Crash quality- an approach for evaluating spending on quality improvement initiatives

2000

Labiche Ferreira
labicheferreira@yahoo.com

Find similar works at: https://stars.library.ucf.edu/rtd

University of Central Florida Libraries http://library.ucf.edu

Part of the Industrial Engineering Commons

STARS Citation

Ferreira, Labiche, "Crash quality- an approach for evaluating spending on quality improvement initiatives" (2000). Retrospective Theses and Dissertations. 1836.
https://stars.library.ucf.edu/rtd/1836

This Doctoral Dissertation (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
CRASH QUALITY - AN APPROACH FOR EVALUATING SPENDING ON QUALITY IMPROVEMENT INITIATIVES

by

LABICHE FERREIRA
B.E., University of Bombay, 1988
M.S., University of Central Florida, 1991

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Industrial Engineering and Management Systems in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Fall Term 2000
© 2000 LABICHE FERREIRA
ABSTRACT

The quality movement has become popular among corporations big and small for one reason: empirical evidence suggests that quality and productivity (and hence profitability) are linked. Unfortunately, while many firms accept that quality and productivity go together, few actually track the gains associated with their quality improvement programs. Companies also tend to spend on quality improvement with no indication or estimation of the impact of funding on the targeted process. It would be of great value to know: (1) the impact of spending to enhance the product/process quality level, and (2) the point at which expenditures for quality improvement are not economical.

This research involves modeling the quality level of a product composed of integrated components/processes and the costs associated with quality improvement. Presented in this research is a methodology for determining the point at which the target quality level is reached. This point signifies when future spending should be re-directed. The research defines this point as the "Crash Quality Point (CQP)." Cases of a single process level and double level three-stage process are modeled to conceptualize CQP. The findings from the output analysis reveal that the quality level approaches the target level at varying points in time. Any spending beyond this point does not have an impact on the quality level compared to the period prior to the Crash Quality Point. Spending past this
point is futile and these funds could be spent on other quality improvement projects. The special case modeled also illustrates the use of this tool in the selection of processes for improvements based on the quality level of the process. This is an added advantage in scenarios where funds are limited and management is constrained to improve process quality with limited funds.

Using a real world example validates the proposed CQP methodology. The results of the validation indicate that the model developed can assist managers in forecasting the budget requirements for quality spending based on the quality improvement goals. The tool also enables managers to estimate the point in time at which allocations of funds may be directed for process reengineering. The CQP method will enable quality improvement professionals to determine the economical viability and the limits in expenditures on quality improvement. It enables managers to evaluate spending alternatives and approximate when the point of diminishing return is reached.
This research is dedicated to my loving wife Germaine. Her encouragement and understanding throughout the Ph.D. program made the completion of my doctorate possible.
I would like to thank the faculty and staff of the Department of Industrial Engineering and Management Systems at the University of Central Florida for making my doctoral study a memorable experience. I am grateful to Drs. Yasser Hosni, Ahmad Elshennawy, James Brown, Timothy Kotnour, Ram Mohapatra, and Samuel Richie for serving on my dissertation committee. Most of all I would like to thank Dr. Hosni for his guidance and support throughout the dissertation effort.

I would like to thank my friend Dr. James Brown for his guidance and for encouraging me during my dissertation effort. He was always available when I needed to discuss with him on any research issue. Also, would like to thank Jeff Hawkins for his insight on modeling and systems thinking.

To my parents Martin and Carrie Ferreira, I am grateful for all the sacrifices they made so that I could pursue my education in the U.S.A. They placed the needs of my brother and myself before their own.

The birth of my son Liam has brought great joy to me and did motivate me to complete this dissertation in a timely manner. To my loving wife Gemaine, her relentless motivation during this long journey made the completion of my dissertation possible. She stood by me throughout this effort.

Above all, I give glory to my Lord Jesus for making everything possible.
# TABLE OF CONTENTS

**LIST OF TABLES** ................................................................................. ix

**LIST OF FIGURES** .................................................................................. x

**CHAPTER 1 - INTRODUCTION** ................................................................ 1
  - The Research Objective ........................................................................ 4
  - The Significance of the Research ......................................................... 5
  - Outline of Subsequent Chapters .......................................................... 7

**CHAPTER 2 - LITERATURE REVIEW** ...................................................... 8
  - Productivity Based Models ................................................................. 9
  - Indirect Productivity Gains from Quality Improvement ....................... 14
  - Cost of Quality (COQ) / Quality Costs Based Models ......................... 16
  - Models Based on Taguchi’s Loss Function .......................................... 21
  - Miscellaneous Models ......................................................................... 23
  - Summary and Discussion ..................................................................... 28

**CHAPTER 3 - RESEARCH METHODOLOGY** ............................................ 35
  - Model Development ............................................................................ 36
  - Model Formulation .............................................................................. 38
  - “Crash Quality Point” Concept ............................................................ 42
  - Significance of the “Crash Quality Point” Methodology ....................... 45
    - Continuous Improvement and Innovation ........................................... 47
      - Case 1- CI pursued as a means of organization improvement ............ 49
      - Case 2- Innovation as an organizational improvement intervention .... 49

**CHAPTER 4 - PROOF OF CONCEPT** ......................................................... 52
  - Software Selection ................................................................................ 52
  - *ithink®* Model Entities ..................................................................... 53
    - Stocks .............................................................................................. 54
    - Flows ............................................................................................... 55
    - Converters ....................................................................................... 56
    - The Connector .................................................................................. 58
  - The CQP Model ................................................................................... 59
    - The Modeling of the Pursuit of Target Quality Level ......................... 59
    - Base Quality Per Dollar (BQ/$) ......................................................... 61
    - Quality Level (QL) ............................................................................ 62
LIST OF TABLES

2.1 Summary of Reviewed Literature ............................................................................. 29

4.1 ithink® Building Blocks.......................................................................................... 54

4.2 Crash Quality Point for Case 1 Sensitivity Runs ...................................................... 74

4.3 Crash Quality Point for Case 2 Sensitivity Runs ...................................................... 86

4.4 Summary data from Case 3 runs ............................................................................. 93

4.5 Quality levels for the case study ............................................................................. 101

4.6 Summary of CQP for each process ....................................................................... 105
LIST OF FIGURES

1. Transitions in Quality Costs ................................................................. 10
2. Exploded view of the Zone of Indifference ........................................... 12
3. Traditional Cost of Quality Model ......................................................... 17
4. Cost of Quality versus Value of Quality ............................................... 18
5. Quality and Productivity Economics ...................................................... 20
6. Quality Cost Curves .............................................................................. 21
7. Quality versus performance- Pessimistic Case ..................................... 25
8. Quality versus performance- Optimistic Case ....................................... 26
9. Manufacturing Network ......................................................................... 37
10. The concept of Crash Quality on the process quality level .................. 42
11. Going beyond Crash Quality Point to a new level of customer expectation 43
12. The concept of Crash Quality on the component level .......................... 45
13. Pattern for Innovation ........................................................................... 47
14. Innovation without CI ........................................................................... 48
15. Innovation and CI ................................................................................... 48
16. The S-Curve of Performance versus Funds Spent ................................ 50
17. Series of S-Curves for various improvement/innovation stages ............ 51
18. The accumulation of stocks as a result of flows in the CQP model ........................................ 55
19. Spending and Total Spent converters in the CQP Model ...................................................... 56
20. Converters .................................................................................................................................. 57
21. Dialog Box for Converter- gap 1 ............................................................................................... 57
22. The quality per dollar converter (qual\$) .................................................................................. 58
23. Generic structure of the stock-adjustment template .................................................................... 60
24. Behavior produced by the stock-adjustment process ................................................................. 61
25. The modeling of the pursuit for target quality ........................................................................... 61
26. Quality Level dialog box ............................................................................................................. 63
27. Impact of process quality level gap ............................................................................................ 64
28. Tracking of funds spent on quality improvement ...................................................................... 65
29. Illustration of a sequence of processes used in Case 1 ............................................................ 66
30. Interface level for Case 1 ............................................................................................................. 67
31. Model for Case 1: Single Level Process .................................................................................... 68
32. Screen shot of Case 1 variable values for six sensitivity runs .................................................. 70
33. Output from Run #1 .................................................................................................................. 71
34. Output from Run 2 ..................................................................................................................... 71
35. Output from Run # 3 .................................................................................................................. 72
36. Output from Run # 4 .................................................................................................................. 72
37. Output from Run # 5 .................................................................................................................. 73
38. Output from Run # 6 .................................................................................................................. 73
39. Quality level versus funds spent on process improvement ........................................................ 75
40. A Double Level Three Stage Process (process with one or more sub-processes) .... 76
41. Interface Level for Case 2 .............................................................................. 77
42. Sub-process details interface layer for Case 2 ................................................ 78
43. Sector representation for process 1 and sub-process 1A and 1B ...... .............. 79
44. Process 2 and sub-processes represented by a space compression object ..... 80
45. Sub-process 2A and 2B ................................................................................... 80
46. Calculation of the final quality level (Process 3) ........................................... 80
47. Screen shot of Case II variable values for six sensitivity runs ..................... 81
48. Output from Run # 1 ................................................................................... 82
49. Output from Run # 2 ................................................................................... 83
50. Output from Run # 3 ................................................................................... 83
51. Output from Run # 4 ................................................................................... 84
52. Output from Run # 5 ................................................................................... 84
53. Output from Run # 6 ................................................................................... 85
54. Interface Level- Case 3 ................................................................................ 87
55. Model Layer Case 3 .................................................................................... 88
56. Process selection based on quality level ...................................................... 89
57. Output from run # 1 .................................................................................... 90
58. Output from run # 2 .................................................................................... 91
59. Output from run # 3 .................................................................................... 91
60. Output from run # 4 .................................................................................... 92
61. Output from run # 5 .................................................................................... 92
CHAPTER 1
INTRODUCTION

Over the years, a variety of efforts have been made in the development and implementation of quality improvement programs and methods. The goal being to improve overall organizational performance, process and product quality. Top managers are linking quality with profitability and are including quality in their strategic planning process (Garvin, 1987). Despite the great successes in many organizations (United States General Accounting Office, 1991; Hotard, 1988; Adam, 1994; Larson, 1995), there have also been failures and disappointments (Sixel, 1991; Fuchsberg, 1992). Practitioners and theoreticians are puzzled by the fact that despite the appropriate strategy and proper implementation procedures, and in many cases initial successes, the final outcome could be a relative deterioration in quality and productivity. According to a 1996 Cost of Quality Survey of the Cost Management Group (CMG), 82% of the members said that their company is currently involved in some kind of quality program (IMA, 1996). One third (i.e., 33%) of the members calculate the cost of quality and 40% believe that knowing the cost of their quality programs is a good idea. Of the CMG members who did calculate the cost of their quality programs, 41% said the quality programs were worth the costs, 46% said it was too early to tell, and 13% said the quality programs were not worth
the implementation costs. Forty-four percent of the members reported that the quality programs met the desired results they were first intended to achieve. Twenty-seven percent stated that it was too early to tell whether the programs achieved the intended purpose, and 29% said their programs did not obtain their goals.

Many companies use a quick fix approach and give up when quality improvement programs do not result in immediate success. The study by the United States General Accounting Office (1991) stated that, on average, 3.5 years were required before companies would begin to see significant results from quality improvement processes. In a study of the U.S. auto industry, Narasimhan, Ghosh, and Mendez (1993) found a 2.26-year lag between quality improvement and customer recognition of the quality improvement.

In some cases, companies’ stress on winning a Quality award with minimal emphasis on the monitoring of costs and the associated improvements. Florida Power and Light (FPL) won the coveted Deming Prize for quality in 1989. FPL spent $2.85 million in the pursuit for the prize and tried to pass along $708,378 to ratepayers (Sixel, 1991). According to the U.S. General Accounting Office (GAO) study (1991), only five of the 22 companies in the final round of the Malcolm Baldridge National Quality Award competition calculated their quality costs. Companies that have won the big prizes have found themselves in financial trouble after concentrating too much on winning while neglecting their core business. Winning the Baldridge award has not always translated into success (Sixel, 1991). The Wallace Company won the Baldridge award in 1990, yet found itself in financial difficulty and filed for Chapter 11 bankruptcy protection.
By the same token, quality is a buzzword that companies cannot ignore and has become their rallying cry. The quality movement has become popular among small and large corporations for one reason: empirical evidence suggests that quality and productivity (and hence profitability) are linked (Luchs, 1988; Maani, 1989; Young, 1993; Maan, 1994). Many corporations have some form of quality improvement program, but studies (Feigengauz, 1987; Arora, 1993; Adam, 1994; Larson, 1995; Cunningham, 1996) suggest that most fail to evaluate the impact of quality improvement initiatives on: product quality, product value, productivity and profitability. Unfortunately, while many firms accept that quality and productivity go together, few actually track the gains or the impact associated with quality improvement programs. Sixty percent of companies surveyed by the Electronic Assembly Association failed to reduce internal defects by 10%, despite having the programs in place for an average of three years. After having programs in place for an average of 2.5 years, 80% of the companies surveyed failed to reduce supplier defects by 10% or more (Boyett, 1992).

Top management support for quality programs has always been a frustrating issue for quality managers and engineers. This frustration is sometimes justified due to: (1) lack of evidence of the impact of quality improvement programs, and (2) an ever-increasing need to improve what could be a “mature” process or product. A method to enable managers to predict or track the expected impact of funds spent on quality improvement would be beneficial.
The Research Objective

Companies have reported that the implementation of quality improvement programs did not result in a proportional increase in profit (Forker, 1996). In some market sectors, customer expectations regarding quality increase subsequently through competition (Philips, 1983). In other sectors, customers must be enlightened through awareness programs. The quality of a finished product depends substantially on the quality of the individual components and sub-processes that form the manufacturing chain leading to a final product. While quality improvement efforts are directed towards ensuring and improving the quality levels of each process, the overall impact of the improved quality level is often ignored or forgotten. Nearly two-thirds of the 30 quality improvement programs studied by Mckinsey Co., were either stalled or fell short of delivering real improvements (Schaffer and Thomson, 1992). The impact of spending to improve the quality levels of individual processes and sub-processes on the final product or process quality is essential to assess the gains due to the quality improvements.

Zero defects, Kaizen/Continuous Quality Improvement, conformance to requirements, and others have been advocated as a quality goal for products and services. In a majority of the cases (Atkinson, 1994), the purpose of quality improvement is to increase the degree of conformance of the product to the customer requirements. The gap between the product and the customer's needs and expectations is usually so wide that it is impractical to close this gap with a single quality improvement effort. This leads companies into the continuous quality improvement cycle to narrow this gap. However, after considerable improvements, the value of additional improvements to the product
may not result in an equal amount of customer perceived value. The improvement of the 
product or process quality level may not be economical, and only after a number of 
"continuous improvement iterations" and a stable level of quality, will it be necessary to 
re-engineer the product or the process. If quality improvement efforts are to be effective, 
companies must be aware of the impact of funds spent on quality improvement and the 
quality level at various steps in the continuous improvement cycle. This is crucial in 
deciding when further product or process quality improvements will no longer provide 
added value. This forms the basis of the proposed research.

This research focuses on developing a methodology for determining the point at 
which the quality target is reached, both in terms of capability and stability, and seeks to 
prove through modeling and analysis that there is a point at which expenditure on quality 
programs is not justified. Instead, expenditure should be directed towards re-engineering 
the process. This point is termed the "Crash Quality Point (CQP)" in this research. The 
research involves the modeling of process quality and the associated costs for quality 
improvement. The research assumes that the quality program is directed at improving a 
process and its sub-processes that are used to manufacture a product and its sub-assemblies.

The Significance of the Research

Companies tend to spend time and money on quality improvement programs 
without tracking the limits on these expenditures. The belief is that the increased 
expenditure on quality will be offset by increased revenues generated at the same level of 
customer expectation. In reality, the customer’s expectation may or may not change. In
some cases, the existing product mix offered by competition may not justify increasing the quality level. This research defines the “Crash Quality Point” (CQP) as a point, that when reached, may not result in substantial gains in quality improvement. Spending past the CQP will result in the loss of allocated funds, which could have been utilized for other quality improvements within the business. However, continued expenditure on quality improvement past the CQP, coupled with increased customer expectation or re-engineering of the process, may result in revising the quality level. This scenario would also justify the continued spending on quality improvement initiatives. The “Crash Quality Point” signifies the point at which companies need to evaluate continuous improvement programs versus re-engineering objectives.

The CQP is a new method for forecasting or evaluating the impact of expenditures of quality improvement. This method is modeled to be effective for single level processes of a multiple level process (i.e., a process with one or more sub-processes) so that it lends itself to practical usage for a variety of applications. Previous research on cost of quality has focused on methods for tracking various elements of prevention, appraisal and failure costs (Plunkett, 1988). The new CQP model allows managers to perform “what-if” analysis on the impact of spending the dollars currently available for quality improvement. Program managers and quality professionals of all ranks are faced with these decisions at the launch of quality improvement initiatives of any magnitude.
Outline of Subsequent Chapters

This dissertation is organized as follows.

- Chapter 2, "Literature Review," reports a literature search built around productivity-quality relationships, cost of quality and methods for determining the impact of quality improvement programs. A summary and a discussion of the literature review on key approaches are also included.

- Chapter 3, "Research Methodology," discusses the research and outlines the basis for the Crash Quality Point model.

- Chapter 4, "Proof of Concept," describes:
  1. the CQP model,
  2. the three cases considered in this research,
  3. validation and analysis of the results.

- Chapter 5, "Summary, Limitations and Future Research," summarizes the outcome of this research and the associated limitations. Finally, the implications and important issues for future research are presented.
CHAPTER 2
LITERATURE REVIEW

The aim of the research, as stated in the previous chapter, is to determine a point at which additional spending on quality improvement initiatives may not be economical. On embarking on the literature search, various avenues were pursued to assess the work done in this area or approaches developed. The literature search targeted literature that covered subject areas such as: performance measurement, productivity-quality relationships, impact of quality/productivity on business performance, cost of quality, models for quality, results of quality improvements, and total productivity. Numerous journal articles, dissertations, and research reports dated since 1991 were reviewed on these subjects. This chapter presents some key models developed for the analysis of quality improvements. The majority of these efforts are based on the impact of quality on the productivity of operations. These range from the traditional productivity equations to productivity/quality indices. Since the costs associated with quality improvement are important, if not significant, methodology and relationships in the form of equations from selected articles are also presented in this section. The latter portion of the chapter discusses the methods presented and summarizes the approach of each of the methods.
reviewed. Equations for the models discussed are excluded from the main body of the text where applicable, however, relevant equations are listed in Appendix A.

**Productivity Based Models**

Arora (1993) proposes a conceptual framework to determine the link between total productivity and quality using Summanth’s “Total Productivity Model” (Summanth, 1979) and Juran’s Model of Optimum Quality Costs. The total productivity at any time (t) is evaluated as:

\[
TP_t = \frac{O_t}{I_{ot} + TQC_t}
\]

Where:

\( TP_t \) = total productivity at period ‘t’

\( O_t \) = total output for period ‘t’

\( TQC_t \) = total quality cost = \( I_{at} + I_{pt} + I_{ft} \)

\( I_{at} \) = appraisal costs in dollars

\( I_{pt} \) = prevention costs in dollars

\( I_{ft} \) = failure costs in dollars

\( I_{ot} \) = Total input without the ‘conscious consideration of the Quality System’
Arora (1993) discusses the effect of improvement in quality levels on the total productivity in reference to Figure 1. The analysis considers two extreme levels of quality chosen: a minimum level when quality is at a minimum level and a maximum level when the quality approaches perfectionism.

![Figure 1. Transitions in Quality Costs (Arora, 1993).](image)

Referring to Figure 1, in period 1 when the quality level is $q_1$, the total input and output is $O_1$, and total productivity is given by:

$$TP_1 = \frac{O_1}{I_1} = \frac{O_1}{I_{a1} + I_{p1} + I_{f1}}$$  \(2\)
In period 2, the prevention and appraisal costs have increased from the level in period 1 to \( (A+P)_{1-2} \), failure costs have reduced by \( F_{1-2} \), and the quality level has increased to \( q_2 \). The model assumes that without the conscious quality effort, the total input and the input factor, remain constant. The Total productivity in period 2 is given by:

\[
TP_2 = \frac{O_2}{I_2} = \frac{O_2}{I_1 + (I_{i1} + I_{p1} + I_{f1} + (A + P)_{1-2}) - F_{1-2}}
\]  

(3)

The denominator in the above expression for period 2 decreases by the term \[ (A+P)_{1-2} - F_{1-2} \] when compared to period 1 (i.e., \( I_2 < I_1 \)). Therefore:

\[
TP_2 > TP_1
\]

(4)
As demonstrated in Figure 2, the trend continues until the 'optimum point' is reached in the 'Zone of Indifference'. Beyond this point, the total quality curve approaches the 'Zone of Perfectionism', which indicates that instead of continuing to divert funds towards prevention and appraisal, the funds could be more effectively used elsewhere. This means that increased efforts in appraisal and prevention activities lead to an increase in total productivity (TP). Total productivity increases in the 'Zone of
Improvement' until it reaches optimum value in the 'Zone of Indifference', and declines in the 'Zone of Perfectionism'. In the zone of indifference, the total quality cost is minimum (i.e., the sum of prevention, appraisal and failure costs). Referring to Figure 1, these costs are least at the break-even point. Any positive change in prevention and appraisal costs causes an almost equal amount of negative impact on the failure costs. From Figure 2, quality increases from Point 1 to Point 2. As the quality level advances with an increase in prevention and appraisal costs from Point 2 to the break-even point, the algebraic sum of the change in prevention, appraisal and failure costs remains approximately equal to zero. This trend continues, as quality increases in the zone of indifference to the right side of the break-even point. As the total quality costs pass from the zone of indifference to the zone of perfectionism, the cost of prevention and appraisal rises steeply for a marginal decrease in the cost of failure and causes a drop in total productivity. This shows that the assumption, with an increase in quality there is always an associated positive change in total productivity, is not always true. A positive change is associated, but not indefinitely.

_Eodosomwan (1991) presents Productivity and Quality Evaluation Procedure (PAQEP) to assist managers in balancing quality and productivity requirements at the source of production. PAQEP is based on the following assumptions: (1) There are standards for quality and productivity at the firm level, and (2) The strategies for quality and productivity improvement are error prevention, defect elimination, and effective utilization of all resources to produce useful output. The related equations are listed in Appendix A. A hypothetical example is presented for computer assembly tasks. The_
method calls for the estimation of several weighting factors including factors for quality, productivity, and error rate. The PAQEP calculations result in a Quality and Productivity Rating (QPR) score, which may be used to prioritize tasks for improvement.

**Indirect Productivity Gains from Quality Improvement**

A number of recent studies have provided empirical support for the argument that improvements in quality lead to increases in productivity. Schmenner and Cook’s cross-sectional analyses (Schmenner and Cook, 1985; Schmenner, 1988) indicated that factories that paid more attention to quality experienced higher rates of productivity growth. Garvin (1987) found that direct labor productivity at the highest quality room-air-conditioner manufacturing plants was five times higher than that at the poorest quality plants. Hayes and Clark's (1985) examination of the sources of productivity at 12 factories showed that reduction in waste or reject rates generally led to an increase in total factor productivity. Companies typically focus on the direct effects of poor quality, such as scrap and rework, while ignoring significant indirect effects, such as disruptions in operations resulting from non-conformance in purchases, changes in production schedules and downtime. Mefford (1989) claims that indirect efficiency gains from quality-related process improvements are overlooked in traditional quality-cost trade-off analyses, leading firms to choose quality levels that are far lower than optimal.

Nandakumar, Datar, and Akella (1993) present a model that incorporates the impact of quality on lead-time variance and on service reliability. The model captures all costs of poor quality in addition to the costs of materials and labor, and the effect of poor
quality on timeliness of delivery and faster response time is also considered. The analysis showed that an increase in defects of one product affects other products as well by delaying deliveries of all other products. The inclusion of time based costs in the analysis showed that the total cost of poor quality is an increasing function of defects.

Ittner (1994) examines direct and indirect productivity and manufacturing gains from quality improvement using time series data from two consumable durables manufacturing plants. In the cases examined, Ittner models the impact of quality on: plant-level productivity, schedule realization, inventory levels, and the combination of these factors. Path Analysis is used to procure a general estimate of manufacturing gain from quality improvement. Results indicate that the indirect gains from improved quality are at least two to three times the direct benefits attributed to lower scrap, rework, and inventory holding costs. The analysis found indirect productivity gains to arise from reductions in quality related bottlenecks, lower inventories, and fewer schedule interruptions due to out-of-conformance processes. The author proposes that companies must identify sources of indirect benefits from quality improvement, and develop incentive mechanisms to achieve these gains.

Keats and Sink (1982) proposes the integration of quality cost measurement and a multi-factor, dynamic, price weighted productivity measurement model. A hypothetical example (tabulated data, ratios) is used to develop a management decision aid. The productivity equations for two periods are used to illustrate the increase in productivity due to quality improvement activities. Data used in the example include labor, material, energy, and capital (working, costs of accounts receivable, land, buildings, equipment,
and services). The method described, demonstrates that quality measures already being used may be incorporated into a multi-factor productivity model.

Ramadan (1991) proposes an integrated framework and mathematical model for productivity and quality planning. The author presents an application of a knowledge-based computer decision support system for evaluating and ranking a set of proposed improvement programs characterized by multiple attributes of productivity and quality measures. This method enables the ranking of different productivity and quality attributes in order of increasing value or utility. A case study of a service unit (hospital) with multiple services is discussed. Ten departmental heads, managers, and planners contributed opinions about the number of attributes, the nature of the hierarchical tree, rating of alternatives and the shape of utility curves. A “service tree,” with attributes and sub-attributes, is constructed for the hospital with the goal to determine the optimum utility index “U” of the hospital unit associated with each of the five improvement programs selected. These programs have similar budget requirements, installation times and rate of return.

Cost of Quality (COQ) / Quality Costs Based Models

Quality costs are traditionally categorized as prevention, appraisal or failure related. The traditional P-A-F model of quality costs is based on costs of prevention, appraisal and failure. This gives rise to the concept of an economic cost of quality and the “optimum point,” which as shown in Figure 3, is the intersection of the failure cost and the appraisal and prevention cost curves. Further prevention beyond the optimum
point is seen as exceeding the benefits of the improved quality and thus economically unjustifiable. Over the years, it has been proposed that further prevention beyond the “optimum point” does not result in an increase in quality, and hence improvement efforts may be economically unjustifiable. Many researchers (Morse, 1987; Bajpai, 1988) have argued the possibility of companies measuring the exact optimum point. This section describes methods that use the cost of quality methodology to quantify the gains from quality improvement efforts.

![Traditional Cost of Quality Model](image-url)

Figure 3: Traditional Cost of Quality Model.

Plunkett and Dale (1988) reviewed most of the quality cost models proposed by different researchers over the years. Many of the models reviewed failed to include any time scale. This meant that cost is portrayed by these models as a static variable, and the models simply relate costs and quality without advancing any mechanism of how they interact dynamically. Perhaps more serious, is the fact the benefits arising from product and process quality improvement are ignored in all models including those factoring a
time scale. There is clearly a need to develop a method or model to show the benefits and must be related to time scales over which quality is improved. The total cost in the Lundvall-Juran model (Juran, 1988) is defined as the sum of prevention, appraisal, and failure costs. The weakness of the model is that it only considers prevention, failure and appraisal costs when determining optimal quality strategy.

Bester (1993) defines the value of quality as an index of consumer taste. The author states that the value of quality is the price that the consumer is willing to invest in return for a level of quality that meets his/her expectations. This is in contrast to cost of quality, which is the cost associated with implementation of quality related programs within the producer’s company.

![Figure 4. Cost of quality versus value of quality (Bester, 1993).](image-url)
The concept illustrated in Figure 4, is a relationship between quality and cost. The area enclosed between the total cost of quality and the value of quality curves constitutes the range of economic viability. A reduction in the cost of quality, while simultaneously increasing the value of quality, creates a greater range of economic viability. The equation for Net Value Productivity (NVP) is presented as:

\[ NVP = \frac{VA}{C+E+L+D} \]  

(5)

Where:

VA = Value Added = (accepted outputs) - (external services)

C = Capital Input

E = Fixed Expenses

L = Labor (direct & indirect)

D = Damages (direct and indirect, external and internal, Non-Quality Costs)

From the equation above, if C and E are held constant, NVP is dependent on the ratio between the value added (VA), the sum of the labor invested (L), and the damages (D). That is, NVP is a function of the value added, labor and damage costs and is expressed as:

\[ NVP = f\left[\frac{VA}{L+D}\right] \]  

(6)
The challenge lies in finding the optimum by refining the total labor value, so that the total labor invested will be reduced, and consequently, the cost of damages.

Esterby (1981) combines quality costs analysis and productivity into a quality productivity relationship. The paper examines the technique of combining quality costs analysis with measures of output (i.e., productivity). A productivity index is defined in terms of prevention, appraisal and failure costs. The components of the productivity equation are redefined in terms of quality activities. In the model presented, labor is an aggregate of: effective labor, labor that produces totally conforming or satisfactory products or services, and the labor component of failure costs, failure labor, appraisal labor, and prevention labor. The relations for the method presented are included in Appendix A. The index is compared for different quality levels on the Cost of Quality.
curves (Figure 6) to illustrate the changes in the index. Referring to the figure, the increase in the productivity index may continue beyond the point of minimum total quality costs as perceived quality is improved. This represents an increase in real quality (and an associated increase in perceived quality). At this point, a higher price can be charged for quality level at $q_3$ than $q_1$, thus resulting in a higher total revenue and higher productivity index. Based on this reasoning, the author proposes that the maximum productivity index is somewhere between $q_2$ and $q_3$.

![Figure 6. Quality Cost Curves (Esterby, 1981).](image)

**Models Based on Taguchi’s Loss Function**

Various forms and applications of the quality loss function (QLF) have been developed and presented over the years. The QLF measures the loss as a quadratic
function of the deviation of the actual value from the target value of a product characteristic. Mathematically, the loss is determined by:

\[ L(y) = k(y - T)^2 \]  

Where:

\( k \) = a proportionality constant
\( y \) = actual value of the quality characteristic
\( T \) = target value of the quality characteristic

The value of \( k \) can be estimated by dividing the loss by the squared deviation of the specification limit from the target value. That is:

\[ k = \frac{c}{d^2} \]

Where:

\( c \) = loss associated with the specification limit, and
\( d \) = deviation of the specification from the target value.

The value represents intangible quality costs such as customer dissatisfaction, loss due to bad reputation, and loss of market share. Proponents for QLFs stress that, in order to improve product quality, it is important to understand the costs incurred due to the deviation of a product characteristic.

Kim and Liao (1994) present various forms of quality loss function and use Taguchi’s Quality Loss function (QLF) for estimating hidden quality costs. Current
accounting systems do not capture all the costs associated with product quality. These unrecorded quality costs are the opportunity costs for non-conforming product quality. Realistic estimates of hidden quality costs are necessary in order for managers to understand and control the costs. The QLF in most literature is presented as a symmetric function case of a loss function. For many products, however, different forms of a loss function, and different levels of sensitivity along a loss function, may be more applicable. This is due to the fact that when the product quality is closer around the target value, the loss is less sensitive. The authors developed an asymmetric quality loss function and considered different levels of sensitivity along a QLF in estimating hidden quality costs. The authors propose that, in some applications, a certain amount above the target value and the same value below the target may have different sensitivities of loss. This means that the variation from the target value on one side of the loss function may be more or less sensitive than the same amount of variation on the other side of the loss function. Equations for the model are listed in Appendix A. Five cases with examples are presented to illustrate the use of the equations.

Miscellaneous Models

Using the profit impact of market strategy (PIMS) database, Phillips, Chang, and Buzell (1983) and Jacobson and Aaker (1987) found little or no significant direct relationship between productivity and perceived quality. Phillips, Chang, and Buzell (1983), using a sample of 623 businesses in six industry groups, tested the hypothesis that higher relative quality results in higher relative direct costs per unit. They found that
higher quality led to higher costs in only one (capital goods manufacturers) of the six sectors investigated. In another sector—components businesses—higher quality resulted in lower direct costs. The relationship was insignificant in the other four groups. Overall, there was limited support for the view that high relative quality leads to high relative direct costs. Jacobson and Aaker (1987) reanalyzed the Phillips, Chang, and Buzell (1983) hypotheses using the same data. Though their results were somewhat different, Jacobson and Aaker also concluded that high quality was not related to higher costs. The examples in the PIMS studies were manufacturers. The PIMS database measures quality as a customer’s perceptions of quality for a business unit’s product relative to competitors.

Hotard (1988) examines the possible relations between productivity improvement and quality. Two hypothetical mathematical relations between quality and productivity are presented. The consequences on product quality and cost are explored for each case. An empirical case is presented to develop a mathematical link between quality and labor productivity. The cases address the following two conditions: (1) Pessimistic Case: Quality Decreases with Increased Productivity, and (2) Optimistic Case: Quality Increases with Increased Productivity. The pessimistic case involves a negative exponential relation. A large reduction in quality for a slight increase in effort could increase if the labor force were unaware that their increase in effort caused the drop in quality level. The reduction also could be due the perception that the increased effort was of primary priority with no concern with quality. Once the levels of performance become higher than the 100% norm, the rate of quality deterioration would become less because some
members of the work force cannot perform at these levels. The equations for this case are listed in Appendix A. Figure 7 illustrates the pessimistic case.

![Graph](image)

**Figure 7.** Quality versus performance- Pessimistic Case. (Hotard, 1988).

The optimistic case argues that along with worker’s increased efforts, there will be an increase in attentiveness and concentration, and fewer distractions. These will contribute to an improved quality of output so that overall quality performance is improving as productivity increases. The equations are listed in Appendix A and Figure 8 illustrates this case. The study recommends small changes be made at a time to examine the quality effects so as to project the impact of full scale alterations.
Malen (1995) proposes a model that structures the design process, and a methodology to factor in customer preferences. Intermediate transfer functions within the model link design variables to system responses, and link specific responses to value. An iterative design improvement method is considered, in which current design and a new design are compared. The comparisons are made by mapping the design into customer value space and applying a measure of overall customer preference that considers both cost and quality attributes. The mapping of design alternatives is accomplished by using transfer functions of the overall model. These transfer functions are the cost preference function and the quality attribute preference function. Each block in the model contains a transfer function that transforms a numerical quantity related to customer preference.
Design improvements ("Challenger") are compared to the existing alternative ("Defender") on the basis of customer preference, and the preferable design is selected as the new Defender. If all design targets are still not met, a new Challenger is created and the process is repeated iteratively.

Metzger (1993) describes the use of Data Envelopment Analysis (DEA) to measure the effects of appraisal and prevention costs on productivity. In the paper, DEA was used to measure the efficiency of a specific department through time. The reasoning for using DEA over time is that departments may not be similar enough in nature to warrant direct comparisons. The DEA efficiency measurement is obtained as the maximum of a ratio of weighted outputs to weighted inputs. However, the ratios for every Decision Making Unit (DMU) should be less than or equal to one.

Son (1987) combines productivity, quality and flexibility to obtain an overall performance measure of a typical manufacturing activity. This measure would allow firms to make investment decisions on advanced manufacturing systems. Partial-Productivity, Quality and Flexibility measures are defined and equations developed. Equations presented in the paper are listed in Appendix A. A hypothetical FMS and a Job Shop (JS) are compared to illustrate the performance measures using a simulation model in SIMAN. The results of the hypothetical case indicate that the adoption of an FMS improved the integral manufacturing performance, compared with a conventional Job Shop.
Summary and Discussion

The fact that quality and productivity go hand-in-hand and not against each other has gained extensive support in literature. Companies keep investing in quality related activities, in pursuit of excellence to a point that these investments become counter-productive. The impact of quality on an organization’s performance has been extensively studied over the years. The models presented in the earlier section cover a broad spectrum of measurement of quality. The methods vary in methodology and target of application, and primarily address the impact of quality on the overall manufacturing performance or organizational performance. Product based quality improvements are either design or manufacturing related. Table 2.1 presents a summary of models discussed in the previous section classified by objective, approach, and source of data.
Table 2.1: Summary of Reviewed Literature

<table>
<thead>
<tr>
<th>Researcher \ Study</th>
<th>Continuous Improvement</th>
<th>Quality and Productivity</th>
<th>Organizational Performance / Profit &amp; Quality</th>
<th>Cost of Quality</th>
<th>Reengineering / Innovation</th>
<th>Model / Equations</th>
<th>Simulation</th>
<th>Discussion</th>
<th>Survey</th>
<th>Mail in Questionnaire</th>
<th>Hypothetical Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cunningham &amp; Ho (1996)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Service Construction, and Maintenance</td>
</tr>
<tr>
<td>Davenport (1993)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IT</td>
</tr>
<tr>
<td>Esterby (1981)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edosomwan (1991)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Computer Assembly tasks</td>
</tr>
<tr>
<td>Flynn, Schroeder and Sakakibara (1995)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Machinery, transportation components, electronics</td>
</tr>
<tr>
<td>Forker (1996)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Furniture industry</td>
</tr>
<tr>
<td>Adam (1994)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SIC codes</td>
</tr>
<tr>
<td>Arora (1993)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fabricated part</td>
</tr>
<tr>
<td>Bester (1993)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hotard (1988)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huff, Fornell, and Anderson (1996)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Manufacturing and services</td>
</tr>
<tr>
<td>Harrington (1981)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Generic process / service</td>
</tr>
<tr>
<td>Researcher \ Study</td>
<td>Continuous Improvement</td>
<td>Quality and Productivity Relationship</td>
<td>Organizational Performance / Profit &amp; Quality</td>
<td>Cost of Quality</td>
<td>Reengineering / Innovation</td>
<td>Model / Equations</td>
<td>Simulation</td>
<td>Discussion</td>
<td>Survey</td>
<td>Mail in Questionnaire</td>
<td>Hypothetical Case</td>
</tr>
<tr>
<td>-------------------</td>
<td>------------------------</td>
<td>----------------------------------------</td>
<td>---------------------------------------------</td>
<td>----------------</td>
<td>----------------------------</td>
<td>-----------------</td>
<td>------------</td>
<td>------------</td>
<td>--------</td>
<td>---------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Ittner (1994)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keats (1982), Sink (1983)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kim &amp; Liao (1994)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metzger (1991)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malen (1995)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mann (1994)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matta (1988)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nandakumar and Akella (1993)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phillips, Chang, and Buzzell (1983)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plunkett and Dale (1988)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramadan (1991)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Son (1987)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labiche Ferreira (2000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Productivity Based Models (Arora, Edosomwan, Ittner, Keats, Ramadan) presented in the previous section attempt to capture the gains from quality/productivity improvements. Per Arora’s model, total productivity reaches a maximum level corresponding to the optimal point for quality costs. One could speculate that quality costs, upon reaching the optimum point, would remain constant instead of increasing as indicated in the previous section. The reason for this lack of change is that quality programs, once implemented and refined over the years, would not incur the same level of costs as during the inception stage. A hypothetical example is presented to clarify the model. The model does not consider other quality costs such as loss of good will, loss of market share and quality as perceived by the customer.

Edosomwan’s procedure (1991) enables managers to rank and prioritize tasks for improvement based on the Quality Productivity Rating (QPR) score. The limitations associated with this method include: (1) difficulties involved in obtaining quality and productivity data, (2) as the number of tasks get larger, the manipulation and tracking required for PAQEP can become cumbersome, and (3) the selection of weighting factors.

Ittner (1995) illustrates the fact that most traditional accounting and cost of quality systems underestimate the costs of poor quality. Companies need to identify indirect benefits from quality improvement and Ittner recommends that incentives be developed to motivate managers to achieve these gains. The method described may apply to only one type of industry and equations need to be tailored for each application.
Keats and Sink (1982) demonstrate that quality measures currently used by management could be incorporated into a multi-factor productivity model. The example presented uses hypothetical data to compare the ratios of two periods. The method does not focus on product quality improvement efforts, but is based on comparing ratios of different periods to arrive at a profitability change ratio. Limitations also include the difficulty in the data collection and that the model may not be applicable for all "systems."

Ramadan's framework (1991) demonstrates the capability to select the most appropriate improvement program within a group of suggested alternatives. A key requirement is to obtain attribute weights for the generation of utility curves. This method does not enable managers to quantify the benefits or costs involved after the selection of the quality improvement alternative has been made.

Bester's model (1993) is one of the few models that incorporates the concept of value of quality to the customer. The model does not require the classification of quality costs; instead, it focuses on identifying the deficiency and damage costs. The labor costs defined in the model also include white collar labor costs. The article does not present any examples to illustrate the model. The challenge in using Bester's model is finding an optimum Net Value Productivity (NVP) by reducing the total labor value, so that the total labor invested will be reduced and followed by a reduction in the cost of damages.

Kim's (1994) model based on the Taguchi's Loss function argues that not all deviations from the target cause the same amount of loss to the end user. The asymmetric loss functions aim to factor the different levels of sensitivity along the loss function. Kim
stresses the need to understand the hidden quality cost that may be incurred when the actual characteristic value is within specification limits or even within insensitive regions.

Hotard (1988) considered two cases of impact of productivity on quality; one in which quality decreases, and one where quality increases with increased productivity. The proportion of total units produced, which are of good quality, is used as a quality measure. To measure productivity improvement due to the increased effort, Hotard uses the ratio of the output per man-hour under increased performance conditions to the output per man-hour under normal levels of performance. The basis of quality deterioration is based on the lack of awareness of quality on increasing performance. Alternately, the basis of an increase in quality is assumed to be due to the increased attentiveness during the operation as a result of increased worker performance. This method/model is based on the impact of worker performance on quality. The developed cost equation factors the cost of obtaining a unit increase in performance level. The author illustrates that the change in quality differs from the change in performance by means of a hypothetical example.

Malen’s model focuses on the selection between alternative design concepts based on customers’ preference. The methodology involves comparing the “challenger” versus the “defender.” Quality product designs are generated as a result of weeding out poor designs on the basis of quality attributes. The method presented is structured and makes the design activity less dependent on designer skill level. The method is not applicable to design iterations of the same product and is heavily dependent on physical system models for developing customer preferences.
Referring to Table 2.1, the research presented here addresses the continuous improvement process and the expenditures associated with spending on process improvements. Based on the literature search, none of the approaches reviewed have presented a method to indicate when spending on quality improvement needs to be halted or directed at another improvement initiative. The model developed in this research captures the quality improvement due to spending on quality improvement programs. The model suggests that process re-engineering may be required once the processes involved in the fabrication of the product have reached a maturity level. This may warrant re-defining the quality level through re-engineering of the process. The research is based on a model presented in the next chapter and it uses simulation as a proof of concept based on a hypothetical case.
CHAPTER 3
RESEARCH METHODOLOGY

In the previous chapter, the approaches for quantifying quality improvement vary in methodology and application. Methods described in Chapter 2 address the impact of quality on the overall manufacturing or business performance. A method is needed to assess when quality improvement is beneficial and economically feasible. This research proposes a tool by which quality managers can evaluate whether to maintain the achieved quality level, pursue a higher quality level by increased investment in quality improvement, or completely re-engineer the product or process. The tool also enables quality improvement professionals to forecast an expected point in time when the desired improvement should be realized.

This research focuses on developing a methodology for determining the point at which the selected target quality level is reached. Beyond this point, future spending does not result in enough improvement of quality to warrant further spending. This point is defined as the "Crash Quality Point (CQP)." The research involves modeling the process quality level of a product and the associated costs of quality improvement. The process quality level has direct impact on the quality level of the product and sub-assemblies during
the manufacturing process. The objectives of this research include:

- the modeling of the process quality level,
- a methodology for estimating the “Crash Quality Point.” Details on the definition of the “Crash Quality Point” are covered in the following sections.

**Model Development**

The research involves the modeling of a manufacturing process for a product. The product in this research is considered to be fabricated through a sequence of processes either in parallel or in series. The product is an assembly of $n$ components and sub-assemblies in a manufacturing chain/network. The manufacturing network for the product results in the integration of $n$ components (A, B, .., J) and sub-assemblies, each being produced by a process. Each of the processes in the manufacturing network is at a certain quality level ($q$). Figure 9 is a schematic of the product manufacturing network, where the arcs represent processes, and the nodes represent integration points. The entire network represents a complete process (i.e., manufacturing chain) for manufacturing the product. Representing the manufacturing process as a network, is not a new concept. What is new, is associating quality levels of the process in a network in support of this research objective.

Improvement in process quality level (and thus the product quality level) can be achieved through successive measures on the component and the processes. This would result in decreasing the gap between the current process quality level and the target quality level. Quality improvement programs are targeted towards the processes in the
manufacturing network, resulting in improvements in product quality. These improvements would be a result of spending allocated funds on component quality improvement, fabrication processes, and integration processes.

Figure 9. Manufacturing Network.

Based on the assumptions that a current and target quality level is known, a cost model is developed. The model includes the costs associated with improving the quality level or funds available to spend on a quality improvement effort. This will include costs for improving the process quality level (and therefore the product quality level) from one level to next. A concept of closing the gap between the current quality level and the "Target Quality Level" is modeled for each process in the manufacturing network. This concept is similar to the Taguchi's loss function which suggests that the loss is zero when
a product meets the target value of the characteristic. The behavior of the improvement in quality level due to spending of allocated funds is modeled for each process in the product’s manufacturing network. The goal of the research is to conceptualize the “Crash Quality Point (CQP)” as the point in the quality improvement cycle when any further expenditure on process quality improvement may be wasted if not offset by increased market share, re-engineering or increased customer satisfaction.

Model Formulation

The product in the research is manufactured through a sequence of processes either in parallel or in series. This research focuses on the impact of spending on the quality level of the process. Funds are budgeted on a monthly basis to processes in the manufacturing chain with the goal of increasing the quality level to a point where it is no longer economical. The pursuit of improvement in the quality level is based on the assumption that there is a target value of the quality level based on market conditions, customer expectations, and company reputation. This value in the model is defined as the “Target Quality Level.” The company may also opt to pursue different values of the target quality levels at various points in the product’s life cycle. The target quality level could also be dependent on the complexity and maturity of the process. The rate of improvement is factored as a function of the funds allocated and the value of the current quality level. The value of the quality level versus time is tracked to determine the point at which the rate of improvement in quality level is not significant when compared to the funds invested. This point in the research is defined as the Crash Quality Point.
The quality level for the process during the complete improvement cycle is a sum of the improvements in quality level due to each event of spending on quality improvement for that process. The quality level (QL) for each process at any given time can be expressed as:

\[ QL_t = QL_{t=0} + \sum_{t=1}^{n} \Delta IQL \]  

Where:

- \( QL \) = process quality level at time “t”,
- \( QL_{t=0} \) = initial process quality level, and
- \( \sum_{t=1}^{n} \Delta IQL \) = summation of the incremental improvements in process quality level.

In this research, the incremental improvement in process quality level (\( \Delta IQL \)) is dependent on base quality per dollar, the impact of gap (difference in Quality Level and Target Quality Level), and the funds spent for quality improvement. Quality can be improved by applying various strategies at the process and sub-process level in the manufacturing network. The incremental improvement in quality level represents the change in quality level due to process improvements and is computed as:

\[ \Delta IQL = (BQ/$) \times G_{TQL-QL} \times (C_i) \]  

Where:

- BQ/$ = base quality per $
\( G_{TQL-QL} \) = impact of gap in quality level from target, \( 0 < G_{TQL-QL} < 1 \)

\( C_t \) = funds available for quality improvement or dollars spent per improvement cycle.

Total expenditure related to quality improvement can be expressed as:

\[
C_{\text{Total}} = \sum_{t=1}^{t=CQPi-1} C_t
\]

where:

\( C_t \) = funds spend on quality improvement at time \( t \),

\( C_{\text{Total}} \) = funds spent on quality improvement until the period before Crash Quality Point is reached.

These funds are required for improving the quality level of a process based on a desired target quality level. Defining “TQL” as the target quality level for the product and “QL” as the quality level at time “t” for the product, the value of the quality level gap is calculated. This can be defined as:

\[
\text{Quality Level Gap} = \text{TQL} - \text{QL}
\]

where:

\( \text{TQL} \) = Target Quality Level, and

\( \text{QL} \) = Quality Level of the process.

“TQL” at this stage is assumed to be the process quality level at which a product is produced that meets the current customer expectations. The factor: \( G_{TQL-QL} \) in
Equation 10 is a function of the value of the gap between the Quality Level (QL) and the Target Quality Level (TQL). The calculation of the gap and its impact on the improvement of the quality level resembles in some aspects the concept of Taguchi’s Loss Function. The quality loss function represents the costs associated with variation of the actual value from the target value. Taguchi’s Loss function is the cost associated with not having the required quality. Quality improvement programs, if implemented effectively, will result in the reduction of the gap between the current quality level and the desired target level. In the initial phases of quality improvement cycle, substantial improvements are relatively easy to attain due to the state of the process. These improvements, though relatively small, get management’s attention and funds continue to be allocated to the quality improvement cycle. In a typical manufacturing environment, quality improvement initiatives are frequently targeted to get the “low hanging fruit” first. As the process improves, the opportunities for improvement decrease. The once substantial or noticeable improvements are difficult to achieve as the process quality level approaches its maximum. The factor $G_{TQL-QL}$ captures the difficulty associated in attaining improvement in quality level as the process becomes stable and mature.

The relationship of quality level (QL) is plotted against time to capture the Crash Quality Point (CQP) for each process in the manufacturing chain. The quality level of the final node of the manufacturing network is computed as the sum of the allocated percentages of the proceeding processes in the manufacturing chain. The details on this methodology are discussed in the following chapter. The Crash Quality Point can be determined either at the sub-process or at the final process level.
"Crash Quality Point" Concept

Assuming a linear relationship, Figure 10 is a schematic representation of Quality Improvement Expenditure versus Quality Level.

![Diagram](image)

Figure 10. The concept of Crash Quality on the process quality level.

The Normal Point (NP) represents the state at which a company is producing a product with the process quality level (QL) at an expenditure of $C_N$. The product at this process quality level (i.e. QL) is below the customer’s expectation and there is room for improvement. The company may then resort to implementing quality improvement.
measures in an attempt to raise or meet the customer's expectation of quality. The component quality can increase through the implementation of quality improvement measures at the component and process level. This research defines "Crash Quality Point" (CQP) as the quality level (QL_{CQP}) at which, no matter what the increase in expenditure for quality improvement, the process quality level and hence the product quality will not improve. In fact, the productivity and quality may decrease to QL_{DR} as the expenditure increases to C_{DR} beyond the Crash Quality Point. The level of funding should be allowed for maintaining the quality level or until the process becomes stable.

Figure 11. Going beyond Crash Quality Point to a new level of customer expectation
Referring to Figure 11, several levels of customer expectation are depicted for the final product based on process quality levels $QL, QL_1, QL_2, \ldots QL_j$, where level $QL_{j+1}$ is a superior quality than $QL_j$. A linear relationship between one quality level and the next is assumed for simplicity. Each plane in the Figure 11 can also represent one generation for the product. At $QL$, a company may adopt quality improvement initiatives or re-engineering on the process and sub-process level, which may result in raising the quality level of the process to $QL_1$. To increase customer’s expectation, or to “delight” the customer, the company may consider redefining the quality level (i.e., moving from $QL$ to $QL_1$ to $QL_2$, etc.) through customer awareness programs. This is similar to searching for a new S-Curve as in the case for innovation (Foster, 1986). The CQP concept can be applied in case of an organizational intervention that is classified as an “innovation.” The CQP concept enables the organization to decide when to maintain the quality improvement program or re-engineer the process.

The relationship of quality level and the expenditure between the normal point, the Crash Quality Point and beyond, is a function of the measure(s) adopted for improvement. In a linear relationship, the slope represents the rate of expenditure with respect to improvement in quality. Companies, in their quest for “continuous improvement,” may continue spending on quality improvement with the same rate, without paying much attention to amount of improvement attained through each improvement iteration. The result could be a loss of quality and productivity. Unless there is an increase in customer expectation and value, additional expenditure in some cases may not be justified. Considering Figure 12, and assuming customer expectation
has increased, expenditure can then be justified, which would contribute to the increase of the final product in its quest to the "new and higher" customer expectation.

Figure 12. The concept of Crash Quality on the component level.

**Significance of the "Crash Quality Point" Methodology**

Organizational performance is the degree to which an organization attains the pre-defined goals, strategic plans, or Hoshins (King, 1989). Measures of organizational performance include: effectiveness, efficiency, quality, profitability, quality of work life, and innovation (Sink, 1985). Thor (1993) proposes "The Family of Measures", which
include: productivity, quality, timeliness, cycle-time, utilization, creativity or innovation, and outcome. Mann (1994) lists a set of Strategic Business Performance (SBP) measures and Operational Business Performance (OBP) measures. Some SBPM includes profitability, market share, productivity, sales turnover, and changes in customer base. The OBP measures include Supplier measures, process measures, policy deployment measures, people measures and customer relationship measures. Some organizations define a set of Key Process Indicators (KPIs). Of the 15 organizations surveyed by Sinclair (1995), 14 had developed KPIs. These included: customer satisfaction, quality, delivery, employee factors, productivity, financial performance, and safety. The tracking of these KPIs is performed through period performance appraisal and assessment by senior and mid-level management. The assessment could be “Break-Point” Assessment techniques, which are intended to provide evidence of significant gaps in current performance, thereby providing performance targets and directing improvement efforts.

Organizational improvement initiatives can be confusing since similar activities and initiatives carry a variety of names, depending on whether the major theme is quality, productivity, customer satisfaction, excellence, competitiveness, zero-defects, continuous improvement, kaizen, etc.

The concept of “Crash Quality Point” can be used to evaluate when further spending on quality initiatives has minimum or no impact. This data in turn can be linked to measure the overall organizational performance. Organizational improvement at all levels could be via continuous improvement, re-engineering or innovation. Various cases of continuous improvement in reference to Crash Quality Point are discussed next.
Continuous Improvement and Innovation

The concept of CQP applies to continuous improvement (CI) and innovation. Continuous improvement (CI) versus innovation are two contrasting methods of organizational improvement. One is a gradual incremental approach and the latter is a "leap-frog" approach (Imai, 1986). The effects of CI are subtle, while innovation is dramatic. Figure 13 depicts a case of innovation that is characterized by a step pattern.

The investment related to innovation is huge in comparison to CI. Innovation results in a sudden burst of progress, while CI is a gradual progress. In most cases, innovation requires CI to sustain the change. This is due to the fact that once an "innovation" is implemented or launched, efforts are required to maintain and improve the innovation. Figure 14 illustrates the case of innovation without CI.

47
Continuous improvement is required to change, sustain, and maintain the status quo of organizational improvement. Figure 15 depicts the case of CI and innovation.
Case I: CI pursued as a means for organizational improvement

In the case of CI, quality could be one of the measures of organizational performance (*one could also look at CI as being made up of a series of infinitesimally small innovations*). The voice of the customer plays a role in determining whether further CI is required passed the CQP, or if CI efforts can be limited. The need for CI may also hinge on organizational goals/Hoshins. The concerned manager will have to decide on re-defining or setting the measure to a new level. The outcome of this research will enable managers to determine if additional expenditure on improvement is feasible or whether to continue "As-Is" if CQP is reached. The state of continuing in the "As-Is" mode after CQP is reached is important, since in the absence of an assessment tool, there is a tendency to implement improvement programs on stable and mature products or processes, resulting in poor results. However, there is also a need for maintaining the quality effort and initiatives to maintain the status quo.

Case II: Innovation as an organizational improvement intervention

Sink (1989) defines innovation as "*the creative process of changing to successfully respond to internal and external pressures, opportunities, challenges, threats.*" Innovation from this definition depends highly on the change and the success it brings along with the event. Innovation results in immediate gains (tangible and intangible), and instant attention and recognition. The proposed methodology for CQP resembles the S-Curve presented by Foster (1986).
Figure 16 describes the S-Curve and is a relationship between the effort put into improving a product or process, and the return on investment (ROI) associated with the improvement. The performance during the initial phases of the life cycle of a new product or process is very slow. With the accumulation of knowledge and the definition of performance measures, performance grows. Foster proposes that the top of the S-Curve is where the point of diminishing returns is reached. At this point, one may improve the current process or innovate (i.e., focus efforts on developing and searching for another S-Curve). Figure 17 illustrates this concept. There is an analogy between the S-Curve theory and CQP concept. In the CQP concept, one looks for a new quality level and this level could also be considered similar to a S-Curve (refer to Figures 11, 12 and 17).
The next chapter presents the proof of concept and elements of the Crash Quality Point.
The concept of Crash Quality Point (CQP) is unique when compared to the methods found in literature. This approach enables managers to evaluate spending alternatives and also identify when further spending on quality improvement activities may not be justified. The CQP concept also involves some high level decision making with minimum data. The *ithink®* language is used to illustrate and model the concept of Crash Quality Point as proposed in this research. To facilitate a greater understanding of the CQP concept, prompted the use of mapping language. The process of mapping produces operating relationships within an organization or a map of the underlying strategy.

**Software Selection**

The concept of Crash Quality Point presented in the previous chapter does not lend itself easily for modeling with simulation languages such as MODSIM, SIMAN, etc. A review of the literature in the area of continuous improvement and modeling of complex systems revealed a better option. This is the *ithink®* language by High Performance Systems, NH. Besides the simulation feature, the package serves as a
business-mapping tool. The software enables visualization of the interrelationships that constitute a process, a strategy, or an underlying organizational issue. The *ithink®* language helps to focus attention in equal measure on all component parts of a process/system. The *ithink®* mapping language also lends itself to an easy extension of the future CQP model. This was a major advantage for future model customization based on business specific data and quality improvement initiatives.

*ithink® Model Entities*

The *ithink®* mapping language software is icon built around three fundamental building blocks of processes: flows, accumulations and information feedback linkages. Accumulations occur in all functional areas within an organization. Examples of accumulations in a manufacturing environment include raw materials, work in process inventories, finished goods, labor, etc. Examples of flows include deliveries, productions, consumption of materials, etc. Key *ithink®* model entities that are used in the modeling of the CQP concept are described next. Table 4.1 lists the basic building blocks used modeling the CQP concept.
Table 4.1: *ithink®* building blocks.

<table>
<thead>
<tr>
<th><em>ithink®</em> Building Block Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Stock symbol" /></td>
<td>Stock</td>
</tr>
<tr>
<td><img src="image" alt="Flow symbol" /></td>
<td>Flow</td>
</tr>
<tr>
<td><img src="image" alt="Converter symbol" /></td>
<td>Converter</td>
</tr>
<tr>
<td><img src="image" alt="Connector symbol" /></td>
<td>Connector</td>
</tr>
</tbody>
</table>

**Stocks**

Stocks are signified by rectangles as illustrated in Table 4.1 and are the nouns of the *ithink®* language. The magnitude of the stock at a point in time indicates how things “are” at that point in the time. The magnitudes of Stocks persist even if the magnitudes of all the activities fall to zero. Stocks thus serve as barometers of conditions within the system. In the model for Crash Quality Point, the following were modeled as stocks: individual process quality levels, final quality level of the end process, and the total funds spent on quality improvement in the model for the proposed research.
Flows

Flows are the verbs and only they can change stocks. Flows are used to depict activities and are of several types. Flows are signified by a spigot, flow regulator, and one or two attached arrowheads. The schematic of a flow is indicated in Table 4.1. The flow follows the pipe, in the direction indicated by the arrowhead. The algebraic expression or number that is entered in the flow regulator calculates the flow volume.

Figure 18 indicates the use of stocks and flows in the model for this research. Referring to the figure, the value of the quality level stock increases as a result of the flow, “improving quality.” The stock, “Cume Spending 1,” tracks the total dollar value of the funds spent on quality improvement.

Figure 18. The accumulation of stocks as a result of flows in the CQP model.
Converters

Converters often function as adverbs, modifying the flows within a system. They are represented as a circle (refer to Table 4.1). Converters convert inputs into outputs and represent either information or material quantities. They are often used to break out the detail of the logic which otherwise would be buried within a flow regulator. Frequently they represent “score-keeping” variables such as cost, cycle-time, profit, etc. Unlike stocks, converters do not accumulate. The value for a converter is recalculated each time calculations are performed. Figure 19 shows converters, “Spending Rate 2” and “Total Spent Process 2,” as modeled for the proposed CQP concept.

![Figure 19. Spending and Total Spent converters in the CQP Model.](image)

Figure 20 illustrates various converters in the CQP model that impact the flow, “Improving Quality 1,” which in turn affects the value of the stock, “Quality Level Process 1.” From Figure 20, the converter, “gap 1,” calculates the difference between
target quality (i.e., converter-target qual Process 1) and quality level at any given point in time (i.e., stock: Quality Level Process 1). The dialog box for the converter, "gap 1," is shown in Figure 21.

Figure 20. Converters

Figure 21. Dialog box for converter- gap 1.
The converter, "qual\$ Process 1" (for process 1), combines input from two converters; base qual\$ Process 1 and impact of gap 1 (refer to Figure 22).

Figure 22. The quality per dollar converter (qual\$).

The Connector

Connectors link stocks to converters, stocks to flow regulators, flow regulators to flow regulators, converters to flow regulators and converters to converters (refer to Table 4.1, Figures 19 and 20). Connectors represent inputs or outputs and do not take on numerical values. They merely transmit values taken on by other building blocks within the model.
The CQP Model

As proposed in the earlier chapter, the processes that form the manufacturing sequence for a product and the associated quality are represented in the form of a network. The nodes of the network represent an integration process with a given quality level. The key elements of the concept include the following:

1) Sequence of processes subject to quality improvement initiatives. The goal of the initiatives is to improve the quality level of the process from its initial level to a higher quality level, or the desired "target" quality level.

2) The funds available for these quality improvement initiatives are consumed on a monthly basis.

3) The rate or pattern of quality improvement over time.

4) Relationship of the spending of the funds available and the associated improvement in quality level. The plot of this relationship and analysis of the output is used to illustrate the concept of Crash Quality Point (CQP).

The Modeling of the Pursuit of Target Quality Level

The quality improvement initiative in the context of this research involves the improvement of the quality level of the targeted process(es). The goal is to improve the quality from its current state to a desired or target value. This target value in the model is defined as the Target Quality Level. This target value for some processes may not equal the maximum improvement possible. The target quality level could be a factor of company reputation, customer expectation, inherent process characteristics, market,
company policy, and the competition. The stock adjusting template was incorporated when modeling for the Crash quality point. A schematic representation and equations of this template are shown in Figure 23.

\[
\text{flow} = (\text{target for stock} - \text{Stock}) \times \text{loss fraction} \\
\text{units/t} \quad \text{units} \quad \text{(units/units)t or 1/t}
\]

or

\[
\text{flow} = (\text{target for stock} - \text{Stock}) / \text{time constant} \\
\text{units/t} \quad \text{units} \quad t
\]

Figure 23. Generic structure of the stock-adjustment template.

In this case, the target quality level is modeled as a stock. The stock-adjusting template is used in scenarios to represent a flow of activity which adjusts a stock to target value. Whenever a gap or discrepancy exists between the stock and target, the flow will gradually adjust the stock toward its target level. Both the target and adjustment fraction are usually converters. The behavior of the stock-adjusting process is shown in Figure 24. Referring to the plot, the top curve is the pattern generated when the stock adjusts from above its desired level. The bottom curve is the pattern of stock adjustment from below. The pursuit of target quality level as used in the model is shown in Figure 25.
Figure 24. Behavior produced by the stock-adjustment process.

Figure 25. The modeling of the pursuit for target quality.

Base Quality Per Dollar (BQ/$)

It is evident from literature that many studies address quality improvement; however, many allude to, but do not specifically address the quality improvement
variables of time and rate of quality improvement. The factor Base Quality Per Dollar (BQ/$) is introduced in the model to indicate the rate of quality improvement in process quality level per dollar spent. It can be considered as equivalent to "rate or speed of quality improvement." The Base Quality Per Dollar in the model for Crash Quality Point represents the building of quality improvement per improvement dollar spent on a process. The values in the simulation vary between 0.01 and 0.1 or 1% to 10% of quality improvement per dollar. A high value of base quality per dollar (i.e., higher rate of quality improvement) might or might not benefit the organization. Perhaps, this could explain some quality program failures. The interface layer allows the user to select values appropriate to the business goals.

Quality Level (QL)

The quality level of the process in the model is modeled as a stock. The dialog box lists all the allowable inputs (refer to Figure 26) and a window to define the initial value of the stock (i.e., quality level of the process). This entity in the model will be identical for other processes captured; however, the initial quality levels can be varied for component to component.

The initial values of the Quality Level (QL) of each process are required as input for the dialog box above. This value is translated to a scaled value from 0 – 100 Quality Level units, with a value being the Target Quality Level or the maximum level pursued through the quality improvement program. The current state of the process and its impact on the final process quality is required for the definition in the CQP model.
Impact of Gap (G_{TQL-QL})

The stock adjusting template attempts to close the gap between the current quality level and the target quality level. In the initial phases of a quality improvement program, substantial improvements are relatively faster to attain due to the state of the process. The factor from the "impact of gap" converter used in the model serves to capture this concept. The output from the converter is a number between 0 and 1, and is based on the gap between the Target Quality Level and the value of the process quality level during the simulation.
As the gap between target quality level and current quality level narrows (i.e., approaches 1), the incremental improvements are smaller in proportion to those early in the process improvement cycle. From the graph illustrated in Figure 27, the output value from the converter for a gap of 100 quality level units is equal to 1 unit of the factor.

Relationship of Spending on Quality Improvement

The funds spent on quality improvement at each process are captured in stock and flow representation shown in Figure 28.
Figure 28. Tracking of funds spent on quality improvement.

The stock, "Cume Spending 1," tracks the total funds ($C_{Total}$) spent on improvements in process 1. The converter, "Spending Rate," represents the total funds available for quality improvement activities for that process per month ($C_t$). As seen from Figure 28, an ithink® slider is incorporated to allow for experimenting with the allocation of funds available. This representation can be duplicated for more than one process in the manufacturing chain.

**Verification of Concept**

The elements discussed earlier in the chapter, form the basis of the model used to illustrate the concept of Crash Quality Point. To depict a typical sequence of the manufacturing/fabrication process, two scenarios were modeled: a single level three-stage process and a double level three stage process (i.e., a process with one or more sub-
processes). Both cases involve spending equal amount of funds for improving the quality level. These two cases are discussed in detail below.

Case 1: A Single Level Three Stage Process

In this scenario, the concept of CQP was applied on a sequence of three processes. Referring to Figure 29, Process 3 is the final process in the manufacturing sequence for a product.

![Illustration of a sequence of processes](image)

Figure 29. Illustration of a sequence of processes used in Case 1.

The quality level of process 3 is a result of the quality levels of the preceding two processes. Therefore, the resulting quality level (i.e., quality level for Process 3) is a summation of the individual quality levels of Process 1 and Process 2. Prior to directing any quality improvement efforts to the processes involved, it is imperative that the impact of each process on the final quality level within the manufacturing chain be estimated.
This requires the allocation of the resulting quality level of the final process in terms (i.e., percentage) of the quality level in preceding processes. The interface level of this case is shown in Figure 30. The interface enables the users to change settings on the variables within the model without changing the model code. The listing of the code is included in Appendix B.

Referring to Figure 30, the following values can be varied at the interface level: target quality levels, spending rate (funds available), base quality per dollar, and the allocation per process. The Target Quality levels, spending rates per process and base quality per dollar are varied at the interface level. The impact of gap factor (GTQL-QL) is
modeled as a graph and is displayed at the interface level via a graphical input device.

The stock adjustment template is used to capture the improvement in the quality level and the associated costs. The final (or total) quality level of the end process is a function of the quality levels of the two preceding processes. This is only required in the event of determining the impact of quality improvement on the final or end process. The allocation of the quality level of each process at the final process stage is based on a pre-calculated percentage. In this case the initial allocation of Process 1 is 35% and Process 2 is 65%. Figure 31 is a representation of the model layer.

Figure 31. Model for Case 1: Single Level Process.
Crash Quality Point- Case 1

The model was run using six sensitivity analysis settings and a time period of 24 months. The variables included in the sensitivity runs were target quality level, base quality per $, spending rates, and % allocation. The target quality levels were varied to capture the concept of moving from one target quality level to another. The variable settings for the six runs are listed in Figure 32. The ascending values of Target Quality levels for the runs illustrate the improvement of one quality level to the next (QL$_1$ to QL$_2$). The spending for these runs was varied from $1000 to $10,000 per month. The output from each of these runs for Case 1 is analyzed in the next section.
Output Analysis Case 1

The quality levels versus time for each of the sensitivity runs is shown in Figures 33-38. The numbers (1, 2, and 3) on each graph indicate the quality level plotted.
Figure 33. Output from Run #1.

Figure 34. Output from Run 2.
Figure 35. Output from Run # 3.

Figure 36. Output from Run # 4.
Figure 37. Output from Run # 5

Figure 38. Output from Run # 6.
On comparing the seven graphs, it is apparent that at spending rates below $6400 per month, the level of process improvement (quality levels) for the processes does not approach the target quality level. Funds, in this case, would have to be spent for longer periods before reaching the target quality value for the process. Referring to the graphs, when the spending rate is $10,000 per month, the target quality level is reached after the sixth month. Table 4.2 summarizes the time in months when the Crash Quality Point is reached for each run.

Table 4.2: Crash Quality Points for Case 1 sensitivity runs.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Funds Spent Per Process ($)</th>
<th>Target Quality Level Pursued</th>
<th>Time When Crash Quality Point reached (month)</th>
<th>Quality Level at End of Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>80</td>
<td>&gt;&gt;24</td>
<td>41</td>
</tr>
<tr>
<td>2</td>
<td>2800</td>
<td>84</td>
<td>&gt;&gt;24</td>
<td>71</td>
</tr>
<tr>
<td>3</td>
<td>4600</td>
<td>88</td>
<td>24</td>
<td>87</td>
</tr>
<tr>
<td>4</td>
<td>6400</td>
<td>92</td>
<td>12</td>
<td>91</td>
</tr>
<tr>
<td>5</td>
<td>8200</td>
<td>96</td>
<td>9.5</td>
<td>96</td>
</tr>
<tr>
<td>6</td>
<td>10,000</td>
<td>100</td>
<td>6.4</td>
<td>100</td>
</tr>
</tbody>
</table>

The Crash Quality Point for each run, is that point in time where the graph of the quality level begins to level off. Any spending beyond this point does not have an impact on the quality level compared to the period prior to the Crash Quality Point. Spending
past this point is futile and these funds could be spent on other quality improvement projects. In other words, the point of diminishing returns is reached. The model developed will assist managers in forecasting the budget requirements for quality spending based on the quality improvement goals. This tool also enables managers to estimate the point in time at which allocations of funds need to be reviewed. It should be recognized that estimation of expenditure versus quality improvement is a necessity for model implementation.

Figure 39: Quality level versus funds spent on process improvements.

Figure 39 is a plot of quality level and funds spent on the process improvement. The number on each curve corresponds to the simulation run number. The plot of quality level versus funds spent (i.e. expenditure on quality improvement) indicates that the
quality level begins to level-off after the desired target is reached. This could signal the need for re-engineering of the process and defining a new quality level.

**Case 2: A Double Level Three Stage Process**

The double level three-stage process is a process with one or more sub-processes. Case 2 was addressed to capture a scenario in which one or more sub-processes make up a process that is part of another manufacturing chain. This is illustrated in Figure 40.

![Figure 40. A Double Level Three Stage Process (Process with one or more sub-processes).](image)

As seen in Figure 40, Process 3 is the final process, with inputs from Process 1 and Process 2. The interface level for this case is shown in Figure 41. The interface level for this case is similar to that in Case 1. The difference lies in the additional sliders and
knobs for sub-processes within the main process chain (process 1 and 2). A printout of the associated code for this case can be found in Appendix C.

Figure 41. Interface level for Case 2.

The interface level for this case is split into two screens: the main interface level, and the sub-process details of the model. Figure 42 shows the additional details from the interface layer for the model.
Figure 42. Sub-process details interface layer for Case 2.

The model layer for Case 2 is shown in Figures 43-46. The concepts used for case 1 were also used for Case 2. The sector and space compression objects were used to capture the process and sub-process level details for each of the processes. These features enable the user to navigate through the model with ease.
Figure 43. Sector representation for process 1 and sub-process 1A and 1B.
Figure 44. Process 2 and sub-processes represented by a space compression object.

Figure 45. Sub-process 2A and 2B.

Figure 46. Calculation of the final quality level (Process 3).
Crash Quality Point- Case 2

The model was run using six sensitivity analysis settings. The variables included in these sensitivity runs include target quality levels, base quality per $, and spending rates. The different target quality levels were selected to illustrate the increasing of quality level (from QL₁ to QL₂). The spending rates for this case were similar to Case 1. It was varied to assess the impact of funds available for quality improvement. The variable settings for various runs are shown in Figure 47.

<table>
<thead>
<tr>
<th>Setup #1</th>
<th>Sun, Sep 03, 2000 12:25 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Variables</strong></td>
<td></td>
</tr>
<tr>
<td>Run #</td>
<td>target qual Process 1</td>
</tr>
<tr>
<td>1</td>
<td>80.0</td>
</tr>
<tr>
<td>2</td>
<td>84.0</td>
</tr>
<tr>
<td>3</td>
<td>88.0</td>
</tr>
<tr>
<td>4</td>
<td>92.0</td>
</tr>
<tr>
<td>5</td>
<td>96.0</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run #</th>
<th>base qual $ Process 1</th>
<th>Spending Rate 1</th>
<th>base qual $ Process 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>1000</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>0.028</td>
<td>2800</td>
<td>0.028</td>
</tr>
<tr>
<td>3</td>
<td>0.046</td>
<td>4600</td>
<td>0.046</td>
</tr>
<tr>
<td>4</td>
<td>0.064</td>
<td>6400</td>
<td>0.064</td>
</tr>
<tr>
<td>5</td>
<td>0.082</td>
<td>8200</td>
<td>0.082</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>10000</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run #</th>
<th>base qual $ Process 1</th>
<th>Spending Rate 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>0.028</td>
<td>2800</td>
</tr>
<tr>
<td>3</td>
<td>0.046</td>
<td>4600</td>
</tr>
<tr>
<td>4</td>
<td>0.064</td>
<td>6400</td>
</tr>
<tr>
<td>5</td>
<td>0.082</td>
<td>8200</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>10000</td>
</tr>
</tbody>
</table>

Figure 47. Screen shot of Case II variable values for six sensitivity runs.
Output Analysis- Case 2

The quality levels versus time for each of the sensitivity runs is shown in Figures 48-53. The numbers (1, 2, and 3) on each graph indicate the quality level plotted.

Figure 48. Output from Run # 1.
Figure 49. Output from Run # 2.

Figure 50. Output from Run # 3.
Figure 51. Output from Run # 4.

Figure 52. Output from Run # 5.
The model was run using six sensitivity analysis settings. Referring to the graphs on the earlier pages, the final process quality levels and the quality levels of the sub-processes begin to level out at various points in time. This is dependent on the funds spent on quality improvement initiatives. Table 4.3 summarizes the time in months when the Crash Quality Point is reached for each run.
Table 4.3: Crash Quality Points for Case 2 sensitivity runs.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Funds Spent Per Process ($)</th>
<th>Target Quality Level Pursued</th>
<th>Time When Crash Quality Point reached (month)</th>
<th>Quality Level at End of Simulation Process 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>80</td>
<td>&gt;&gt;24 months</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td>2800</td>
<td>84</td>
<td>&gt;24 months</td>
<td>81</td>
</tr>
<tr>
<td>3</td>
<td>4600</td>
<td>88</td>
<td>12.8</td>
<td>94</td>
</tr>
<tr>
<td>4</td>
<td>6400</td>
<td>92</td>
<td>8.1</td>
<td>97</td>
</tr>
<tr>
<td>5</td>
<td>8200</td>
<td>96</td>
<td>6.5</td>
<td>98</td>
</tr>
<tr>
<td>6</td>
<td>10,000</td>
<td>100</td>
<td>5.5</td>
<td>100</td>
</tr>
</tbody>
</table>

For spending levels below $4600 per month, the Crash Quality Point or the Target Quality Level is not reached in the simulation time period. For spending rates of $4600 per month and above, the target value of the quality is reached before the end of the simulation. From Table 4.3, it is apparent that in the absence of the CQP method/tool, funds would have been wasted past the CQP. A higher rate of spending ensures that the improvement in quality level is attained in a shorter time span. Spending past this point does not improve the quality further. The funds at this point in time could be directed for the re-engineering of the process or sub-processes. The model in this case enables program managers to suspend or re-evaluate spending on quality improvement initiatives. The case also shows a saving after the detection of the Crash Quality Point with the optimal allocation of funds based on quality level.
Case 3: CQP with allocation of funds based on the state of the process

Models for Case 1 and Case 2 presented earlier assume that equal amount of funds are spent on the processes for quality improvement. These models do not direct funds to a process based on the quality level of the process. However, in some cases managers, due to budget constraints, are compelled to select between processes for spending allocated funds during the quality improvement cycle. A model was formulated based on principles of the models presented earlier with the option of allocating the available funds.

Figure 54. Interface Level- Case 3.
The interface level for this model is shown in Figure 54 and the model layer in Figure 55. The code listing for this case is included in Appendix D. The selection between process 1 and 2 is based on the comparison of the quality levels of process 1 and 2 at the each time interval.

![Model Layer for Case 3](image)

Figure 55. Model layer for Case 3.

The selection process in the model is shown in Figure 56 and is based on a comparison of the gap between Target Quality Level and the Quality Level for each process. The allocation of funds available is based on a percentage and can be set at the
interface of the model via the slider titled “allocation of monthly funding.” The figure also shows the representation of stocks, flows and converters used in the model to allocate funds between process 1 and 2. The funds are allocated between the processes via the “Process to Spend Switch” which compares the values of Gap 1 and Gap 2.

![Diagram of process selection based on quality level.](image)

**Figure 56.** Process selection based on quality level.

**Output Analysis**

The model for this case was run under five settings of monthly funding ranging from $10,000 per month to $50,000 per month with Target Quality Level for each process.
set at 100 quality level units. Refer to Figures 57-61 for a printout of the graphs for each run. The difference in this model is that the quality level gaps of the two processes are compared at each time interval. The funds are then allocated to the process with the higher value of the difference between Target Quality Level (TQL) and quality level (QL).

Figure 57. Output from run # 1.
Figure 58. Output from run # 2.

Figure 59. Output from run # 3.
Figure 60. Output from run # 4

Figure 61. Output from run # 5.
From Table 4.4 and the graphs, the Crash Quality Point is reached at varying stages in the improvement cycle. The Target Quality Level for this case is set at a 100 quality level units. Table 4.4 summarizes the key values from the sensitivity runs for this case.

Table 4.4: Summary of data from Case 3 runs.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Monthly Funding Rate ($)</th>
<th>CQP Reached at (Month)</th>
<th>Cumulative Funds spent until CQP ($)</th>
<th>Total funds spent during simulation period of 24 months ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Process 1</td>
<td>Process 2</td>
</tr>
<tr>
<td>1</td>
<td>10,000</td>
<td>&gt;&gt; 24</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2</td>
<td>20,000</td>
<td>19</td>
<td>191,297</td>
<td>187,988</td>
</tr>
<tr>
<td>3</td>
<td>30,000</td>
<td>14.88</td>
<td>224,289</td>
<td>220,763</td>
</tr>
<tr>
<td>4</td>
<td>40,000</td>
<td>10.75</td>
<td>219,661</td>
<td>209,911</td>
</tr>
<tr>
<td>5</td>
<td>50,000</td>
<td>8.25</td>
<td>215,430</td>
<td>190,956</td>
</tr>
</tbody>
</table>

From Table 4.4, it is evident that considerable amount of savings could be realized with the tool and methodology developed in this research. The special case also illustrates the use of this tool in the selection of processes for improvements based on the quality level of the process. The higher the allocated monthly funds, the earlier the Crash Quality Point is reached. From the printout of the table, it is apparent that funds are allocated based on the current quality level and a selection is made based on state of the
process. This is an added advantage in scenarios where funds are limited and management is compelled to improve process quality.

**Model Validation**

The access to data required and the format that fit the CQP model for the validation stage posed a challenge for this research. The search for a real world example to validate the CQP concept included this researcher’s company products and vendor supplied assemblies. The examples or cases illustrated in various journal articles reviewed were also analyzed to determine its feasibility for the validation phase. The data presented in most examples included the traditional costs of failures and did not include the costs associated with the improvement initiatives. The additional details required as defined in the CQP model were not included (e.g., funds available at the onset of a quality improvement program, level of improvement sought, rate of improvement, etc.).

The data collected as the cost of quality (COQ) from this researcher’s employer revealed some shortfalls in the method of classification and collection of these costs. The COQ was defined as the sum of dollars in a quarter for:

(a) Installation Net Material Cost,

(b) Gross Labor Cost,

(c) Warranty Net Material Cost,

(d) Warranty Gross Labor Cost,

(e) Installed Bases Service and Support (IBSS) Spares Warranty Cost,
(f) Discrepant Material Report (DMR) Processing Cost,
(g) E & Z Actual Cost,
(h) Spares (IBSS) quality,
(i) Scrap Cost,
(j) Retrofit Cost,
(k) Manufacturing Expediting Cost, and
(l) Final Test Cost.

The data also revealed that the cost associated with improving the various processes were either not captured or were not defined as a COQ metric. Costs associated with quality improvements, if tracked, were difficult to trace in the maze of COQ metrics. This observation is in agreement with those mentioned in the literature reviewed. However, with coordination with several manufacturing engineering (ME) and supplier quality engineering (SQE) groups, an example of a manufactured part was identified. Details on the component and the processes involved are described next.

Case Study- Background Information

The part selected for the validation of the CQP model is a chamber inner shell for a wafer fabrication equipment model. The chamber shell, when installed with the process kits, forms the chamber body. The wafers, and therefore chips (i.e. DRAMS, RAM, etc.), are processed in the chamber body. Each wafer fabrication equipment may have one or more chambers depending on the chip manufactured. A front view of the chamber shell is shown in Figure 62.
The part goes through a series of manufacturing and assembly steps prior to installation on the wafer fabrication equipment. For the validation of the CQP model, the fabrication process of the chamber shell was considered. The manufacturing network for the chamber shell indicating the sequence of operations is shown in Figure 62.

Figure 62. Part used in the validation phase.
There are three deep bores made into the side of the part to create and connect internal passages. These holes form the water channels that penetrate to the outside of the part in three places. These penetrations are plugged and then fusion welded shut in order to seal them off. All of these bores form an acute angle with the side of the part, two of them, extremely acute, are plugged and then welded shut (refer to Figure 64). Two of the holes break out at a $25^\circ$ angle. The configuration leaves a relatively thin wall between the side of the part and the wall of the bore. This results in a large, isometric heat affected zone, which makes one side of the plug respond much differently to the weld process than the other. In addition, this area is sanded flush to the surface and etched through chemical cleaning. The end result is a weld seal where there is no practical way to know or even predict how well the plug has fused to the parent metal. Dimensions in Figure 64 have been concealed to maintain confidentiality.
Figure 64. View of the part after milling, plug weld and a cross-sectional diagram of the plug weld.
The assembly is leak tested through Helium and hydrostatic means. After the change to ISO threads, the special fittings are tested with the hydrostatic method that involved using non-standard fittings. The Lee Plug is then installed in the next step as shown in Figure 66.
The product, in its current design state, is totally dependent upon the effectiveness of end-of-process testing. A quality improvement project included a goal of modifying the design that yields a very high degree of confidence regardless of end-of-process testing.

Quality Improvements

Failures of the chamber (on the wafer fabrication equipment) at the customer's facility led to an internal investigation of the root cause. The cost associated with the wafer fabrication equipment downtime, customer confidence and prospects for future business could easily total in the million-dollar range. Prior to improvements, the failure rate was in the magnitude of 90% (or 9 rejects for every 10 assemblies shipped) when assembled on the wafer fabrication equipment. The Failure Analysis resulted in the findings that the causes of defects were due to: the installation process of the Lee Plugs, the side weld of the plates, and the plug weld and fittings used (i.e., ISO Vs NPT).

A design change was recommended to make the side pockets on the same part where a plate is welded into a designed relief with the weld crown left intact. In this way, the wall thickness is the same all around the weld seam. The penetration and fusion can be more easily controlled and visually evaluated after cleaning. Thus, the integrity of the weld is least affected by hand finishing and cleaning. The design of the side weld with good weld relief was also used for the redesign of the plug weld. To enhance the weld design, there was a need for a chamber to enable weld overflow on all sides of the plug weld. The analysis also led to the training of the workforce for correct installation of the
Lee Plugs. The NPT fitting caused leaks when connected to the Helium leak tester. The change from a NPT to ISO type fittings, and the use of a special o-ring eliminated the leak.

Table 4.5 summarizes the quality levels of each process prior to launching the quality improvements described above.

Table 4.5: Quality levels for the case study.

<table>
<thead>
<tr>
<th>Process</th>
<th>Impact of each process on final Quality Level (percentage)</th>
<th>Initial Quality level (QL)</th>
<th>Target Quality Level Pursued (TQL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Weld</td>
<td>10</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>Install Lee Plug</td>
<td>5</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>Plug Weld</td>
<td>55</td>
<td>45</td>
<td>100</td>
</tr>
<tr>
<td>Install Fitting</td>
<td>30</td>
<td>70</td>
<td>100</td>
</tr>
</tbody>
</table>

The initial quality levels (QL) were translated to a scale from 0 –100 quality level units. This was done on the basis of the impact of each process on the quality level and interviews with the engineering personnel involved with the project. The impact of each process on the final quality level was a result of the failure analysis. These percentages were also verified at the data collection stage for this study. The estimated costs per month budgeted for this project was $7000/month. These included labor costs of engineering and related manufacturing personnel. These personnel were also tasked with
other improvement projects in addition to their daily responsibilities. The allocation of these funds to the four processes targeted for improvement was based on the percentage impact of each process on the final quality level. The interface level for this case is shown in Figure 67.

Figure 67. Interface level for the case study.

The ithink®-chained slider was incorporated at the interface level to allocate the monthly funding available. The target quality level for all processes was set to 100 quality level units. The ithink® numeric display object was used to display the quality
level and total funds spent on the processes targeted for improvement. A time period of 12 months was selected for this case. An additional interface level (refer to Figure 68) was created to allow any user to input the initial quality level for processes under consideration. This screen eliminates the need for the user to search the model entities for definition of key CQP parameters.

The model layer for the model is shown in Figure 69 and the code listing is included in Appendix E. The entities for this model are similar to those formulated in case 1 and 2. The only difference is that the budgeted amount for the improvement project is allocated based on the percentage of impact of each process on the final quality level.
Figure 69. Model layer for case study.
Output Analysis – Validation Case

The output graph for the validation case is shown in Figure 70. Table 4.6 summaries the Crash Quality Points for each process.

![Graph](image)

**Figure 70.** Quality Level versus time for the processes targeted.

**Table 4.6: Summary of CQP for each process.**

<table>
<thead>
<tr>
<th>Process</th>
<th>Initial Quality Level</th>
<th>Crash Quality Point Reached at (month)</th>
<th>Funds Spent Over Entire Simulation Period (i.e. 12 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug Weld</td>
<td>45</td>
<td>2.38</td>
<td>27,720</td>
</tr>
<tr>
<td>Side Weld</td>
<td>90</td>
<td>5.5</td>
<td>5,040</td>
</tr>
<tr>
<td>Install Lee Plug</td>
<td>95</td>
<td>5.25</td>
<td>2,520</td>
</tr>
<tr>
<td>Install Fitting</td>
<td>70</td>
<td>3.5</td>
<td>15,120</td>
</tr>
</tbody>
</table>
From the summary table, it is evident that the funding of the improvement project past the Crash Quality Point results in a waste of quality improvement dollars. The results from the model were discussed with the team involved in this process improvement effort for concurrence on the results. From discussions with the personnel involved, it was evident that the availability of such a tool prior to the launch of an improvement project would be beneficial. This tool, if used, would enable the projection of the expected improvement in the quality level. In addition, the timeframe in which this improvement would be expected can be determined.

The method and tool developed enables quality improvement professionals to forecast the impact of the allocated funds. The method assumed that funds would be allocated based on the quality level of the process in the manufacturing network. However, in some cases, managers may choose to allocate equal amounts to all processes requiring continuous improvement. This may depend largely on the budget constraints and the severity of the need (customer complaints, business conditions) at the time of launching the quality improvement initiative. From this validation case, the CQP model proposed is applicable in a real world scenario.
This research focused on developing a methodology for determining the point at which the target quality level is reached. Spending past this point will not result in substantial improvement of the quality level. The research defined this point as the "Crash Quality Point (CQP)" and signifies the point in time when further spending on quality improvement needs to be re-evaluated. Cases of a single process level and double level three-stage process were modeled to conceptualize CQP. The target quality level was reached based on funds allocated per month for quality improvement. The quality level approaches the target quality level at varying points in time. Businesses are usually faced with a finite amount of funds to allocate towards process improvement. In some settings, the CQP is never reached. Thus, one could continue to spend on quality improvement and never attain the target level sought. A special case of selecting between processes based on process quality level is presented. This model allocated funds available based on the state of the process. The methodology was validated using a real world example from a wafer fabrication equipment model.

The model, with its user-friendly interface, allows management to assess the impact of spending quality improvement dollars. Graphs help to visualize at what period the Crash...
Quality Point is reached. The model could also be used as a forecasting tool to budget the required funds for quality improvement. With the right mix of organizational measures, the concept of “Crash Quality Point” can be used to evaluate the impact of improvement initiatives on the overall organizational performance. The model developed here is versatile and can be used in various situations involving quality improvement.

Limitations

The model used to conceptualize Crash Quality Point assumes that a process will always continue to improve towards its target quality level. The model does not account for any draining or deteriorating of quality due to other factors in the process. In other words, quality improvement initiatives will always result in some improvement. However, machines may lose some capability over time, management/regulations change, employee morale, etc. may impact quality level at various points in time.

The model requires an analysis of the process quality level at the end process in terms of preceding processes. The cases illustrated involve the estimation of the percentage impact of each process in the manufacturing chain on the quality level of the final/end process. In a complex process, this may be difficult to estimate or calculate. The solution in this case would be to treat each process separately and then subject it to quality improvement simulation using the CQP model.
Future Research and Expansions to the CQP Model

There are several opportunities for future research with respect to the model presented for Crash Quality Point. From the sensitivity runs conducted, the impact of the base quality per dollar could not be captured or was found to be minimal. This could be explored further to model the factors that would relate to base quality per dollar. Such issues that could also be included in the new model are new machines, perception of quality level in the market place, and the impact of “word-of-mouth” in the market place. Since the allocation of individual quality level in the quality level at the end process is based on some percentage value, the opportunity exists for developing a more efficient method for calculating these process allocations.

Another area is the development of the acceptable percentage change for quality improvement. Depending on the industry, infinitesimally small change in quality level may be tolerated, and in some cases warranted. This would mean that the area on the curve for the Crash Quality Point for one industry might not be the same for another type of industry. Also, the costs associated with increasing the quality level from one level to the next may result in an increase of production costs, which translates to higher prices for the customers. On the other hand, the improved processes, as a result of increasing the quality level, gives the firm the opportunity to compete (e.g., increased customer perception, increase in the expected life of the product, additional features, etc.). It is essential to understand the trade off between the price of the product and the value of the increased quality level to the customer. After recognizing the customer’s preference, the decision-maker can come up with the level of quality suitable for their market.
Adding resource constraints may also add value to the model. When launched, quality improvement programs shuffle resources from current production, and limit time available for subsequently added improvement programs. The model could be expanded to incorporate the resource availability at each stage of the quality improvement cycle. The expansion of the model could include sequencing/selection of new quality improvement programs. The importance of one quality improvement program over the other may dictate the selection of the quality improvement initiatives. The need to keep pace with competition and satisfy the specific requests of customers forces operational managers to choose one initiative over the other. The CQP method and the tool developed can be expanded to enable managers to make the right decision before embarking on a quality improvement initiative of any magnitude.
Appendix A

Equations to select research reviewed in Chapter 2
EQUATIONS FROM VARIOUS ARTICLES REFERENCED IN CHAPTER 2

Productivity and Quality Evaluation Procedure (PAQEP), Edosomwan (1991)

The mathematical expressions for PAQEP are presented below:

\[ QPR_{(i,t)} = [QP_{(i,t)} \times QF_{(i,t)}] + [PP_{(i,t)} \times PF_{(i,t)}] + [(100 - QP_{(i,t)}) BF_{(i,t)}] + [(100 - PP_{(i,t)}) \times BF_{(i,t)}] \]  
\[ QF_{(i,t)} + PF_{(i,t)} + BF_{(i,t)} = 1 \]  
\[ ER_{(i,t)} = PP_{(i,t)} - QP_{(i,t)} \]  
\[ AP_{(i,t)} = PP_{(i,t)} - [ER_{(i,t)} \times EF_{(i,t)}] \]

Where:

- QPR: Quality Productivity Rating
- QF: Weighting Factor for Quality
- PF: Weighting Factor for Productivity
- BF: Weighting factor for other variables affecting the balance between productivity and quality
- ER: Error Rate in percent
AP: Adjusted Productivity in percent.

\[ i = 1,2,3, \quad n = \text{task} \]
\[ t = 1,2,3, \quad m = \text{period} \]

QP: Quality measure in percent

PP: Productivity measure in percent

RT: Task Ranking based on QPR

Keats and Sink (1982)

The formulae used to build the model are listed below:

\[(P)\text{rice} \times (Q)\text{uantity} = (V)\text{alue} \quad (5)\]

\[(P)\text{rice(outputs)} \times (Q)\text{uantity (outputs)} = (V)\text{alue (revenues)} \quad (6)\]

\[(P)\text{rice (inputs)} \times (Q)\text{uantity (inputs)} = (V)\text{alue (costs)} \quad (7)\]

\[P_{\text{in}} \times Q_{\text{in}} = V_{\text{in}}, \quad (8)\]

Where:

\[i = \text{a type of output or input},\]
\[Q = \text{quantities of output(O) or input(I)},\]
\[n = \text{a given period of time}.\]
Price weighted productivity change ratio = \frac{P_2 Q_2}{P_1 Q_1} \quad (9)

Quantity weighted price recovery change ratio = \frac{P_2 Q_2}{P_1 Q_1} \quad (10)

Profitability Change Ratio = \frac{P_2 Q_2}{P_1 Q_1} \quad (11)

Ramadan (1991)

Equations used in this model include:

\text{MAX./MIN. } U_{i-1,j} = \sum_{k=1}^{n} W_k \ast U_{ik} \quad (12)

\text{S.T. } A \leq U_{ik} \leq B \text{ for all } k \quad (13)

C \leq W_{ik} \leq D \text{ for all } k \quad (14)

\sum_{k=1}^{n} W_k = 1 \quad (15)

Where:

W_{ik} = \text{weight of the attribute } k \text{ at stage 1}

U_{ik} = \text{utility index for attribute } k \text{ at stage 1}
A, B = constant values for attributes’ weights
C, D = constant values for utilities indices

Esterby (1981)

The author proposes a productivity index (PI), which is defined as:

\[ PI = \frac{Q}{L+K+X} \]  \hspace{1cm} (16)

Where:

- Q = output
- L = labor
- K = capital stocks
- X = intermediate products, e.g. purchased components

The author combines quality costs analysis and productivity into quality productivity relationship. The above components of the productivity equation are re-defined in terms of quality activities. Labor is defined as an aggregate of: effective labor \( (L_e) \), labor that produces totally conforming or satisfactory products or services, and the labor component of failure costs, failure labor \( (L_f) \), appraisal labor \( (L_a) \), and prevention labor \( (L_p) \). Thus:

\[ L = L_e + L_f + L_p + L_a \]  \hspace{1cm} (17)
Similarly “K” is defined as:

\[ K = K_e + K_f + K_a \]  \hspace{1cm} (18)

Where:

- \( K_e \) = effective capital, capital that produce totally conforming or satisfactory products or services.
- \( K_f \) = capital associated with scrapped inventories, failure costs
- \( K_a \) = appraisal capital.

Intermediate products (X) are considered an aggregate of effective intermediate products (X_e) and failed intermediate products (X_f). Therefore:

\[ X = X_e + X_f \]  \hspace{1cm} (19)

Based on the above equations, a Quality Productivity Index (PI_q) is defined.

\[ PI_q = \frac{Q}{L + P + A + F} \]  \hspace{1cm} (20)

or

\[ PI_q = \frac{TR}{L + P + A + F} \]  \hspace{1cm} (21)

Where:

- Total Revenue: \( TR = p \times O \), i.e. price x output,
- Effective input: \( I_e = L_e + K_e + X_e \)
Prevention Costs: \( P = L_p \)

Appraisal Costs: \( A = L_a + K_a \)

Failure costs: \( F = L_f + K_f + X_f \)

**Kim and Liao (1994)**

The QLF measures the loss as a quadratic function of the deviation of the actual value from the target value of a product characteristic. Mathematically, the loss is determined by:

\[
L(y) = k(y - T)^2
\]  

(22)

Where:

\( k \) = a proportionality constant

\( y \) = actual value of the quality characteristic

\( T \) = target value of the quality characteristic

The value of \( k \) can be estimated by dividing the loss by the squared deviation of the specification limit from the target value. That is:

\[
k = \frac{c}{d^2}
\]  

(23)
Where:

c = loss associated with the specification limit

d = deviation of the specification from the target value

Therefore, the unit function becomes:

\[ L(y) = k_1[(y - T)^+]^2 + k_2[(T - y)^+]^2 \]  \hspace{1cm} (24)

where: \( k_1 > \) or \( < k_2 \)

The above equation would become a symmetric case of QLF if \( k_1 = k_2 \). In order to use the above equation, \( k_1 = k_2 \) must first be estimated.

\[
k_1 = \frac{c_1}{(U - T)^2}
\]  \hspace{1cm} (25)

\[
k_2 = \frac{c_2}{(T - L)^2}
\]  \hspace{1cm} (26)

Where:

U = upper specification limit of the characteristic

L = lower specification limit of the characteristic

T = target value of quality characteristic
\( c_1 = \text{loss associated with } U \)
\( c_2 = \text{loss associated with } L \)

In addition to presenting the asymmetric QLF, the author proposes different levels of sensitivity for each side of the QLF (i.e., certain parts of the loss function on each side). Variations around the target value are minimal and losses are not significant as compared to those outside the insensitive region. The equations required for each different regions of the loss function are:

\[
L(y) = \begin{cases} 
0 & \text{for } T \leq y \leq s_1 \\
\frac{a_1 k_1 (y-T)^2}{k_1 (y-T)^2 - (1-a_1)(s_1-T)^2} & \text{for } s_1 \leq y \leq U \\
\frac{a_2 k_2 (T-y)^2}{k_2 (T-y)^2 - (1-a_2)(T-s_2)^2} & \text{for } L \leq y \leq s_2
\end{cases}
\]

Where:
\( s_1 = \text{upper insensitive region limit of quality characteristic} \)
\( s_2 = \text{lower insensitive region limit of quality characteristic} \)
\( c_1 = \text{loss associated with } U \)
\( \text{c}_2 = \text{loss associated with L} \)

\( \text{b}_1 = \text{loss associated with s}_1 \)

\( \text{b}_2 = \text{loss associated with s}_2 \)

\( \text{k}_1 \) and \( \text{k}_2 \): two proportionality constants for each side of the loss function

\( \text{a}_1 \) and \( \text{a}_2 \): two adjustment constants used to scale down the loss function for the insensitive region and value ranges between 0 and 1.

Constant variables \( \text{a}_1, \text{a}_2, \text{k}_1, \) and \( \text{k}_2 \) must first be estimated before the above equation can be used to estimate the loss for a product. The formulae listed below are used to calculate these variables:

\[
\text{a}_1 = \frac{\text{b}_1[(U - T)^2 - (s_1 - T)^2]}{(\text{c}_1 - \text{b}_1)(s_1 - T)^2} \tag{30}
\]

\[
\text{a}_2 = \frac{\text{b}_2[(T - L)^2 - (T - s_2)^2]}{(\text{c}_2 - \text{b}_2)(T - s_2)^2} \tag{31}
\]

\[
\text{k}_1 = \frac{(\text{c}_1 - \text{b}_1)}{(U - T)^2 - (s_1 - T)^2} \tag{32}
\]

\[
\text{k}_2 = \frac{(\text{c}_2 - \text{b}_2)}{(T - L)^2 - (T - s_2)^2} \tag{33}
\]
Pessimistic Case: Quality Decreases with Increased Productivity

\[ Q(p) = Q(100) \exp \left[ -\frac{p-100}{100} \right] \]  
(34)

Where:

\( Q(p) \) = quality level (fraction of good items produced at performance level \( p\% \))

\( Q(100) \) = the quality level at normal (100%) performance

Optimistic Case: Quality Increases with Increased Productivity.

\[ Q(p) = Q(100) + \frac{1-100}{p}[1-Q(100)] \]  
(35)

Where:

\( Q(p) \) = quality level (fraction of good items produced at performance level \( p\% \))

\( Q(100) \) = the quality level at normal (100%) performance

The equations for the costs associated with the performance, production and quality
levels is stated as:

\[ \text{Cost} = [\text{Tot}(p) - \text{Tot}(100)] (I + M + Pr) + (p-100) IP + [\text{Tot}(p) [1-Q(p)] - \text{Tot}(100)] [1-Q(100))]D \]  
(36)

Where:

\( P \) = performance level (%)

\( I \) = inspection cost per unit
M = material cost per unit

Pr = processing cost per unit

Q(p) = proportion of good units at performance p

D = cost of defective unit

Tot(100) = total output at 100% performance

IP = cost of obtaining a unit increase in performance level

Total Productivity Measure:

\[ TP = \frac{O_T}{(C_L + C_C + C_R + O_H)} \]  

Where:

\( O_T \) = total output

\( C_L \) = labor cost

\( C_C \) = service cost of using invested capital

\( C_R \) = raw material cost

\( O_H \) = overhead cost

Total Quality Measure:

\[ T_Q = \frac{O_T}{(C_P + C_F)} \]  

Where:

\( C_P \) = prevention cost

\( C_F \) = Failure cost
Total flexibility Measure:

\[ T_F = \frac{O_T}{(C_1 + A + C_W + H)} \]  \hspace{1cm} (39)

Where:

\[ C_1 = \text{idle cost of the equipment} \]
\[ A = \text{setup cost} \]
\[ C_W = \text{waiting cost of parts processed} \]
\[ H = \text{inventory coats of finished products and raw materials} \]

Integrated Manufacturing Performance (IMP) Measure:

\[ \text{IMP} = \frac{(TP \times TQ \times TF)}{(TP \times TQ + TQ \times TF + TF \times TP)} \]  \hspace{1cm} (40)

Taking a partial derivative of the above equation, the Marginal IMP is:

\[ \frac{\partial \text{IMP}}{\partial TP} = \left[ \frac{1}{\left( \frac{TQ + TF}{TQ \times TF} \right)^2 + 1} \right] > 0 \]
CODE LISTING CASE 1

\[ \text{Cume}_1(t) = \text{Cume}_1(t-\Delta t) + (\text{Spending}_1) \ast \Delta t \]

\[ \text{INIT Cume}_1 = 0 \]

\[ \text{INFLOWS:} \]
\[ \text{Spending}_1 = \text{Spending}_1 \]

\[ \text{Cume}_2(t) = \text{Cume}_2(t-\Delta t) + (\text{Spending}_2) \ast \Delta t \]

\[ \text{INIT Cume}_2 = 0 \]

\[ \text{INFLOWS:} \]
\[ \text{Spending}_2 = \text{Spending}_2 \]

\[ \text{Final}_\text{Quality Level}(t) = \text{Final}_\text{Quality Level}(t-\Delta t) + (\text{Resulting}) \ast \Delta t \]

\[ \text{INIT Final}_\text{Quality Level} = 0 \]

\[ \text{INFLOWS:} \]
\[ \text{Resulting} = \text{Total Allocation} \]

\[ \text{Quality Level}_\text{Process 1}(t) = \text{Quality Level}_\text{Process 1}(t-\Delta t) + (\text{improving}_1) \ast \Delta t \]

\[ \text{INIT Quality Level}_\text{Process 1} = 20 \]

\[ \text{INFLOWS:} \]
\[ \text{improving}_1 = \text{quality}_1 \ast \text{Spending}_1 \]

\[ \text{Quality Level}_\text{Process 2}(t) = \text{Quality Level}_\text{Process 2}(t-\Delta t) + (\text{improving}_1B) \ast \Delta t \]

\[ \text{INIT Quality Level}_\text{Process 2} = 20 \]

\[ \text{INFLOWS:} \]
\[ \text{improving}_1B = \text{quality}_2 \ast \text{Spending}_2 \]

\[ \text{Allocation}_\text{Process 1} = 35 \]
\[ \text{Allocation}_\text{Process 2} = 65 \]
\[ \text{base}_\text{quality}_\text{Process 1} = 0.025 \]
\[ \text{base}_\text{quality}_\text{Process 2} = 0.025 \]
\[ \text{gap}_1 = \text{target}_\text{quality}_\text{Process 1} - \text{Quality Level}_\text{Process 1} \]
\[ \text{gap}_2 = \text{target}_\text{quality}_\text{Process 2} - \text{Quality Level}_\text{Process 2} \]
\[ \text{quality}_1 = \text{base}_\text{quality}_\text{Process 1} \ast \text{impact of gap}_1 \]
\[ \text{quality}_2 = \text{base}_\text{quality}_\text{Process 2} \ast \text{impact of gap}_2 \]
\[ \text{Spending Rate}_1 = 1000 \]
\[ \text{Spending Rate}_2 = 1000 \]
\[ \text{target}_\text{quality}_\text{Process 1} = 50 \]
\[ \text{target}_\text{quality}_\text{Process 2} = 100 \]
\[ \text{Total Allocation} = \text{Quality Level}_\text{Process 1} \ast \text{Allocation}_\text{Process 1} + \text{Quality Level}_\text{Process 2} \ast \text{Allocation}_\text{Process 2} \]
\[ \text{Total Spent} = \text{Total Spent}_\text{Process 1} + \text{Total Spent}_\text{Process 2} \]
\[ \text{Total Spent}_\text{Process 1} = \text{Cume}_\text{Spending}_1 \]
\[ \text{Total Spent}_\text{Process 2} = \text{Cume}_\text{Spending}_2 \]

\[ \text{impact of gap}_1 = \text{GRAPH}(\text{gap}_1) \]
\[ (0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00) \]

\[ \text{impact of gap}_2 = \text{GRAPH}(\text{gap}_2) \]
\[ (0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00) \]
Appendix C

Code Equations / Listing Case 2
Process 1: Sub-Processes 1A & 1B

- **Cume_Spending_1(t) = Cume_Spending_1(t - dt) + (Spending_1) * dt**
  - INIT Cume_Spending_1 = 0
  - INFLOWS:
    - δ δ Spending_1 = Spending_Rate_1
  - **Quality_Level_Sub_Process_1A(t) = Quality_Level_Sub_Process_1A(t - dt) + (improving_quality_1A) * dt**
    - INIT Quality_Level_Sub_Process_1A = 20
    - INFLOWS:
      - δ δ improving_quality_1A = qual$_1^A$*Spending_Rate_1
  - **Quality_Level_Sub_Process_1B(t) = Quality_Level_Sub_Process_1B(t - dt) + (improving_quality_1B) * dt**
    - INIT Quality_Level_Sub_Process_1B = 20
    - INFLOWS:
      - δ δ improving_quality_1B (Not in a sector)
  
  - **base_qual$_1^A$ = 0.025**
  - **base_qual$_1^B$ = 0.025**
  - **gap_1A = target_qual_Process_1A-Quality_Level_Sub_Process_1A**
  - **gap_1B = target_qual_Process_1B-Quality_Level_Sub_Process_1B**
  - **qual$_1^A$ = base_qual$_1^A$*Impact_of_gap_1A**
  - **qual$_1^B$ = base_qual$_1^B$*Impact_of_gap_1B**
  - **Spending_Rate_1 = 1000**
  - **target_qual_Process_1A = 100**
  - **target_qual_Process_1B = 100**
  - **Total_Spent_Process_1 = Cume_Spending_1**
  - **Impact_of_gap_1A = GRAPH(gap_1A)**
    - (0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.155), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00)
  - **Impact_of_gap_1B = GRAPH(gap_1B)**
    - (0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00)

Not in a sector

- **Final_Quality_Level(t) = Final_Quality_Level(t - dt) + (Resulting_Quality_End_Process) * dt**
  - INIT Final_Quality_Level = 0
  - INFLOWS:
    - δ δ Resulting_Quality_End_Process = Resulting Qualität_Process_1+Resulting Qualität_Process_2
  - **Final_Quality_Level_Process_1(t) = Final_Quality_Level_Process_1(t - dt) + (Resulting_Quality_Process_1) * dt**
    - INIT Final_Quality_Level_Process_1 = 0
    - INFLOWS:
      - δ δ Resulting_Quality_Process_1 = Total_Allocation_Process_1
\[ \text{Final\_Quality\_Level\_Process\_2}(t) = \text{Final\_Quality\_Level\_Process\_2}(t - dt) + \text{Resulting\_Quality\_Process\_2} \times dt \]

INIT \( \text{Final\_Quality\_Level\_Process\_2} = 0 \)

INFLOWS:
- \( \text{Resulting\_Quality\_Process\_2} = \text{Total\_Allocation\_Process\_2} \)
- improving\_quality\_1B = \text{qual}\_1B \times \text{Spending\_Rate\_1} 

INFLOW TO: Quality\_Level\_Sub\_Process\_1B (IN SECTOR: Process 1: Sub-Proceses 1A & 1B)
- Allocation\_Sub\_Process\_1A = 15
- Allocation\_Sub\_Process\_1B = 20
- Allocation\_Sub\_Process\_2A = 30
- Allocation\_Sub\_Process\_2B = 35
- Total\_Allocation\_Process\_1 = Quality\_Level\_Sub\_Process\_1A \times \text{Allocation\_Sub\_Process\_1A}/100 + Quality\_Level\_Sub\_Process\_1B \times \text{Allocation\_Sub\_Process\_1B}/100
- Total\_Allocation\_Process\_2 = Quality\_Level\_Sub\_Process\_2A \times \text{Allocation\_Sub\_Process\_2A}/100 + Quality\_Level\_Sub\_Process\_2B \times \text{Allocation\_Sub\_Process\_2B}/100

Process 2

\[ \text{Cumue\_Spending\_2}(t) = \text{Cumue\_Spending\_2}(t - dt) + \text{Spending\_2} \times dt \]

INIT \( \text{Cumue\_Spending\_2} = 0 \)

INFLOWS:
- \( \text{Spending\_2} = \text{Spending\_Rate\_2} \)

\[ \text{Quality\_Level\_Sub\_Process\_2A}(t) = \text{Quality\_Level\_Sub\_Process\_2A}(t - dt) + \text{improving\_quality\_2A} \times dt \]

INIT \( \text{Quality\_Level\_Sub\_Process\_2A} = 20 \)

INFLOWS:
- \( \text{improving\_quality\_2A} = \text{qual}\_2A \times \text{Spending\_Rate\_2} \)

\[ \text{Quality\_Level\_Sub\_Process\_2B}(t) = \text{Quality\_Level\_Sub\_Process\_2B}(t - dt) + \text{improving\_quality\_2B} \times dt \]

INIT \( \text{Quality\_Level\_Sub\_Process\_2B} = 20 \)

INFLOWS:
- \( \text{improving\_quality\_2B} = \text{qual}\_2B \times \text{Spending\_Rate\_2} \)

- base\_qua\_2A = 0.025
- base\_qua\_2B = 0.025
- gap\_2A = target\_qual\_Process\_2A - Quality\_Level\_Sub\_Process\_2A
- gap\_2B = target\_qual\_Process\_2B - Quality\_Level\_Sub\_Process\_2B
- quali\_2A = base\_qua\_2A \times \text{impact\_of\_gap\_2A}
- quali\_2B = base\_qua\_2B \times \text{impact\_of\_gap\_2B}
- Spending\_Rate\_2 = 1000
- target\_qual\_Process\_2A = 100
- target\_qual\_Process\_2B = 100
- Total\_Spent\_Process\_2 = \text{Cumue\_Spending\_2}

\( \text{impact\_of\_gap\_2A} = \text{GRAPH}(\text{gap\_2A}) \)

\( (0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00) \)

\( \text{impact\_of\_gap\_2B} = \text{GRAPH}(\text{gap\_2B}) \)

\( (0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00) \)
CODE EQUATIONS / LISTING CASE 3

- Curne_Spent_Process_1(t) = Curne_Spent_Process_1(t - dt) + (Spending_3) * dt
  INIT Curne_Spent_Process_1 = 0
  INFLOWS:
  – Spending_3 = spending_1
- Curne_Spent_Process_2(t) = Curne_Spent_Process_2(t - dt) + (Spending) * dt
  INIT Curne_Spent_Process_2 = 0
  INFLOWS:
  – Spending = spending_2
- Quality_Level_Process_1(t) = Quality_Level_Process_1(t - dt) + (improving_quality_Proc_1) * dt
  INIT Quality_Level_Process_1 = 20
  INFLOWS:
  – improving_quality_Proc_1 = spending_1*qual$_A$
- Quality_Level_Process_2(t) = Quality_Level_Process_2(t - dt) + (improving_quality_Proc_2) * dt
  INIT Quality_Level_Process_2 = 20
  INFLOWS:
  – improving_quality_Proc_2 = qual$_2*$spending_2
- Total_Funds(t) = Total_Funds(t - dt) + (funding - spending_1 - spending_2) * dt
  INIT Total_Funds = 0
  INFLOWS:
  – funding = funding_rate
  OUTFLOWS:
  – spending_1 = IF(Process_to_Spend_on_switch='1')then(dollars_spent_on_1)else(0)
  – spending_2 = IF(Process_to_Spend_on_switch='1')then(0)else(dollars_spent_on_2)
  \[ \%	ext{spent on Process}_1 = 50 \]
  \[ \%	ext{spent on Process}_2 = 50 \]
  \[ \text{base_qual}_1\text{Process}_1 = 0.025 \]
  \[ \text{base_qual}_2\text{Process}_2 = 0.025 \]
  \[ \text{dollars_spent}_1\text{on}_1 = \text{Total_Funds}^*\%	ext{spent on Process}_1 \]
  \[ \text{dollars_spent}_2\text{on}_2 = \text{Total_Funds}^*\%	ext{spent on Process}_2 \]
  \[ \text{Final_Process_target_quality} = \text{target_quality_Process}_1\text{+target_quality_Process}_2 \]
  \[ \text{funding_rate} = 0 \]
  \[ \text{gap_Process}_1 = \text{target_quality_Process}_1\text{-Quality_Level_Process}_1 \]
  \[ \text{gap_Process}_2 = \text{target_quality_Process}_2\text{-Quality_Level_Process}_2 \]
  \[ \text{month} = \text{TIME} \]
  \[ \text{Process_to_Spend_on_switch} = \text{IF}(\text{gap_Process}_1 > \text{gap_Process}_2)\text{then}(1)\text{else}(0) \]
  \[ \text{qual}_2\text{.2 = base_qual}_2\text{Process}_2\text{impact_of_gap}_2 \]
  \[ \text{qual}_A\text{.A = base_qual}_A\text{Process}_1\text{impact_of_gap}_1 \]
  \[ \text{target_quality_Process}_1 = 50 \]
  \[ \text{target_quality_Process}_2 = 50 \]
target_quality_Process_1 = 50

0

target_quality_Process_2 = 50

0

total_gap = Final_Process_target_quality-total_qual

0

total_qual = Quality_Level_Process_1 + Quality_Level_Process_2

0

impact_of_gap_1 = GRAPH(gap_Process_1)

0

(0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00)

0

impact_of_gap_2 = GRAPH(gap_Process_2)

0

(0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00)
Appendix E

Code Equations / Listing: Validation Case
CODE EQUATIONS / LISTING- VALIDATION CASE

- \( \text{Cume}_\text{Spent}_\text{Process}_1(t) = \text{Cume}_\text{Spent}_\text{Process}_1(t - dt) + (\text{Spending}_1) \times dt \)
  - INIT \( \text{Cume}_\text{Spent}_\text{Process}_1 = 0 \)
  - INFLOWS:
    - \( \text{Spending}_1 = \text{dollars}_\text{spent}_\text{on}_1 \)

- \( \text{Cume}_\text{Spent}_\text{Process}_2(t) = \text{Cume}_\text{Spent}_\text{Process}_2(t - dt) + (\text{Spending}_2) \times dt \)
  - INIT \( \text{Cume}_\text{Spent}_\text{Process}_2 = 0 \)
  - INFLOWS:
    - \( \text{Spending}_2 = \text{dollars}_\text{spent}_\text{on}_2 \)

- \( \text{Cume}_\text{Spent}_\text{Process}_3(t) = \text{Cume}_\text{Spent}_\text{Process}_3(t - dt) + (\text{Spending}_3) \times dt \)
  - INIT \( \text{Cume}_\text{Spent}_\text{Process}_3 = 0 \)
  - INFLOWS:
    - \( \text{Spending}_3 = \text{dollars}_\text{spent}_\text{on}_3 \)

- \( \text{Cume}_\text{Spent}_\text{Process}_4(t) = \text{Cume}_\text{Spent}_\text{Process}_4(t - dt) + (\text{Spending}_4) \times dt \)
  - INIT \( \text{Cume}_\text{Spent}_\text{Process}_4 = 0 \)
  - INFLOWS:
    - \( \text{Spending}_4 = \text{dollars}_\text{spent}_\text{on}_4 \)

- \( \text{Quality}_\text{Level}_\text{Process}_1(t) = \text{Quality}_\text{Level}_\text{Process}_1(t - dt) + (\text{improving}_\text{quality}_\text{Proc}_1) \times dt \)
  - INIT \( \text{Quality}_\text{Level}_\text{Process}_1 = 65 \)
  - INFLOWS:
    - \( \text{improving}_\text{quality}_\text{Proc}_1 = \text{spending}_1 \times \text{qual}_\text{}^2 \text{A} \)

- \( \text{Quality}_\text{Level}_\text{Process}_2(t) = \text{Quality}_\text{Level}_\text{Process}_2(t - dt) + (\text{improving}_\text{quality}_\text{Proc}_2) \times dt \)
  - INIT \( \text{Quality}_\text{Level}_\text{Process}_2 = 90 \)
  - INFLOWS:
    - \( \text{improving}_\text{quality}_\text{Proc}_2 = \text{qual}_\text{}^2 \text{spending}_2 \)

- \( \text{Quality}_\text{Level}_\text{Process}_3(t) = \text{Quality}_\text{Level}_\text{Process}_3(t - dt) + (\text{improving}_\text{quality}_\text{Proc}_3) \times dt \)
  - INIT \( \text{Quality}_\text{Level}_\text{Process}_3 = 95 \)
  - INFLOWS:
    - \( \text{improving}_\text{quality}_\text{Proc}_3 = \text{qual}_\text{}^3 \text{Spending}_3 \)

- \( \text{Quality}_\text{Level}_\text{Process}_4(t) = \text{Quality}_\text{Level}_\text{Process}_4(t - dt) + (\text{improving}_\text{quality}_\text{Proc}_4) \times dt \)
  - INIT \( \text{Quality}_\text{Level}_\text{Process}_4 = 70 \)
  - INFLOWS:
    - \( \text{improving}_\text{quality}_\text{Proc}_4 = \text{qual}_\text{}^4 \text{Spending}_4 \)

- \( \text{Total}_\text{Funds}(t) = \text{Total}_\text{Funds}(t - dt) + (\text{funding}) \times dt \)
  - INIT \( \text{Total}_\text{Funds} = 0 \)
  - INFLOWS:
    - \( \text{funding} = \text{funding}_\text{rate} \)
%spent_on_Process_1 = 55
%spent_on_Process_2 = 10
%spent_on_Process_3 = 5
%spent_on_Process_4 = 30
base_qual$Process_1 = 0.025
base_qual$Process_2 = 0.025
base_qual$Process_3 = 0.025
base_qual$Process_4 = 0.025
dollars spent on 1 = Total Funds * %spent on Process 1
dollars_spent_on_2 = Total_Funds * %spent_on_Process_2
Dollars_Spent_on_3 = Total_Funds * %spent_on_Process_3
Dollars_Spent_on_4 = Total_Funds * %spent_on_Process_4
funding_rate = 0
gap_Process_1 = target_quality_Process_1 - Quality_Level_Process_1
gap_Process_2 = target_quality_Process_2 - Quality_Level_Process_2
gap_Process_3 = target_quality_Process_3 - Quality_Level_Process_3
gap_Process_4 = target_quality_Process_4 - Quality_Level_Process_4
month = TIME
Process_1_Quality = Quality_Level_Process_1 * %spent_on_Process_1 / 100
Process_2_Quality = Quality_Level_Process_2 * %spent_on_Process_2 / 100
Process_3_Quality = Quality_Level_Process_3 * %spent_on_Process_3 / 100
Process_4_Quality = Quality_Level_Process_4 * %spent_on_Process_4 / 100
qual$_2 = base_qual$Process_2 * impact_of_gap$_2
qual$_3 = base_qual$Process_3 * impact_of_gap$_3
qual$_4 = base_qual$Process_4 * impact_of_gap$_4
qual$_A = base_qual$Process_1 * impact_of_gap$_1
target_quality_Process_1 = 100
target_quality_Process_2 = 100
target_quality_Process_3 = 100
target_quality_Process_4 = 100
Total$_Spent = Cume_Spent_Process_1 + Cume_Spent_Process_2 + Cume_Spent_Process_3 + Cume_Spent_Process_4
Total_Quality = Process_1_Quality + Process_2_Quality + Process_3_Quality + Process_4_Quality
impact_of_gap$_1 = GRAPH(gap_Process_1)
(0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00)
impact_of_gap$_2 = GRAPH(gap_Process_2)
(0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00)
impact_of_gap$_3 = GRAPH(gap_Process_3)
(0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00)
impact_of_gap$_4 = GRAPH(gap_Process_4)
(0.00, 0.00), (10.0, 0.007), (20.0, 0.01), (30.0, 0.025), (40.0, 0.055), (50.0, 0.1), (60.0, 0.165), (70.0, 0.265), (80.0, 0.45), (90.0, 0.7), (100, 1.00)
LIST OF REFERENCES


Masters Thesis, University of Miami, FL.

Atkinson, J.H., et. al Current Trends in Cost of Quality - Linking the Cost of Quality and
Continuous Improvement” Research Report, National Association of
Accountants, Montvale, New Jersey.

Quality Press.

Annual Quality Congress Transactions, 121-125.

Relationship between Quality Improvement Techniques and Performance- A

Quality American Economic Review, 81(1), 224-239.

One? Productivity & Quality Management Frontiers-IV, Editors Sumanth, et. al.,
779-788.

Journal of Quality and Reliability Management, 6(6) 9-17.

March-April, 28-30.

Manufacturing Systems to Determine Information Product Quality. Management
Science, 44(4), 462-484.

Management Science, 44(9), 1179 - 1192.


145


150


