWISE;
             MODEL LOM = D M DSQ MSQ CROSS/MAXR;

NOTE: 9 observations read.
         9 observations used in computations.
NOTE: At least one W.D format was too small for the number to be printed.
         The decimal may be shifted by the "BEST" format.
NOTE: The PROCEDURE STEPWISE printed pages 1-2.

           PROC STEPWISE;
             MODEL LSOC = D M DSQ MSQ CROSS/MAXR;

NOTE: 9 observations read.
         9 observations used in computations.
NOTE: The PROCEDURE STEPWISE printed pages 3-4.


NOTE: SAS Institute Inc., SAS Circle, PO Box 8000, Cary, NC 27512-8000
```

APPENDIX B

BASIC PROGRAM FOR CALCULATING

PAIRWISE TRANSITION LOSS

```
10    '*****************************************************************
20    '   Program to Calculate the Total Transition Loss From
30    '   Grade 1 to Grade 2 (TTL).  The MVCOPQLF for Grade 1 is FCN1 in
40    '   line 160, and the MVCOPQLF for Grade 2 is FCN2 in line 170.
50    '
60    '   User must input the target for each grade, and the total
70    '   transition time.  Program assumes linear transition will occur.
80    '*****************************************************************
90    INPUT "enter d target for grade 1  :", D1
100   INPUT "enter mi target for grade 1  :", MI1
110   INPUT "enter d target for grade 2   :", D2
120   INPUT "enter mi target for grade 2  :", MI2
130   INPUT "enter transition time (in hours): ", TIME
140   STEPS = 1000
150   DELTA = TIME/STEPS
160   UNIT = TIME/DELTA
170   DSTEP = (D2 - D1)/UNIT
180   MISTEP = (MI2 - MI1)/UNIT
190   LOSS = 0
200   FOR I = 0 TO (UNIT-1)
210        D = D1 + DSTEP/2 + DSTEP * I
220        MI = MI1 + MISTEP/2 + MISTEP * I
230        FCN1 = (D - 5)^2 + (MI - 10)^2
240        FCN2 = (D - 10)^2 + (MI - 5)^2
250        IF FCN1 > FCN2 GOTO 270
260        LOSS = LOSS + DELTA * FCN1:  GOTO 280
270        LOSS = LOSS + DELTA * FCN2
280   NEXT  I
290   PRINT "Transition Loss (Grade 1 - Grade 2) = ", LOSS
300   END
```

2

VITA

Laura Beth Raiman

Candidate for the Degree of

Doctor of Philosophy

Thesis: THE DEVELOPMENT AND IMPLEMENTATION OF MULTIVARIATE COST OF POOR QUALITY LOSS FUNCTIONS

Major Field: Industrial Engineering and Management

Biographical:

Personal Data:
Born in Chicago, Illinois, August 15, 1963, the daughter of Harold and Elizabeth Raiman.

Education:
High School - William Howard Taft, Chicago, Illinois, in June, 1980.
Undergraduate - University of Illinois, Champaign, Illinois.
Received a Bachelor of Science degree in Industrial Engineering, May, 1984.
Graduate - Oklahoma State University, Stillwater, Oklahoma.
Received a Master of Science degree in Industrial Engineering, July, 1986. Completed requirements for the Doctor of Philosophy, with a major in Industrial Engineering, in December, 1991.

Professional Experience:
Assistant Professor, Department of Industrial and Systems Engineering, Pennsylvania State University, August, 1990 to present.
Summer Faculty Fellow, NASA, Johnson Space Center, Houston, Texas, June, 1991 to August, 1991.
Research Associate, School of Industrial Engineering and Management, Oklahoma State University, August, 1988 to July, 1990.
Quality Engineer, Exxon Chemical Company, Baytown, Texas, May, 1989 to August, 1989.
Quality Engineer, Exxon Refinery, Billings, Montana, May, 1988 to August, 1988.

Teaching Assistant, School of Industrial Engineering and Management, Oklahoma State University, August, 1987 to May, 1988 and August, 1984 to May, 1986.

Quality Engineer, AT&T Technologies, Morristown, New Jersey, June, 1986 to July, 1987.

Industrial Engineer, Rockwell International, Tulsa, Oklahoma, June, 1985 to August, 1985.

Professional Activities:

Institute of Industrial Engineers

Americal Society for Quality Control (Certified Quality Engineer)

American Society for Engineering Education

Registered Engineering Intern (Oklahoma)

Tau Beta Pi

Alpha Pi Mu