A Knowledge Management Based Approach
to Quality Management for Large Manufacturing Organizations

by Andreas Garstenauer

B.S. in Mechanical Engineering, December 2001, Old Dominion University
M.Eng. in Mechanical Engineering, August 2003, Old Dominion University
M.B.A., May 2009, Old Dominion University

A Dissertation submitted to

The Faculty of
The School of Engineering and Applied Science
of The George Washington University
in partial satisfaction of the requirements
for the degree of Doctor of Philosophy

August 31, 2014

Dissertation directed by

Timothy D. Blackburn
Professorial Lecturer in Engineering Management and Systems Engineering

and

Bill A. Olson
Professorial Lecturer in Engineering Management and Systems Engineering

The School of Engineering and Applied Science of The George Washington University certifies that Andreas Garstenauer has passed the Final Examination for the degree of Doctor of Philosophy as of May 14, 2014. This is the final and approved form of the dissertation.

A Knowledge Management Based Approach
to Quality Management for Large Manufacturing Organizations

Andreas Garstenauer

Dissertation Research Committee:

Timothy D. Blackburn, Professorial Lecturer in Engineering Management and Systems Engineering, Dissertation Co-Director

Bill A. Olson, Professorial Lecturer in Engineering Management and Systems Engineering, Dissertation Co-Director

Shahram Sarkani, Professor of Engineering Management and Systems Engineering, Committee Member

Thomas Andrew Mazzuchi, Professor of Engineering Management and Systems Engineering & of Decision Science, Committee Member

Paul L. Blessner, Professorial Lecturer in Engineering Management and Systems Engineering, Committee Member

E. Lile Murphree, Professor of Engineering Management, Committee Member

© Copyright 2014 by Andreas Garstenauer
All rights reserved

Dedication

This dissertation is dedicated to the following special persons and organizations:

To my lovely wife Michelle, who shaped the direction for my life, and stood beside me to achieve my ambitions.

To my wonderful son Owen, who was patiently waiting when I was working on my studies for the PhD, including this dissertation. I am so thankful that you are with us my son – every minute with you is priceless.

To my parents Johann and Angela, who instilled the desire to achieve goals through hard work.

To my employer, who provided assistance in my education.

To this great country, which like no other place known to me, provides the opportunities to reach extraordinary goals.

Acknowledgement

I would like to thank my employer for all the support and assistance I received for my education. A special thank you goes to my PhD advisors, Dr. Blackburn, Dr. Olson and Dr. Blessner, for their outstanding support, insightful comments, guidance and responsiveness. I thank Dr. Sarkani, Dr. Mazzuchi, Dr. Blackford, and all my Professors and the Staff at The George Washington University for administering this program, providing proficient resources, and delivering expert knowledge with great dedication and professionalism that enabled me to complete this challenging journey. I thank my friends, colleges, cohort classmates, and all the people who have helped me on my path.

Abstract of Dissertation

A Knowledge Management Based Approach to Quality Management for Large Manufacturing Organizations

The purpose of this dissertation lies in integrating knowledge management (KM) and quality management (QM), and in demonstrating the operational effectiveness of a KM/QM strategy through quantitative empirical research. The research framework proposed herein is based on the KM/QM strategy, reflecting the improvements implemented at the research site. Four manufacturing companies that operate under similar conditions were evaluated. The research consists of a three year pretest period, before the KM/QM strategy was implemented, and a six year posttest period with an implemented KM/QM strategy. Statistical analysis was used to determine the operational effectiveness of the KM/QM strategy.

The quantitative empirical study in this dissertation supports the claim of four main research hypotheses that a company using a KM/QM strategy has a significantly higher product quality than companies without one, that a KM/QM strategy contributes significantly and positively to product quality, significantly reduces the number of quality related improvement activities, and cost of quality over KM/QM strategy application time. The approach applied in analyzing the KM/QM strategy as a holistic system includes the obtainable factors that influenced the results of this study, confounding effects, as well as the dynamic interaction of factors. Determining the actual strength of the individual factors, and the strength of factor interactions, is not part of this research, which is a recommended opportunity for future studies.

Table of Contents

Dedication iv

Acknowledgement v

Abstract of Dissertation vi

Table of Contents vii

List of Figures xi

List of Tables xiii

List of Acronyms xiv

List of Symbols and Definitions of Variables & Terms xvi

Chapter 1. Introduction 1

1.1 Background 1

1.2 Purpose of the Research 3

1.3 Research Outline 3

1.4 Contribution to the Body of Knowledge 4

Chapter 2. Literature Review 5

2.1 History, Background and Movements 5

2.1.1 Knowledge Management 6

2.1.2 Quality Management 8

2.1.3 Manufacturing 11

2.2 Graphical Timeline 19

2.3 Review of KM/QM Specific Literature 21

2.3.1 Organizational Knowledge Creation 22

2.3.2 The KM/QM Link 27

2.3.3 Metrics in KM and QM 35

2.4 Gaps and Problem Areas 38

2.4.1 Problems with Qualitative KM/QM Research 38

2.4.2 Problems with Survey Based KM/QM Research 39

2.4.3 A Summary of Gaps and Problem Areas 40

Chapter 3. Research Approach and Methodology 42

3.1 Problem Statement 42

3.2 Research Environment 44

3.3 The KM/QM Strategy in Practice at Company B 46

3.3.1 KM/QM and socialization in practice 47

3.3.2 KM/QM and externalization in practice 48

3.3.3 KM/QM and combination in practice 49

3.3.4 KM/QM and internalization in practice 50

3.4 Conceptual Framework 51

3.5 Research Hypotheses and Methodology 54

3.5.1 Hypothesis 1 55

3.5.2 Hypothesis 2 57

3.5.3 Hypothesis 3 61

3.5.4 Hypothesis 4 67

Chapter 4. Data Analysis and Results 75
4.1 Hypotheses Summary 75
4.2 Hypothesis 1 75
4.2.1 Evaluation of Research Data: Hypothesis 1 75
4.2.2 Analysis: Hypothesis 1 77
4.2.3 Results of Analysis: Hypothesis 1 83
4.3 Hypothesis 2 84
4.3.1 Evaluation of Research Data: Hypothesis 2 84
4.3.2 Analysis: Hypothesis 2 91
4.3.3 Results of Analysis: Hypothesis 2 97
4.4 Hypothesis 3 99
4.4.1 Evaluation of Research Data: Hypothesis 3 99
4.4.2 Analysis: Hypothesis 3 104
4.4.3 Results of Analysis: Hypothesis 3 107
4.5 Hypothesis 4 109
4.5.1 Evaluation of Research Data: Hypothesis 4 109
4.5.2 Analysis: Hypothesis 4 121
4.5.3 Results of Analysis: Hypothesis 4 128
4.6 Discussion of Results: Factors, Confounding Effects and Interactions 130
Chapter 5. Conclusions 135

Chapter 6. Future Areas of Research.....138

References.....140

List of Figures

Figure 2-1: Holistic QM System within Lean Six Sigma and KM/QM Elements 11

Figure 2-2: U.S. Manufacturing Employment 14

Figure 2-3: U.S. Trade of Goods Balance with China 15

Figure 2-4: U.S. Trade of Goods Balance with All Trading Countries..... 15

Figure 2-5: KM/QM Graphical Timeline 21

Figure 2-6: Enhanced Model of Organizational Knowledge Creation..... 24

Figure 2-7: Factors Responsible for Individual Commitment 26

Figure 2-8: Baldrige Criteria for Performance Excellent Framework 33

Figure 3-1: KM/QM Practices Classified by SECI Elements..... 47

Figure 3-2: Conceptual Framework of a KM/QM Strategy 52

Figure 3-3: Juran et al.'s (1999) Optimum Quality Costs Model 68

Figure 4-1: ANOM for Product Quality Score 80

Figure 4-2: ANOM for Product for Quality Issue Rate..... 80

Figure 4-3: Posttest Residual Analysis of Quality Score vs. Time 86

Figure 4-4: Posttest Residual Analysis of Quality Issue Rate vs. Time 87

Figure 4-5: Pretest Residual Analysis of Quality Score & Issue Rate vs. Time..... 88

Figure 4-6: Quality Performance Trend at Company B 92

Figure 4-7: Residual Analysis of Quality Improvement Activities vs. Time 100

Figure 4-8: Residual Analysis of Improvement Activities with Subsampled Data 103

Figure 4-9: Normal Probability Plot with AD Test of Quality Improvement Activities Residuals..... 104

Figure 4-10: Quality Improvement Activity Trend at Company B 105

Figure 4-11: Normal Probability Plot with AD Test of Pretest COQ 110
Figure 4-12: Residual Analysis of Pretest COQ Score vs. Time 111
Figure 4-13: Normal Probability Plot with AD Test of Pretest COQ Residuals 112
Figure 4-14: Residual Analysis of COQ vs. Time from KM/QM Strategy Implementation Year 114
Figure 4-15: Normal Probability Plot with AD Test of COQ Residuals from KM/QM Strategy Implementation Year 115
Figure 4-16: Boxplot of COQ from KM/QM Strategy Implementation Year 116
Figure 4-17: Normal Probability Plot with AD Test of 10%Trimmed COQ Residuals from KM/QM Strategy Implementation Year 117
Figure 4-18: Residual Analysis of 10% Trimmed COQ vs. Time from KM/QM Strategy Implementation Year 118
Figure 4-19: Residual Analysis of Posttest COQ Score vs. Time 119
Figure 4-20: Normal Probability Plot with AD Test of Posttest COQ Residuals 120
Figure 4-21: Normal Probability Plot with AD Test of Final Posttest Year COQ 121
Figure 4-22: COQ Trend at Company B 122
Figure 4-23: Boxplot of Pretest COQ and Final Posttest Year COQ 126

List of Tables

Table 2-1: Quality Evolution Movements 9

Table 2-2: Linderman et al.'s (2004) Knowledge Creation and QM Propositions 28

Table 2-3: Elements of Knowledge Management Metrics 35

Table 3-1: Experimental Design for Hypothesis 1 57

Table 3-2: Experimental Design for Hypothesis 2 58

Table 3-3: Experimental Design for Hypothesis 3 64

Table 3-4: Experimental Design for Hypothesis 4 70

Table 4-1: ANOVA with Descriptive Statistics for Product Quality Score 78

Table 4-2: ANOVA with Descriptive Statistics for Quality Issue Rate 78

Table 4-3: Non-Parametric ANOVA Verification with Kruskal-Wallis Test for Quality Score 82

Table 4-4: Non-Parametric ANOVA Verification with Kruskal-Wallis Test for Issue Rate 82

Table 4-5: Test for Independence for Quality Score and Issue Rate vs. Time 91

Table 4-6: Regression Analysis of Product Quality Score vs. Time 94

Table 4-7: Regression Analysis of Quality Issue Rate vs. Time 94

Table 4-8: Non-Parametric Regression Analysis Verification with Spearman Rank T.... 97

Table 4-9: Test for Independence for Quality Improvement Activities vs. Time 102

Table 4-10: Regression Analysis of Quality Improvement Activities vs. Time 106

Table 4-11: Durbin-Watson Statistics for Fourth Hypothesis Test 113

Table 4-12: Regression Analysis of COQ vs. Time 125

Table 4-13: Two sample t Test with Descriptive Statistics for COQ Score 126

List of Acronyms

AD	Anderson-Darling
ANOM	Analysis of means
ANOVA	Analysis of variance
COQ	Cost of quality
CR	Customer requirements
DMAIC	Define, measure, analyze, improve and control
DOF	Degrees of freedom
DR	Design requirements
ERP	Enterprise resource planning
GDP	Gross domestic product
HOQ	House of quality
IT	Information technology
KM	Knowledge management
KM/QM	Knowledge management/quality management
MBNQA	Malcolm Baldrige National Quality Award
MEW	Material, energy and waste
PDSA	Plan, do, study and act
PPMCC	Pearson product-moment correlation coefficient
QA	Quality assurance
QC	Quality control

QFD	Quality function deployment
QIR	Quality issue report
QM	Quality management
SECI	Socialization, externalization, combination and internalization
SPC	Statistical process control
TQM	Total quality management
U.S.	United States of America
8D	Eight disciplines problem solving method

List of Symbols and Definitions of Variables & Terms

AD	Anderson-Darling test statistic
b_1	Sample slope of regression line
$ß_1$	Population slope (Beta) of the regression line
$cov\ (X,Y)$	Sample covariance
F	Test statistic for F-distribution (F-statistic)
F_{CVL}	Lower critical value for F-distribution
F_{CVU}	Upper critical value for F-distribution
D	Durbin-Watson statistic
k	Number of independent variables
μ_1, μ_2	Population mean (Mu) for population 1 and population 2
MSE	Error mean square
MSR	Regression mean square
N, n	Sample size
p	Probability of obtaining a test statistic (p value)
ρ	Population correlation coefficient (Rho)
r	Sample correlation coefficient
R^2, r^2	Coefficient of determination
S_1^2, S_2^2	Sample variance from population 1 and population 2
S_{b1}	Standard error of slope
S_p^2	Pooled variance
S_X, S_Y	Sample standard deviation for X and Y variables

$\sum_a^b$	Summation from a to b
$\boldsymbol{t}$	Test statistic for t-distribution (t-statistic)
$\boldsymbol{t_{CV}}$	Critical value for t-distribution
$\boldsymbol{X, Y}$	Individual X and Y variable score
$\overline{\boldsymbol{X_1}}, \overline{\boldsymbol{X_2}}$	Sample mean taken from population 1 and population 2

Chapter 1. Introduction

1.1 Background

Large size manufacturing organizations use established quality management tools that are administered electronically either through a single dedicated QM system, integrated within a corporate enterprise resource planning (ERP) system, or as standalone software solutions from several different suppliers. Today's established quality management tools are complex and difficult to operate. Relying on the electronic administration of quality related data can result in time delays from the detection of a quality issue until its completion with corrective and sustained preventive actions. Knowledge management or knowledge creation processes are not included with today's established quality management tools to limit or stop the cross contamination of quality related issues into other areas of the supply chain, and to keep pace with a fast changing business environment. High cost of quality, inefficiencies in operations, substandard products reaching the customer, product recalls, deteriorating customer satisfaction, a declining market share, disproportionally high product liability and legal expenses are still seen as a result of deficient quality (Chao, Iravani, & Savaskan, 2009).

A number of scholars inform that effective quality management results in performance improvements for a firm, and is an important factor to maintain customer satisfaction and competitive advantage (Ansari Ch, Khobreh, Nasiri, & Fathi, 2009; Douglas & Judge, 2001; Easton & Jarrell, 1998; Flynn, Schroeder, & Sakakibara, 1995; Hendricks & Singhal, 1996, 1997, 2001; Kaynak, 2003; Kull & Wacker, 2010; Linderman, Schroeder, Zaheer, Liedtke, & Choo, 2004). Knowledge management

increased in importance to improve organizational and operational performance, and gain competitive advantage. Knowledge is now seen as one of the most important assets of an organization (Porter, 1985). Drucker (1993) introduced the term "*knowledge worker*" and predicted that capital will be replaced by knowledge as the basic economic resource (Drucker, 1994). It is predicted that traditional resources such as land, labor and financial capital will be overtaken by knowledge as the main contributor for competitive advantage (Hoskisson, Hitt, Ireland, & Harrison, 2008; Stankosky, 2005). Research on knowledge management has been wide-ranging in the past decades (Ma & Yu, 2010). Kakabadse et al. (2003) identify five dominant knowledge management models: The philosophy-based model, the cognitive-based model, the network-based model, the community of practice-based model, and the quantum-based model. The fundamental goals of knowledge management and quality management are the same since both aim to improve a firm's performance by creating organizational knowledge (Linderman et al., 2004). Previously published work in the world's body of knowledge indicates that research on the combined field of KM and QM is scarce, mostly qualitative or based on surveys, and in most cases not specific to manufacturing (Anand, Ward, & Tatikonda, 2010; Linderman et al., 2004; McFadden, Lee, Gowen, & Sharp, 2014; Mukherjee, Lapré, & Van Wassenhove, 1998; Shan, Zhao, & Hua, 2013; Waddell & Stewart, 2008). A literature review that is presented in chapter 2 found that the effectiveness of a KM/QM strategy has not been determined through quantitative empirical research that is based on operational performance data.

1.2 Purpose of the Research

The novelty of this research lies in integrating two key focus areas of engineering management and systems engineering: Knowledge management and quality management, and demonstrating the effectiveness of a KM/QM strategy through quantitative empirical research using operational performance data. The primary stakeholders that will benefit from this research are in the field of engineering management (especially knowledge management and quality management) and the field of systems engineering associated with performance and efficiency improvements. The stakeholders will be interested in the research findings since the integration of knowledge management and quality management can improve a firm's performance, increasing the firm's competitive advantage.

1.3 Research Outline

The author researched existing literature on knowledge management and quality management. A KM/QM strategy framework and the research methodology are developed. Through quantitative empirical research, the effectiveness of a KM/QM strategy is determined. The research resolves four main hypotheses. The first hypothesis explains if there is a difference between a company that uses a KM/QM strategy and companies without a KM/QM strategy in terms of product quality. The second hypothesis determines if the employment of a KM/QM strategy results in a significant relationship between the KM/QM strategy application time and a firm's product quality. The KM/QM strategy application time can be explained as observations that occur over time, after the KM/QM practices go in to place. The third identifies if there is a relationship between the

KM/QM strategy application time and the number of quality related improvement activities. Finally, the fourth hypothesis determines if the employment of a KM/QM strategy can explain the relationship between the KM/QM strategy application time and a company's cost of quality. The results of the analysis are discussed prior to a conclusion. Suggested opportunities for future research derived from this dissertation research are offered in the final chapter.

1.4 Contribution to the Body of Knowledge

This research adds to the body of knowledge by providing practicing engineering managers and systems engineers with a quality management strategy in which KM is integrated into QM, and demonstrates the effectiveness of the KM/QM strategy through quantitative empirical research using operational performance data. The KM/QM strategy is capable of addressing today's challenging business environment, it can result in significantly higher product quality, provide operational performance improvements and competitive advantage for large manufacturing firms. The KM/QM strategy outlined in this dissertation provides a framework that practicing engineering managers and systems engineers can implement to obtain similar improvements. The strategy presented in this dissertation to integrate knowledge management into an existing management function is not isolated to quality management or the manufacturing sector. Many engineering management disciplines could benefit in a similar fashion as quality management by integrating a knowledge management strategy that has organizational knowledge creation at its core.

Chapter 2. Literature Review

This research extends the existing body of knowledge by integrating knowledge management and quality management, and demonstrating the effectiveness of a combined KM/QM strategy through quantitative empirical research. To better understand the KM/QM strategy, the following review of relevant literature is included in this dissertation. In the first section of this literature review, the background, important historical events, as well as movements in knowledge management, quality management and the manufacturing industry are explored. The second section of this chapter contains a historical timeline of literature directly related to a KM/QM strategy. The third section of this chapter offers a detailed review of relevant KM/QM literature, including the important topic of KM metrics. Gaps and problems in academic literature that explore the combined field of knowledge management and quality management are discussed in the fourth and final section of this chapter.

2.1 History, Background and Movements

Previously published work within the world's body of knowledge does not include a management strategy where KM and QM are integrated and where the effectiveness of a KM/QM strategy was established through quantitative empirical research using operational performance data. A literature search found that existing academic literature that researches the combined KM and QM approach is scarce, mostly qualitative or based on surveys, and in most cases not specific to manufacturing (Anand et al., 2010; Linderman et al., 2004; McFadden et al., 2014; Mukherjee et al., 1998; Shan et al., 2013;

Waddell & Stewart, 2008). Previously published literature specific to engineering management and systems engineering include the knowledge management focus area and connects to this research such as the knowledge worker's impact on team performance at large-sized companies (Waters & Beruvides, 2012), the engineering management challenges of transferring explicit knowledge within large organizations (Tolk & Aaron, 2010), stretching organizational members capabilities to encourage knowledge creation (Choo, 2011), and the development of an engineering knowledge management framework for large financial firms (Schell, 2008). Another related study within engineering management and systems engineering specific literature presents lessons learned from a military workshop activity that focuses on organizational learning and knowledge transfer with different operating elements such as mission and geographic location (Trainor, Brazil, & Lindberg, 2008). The previously published work within engineering management and systems engineering specific literature connects to this research by applying knowledge management processes under comparable general conditions. However, it lacks the key connection and integration with quality management or manufacturing. This dissertation will add to the existing body of knowledge by integrating KM and QM, and establishing the effectiveness of a KM/QM strategy through quantitative empirical research using operational performance data.

2.1.1 Knowledge Management

Knowledge management has gained in importance in recent decades. Drucker (1993) introduced the term "*knowledge worker*." The author predicted that capital will be replaced by knowledge as the basic economic resource (Drucker, 1994). This prediction

is reinforced by other scholars who inform that traditional resources such as land, labor and financial capital is overtaken by knowledge as the main contributor to competitive advantage (Hoskisson et al., 2008; Stankosky, 2005). Knowledge assets are considered *"principal factors of production,"* similar to physical assets that are vital to the industrial economy (Stankosky, 2005). But what is knowledge? Knowledge is defined as, "*A fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information*" (Davenport & Prusak, 2000). Knowledge resides in the mind of the knowers. In organizations, knowledge is not only found in documents but is also rooted in organizational processes, habits and culture (Davenport & Prusak, 2000).

Knowledge has to be managed to create value for an organization. Kakabadse et al. (2003) captures five dominant knowledge management models. The philosophy-based model includes Polanyi's (1966) two dimensions of tacit and explicit knowledge. Based on this model, KM is people intensive and does not need to be technology driven (Kakabadse, Kakabadse, & Kouzmin, 2003). In the cognitive-based model, scholars have theorized that KM is a strategic asset. In order to stay competitive, the organization must effectively generate and transfer knowledge (Drucker, 1991; Kogut & Zander, 1992; Winter, 1998). The network-based model focuses on acquisition, sharing and transfer of knowledge (Kakabadse et al., 2003). The Community of practice-based model is very frequently applied at workplaces and other activities. Knowledge is created and shared through mutual engagements amongst the participants in groups with a shared domain (Wenger, 2011). The quantum-based model originates from quantum physics. In addition to knowledge, decision makers must also possess the wisdom to manage changing

complexities (Kakabadse et al., 2003). The approach to combine quantum clustering with intelligent models is used for knowledge management tasks such as knowledge extraction and knowledge representation (Kim, Choi, & Kwak, 2012).

Research on knowledge management has been wide-ranging in the past decades (Ma & Yu, 2010). With the purpose to investigate the acceptance of different models of modern knowledge management studies, Ma & Yu (2010) analyzed its citations and co-citations between 1998 and 2007. When combining books and journal articles, Nonaka, Davenport and Polanyi were the most cited scholars respectively (Ma & Yu, 2010). Nonaka (1995) was the most cited document in the 1998 – 2007 timeframe. During the 1998 – 2002 timeframe, Nonaka (1994) was the third most cited document (Ma & Yu, 2010). Nonaka (1994) presents the theory of organizational knowledge creation which is the underlying principle for the KM/QM strategy researched in this dissertation.

2.1.2 Quality Management

The basic definition for quality management is as follows: "*All activities of the overall management function that determine the quality policy, objectives and responsibilities, and implements them by means such as quality planning, quality control, quality assurance and quality improvement*" (Gee, Richardson, & Wortman, 2005). The quality management movement was introduced through the teaching of well-known quality pioneers such as W. Edwards Deming, Joseph M. Juran, Philip B. Crosby, Armand V. Feigenbaum and Kaoru Ishikawa (Sousa & Voss, 2002; Wortman, Carlson, & Richardson, 2006). Nonetheless, quality management has a much longer history. The quality evolution started in the middle ages. It builds and expands on its prior

movements, philosophies and ideas (Wortman et al., 2006). Examples of the quality evolution, movements, philosophies and ideas are shown in Table 2-1.

Table 2-1: Quality Evolution Movements

Movement	Start of movement	Explanation
Craftsmanship	Middle ages	A person is highly skilled in a craft to perform specialized tasks or a trade (Wortman et al., 2006).
Standardization	1798	Eli Whitney developed a system that allowed interchangeability of parts (Wortman et al., 2006).
Scientific management & definition of a system	1911	This movement consists of the scientific study of tasks to improve economic efficiency (Taylor, 1911).
Quality control (QC)	1931	Focused on techniques and activities to produce within specifications (Yong & Wilkinson, 2002). It started with the introduction of statistical methods to control product characteristics. It recognized variability as a key concern for and manufacturing process (Shewhart, 1980).
Quality assurance (QA)	1950s	QA is a planned and systematic method to ensure sufficient confidence that a product or service satisfies quality requirements. QA shifts the focus from inspection in QC to prevention and quality planning (Yong & Wilkinson, 2002).
Total quality management (TQM)	1980s	Total quality management is a quality centered and customer focused management philosophy that involves everyone associated with creation and consumption of a product or service (Powell, 1995).
Six Sigma	1990s	Grounded in statistical methods, Six Sigma is a structured and systematic method to reduce defects and improve processes (Brady & Allen, 2006; Schroeder, Linderman, Liedtke, & Choo, 2008).
Lean Six Sigma	2000	Combines lean business improvement philosophies that focuses on waste reduction with the data driven Six Sigma methodology (George & George, 2003; Hilton & Sohal, 2012; Pepper & Spedding, 2010).

Pepper & Spedding (2010) demonstrate how the most resent Lean Six Sigma movement grew from TQM and Six Sigma quality management movements. To illustrate this shift, the authors use the Joiner Triangle (Joiner, 1994). The initial Joiner Triangle is shown by the authors equilateral and in balance, with three equally important elements: quality, all one team, and scientific approach (Pepper & Spedding, 2010). The onset of TQM philosophies skewed the Joiner Triangle towards the organizational and philosophical "*all one team*" direction with the assistance of popular teachings from Deming, Juran, Crosby and Feigenbaum, etc. (Pepper & Spedding, 2010). The authors referred to the TQM movement with its philosophies as "*One God, many prophets*." The data driven Six Sigma movement skewed the Joiner Triangle toward the scientific approach direction (Pepper & Spedding, 2010). The Six Sigma improvement process steps were defined by Hahn et al. (1999) as define, measure, analyze, improve and control (DMAIC). This process provides a structured and analytical approach for quality improvement initiatives (Hahn, Hill, Hoerl, & Zinkgraf, 1999). Pepper & Spedding (2010) predict that a holistic quality management system where people, data and the goal of improved quality are equally interrelated within a system to enable uniform growth in all directions that can be realized through Lean Six Sigma. This state combines the cultural aspect of Lean with the scientific aspect of Six Sigma (Pepper & Spedding, 2010). Other scholars inform that it has to be seen if Lean Six Sigma can reach this holistic state (Hilton & Sohal, 2012), which provides an opportunity for future research. A KM/QM strategy as presented and analyzed in this dissertation could further facilitate a dynamic environment between the elements outlined by Pepper & Spedding (2010) to achieve a holistic QM system within Lean Six Sigma. In addition, a KM/QM strategy

could function as an enabler for uniform Joiner Triangle growth in all the directions. Figure 2-1 shows a graphical Joiner Triangle representation of Pepper & Spedding's (2010) holistic QM system within Lean Six Sigma, including the KM/QM strategy organizational knowledge creation principle that is based on Nonaka's (1994) theory, to facilitate a dynamic environment.

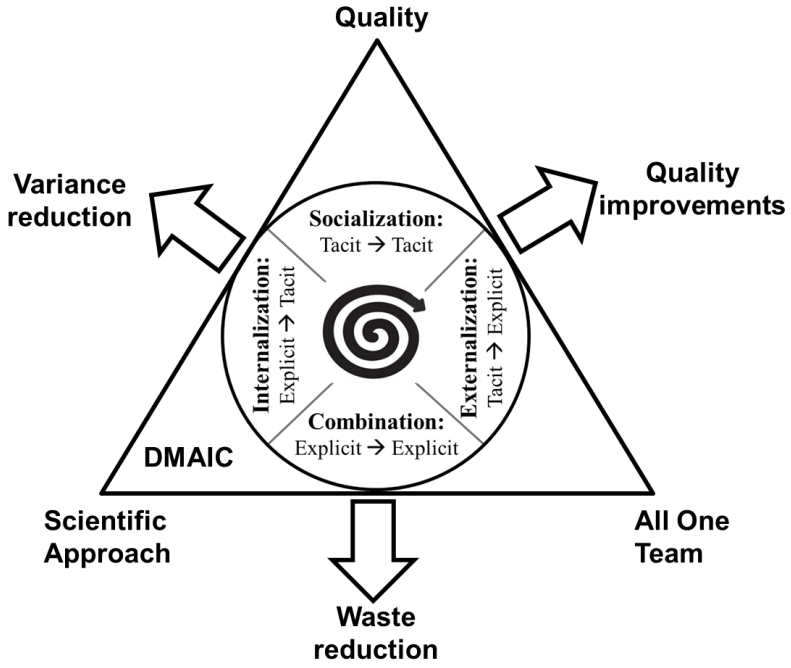


Figure 2-1: Holistic QM System within Lean Six Sigma and KM/QM Elements

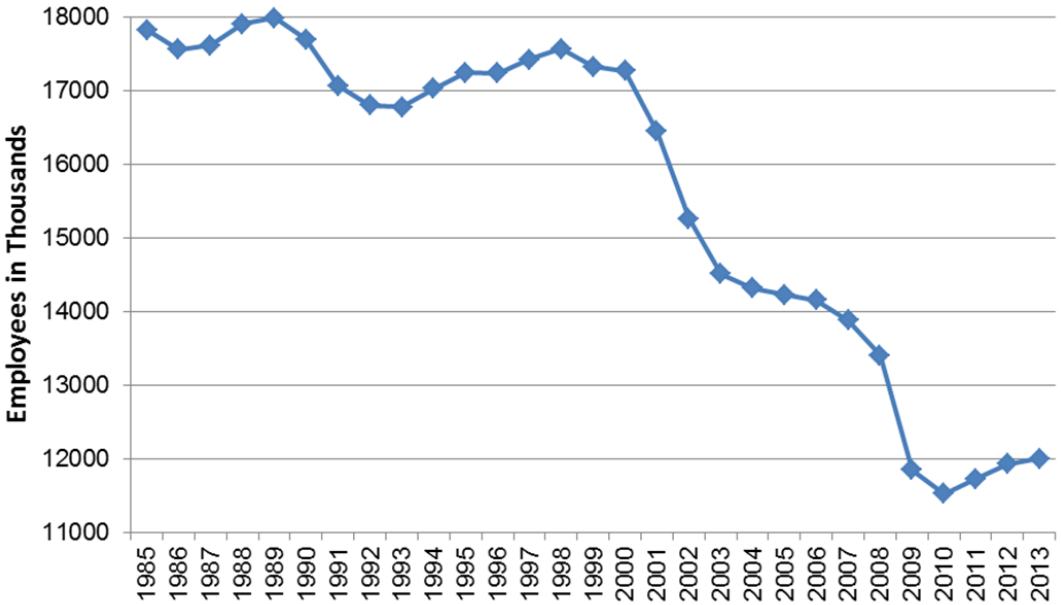
2.1.3 Manufacturing

Practicing engineering managers and system engineers in the manufacturing sector continuously evaluate manufacturing processes and technologies. They improve or replace manufacturing processes and technologies for optimum operational efficiency and system performance, which is essential for competitiveness on a global stage. The following is a brief overview of the manufacturing industry including current movements within the manufacturing sector.

By definition, manufacturing includes organizations that are involved in the mechanical, physical, or chemical conversion of materials, substances, or components into new products (BOC, 2013). This dissertation looks at a knowledge management based approach to quality management at large manufacturing operations. This taxonomy pertains to manufacturing companies with more than 1,000 employees (SBA, 2013). BOC (2013) categorizes manufacturing in the following primary sectors:

- Food manufacturing
- Beverage and tobacco product manufacturing
- Textile mills
- Textile product mills
- Apparel manufacturing
- Leather and allied product manufacturing
- Wood product manufacturing
- Paper manufacturing
- Printing and related support activities
- Petroleum and coal products manufacturing
- Chemical manufacturing
- Plastics and rubber products manufacturing
- Nonmetallic mineral product manufacturing
- Primary metal manufacturing
- Fabricated metal product manufacturing
- Machinery manufacturing
- Computer and electronic product manufacturing
- Electrical equipment, appliance, and component manufacturing
- Transportation equipment manufacturing
- Furniture and related product manufacturing
- Miscellaneous manufacturing

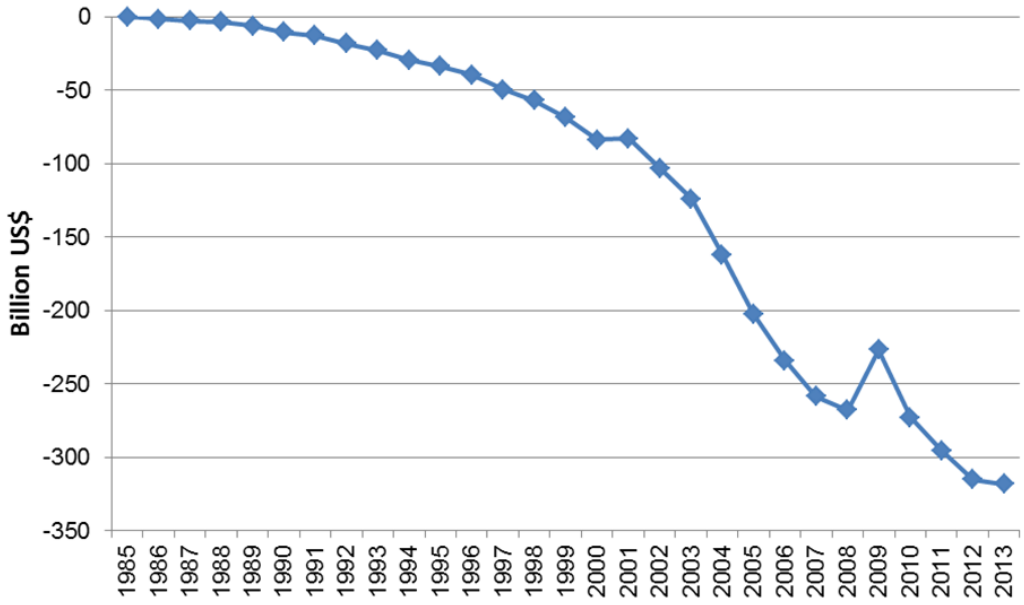
The extensive history of manufacturing and industrialization and how it affected societies is widely documented in existing literature (Inglehart, 1997), and outside the scope of this dissertation. Manufacturing is a vital part of developed and developing counties' economy. A large part of countries national gross domestic products (GDP) originates from manufacturing. For example, the manufacturing industry accounts for 12.5% of the 2012 U.S. GDP, 17% of the German GDP and 21% of Japan's GDP (BEA, 2013; Swezey & McConaghy, 2011). China's manufacturing industry accounted for 30% of its 2010 GDP (Worldbank, 2012). To put this in perspective, if the Unites States manufacturing sector would be a country, it would be the world's tenth largest economy (Manufacturing Institute, 2012). In 2013, the U.S. manufacturing sector employed 12 million people, accounting for 9% of total U.S. nonfarm employment (BLS, 2014). After a sharp decline in U.S. manufacturing employment, it is showing a slight increase since 2010 as presented in Figure 2-2. It is predicted that U.S. domestic manufacturing employment will further grow in areas that have a high value such as advanced manufacturing technologies and products with high shipping cost such as construction equipment and industrial goods (Stangler & Maxwell, 2012).



Source: United States Bureau of Labor Statistics (BLS, 2014)

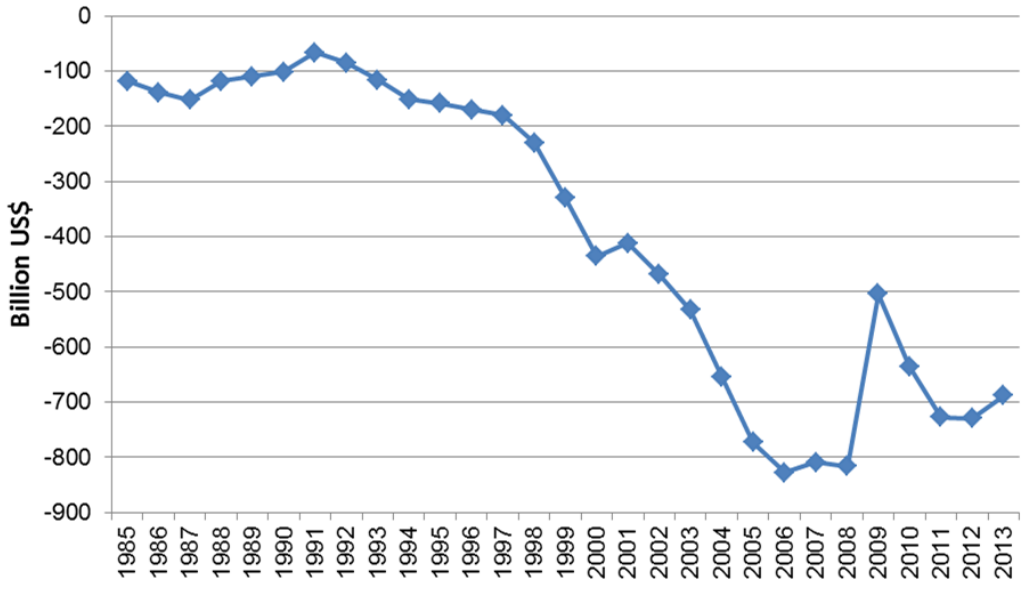
Figure 2-2: U.S. Manufacturing Employment

Successful economies are engaged in trading of high valued manufactured goods. From the perspective of the United States, eighty percent of its exports are from high valued manufactured products such as capital products, transportation goods and industrial supplies (Bonvillian, 2012). Developing countries such as China recently joined the World Trade Organization and are gaining on competitiveness, resulting in higher exports of goods to developed countries such as the United States (Breznitz & Murphree, 2011; Scott, 2012). The United States has an increasing deficit in trading manufactured goods with nations such as China as revealed in Figure 2-3. The $318 billion deficit in 2013 comprises of exports from the U.S. in the amount of $122 billion in goods to China and imports to the U.S. in the amount of $440 billion of goods from China (BOC, 2014a). The trade of goods with all U.S. trading partners, including China, resulted in a $688 billion total deficit as displayed in Figure 2-4 (BOC, 2014b).



Source: United States Census Bureau (BOC, 2014a)

Figure 2-3: U.S. Trade of Goods Balance with China



Source: United States Census Bureau (BOC, 2014b)

Figure 2-4: U.S. Trade of Goods Balance with All Trading Countries

The argument can be made that a country such as the United States lost its competiveness in manufacturing since it is importing $688 billion more manufactured goods than it is exporting. One recent paper reports that the U.S. trade deficit with China resulted in more than 2.7 million lost U.S. manufacturing jobs between 2001 and 2011 (Scott, 2012). However, in advanced economies such as Europe and the United States, a general shift towards services industries was also observed that can contribute to a loss in manufacturing employment (Freeman & Schettkat, 2005; Schettkat & Yocarini, 2006). The interaction between manufacturing and service industries is important to sustain a nation's competitiveness, which can be achieved by providing knowledge, services that support infrastructure, and a strong manufacturing base (Castellacci, 2008). This dissertation provides a KM/QM strategy that leverages important Engineering Management and Systems Engineering focus areas such as quality management, knowledge management, efficiency improvements, and systems performance to improve and sustain the competitive advantage for manufacturing firms in a competitive global environment.

Bonvillian (2012) informs that innovation is directly related to the strength in manufacturing. Sixty-four percent of U.S. scientists and engineers are employed by industrial firms and the manufacturing sector performs 70% of industrial R&D (Bonvillian, 2012). Stangler & Maxwell (2012) inform that innovative potentials are maintained when R&D and manufacturing are at the same geographic location. If at separate locations, designs can become less manufacturing conform and valuable knowledge and skills go untapped (Stangler & Maxwell, 2012).

The following paragraphs will present current movements within manufacturing as they pertain to this dissertation's KM/QM strategy research. The manufacturing industry is moving from mass production to mass customization (Michalos, Makris, Papakostas, Mourtzis, & Chryssolouris, 2010). Increased customization, the need for uncompromising high product quality and rapid responses to quality issues, cost pressures to minimize investment and production costs, frequent quantity changes due to seasonality and swings in customer demands, the desire to have minimum raw material and finished goods inventories, and the necessity to gain maximum capital utilization for buildings and equipment is causing a shift from single purpose high volume manufacturing systems, such as assembly lines devoted to one product and special purpose machines for mass-production, to flexible manufacturing systems (Groover, 2001). Flexible manufacturing systems manufacture different products so they are fully utilized, allow fast change-over times between products and models, use minimum labor through automation, are relatively easy to maintain and operate (Krajewski, Ritzman, & Malhotra, 2007). They apply advanced technologies such as robotics, sensors, vision systems and high speed computer control systems, and are housed in modern facilities (Groover, 2001). Industrial automation and robotics are applied in all sectors of manufacturing to reduce labor, perform hazardous and difficult operations. Collaborative automation is an evolutionary approach were manufacturing systems are never fully formed. Through direct collaboration between the component systems, i.e. operator and robot, the manufacturing system flexibility increases, implementation time and investments decrease, resulting in completive advantage (Colombo, Bangemann, & Karnouskos, 2013). Modern manufacturing practices that apply advanced manufacturing

systems replace the stereotype of manufacturing in dirty and loud factories with high smoke stacks. It is replaced with manufacturing plants that are state of the art, have a clean and quiet environment with only a few people on the shop floor (Bonvillian, 2012). Manufacturing firms continuously strive for improvements to reduce cost and eliminate waste in order to achieve competitive advantage. Traditional manufacturing processes such as machining, casting, forging or molding generate material waist in the form of chips, overflow runners or gates. New additive manufacturing processes enable parts production layer by layer without excess material (Hart, 2012). Additive manufacturing is gaining acceptance, especially through 3D printing of prototype parts and in the medical industry for customized implants such as bone replacements (Bergmann et al., 2010). Modeling and simulation is widely used in modern manufacturing to simulate processes and equipment before making financial an contractual commitments for large capital investment projects (Hart, 2012). Other evolving advanced manufacturing technologies mentioned by Hart (2012) are advanced materials, coatings, intelligent controls, nanomanufacturing and biomanufacturing.

The objective to continuously improve manufacturing processes, reduce waste also referred to as Lean Manufacturing, and the increased use of advanced manufacturing technologies with the objective to gain competitiveness, generates a spillover into sustainability. Products should be manufactured with the least amount of resources for the common good and to increase profitability for manufacturing organizations (Shipp et al., 2012). Sustainable manufacturing is becoming more important due to the rapid growth in consumption, the associated depletion of finite nonrenewable natural resources, and pollution. Manufacturing organizations with sustainability in mind engage in

material, energy and waste (MEW) evaluations. MEW process flow models can identify environmental and economic performance improvement opportunities (Smith & Ball, 2012). Examples include the use of polymer regrind material. Traditionally, virgin polymer resins that originate mostly from hydrocarbons were used at a relatively high cost. Nowadays, recycled polymer regrind materials that originate from production scrap or salvaging operations are increasingly used to produce new injection molded, extruded or blow molded parts at a lower cost. Crude oil based metal cutting oils are replaced by more environmental friendly vegetable oil based metal cutting fluids. Metal cutting fluids are sometimes replaced entirely with near-dry or cryogenic machining processes (Jayal, Badurdeen, Dillon Jr, & Jawahir, 2010). The successful application of sustainable and lean manufacturing have a compounding positive impact on operational performance for manufacturing firms (Miller, Pawloski, & Standridge, 2010).

2.2 Graphical Timeline

Modern knowledge management literature as it relates to a KM/QM strategy starts in the 1960s when knowledge was classified into tacit and explicit knowledge by Polanyi (1966) as shown with the graphical timeline in Figure 2-5. In 1994 Nonaka proposed the socialization, externalization, combination, and internalization (SECI) model which is the governing knowledge management theory for this research. It is a dynamic organizational knowledge creation process with rich interaction between tacit and explicit knowledge (Nonaka, 1994). In the late 1990s, academic literature about Total Quality Management (TQM) and organizational learning constructs were presented (Mukherjee et al., 1998). KM/QM relevant qualitative research was provided by Linderman et al. (2004) who

consider Nonaka's (1994) theory of knowledge creation and quality management. The authors present thirteen qualitative propositions that are not supported by empirical research. The effects of knowledge creation processes on Six Sigma quality improvement projects are researched by Choo et al. (2007). Similar to Linderman et al. (2004), Choo et al. (2007) present qualitative propositions and a theoretical framework which show that explorative learning, explicit knowledge, exploratory learning and tacit knowledge are factors affecting sustainability in quality. In the following year, a survey conducted by Waddell & Stewart (2008) suggests that quality management is the beneficiary of successful knowledge management. One year later, qualitative research performed by Akdere (2009) investigated the role of knowledge management on quality management for human resource processes. The author relates the Baldrige framework for performance excellence to knowledge management. The following year, Anand et al. (2010) conducted a survey to demonstrate that explicit and tacit knowledge creation influences Six Sigma improvement project success. Shan et al. (2013) performed a survey of Chinese aviation firms to determine the effect of quality management factors on knowledge management. In the most recent paper that relates to a KM and QM integration, McFadden et al. (2014) conducted a survey in the health care industry. The authors show that patient safety learning is enhanced by quality improvement activities that are mediated by a three stage KM process of knowledge acquisition, dissemination and application (McFadden et al., 2014).

From the first paper by Mukherjee et al. (1998) that combined knowledge management and quality management to the most recent work by McFadden et al. (2014), research in the combined field of knowledge management and quality

management consisted of qualitative research or research based on surveys. There was no literature found that applies quantitative empirical research using operational performance data to determine the effectiveness of a KM/QM strategy.

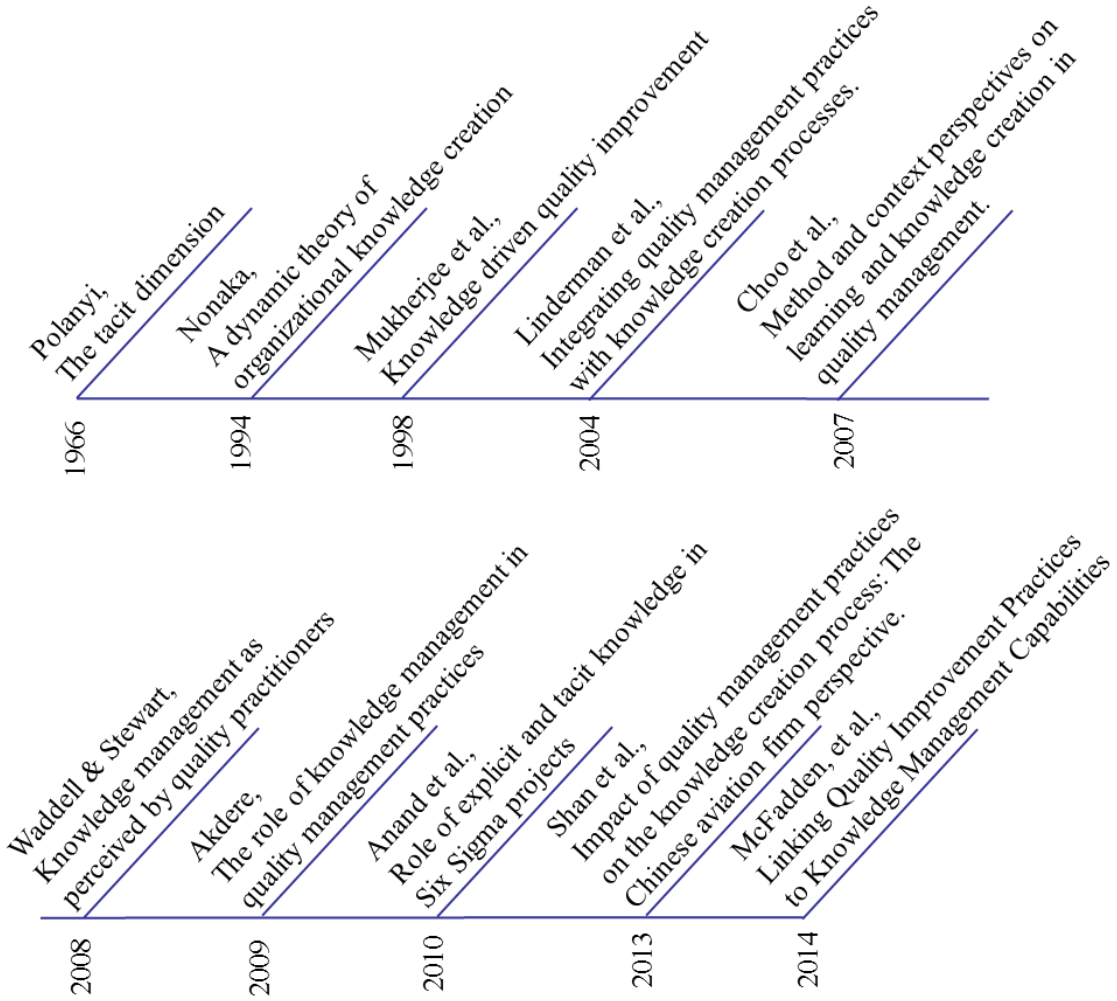


Figure 2-5: KM/QM Graphical Timeline

2.3 Review of KM/QM Specific Literature

The initial part of this KM/QM strategy specific literature review provides an overview of Nonaka's (1994) organizational knowledge creation process which is the foundation for the KM/QM strategy. The link and the integration of knowledge

management and quality management are established in the second part of this KM/QM specific literature review. Since effective management requires measurements and metrics, the important topic of KM and QM metrics is discussed in the last part of this KM/QM specific literature review. Initial sections of this work were presented in the Proceedings of the American Society for Engineering Management 2013 International Annual Conference (Garstenauer, Blackburn, & Olson, 2013).

2.3.1 Organizational Knowledge Creation

Nonaka (1994) developed the theory of organizational knowledge creation. Although composed in 1994, the literature review reveals that Nonaka's (1994) theory of organizational knowledge creation remains state of the art and still serves as an anchor paper for knowledge management research (Anand et al., 2010; Argote & Miron-Spektor, 2011; Shan et al., 2013; Von Krogh, Nonaka, & Rechsteiner, 2012). In later research, Nonaka et al. clarify how the elements of organizational knowledge creation interact organically and dynamically with each other (Nonaka, 1995; Nonaka & Konno, 1998; Nonaka & Toyama, 2003; Nonaka, Toyama, & Konno, 2000). An answer on the academic debate about the theory of organizational knowledge creation is offered by the authors in recent work (Nonaka & Von Krogh, 2009).

Nonaka's (1994) organizational knowledge creation theory originates from Polyani's (1966) categorization of human knowledge into two fundamental types, tacit knowledge and explicit knowledge. Explicit knowledge is expressed in words, numbers, reports, data, and is relatively easy to communicate. Tacit knowledge on the other hand includes

the action and experience of individuals and is more difficult to communicate (Polyani, 1966).

Polanyi (1966) is credited with the statement "*we can know more than we can say*". He defines tacit knowledge as tasks such as bicycle riding or swimming which are inherently difficult to describe (Polyani, 1966). Similar examples illustrate somebody recognizing another person's face among many, but not being able to tell how the other person's face was recognized (Polyani, 1966). Polanyi (1966) also explains that tacit knowledge has a personal quality, such as action, commitment and involvement, making it naturally difficult to transmit it using formal communication methods. Tacit knowledge is labeled as analogue since it involves parallel and simultaneous processing between individuals with the aim to build mutual understanding (Bateson & Bateson, 2000). Contrary, explicit knowledge is codified knowledge that is communicated in formal and systematic ways (Nonaka, 1994). Explicit knowledge can be seen as digital or discrete since it is logged in the form of historical records, databases, reports and is evaluated in sequential order (Bateson & Bateson, 2000).

Knowledge is generated by individuals. The development of knowledge, ideas and innovation takes place mainly through dynamic interaction of individuals, referred to by Nonaka (1994) as "*communities of interaction*." Ideas, innovations and knowledge that are developed at one area of the organization foster a stream of related ideas, innovations and knowledge within the entire organization, contributing to the magnification and growth of further knowledge (Nonaka, 1994). Ideas, innovation and knowledge that are of value gradually increase in acceptance and become crystallized as they resonate in the growing communities of interaction (Nonaka, 1994). Research shows that strong

interpersonal ties are required to capture tacit knowledge while weak interpersonal ties are sufficient to harness explicit knowledge (Granovetter, 1973).

Organizational knowledge is created through a continuous cycle of interaction between an epistemological and an ontological dimension of knowledge, also referred to as the spiral of knowledge creation (Nonaka, 1994). Figure 2-6 shows an enhanced graphical representation of Nonaka's (1994) model. The spiral of organizational knowledge creation has four elements of interaction between tacit and explicit knowledge: Socialization, externalization, combination, and internalization (SECI). In each of the four phases, existing knowledge is converted into new knowledge. While each of the four elements of knowledge conversion can create knowledge autonomously, the theory of organizational knowledge creation centers on the dynamic and continuous interaction between the elements (Nonaka, 1994).

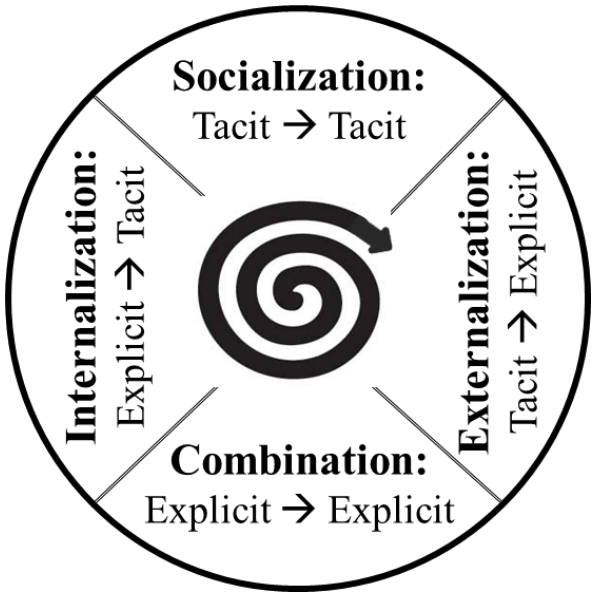


Figure 2-6: Enhanced Model of Organizational Knowledge Creation

The first of the four elements of knowledge conversion is socialization. This phase deals with the shared experience of individuals to create knowledge. Existing tacit knowledge is converted into new tacit knowledge. In many instances, western organizations focus on the explicit part of knowledge creation by paying close attention to documented processes, procedures and standards such as the established ISO 9001 quality standard (Nonaka & Konno, 1998). However, literature shows that certification to established standards such as the ISO 9001 quality standard does not always provide superior quality compared to companies without such certification (Blessner, Mazzuchi, & Sarkani, 2013). Focusing solely on documented processes, procedures and standards shifts the attention away from people and into disembodied information. On the contrary, focusing on people shifts the attention towards the "*knowers*" (Brown & Duguid, 2000). Close proximity of individuals in order to capture the tacit knowledge, i.e. through direct interaction between customers and suppliers, is essential (Nonaka & Konno, 1998).

The second element of knowledge conversion is externalization which is the translation of highly personal knowledge into an explicit form that is easy to understand. Tacit knowledge is converted to explicit knowledge using techniques that help to express an individual's knowledge or idea. As the tacit knowledge moves into an explicit phase, it turns into collective group knowledge, which generates new knowledge (Nonaka, 1994).

The third element of knowledge conversion is combination. Explicit knowledge is converted into a new and a more advanced set of explicit knowledge. The heart of traditional western QM is within the combination element of SECI (Nonaka, 1994).

The fourth and final element of knowledge conversion is internalization where explicit knowledge is converted to tacit knowledge. In this phase, an organization's

explicit knowledge comes to life in action and practice or through simulation and experiment (Nonaka & Konno, 1998).

Nonaka (1994) also points to the importance of individual commitment for organizational knowledge creation. This echoes Polanyi's (1966) work that states commitment causes human knowledge creation. Figure 2-7 shows the three factors that are responsible for individual commitment in an organization: Intention, autonomy and fluctuation (Nonaka, 1994). Intention is an action oriented approach. Individuals have different intentions within an organization, and when given sufficient autonomy, the right intentions can generate unexpected opportunities (Cohen, March, & Olsen, 1972). With more autonomy individuals also have a higher level of self-motivation which helps to form new knowledge (Nonaka, 1994). Fluctuation that can be triggered by chaos, breakdowns or discontinuity leads to different forms of interaction between individuals and realignment of commitment (Nonaka, 1994).

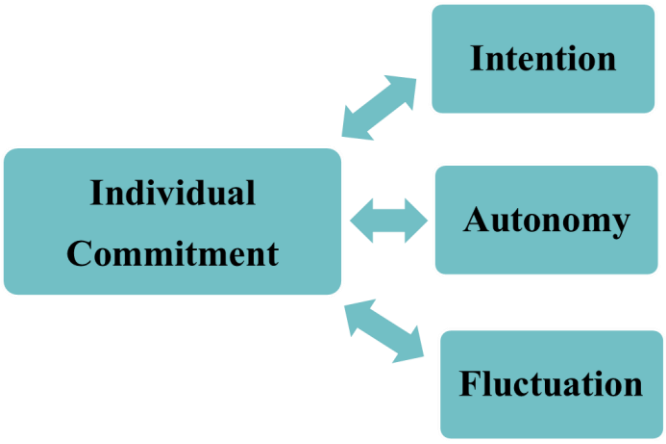


Figure 2-7: Factors Responsible for Individual Commitment

2.3.2 The KM/QM Link

In their conceptual research, Linderman et al. (2004) apply Nonaka's (1994) theory of knowledge creation to quality management. However, the authors do not extend their research past thirteen qualitative and do not apply quantitative empirical research. Linderman et al. (2004) selected Nonaka's (1994) theory because it explicitly analyzes the process of knowledge creation. The authors state that the fundamental goals of quality management and knowledge management are the same. Both aim to improve a firm's performance by creating organizational knowledge (Linderman et al., 2004). In an attempt to describe quality management, Linderman et al. (2004) adopts Sitkin & Sutcliffe's (1994) definition of customer satisfaction, continuous improvement and the systems view. Table 2-2 shows Linderman et al.'s (2004) propositions. The rows in the table denote Sitkin & Sutcliffe's (1994) quality management dimensions while the columns represent Nonaka's (1994) knowledge creation processes. The cells contain the propositions that relate quality management dimensions and knowledge creation processes. The thirteenth and final proposition shown at the bottom of Table 2-2 addresses the creation of organizational knowledge through effective deployment of quality management that results in performance improvements for an organization (Linderman et al., 2004).

Table 2-2: Linderman et al.'s (2004) Knowledge Creation and QM Propositions

Quality management dimensions (Sitkin & Sutcliffe, 1994)	Knowledge creation processes (Nonaka, 1994)			
	Socialization	**Externalization**	**Combination**	**Internalization**
	Tacit to tacit	**Tacit to explicit**	**Explicit to explicit**	**Explicit to tacit**
Customer satisfaction	QM activities which nurture close contact and interaction with customers through socialization create knowledge.	QM activities that describe or conceptualize customer needs through externalization create knowledge.	QM activities that analyze customer information through combination create knowledge.	QM activities that endorse monitoring and feedback of customer information through internalization create knowledge.
Continuous improvement	QM activities that nurture close communication in improvement activities through socialization create knowledge.	QM activities that articulate or describe improvements through externalization create knowledge.	QM activities that analyze information to promote problem understanding and diagnosis through combination create knowledge.	QM activities that promote process monitoring and control through internalization create knowledge..
Systems view	QM activities that foster contact and interactions between diverse team members through socialization create knowledge.	QM activities that conceptualize the objective of systems through externalization create knowledge.	QM activities that synthesize information from diverse sources through combination create knowledge.	QM activities that help a firm to be consistently aligned with its strategy through internalization create knowledge.
Proposition 13:	Quality management activities that produce knowledge result in organizational performance improvements.			

Quality management is defined as customer satisfaction, continuous improvement, and the systems view of an organization (Sitkin & Sutcliffe, 1994). In a modern manufacturing organization, this manifests itself through the intensive use of ERP based QM systems. Sitkin & Sutcliffe's (1994) work is based on the total quality management (TQM) philosophy and was selected by Linderman et al. (2004) because it contained the systems view of an organization which is also aligned with quality scholars such as Deming (2000a, 2000b), and is part of The Deming System of Profound Knowledge ™ (Deming, 2000a, 2000b). Deming (2000b) proposed the plan, do, study, act (PDSA) quality management process steps. With the advent of the Six Sigma management strategy, Hahn et al. (1999) described quality management process steps as define, measure, analyze, improve and control (DMAIC). The DMAIC quality management steps provide a structured approach for quality improvement initiatives (Hahn et al., 1999). From Linderman et al.'s (2004) perspective, it is not sufficient to simply install quality practices that only satisfy the dimensions of quality management. The authors state that quality practices must also include the organizational knowledge creation elements of socialization, externalization, combination, and internalization (Linderman et al., 2004; Nonaka, 1994). Companies might have elaborate systems in place to analyze and report quality issues but miss the opportunity to fully communicate these or find their root causes. Linderman et al. (2004) conclude that future research is required to operationalize the proposed construct, and to perform empirical testing of their propositions and theories.

Mukherjee et al. (1998) did not reference Nonaka's (1994) theory when they researched TQM improvement projects and KM in manufacturing. This fairly dated literature is mentioned since it is one of the few research articles that apply knowledge management to a quality management related process in the manufacturing industry. Mukherjee et al. (1998) analyze three learning constructs at one Belgian manufacturing plant. The three learning constructs are conceptual learning, operational learning and scope (Mukherjee et al., 1998). The results of an ordinary least square regression analysis of the three learning constructs shows a significant positive effect of operational learning on achieving the project goal, a significant positive effect of scope and conceptual learning on the ability to specify the impact of changes, and a very strong positive relationship of operational learning and conceptual learning on the change in attention as a result of the project (Mukherjee et al., 1998). In their research, Mukherjee et al. (1998) collected data via survey of only one firm. Mukherjee et al. (1998) point to the need of future research by empirically testing the applicability and generalizability of their work at a larger scale in different sectors of the manufacturing industry and at various locations.

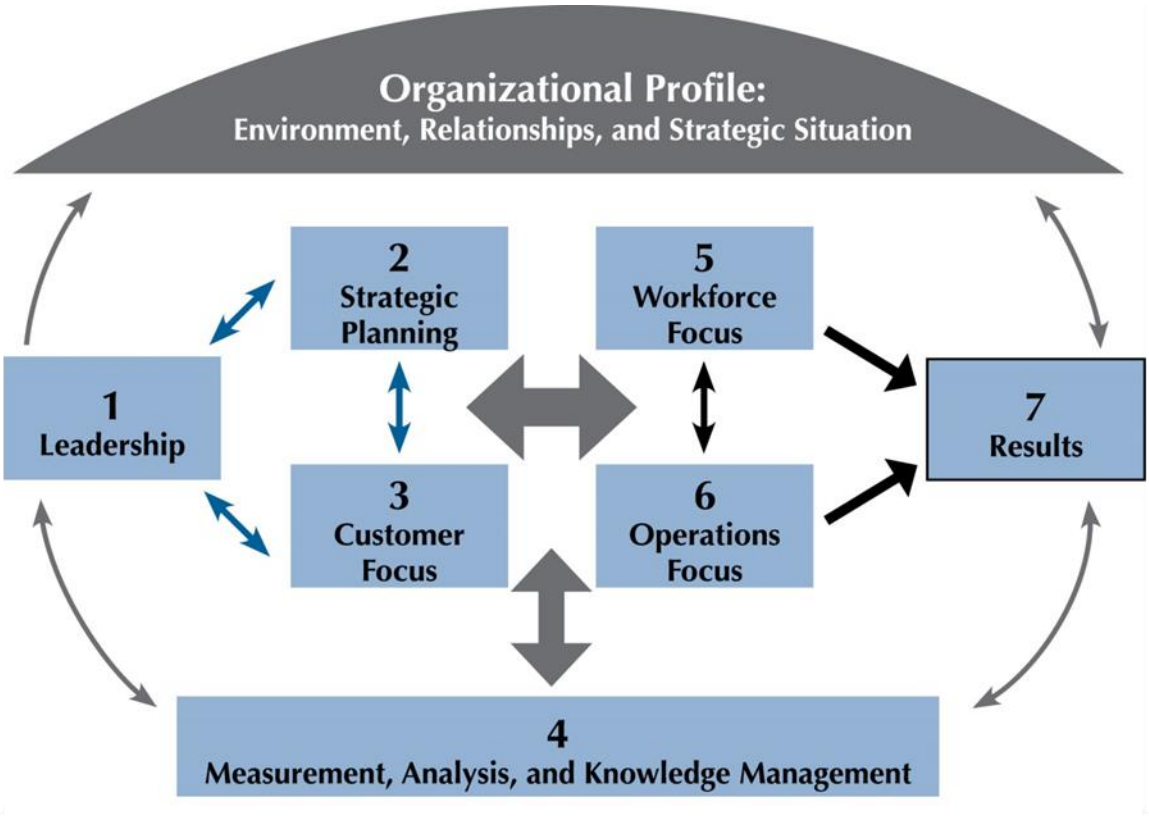
Choo et al. (2007a) present a theoretical study that a firm's quality advantages are more sustainable when knowledge based quality improvement processes are comprised of contextual and methodological learning elements. The authors show a theoretical framework and six propositions that inform of explorative learning, explicit knowledge, exploratory learning, and tacit knowledge as the contributing factors for sustainability in quality (Choo, Linderman, & Schroeder, 2007a). Empirical research to support this claim was not included by Choo et al. (2007a). The authors tested part of their framework and

reported it in two subsequent papers. One journal article concludes that an organization needs to motivate a strong sense of challenge to its members in order to inspire knowledge creation and innovation (Choo, 2011). A second paper informs that the choice of method and degree of adherence while implementing quality programs such as Six Sigma projects affects knowledge creation and innovation. Empirical tests presented in the same paper reveal that learning behaviors affect a firms performance (Choo, Linderman, & Schroeder, 2007b).

Waddell & Stewart (2008) performed a survey of 230 quality managers in Australia. The authors inform that quality management is the beneficiary of successful knowledge management. In addition, Waddell & Stewart (2008) report that a proactive quality culture is a link between knowledge management and quality management and greatly impacts an organization's competitive advantage (Waddell & Stewart, 2008). The authors propose that an organization's quality management system will gain in importance through progress in knowledge management. Waddell & Stewart (2008) did not support their paper with statistical analysis. The authors merely state that the results of their work are based on the "*analysis of the response to the survey*," and "*through the examination of relevant literature*" (Waddell & Stewart, 2008). It would be beneficial to the reader if Waddell & Stewart (2008) supported their work with statistical methods. The author's argument that through development of KM practices the quality in an organization or the quality management system will improve is not fully supported in their research. This dissertation expands on Waddell & Stewart's (2008) paper by applying quantitative empirical research to evaluate the effect of a knowledge management based approach to quality management on a firm's operational performance in terms of product quality. In

addition, this dissertation provides a framework for the relationship between a KM/QM strategy and an organization's operational performance, which is not included in Waddell & Stewart's (2008) research.

Akdere (2009) performed qualitative research on the role of knowledge management on quality management for human resource processes without applying Nonaka's (1994) model. The work is of interest since it is the only research emerging from the literature review that applies knowledge management to the Baldrige criteria for performance excellent framework (Akdere, 2009). The research finds that the Baldrige framework should be updated so it includes knowledge management as a core quality management component on the same level as leadership, strategic planning, customer and employee focus, and process management (Akdere, 2009). The author sees the Baldrige framework as insufficient since knowledge management is only considered for explicit knowledge creation processes (Akdere, 2009). The Baldrige criteria for performance excellence framework were updated since Akdere (2009) published his paper. In the most recent version, the category "*Process Management*" changed to "*Operations Focus*" as shown in Figure 2-8 (NIST, 2013). Knowledge management is still not a core quality management component and remains in conjunction with measurement and analysis as illustrated in the most recent Baldrige criteria for performance excellent framework of Figure 2-8.



This figure is used with permission of the Baldrige Performance Excellence Program. 2013. 2013–2014 Criteria for Performance Excellence. Gaithersburg, MD: U.S. Department of Commerce, National Institute of Standards and Technology. Obtain a copy of the full Criteria at www.nist.gov/baldrige/publications/criteria.cfm.

Figure 2-8: Baldrige Criteria for Performance Excellent Framework

Anand et al. (2010) use an empirical approach to determine if explicit and tacit knowledge creation influences Six Sigma improvement project successes. The authors apply Nonaka's theory of organizational knowledge creation. The data for Anand et al.'s (2010) research was gathered from five U.S. companies using a survey. Anand et al. (2010) test two hypotheses and finds that explicit oriented knowledge creation practices such as combination (explicit to explicit) and internalization (explicit to tacit) contribute significantly and positively to Six Sigma improvement project success. By testing the second hypothesis they find that tacit oriented knowledge creation practices such as socialization (tacit to tacit) and externalization (tacit to explicit) contribute with marginal

significance and positively to a Six Sigma improvement project success (Anand et al., 2010). Anand et al. (2010) quote Albert Einstein, "*the formulation of a problem is more important than the solution because it requires creativity while the solution mostly results from applying known analytical tools*." The authors emphasize that tacit knowledge should be captured by and from the team members at the beginning of the project (Anand et al., 2010). To capture the tacit knowledge from team members, Anand et al. (2010) stresses the importance for team leaders to form cohesive teams.

Shan et al. (2013) surveyed five Chinese aviation firms which apply Nonaka's (1994) model of knowledge creation. Shan et al. (2013) state that employee training, employee participation, product design, benchmarking, and a vision statement have a significant effect on knowledge management for Chinese aviation firms (Shan et al., 2013). For the same five Chinese aviation firms, the survey revealed that upper level management support, customer focus, supplier quality management, quality information, and recognition and reward have an lesser effect on knowledge management (Shan et al., 2013). Future studies were recommended by the authors due to the limited survey sample size and the cultural and geographic aspect of conducting this survey in only one geographic region, eastern China.

In a recent paper, the results from a survey of 274 hospitals in the United States show that quality improvement initiatives that are mediated by a three stage KM process of knowledge acquisition, knowledge dissemination, and knowledge application enhance patient safety learning in the health care industry (McFadden et al., 2014).

2.3.3 Metrics in KM and QM

Metrics are essential in order to measure an organization's achievement of its goals and objectives. Based on a survey by KPMG, 85% of companies have no stated objective for knowledge management (Armacost, 2011). Knowledge management activities and its metrics have to be developed based on business goals (Milton, 2009; Milton, Shadbolt, Cottam, & Hammersley, 1999). Metrics are designed to answer one or more important questions to stakeholders. Milton (2009) states that knowledge management metrics should address the key elements outlined in Table 2-3.

Table 2-3: Elements of Knowledge Management Metrics

Key Elements of a KM Metric	Stakeholder Questions and Actions
Completeness of KM efforts	Is the KM system complete compared to other peer groups?
Justification	Is value generated for the organization by applying KM? If it is, the organization will invest in KM and support it.
Compliance with KM expectations	Are all the parts that are required to operate a successful KM system available? If not, are there any components missing?
Activities	Is the KM implementation on schedule? What needs to be corrected, and in what area, if it is not on track? Are all stakeholders engaged in KM? Identify who is not doing well, and address the problem.
Outputs	Is value generated with our approach to KM? If there is no value created, stop the KM activities or find an improved KM process.

A large number of quality management metrics exist (Gee et al., 2005; Wortman et al., 2006). Metrics that measure quality evolved as the QM field transitions from quality control (QC), where the focus was on the inspection of parts and services according to the prescribed specifications, to quality assurance (QA), where the focus was on ensuring confidence that the product or service meet the customers' expectations, to total quality management, with its all-inclusive view of an organization's quality. The most recent evolutions in quality management are Six Sigma and Lean Six Sigma methods with a focus on continuous improvements (Pepper & Spedding, 2010; Yong & Wilkinson, 2002).

Quality metrics should be based on facts. Fact-based management is one of the ideologies of TQM and a main principle for the Malcolm Baldrige National Quality Award (Rodchua, 2009). In order to measure the achievement of an organization's goals, the correct measuring method for a metric needs to be selected (Juran & Gryna, 1993). According to Juran & Gryna (1993), the following factors need to be considered when developing a measurement system for a metric:

- The measurement should be standardized.
- The data from the measurement should assist in making decisions.
- The metric should provide valuable information.
- The measurement should be easy to install.
- It should be possible to benchmark the results.

To drive performance, many companies use quality function deployment (QFD) metrics (Gee et al., 2005). QFD is a manageable, attractive, useable, and profitable tool

for translating customer WANTs into relevant engineering design requirements, the HOWs (Mehrjerdi, 2010). According the Mehrjerdi (2010), QFD offers the following:

- The knowledge and appreciation of customer requirements.
- Development of strategic advantages.
- Value creation by maximizing quality and customer satisfaction.
- A quality centered approach.
- A quality system approach focused on customer satisfaction.

According to Chin (2009), QFD starts with entering customer requirements (CR or WANTs) to a so called house of quality (HOQ). The QFD inputs are subsequently mapped to the engineering design requirements (DR or HOWs). The relative weights of the customer wants are shown in the w-fields of the matrix. The R-fields represent the relationship matrix between WANTs and HOWs while the r-fields represent the interrelationship matrix between the HOWs (Chin, Wang, Yang, & Gary Poon, 2009).

The QFD approach only illustrates one example of a QM metric for this literature review. A detailed study of the numerous QM metrics is not in the scope of this dissertation. For a comprehensive review of quality metrics, the reader is referred to quality management literature such as Gee et al. (2005), Juran & Gryna (1993) or Wortman et al. (2006). In summary, KM and QM metrics are both measures of an organization's performance and activities. In order to manage, measurements and metrics are essential. Metrics are only useful to an organization if they satisfy certain criteria. KM and QM metrics should enable value creation, decision making and benchmarking. Valuable resources can be lost for an organization by using flawed metrics, too many metrics, measuring unnecessary characteristics or applying measurements incorrectly

(Milton, 2009). This literature review found that metrics that are specific to a combined knowledge management and quality management approach, such as the KM/QM strategy, are lacking in scholarly papers, which is the focus of this dissertation work.

2.4 Gaps and Problem Areas

There is a substantial amount of literature on the two discrete areas of knowledge management and quality management (Ives, Torrey, & Gordon, 1997; Kakabadse et al., 2003; Ma & Yu, 2010; Sousa & Voss, 2002; Yong & Wilkinson, 2002). However, a significant gap in the available academic literature was observed that explores a strategy where knowledge management and quality management are integrated to form an enhanced quality management system and where its effectiveness is assessed with quantitative empirical research methods using operational performance data. The emphases in this literature review are on the joint KM/QM topic area with a quantitative empirical research focus. An attempt was made to further narrow the literature review to the manufacturing industry. However, this literature search did not yield substantial returns. Only the paper by Mukherjee et al. (1998) was found that explores knowledge management elements in the manufacturing industry. Their research is based on a survey, limited to one manufacturing plant in Belgium, and is not of quantitative empirical nature.

2.4.1 Problems with Qualitative KM/QM Research

Existing literature on the combined KM/QM field consist of qualitative propositions where the authors do not extend their research past those propositions (Choo et al.,

2007a; Linderman et al., 2004). Linderman et al. (2004) conclude that future research is required to operationalize the proposed construct, and to perform empirical testing of the propositions and theories. Choo et al. (2007a) only partially tested their propositions in subsequent papers (Choo, 2011; Choo et al., 2007b). An additional qualitative research paper that is related to the combined knowledge management and quality management field addresses the potential limitations with the prestigious Malcolm Baldrige National Quality Award (MBNQA). It critiques the framework of the MBNQA as insufficient since knowledge management is only considered for explicit knowledge creation processes (Akdere, 2009). The author recommends that the MBNQA framework should be updated to include knowledge management as a core quality management component on the same level as leadership, strategic planning, customer and employee focus, and process management. Akdere's (2009) qualitative research is also not directly associated with the manufacturing industry since it researches KM and QM in the human resource arena.

2.4.2 Problems with Survey Based KM/QM Research

In several additional papers, surveys were used for KM/QM related research (Anand et al., 2010; McFadden et al., 2014; Mukherjee et al., 1998; Shan et al., 2013; Waddell & Stewart, 2008). Operational performance data to test the proposed concepts was not used by those authors. Mukherjee et al. (1998) only surveyed one firm, with the recommendation of future research by empirically testing their findings at a larger scale in different sectors of the manufacturing industry and at various locations. Waddell & Stewart (2008) did not support the survey conclusion that the development of a KM

discipline would improve an organization's quality with statistical methods. In another related research that uses a survey, Shan et al. (2013) draws general conclusions based on a limited survey sample size from one geographic region (eastern China), one industry (aerospace), and was not able to include cultural or geographical impacts. McFadden et al. (2014) conduct a survey in the health care industry to evaluate the effect of KM processes on patient safety learning, which does not relate to the manufacturing industry.

2.4.3 A Summary of Gaps and Problem Areas

This literature review found no quantitative empirical research that analyzes the effects of integrating knowledge management methods and quality management on a manufacturing firm's performance based on operational performance data. The available academic literature showed that existing research of the combined knowledge management and quality management field is qualitative or survey based. Operational performance data to test proposed concepts were not applied in the available literature. In certain cases, survey based research results were not supported by statistical methods, rendering the results not defendable. Other papers evaluated for this dissertation had survey samples from a single company or sample sizes too small and not culturally diverse, rendering the results as inconclusive. Prestigious quality award criteria such as the Malcolm Baldrige National Quality Award are missing knowledge management as a core component.

This dissertation research will close these gaps in research and contribute to the body of knowledge by offering a quality management strategy where KM is integrated in QM,

and the effectiveness of the KM/QM strategy is validated in the manufacturing industry through quantitative empirical research methods using operational performance data.

Chapter 3. Research Approach and Methodology

3.1 Problem Statement

Scholars have researched knowledge management in quality management, using surveys, developing qualitative concepts, theories, and propositions (Akdere, 2009; Anand et al., 2010; Choo et al., 2007a; Linderman et al., 2004; McFadden et al., 2014; Mukherjee et al., 1998; Shan et al., 2013; Waddell & Stewart, 2008). This literature review found that the body of knowledge does not include quantitative empirical research based on operational performance data that analyzes the effects of integrating knowledge management and quality management on a firm's performance. This study provides the answer to the following basic research question: Does a KM/QM strategy improve an organization's performance?

Manufacturing firms have vast amounts of quality related knowledge that needs to be processed in a timely manner to be used by numerous stakeholder groups within an organization. It was found that current traditional quality management methods and systems used in various industry sectors are effective in collecting, analyzing, and the automatic (electronic) administration of quality related information and data (Gee et al., 2005; Juran & Godfrey, 1999; Wortman et al., 2006). However, it was also found that current traditional quality management methods and systems do not include processes that enable rapid and dynamic responses to quality issues, knowledge transfer and knowledge creation, which is essential in today's fast changing, unpredictable, complex, and ever-increasing paced global business setting (Choo et al., 2007a; Linderman et al., 2004). As a result, response times for quality issues, identified during manufacturing or

from a customer level, are sometimes not communicated and addressed fast enough to the stakeholder groups using the current traditional quality management methods and systems. Current traditional quality management processes and systems that are often supported by modern and sophisticated ERP systems have inherent delays. The processes include the initial collaboration of potential quality issues, entering quality issues in an electronic database, electronic distribution of quality issue reports based on predefined distribution lists, receipt of the quality issue reports by the responsible stakeholder groups, and the communication, verification and validation of corrective and preventive measures. By the time the responsible stakeholder group is informed of an issue, valuable time and the opportunity to address the quality issue at a much earlier state can be lost. Consequently, such delays can cause additional quality issues since it was not sufficiently addressed in a timely manner, potentially causing other areas of the supply chain to be infected with the same quality issue. As a result, companies can have an overwhelming number of quality improvement projects that need to be managed at the same time with finite available resources. Predefined quality issue report distribution lists that are used with current ERP supported traditional quality management methods and systems can be addressed to an insufficient number or incorrect stakeholder groups, resulting in further delays to properly address quality issues. It was further found that current traditional quality management methods and systems do not facilitate socialization activities to communicate quality related issues, i.e., the personal interaction between the stakeholders, to allow rapid knowledge creation and knowledge transfer on a tacit level, which is vital in today's fast paced competitive business environment.

3.2 Research Environment

The four companies in this research belong to one large multinational organization and are labeled company A through company D. Each of the four geographically different companies is locally managed, manufactures the same products using similar manufacturing processes, has identical quality measuring methodologies, and the same performance metrics. Their products have a reputation of high-quality and are for sale in the U.S. and around the world. To protect proprietary and confidential information of the sponsoring organization, this research was populated with representative data. The representative data were obtained utilizing mathematical functions that proportionally allocated actual data from the sponsoring organization. The results of the analysis in this study are unaffected by the use of representative data. The same results can be observed by running the analysis both ways, using redacted and unredacted data.

The quality performance metrics, as measured by the four companies, are the product quality score and quality issues rate. The product quality score is a comprehensive measure of quality since it includes all possible quality issues for a large number of audited products. It is weighted, with severe quality audit findings resulting in lower product quality scores than minor findings. In other words, superior product quality is represented by a high product quality score and inferior product quality is characterized by a low product quality score. The second quality performance metric is the quality issue rate, which provides a measure for the number of product quality related issues. This metric is also measured during product audits. Contrary to the product quality score, the quality issue rate metric is a non-weighted metric. All quality issues, independent of severity, have the same weight. A low quality issue rate signifies better quality than a

high quality issue rate. Since the manufacturing processes and the quality measurement methodologies are standardized among the four companies, the measurement results are directly comparable between the four sites. The product quality measurement process is frequently audited by the corporate quality department to ensure compliance and uniformity between the four companies. In addition to the product quality score and quality issue rate metrics, the number of quality related improvement activities and cost of quality (COQ) elements are recorded by the company that implemented a KM/QM strategy. The last two metrics provide additional insights about the effectiveness of a KM/QM strategy.

The research consists of a three year pretest period, before the KM/QM strategy was implemented, and a six year posttest period with an implemented KM/QM strategy. Prior and during the pretest period, all four companies universally applied the traditional corporate QM strategy, which does not include a formal KM component. Company B was challenged by its local management to improve quality and take a sustained quality leadership role within the organization. Company B found that the traditional QM system offered the convenience of automatic (electronic) distribution of data but had slow response times to communicate quality issues, was complex to operate, resource intensive to administer and maintain, did not support knowledge creation, knowledge sharing, and mutual learning between different departments. The organization's traditional QM system is integrated in a modern corporate Enterprise Resource Planning (ERP) structure as an ERP module that is considered state of the art within the manufacturing industry. To address the identified system deficiencies, company B adopted a knowledge management approach which resembles Nonaka's (1994) theory of organizational knowledge creation

and integrated it in their existing QM system at the beginning of a six year posttest research period. The KM/QM strategy at company B evolved naturally with frequent updates and adjustments, especially during the early stages of the roll-out. The KM/QM system is still updated when necessary for different needs, such as enhancements. The KM/QM strategy was not implemented at companies A, C, and D during the six year posttest period, despite noticeable quality improvements at company B. This situation provides fertile grounds for research since we are able to compare the long-term impacts of a company that uses a KM/QM strategy to similar companies that apply traditional quality management methods without a formal KM component.

3.3 The KM/QM Strategy in Practice at Company B

In this section the KM/QM strategy and its practical applications are presented. It is further summarized in Figure 3-1 by classifying real-world practices of a KM/QM strategy as implemented at company B using Nonaka's (1994) theory of organizational knowledge creation elements. In practice, the sequence in which the SECI elements are applied is insignificant since the spiral of knowledge creation is an organic and dynamic process where the SECI elements take place as needed, somewhat naturally, unintentional from a KM perspective, and often simultaneously throughout the company. The knowledge creation processes and KM tools shown below under the SECI elements are merely highlights of the KM/QM strategy in practice at company B.

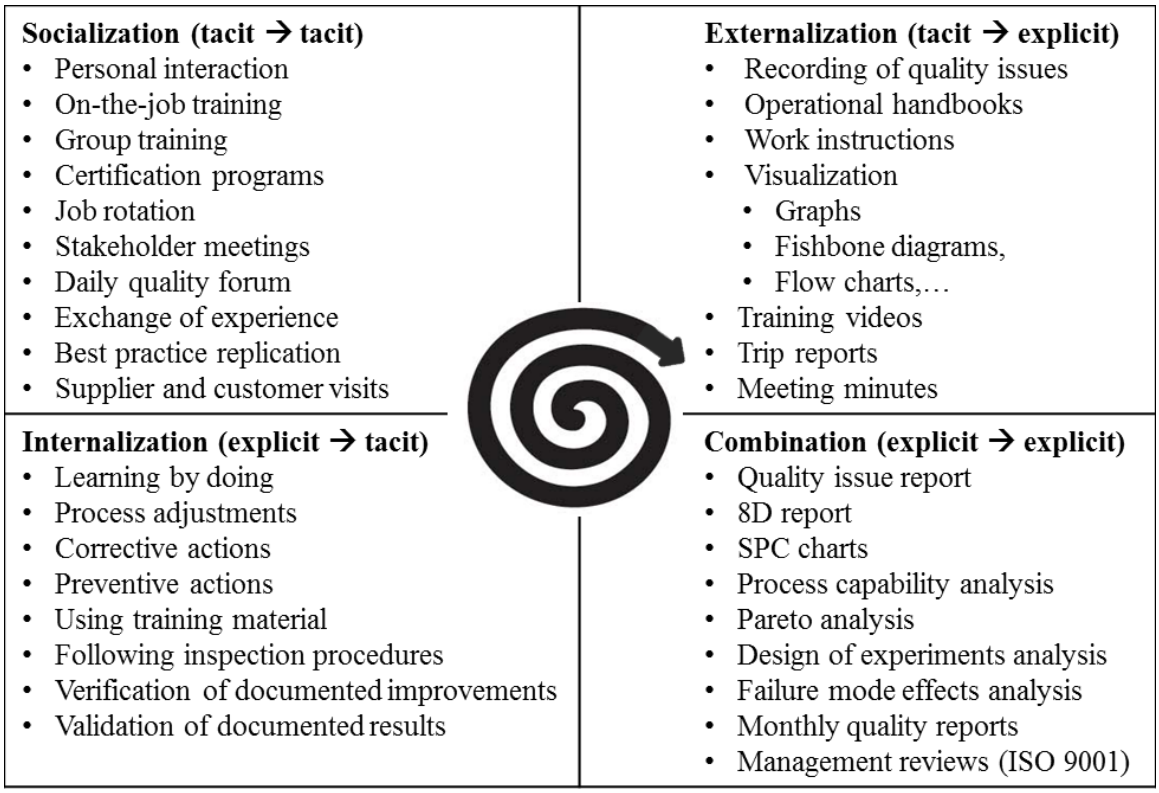


Figure 3-1: KM/QM Practices Classified by SECI Elements

3.3.1 KM/QM and socialization in practice

The company encourages personal interaction between stakeholders to foster tacit to tacit knowledge transfer. On the manufacturing shop floor, an extensive on-the-job training program for current and new employees is in place. Less experienced employees work hand-in-hand with experienced colleagues for an extended period of time. Tacit knowledge is naturally converted to new tacit knowledge through shared experience by spending time and working together. Professional certification programs for employees are encouraged and funded by the company. In the first year of the KM/QM implementation, a vast majority of quality engineers registered for the certified quality engineer examination. Prior to the exam, a local university administered a one semester

preparation course to a cohort of company quality engineers. During such periods, tacit knowledge is converted to new tacit knowledge as engineers study and share their experiences together. The company has job rotation programs with participation by all departments. The exchange of employees between departments fosters tacit to tacit knowledge transfer as employees work hand-in-hand with colleagues from other departments. To further increase the transfer of tacit to tacit knowledge and best practice replication, the company holds numerous short meetings between stakeholders. For example, a daily quality forum, attended by all stakeholders, forms communities of interaction. Current quality related issues are discussed and evaluated. Experienced attendees offer solutions to specific quality issues on the spot, avoiding "*reinventing the wheel*." The flow of tacit knowledge is instantaneous, reaches all stakeholders, and creates more tacit knowledge. In addition, company representatives frequently visit its suppliers and customers to create and sustain an environment where stakeholders freely exchange their experience, resulting in the transfer of tacit to tacit knowledge.

3.3.2 KM/QM and externalization in practice

Tacit knowledge from manufacturing shop floor personnel, quality assurance personnel, suppliers and customers is continuously converted to explicit knowledge by recording all quality related issues using the KM/QM enterprise system. Departments within the company develop and maintain operational handbooks that include work instructions for specific areas. Tacit knowledge housed in the minds of experienced employees is converted to understandable explicit knowledge that can be used by others. This greatly reduces mistakes, improves efficiency, reduces training time and improves

training results for the company. Corrective and preventive action processes from quality issues are transformed to understandable explicit knowledge. The company uses written documentation, graphs, images, flow charts, and videos to transfer tacit to explicit knowledge. After business related travel, trip reports are prepared and distributed to all stakeholders. Business trips take place for supplier and customer visits, trade shows, and other company related activities. After meetings, brief meeting minutes are written in a standard format and issued in a timely manner to participants and stakeholders.

3.3.3 KM/QM and combination in practice

Explicit to explicit knowledge transfer examples are so numerous that only a fraction of their applications can be presented in this dissertation. If a quality issue, recorded in the KM/QM enterprise system, meets a predefined severity threshold, the company converts explicit to explicit knowledge by generating a quality issue report (QIR). Further escalation and explicit to explicit knowledge conversion takes place by linking the QIR to an eight disciplines (8D) problem solving method report (Behrens, Wilde, & Hoffmann, 2007). Data from the KM/QM enterprise systems can be used to develop Pareto analysis to pinpoint major factors that impact customer satisfaction, quality and production. For example, a Pareto analysis of customer warranty data can provide input for manufacturing improvement projects and engineering changes. Documented results from experiments are further analyzed using design of experiments. Many of the company's production and inspection systems automatically acquire and record data which is used to compile specialized reports. The company generates statistical process control (SPC) charts from inspection results. For critical characteristics, the company uses inspection

data to generate process capability analysis. Quality audit results are used to generate reports with monthly product quality score and monthly quality issue rate. Supplier inspection data such as inspection certificates are used to generate internal inspection reports. Data such as inspection rates, number of shipments, rework cost, quality audit results and others can be used to create comprehensive quality and operations reports. Tasks from ISO 9001 audit reports are used to generate the management review (Gee et al., 2005).

3.3.4 KM/QM and internalization in practice

Explicit knowledge that was created is shared throughout the company and converted into tacit knowledge by individuals through "*learning by doing*." Explicit knowledge found in operational handbooks is converted to tacit knowledge when employees apply it to their work. The company makes SPC charts available at the manufacturing process so operators can use explicit data and convert it to tacit knowledge via process adjustments. After implementation, process adjustments are monitored and verified. Supervisors review and discuss QIR and 8D reports with the impacted personnel, creating tacit knowledge. The results of corrective and preventive actions, documented in QIR and 8D reports, are validated. Quality audit reports are evaluated in stakeholder groups where the conclusions and findings represent tacit knowledge. As the tacit knowledge accumulates at the individual level, it can start a new spiral of organizational knowledge creation as it is shared with others.

The flow of knowledge is free and unrestricted during all four SECI phases. During and after implementation of the KM/QM strategy at company B, it was observed that the

company culture improved in favor of quality consciousness and employee motivation towards quality improvement projects. Academic literature reveals that good quality has a positive effect on employee motivation, employee vision and organizational learning (Hays & Hill, 2001).

3.4 Conceptual Framework

The research framework proposed herein is based on the KM/QM strategy, reflecting the improvements implemented at company B. It utilizes Nonaka's (1994) theory of organizational knowledge creation as its underlying principle. The conceptual framework for this research is depicted in Figure 3-2. It graphically shows the relationship between the KM/QM strategy, as implemented at company B, and the manufacturing firm's performance, using knowledge creation at the center. The study asks the basic research question: Does a KM/QM strategy improve an organization's performance? While developing the framework using Nonaka's (1994) theory, it was found that company B included the elements and realized superior results to other companies.

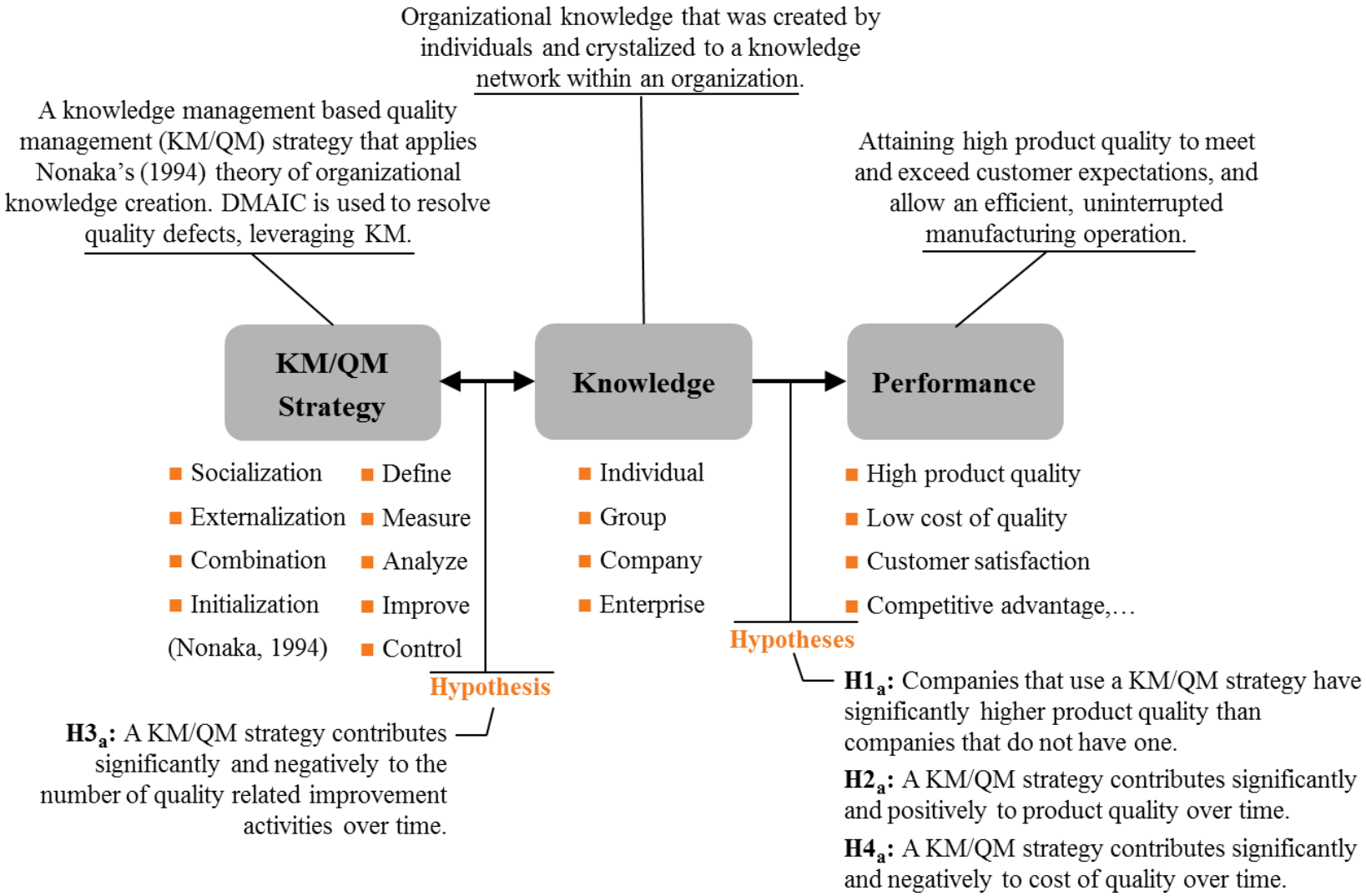


Figure 3-2: Conceptual Framework of a KM/QM Strategy

The elements of the KM/QM strategy, socialization, externalization, combination, and internalization are defined in detail within the literature review of this paper. In addition, the practical applications of the SECI elements are offered in a previous section of this chapter. The QM components, customer satisfaction, continuous improvement, and the systems view of an organization, used by Linderman et al. (2004) who applied Nonaka's (1994) knowledge creation theory to their theories and propositions of knowledge creation and quality management, also apply to the conceptual framework of a KM/QM strategy. However, further segmenting these QM components reveals that Hahn et al.'s (1999) DMAIC quality management process steps of define, measure, analyze, improve, and control are also applicable to the KM/QM framework and bear profound resemblance to the QM processes found at company B. As knowledge is created by individuals and groups in a dynamic spiral of knowledge creation, it gradually increases in acceptance and crystallizes while the knowledge resonates in growing communities of interaction to form a knowledge network within the company and the enterprise. Comparable research frameworks found in academic literature reflect the relationship of dynamic knowledge creation capabilities in an organization and its crucial role to continuous improvement project success, as well as the maintenance and creation of an organization's competitive advantage (Anand, Ward, Tatikonda, & Schilling, 2009; Choo et al., 2007a; Fredendall, Kovach, & LaGanga, 2010; McFadden et al., 2014). This framework extends the existing body of knowledge by suggesting that a manufacturing firm's performance is positively impacted by the successful implementation of a KM/QM strategy. A substantial number of scholars report that effective quality management result in performance improvements for a firm (Douglas & Judge, 2001; Easton & Jarrell, 1998;

Flynn et al., 1995; Hendricks & Singhal, 1996, 1997, 2001; Kaynak, 2003; Kull & Wacker, 2010; Linderman et al., 2004). In addition, Linderman et al. (2004) point out that the fundamental goals of knowledge management and quality management are the same since both aim to improve a firm's performance. To measure the effectiveness of the KM/QM strategy, a manufacturing firm's performance can be determined through product quality, cost of quality, customer satisfaction, market share and other performance indicators specific to a company. This research focuses on product quality, the number of improvement projects and the cost of quality as a measure of a firm's operational performance and the effectiveness of the KM/QM strategy, which leads to four research hypotheses offered for investigation.

3.5 Research Hypotheses and Methodology

The quantitative research hypotheses herein are predictions made about expected relationships among the variables in this study. Research design literature reveals that in quantitative research, research questions or hypotheses should be used, not both, unless a hypothesis builds on a research question (Creswell, 2009). The hypotheses in this quantitative empirical study build on the conceptual framework for a KM/QM strategy shown in Figure 3-2 and the basic research question: Does a KM/QM strategy improve an organization's performance? Detailed research sub-questions related to this basic research question will precede each of the four main research hypotheses. This study will focus on analyzing the predictions from four main research hypotheses, and as a result, provide answers to corresponding research sub-questions. The four main research hypotheses in this study may also contain several sub-hypotheses.

3.5.1 Hypothesis 1

The first main research hypothesis attempts to shed light on the following sub-question: Is a company with a KM/QM strategy more effective, in terms of product quality, than a company that does not have one? The corresponding null and alternate hypotheses were developed from the conceptual framework of the KM/QM strategy shown in Figure 3-2 and this first research sub-question.

$H1_0$: There is no difference between a company with a KM/QM strategy and a company without a KM/QM strategy in terms of product quality.

$H1_a$: Companies that use a KM/QM strategy have significantly higher product quality than companies that do not have one.

The posttest samples for this first hypothesis test contained six year average monthly quality performance results from the four companies. Eight groups of equal sample size ($n_{i=8}$=72) were collected, containing the monthly average product quality score, an interval scale variable, and the monthly average quality issue rate results, a ratio scale variable, for each of the four companies. Interval variables are on an ordered scale with a meaningful and quantifiable difference between the measurements, but without a true zero point, while ratio scale variables also have a true zero point (Levine, Berenson, Stephan, & Krehbiel, 2005). To ensure that the characteristic of the samples matched the characteristic of the population, stratified random sampling of various product model variations was applied (Salkind, 2012). Dependent variables were the monthly average product quality score and monthly average quality issue rate. Independent variable was the actual usage of a KM/QM strategy (KM/QM administered, KM/QM not

administered). Company B received the treatment (KM/QM strategy administered) and was included in the two experimental groups of this quasi-experimental design. Companies A, C, and D never received the treatment (KM/QM strategy not administered) and were included in the six control groups of this quasi-experimental design. Using control groups in an experiment increases the internal validity of the experimentation (Salkind, 2012). The quasi-experimental design method was selected since it allowed an evaluation of the effects of variables associated with the hypotheses after the fact. Quasi-experimental designs are therefore also referred to as "*post hoc research*" (Salkind, 2012). To determine if there was a difference between the groups before implementing the KM/QM strategy at company B, a pretest was performed based upon three years of data before the KM/QM strategy was implemented, and compared to the other sample groups. Descriptive statistics and a single factor analysis of variance (ANOVA) was used to test the two dependent variables, product quality score and quality issue rate, to determine if there was a significant difference between the groups. In case there was a significant difference, an analysis of means (ANOM) was performed to determine where the differences lie. The level of significance used for this study was $\alpha = 0.05$, meaning there was a 5% chance that a null hypothesis was rejected when it was actually true, also referred to as a type one error (Salkind, 2012). Traditionally, levels of 0.01, 0.05 and 0.10 are used depending on the cost of making a type one error (Levine et al., 2005). Microsoft Excel was used to perform the ANOVA. Minitab 16 statistical software was used to perform the ANOM and the residual analysis. ANOM graphs were generated with Minitab 16 statistical software. The quasi-experimental design for hypothesis 1 of this study is shown in Table 3-1.

Table 3-1: Experimental Design for Hypothesis 1

Step 1	Step 2	Step 3	Step 4
Company B is assigned to experimental groups.	Administer pretest before treatment (KM/QM strategy) is implemented. Method: ANOVA, descriptive statistics and ANOM if applicable.	Treatment in form of a KM/QM strategy is administered.	Administer posttest. Method: ANOVA, descriptive statistics and ANOM.
Companies A, C & D are assigned to control groups.	Administer pretest. Method: ANOVA, descriptive statistics and ANOM if applicable.	No treatment is administered.	Administer posttest. Method: ANOVA, descriptive statistics and ANOM.

3.5.2 Hypothesis 2

The second main research hypothesis tries to answer the following sub-question: Does the employment of a KM/QM strategy explain the relationship between the KM/QM strategy application time and a firm's product quality? The corresponding second set of null and alternate hypothesis builds on the conceptual framework of the KM/QM strategy shown in Figure 3-2 and this second research sub-question.

$H2_0$: There is no linear relationship between the KM/QM strategy application time and product quality.

$H2_a$: A KM/QM strategy contributes significantly and positively to product quality over time.

Pretest, posttest and control group sample sets for the second main research hypothesis were analogous to the first main research hypothesis test. Dependent variables

were the monthly average product quality score and the monthly average quality issue rate. The independent variable was the KM/QM strategy application time. A pretest was administered at company B for a three year time period before the KM/QM strategy was administered to determine if a significant linear relationship existed between time and product quality before the KM/QM strategy was implemented. After the KM/QM strategy was implemented at company B, a posttest was performed over a six year research period at company B as well as the control groups of company A, C, and D. The quasi-experimental design for hypothesis 2 of this study is shown in Table 3-2.

Table 3-2: Experimental Design for Hypothesis 2

Step 1	Step 2	Step 3	Step 4
Company B is assigned to experimental groups.	Administer pretest before treatment (KM/QM strategy) is implemented. Method: Regression analysis, two-tail t test.	Treatment in form of a KM/QM strategy is administered.	Administer posttest. Method: Regression analysis, two-tail t test
Companies A, C & D are assigned to control groups.	Administer pretest. Method: Regression analysis, two-tail t test.	No treatment is administered.	Administer posttest. Method: Regression analysis, two-tail t test

A regression analysis with a two-tail t test was applied for all sample sets to demine if there was a significant linear relationship between the variables. The degree of freedom for the two-tail t test was n-2 and the level of significance was $\alpha = 0.05$. Correlation between the KM/QM strategy application time and product quality performance characteristics was measured by getting the Pearson product-moment correlation coefficient (PPMCC), denoted by r. Various methods solve for r. The most commonly

used method is the Pearson Product Moment Correlation Coefficient (PPMCC) (Rodgers & Nicewander, 1988). The PPMCC was first published by Karl Person when he evaluated the relationship between human organs of parents and those of their children (Pearson, 1895). The sample correlation coefficient r is calculated using equation (3.1) or (3.2). A definition of variables is offered on pages xvi and xvii.

$$r = \frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}} \quad (3.1)$$

$$r = \frac{cov(X,Y)}{S_X S_Y} \quad (3.2)$$

The sample correlation coefficient r has the same sign as the slope of the regression line. Values of r range between -1 and 1, that is to say $-1 \leq r \leq 1$. A strong negative linear relationship exists when r approaches -1, a strong positive linear relationship exists when r approaches +1. There is no linear relationship when r=0 (Pearson, 1920). The square of the correlation coefficient r is the coefficient of determination r^2, which provides a proportional measure of the variation in the dependent variable that can be explained by the linear relationship (Levine et al., 2005). Salkind (2012) presented ranges for the sample correlation coefficient r and its associated estimated relationship strength. In addition to the strength, this hypothesis test also provides evidence for a statistically significant linear relationship between the KM/QM strategy application time and product quality characteristics in the population. The population correlation coefficient is denoted

by ρ. It was hypothesized that the population correlation coefficient is zero. The corresponding null and alternate sub-hypotheses are as follows:

H_0: $\rho = 0$

H_a: $\rho \neq 0$

To determine if there was a significant linear relationship, the test statistic for the existence of a correlation with degree of freedom n-2 was applied, namely

$$t = \sqrt{\frac{n-2}{1-r^2}} \qquad with\ dof = n - 2 \tag{3.3}$$

Based on the selected level of significance, $\alpha = 0.05$ for this study, and the degree of freedom for the two-tailed t test of n-2, the critical value for the two-tailed t test (t_{CV}) and the p value were obtained from tables in Levine et al. (2005). The p value was also derived using Microsoft Excel. If the calculated t-test statistic were in the critical area ($|t| > |t_{CV}|$) or the p value was smaller than the level of significance ($p < \alpha$), the null hypothesis was rejected. In this case, it was concluded that the sample correlation was not due to chance and there was evidence of a significant linear relationship between the KM/QM strategy application time and the product quality characteristics in the population. Microsoft Excel was used to perform regression analysis.

Correlation between two variables is not sufficient to prove causation (Agresti & Franklin, 2009; Levine et al., 2005). Correlation could have been produced by chance or by the effects of other variables which were not considered in this research. To analyze this possibility, a pretest was performed to determine if there was a significant linear relationship between the variables before the treatment (KM/QM strategy) was

administered at company B. In addition, six control groups without treatment (company A, C, and D's product quality score and quality issue rate) were tested and compared to the two control groups with the treatment (company B's product quality score and quality issue rate). The causal assumption of a relationship between the KM/QM strategy application time and product quality characteristics was strengthened by the fact that all four companies (sites) included in this research operated in a similar environment and had a uniform culture since they belonged to the same organization, with the KM/QM strategy implementation at company B as the sole difference. Confounding effects and factor interactions that might have played a role while implementing a KM/QM strategy are addressed in section 4.6 of this dissertation. To validate the results, hypotheses tests for two additional operational performance measures associated with the KM/QM strategy effectiveness were conducted. They are the number of quality related improvement activities and cost of quality. Similar results from the analysis of the additional operational performance measures would support and validate the results of the first two hypotheses tests and also address the basic research question on performance improvements through the employment of a KM/QM strategy.

3.5.3 Hypothesis 3

The third main research hypothesis attempts to answer the following sub-question: Does the use of a KM/QM strategy explain the relationship between the KM/QM strategy application time and the number of quality related improvement activities? The corresponding third set of null and alternate hypothesis builds on the conceptual

framework of the KM/QM strategy shown in Figure 3-2 and the third research sub-question.

$H3_0$: There is no linear relationship between the KM/QM strategy application time and the number of quality related improvement activities.

$H3_a$: A KM/QM strategy contributes significantly and negatively to the number of quality related improvement activities over time.

While the first and the second hypotheses analyze the effects of a KM/QM strategy on product quality performance characteristics, the third hypothesis examines the effects of a KM/QM strategy on the number of quality related improvement activities. It provides insights into KM/QM strategy knowledge creation capabilities. Although, no quantitative empirical research during the literature review was discovered, scholars reported that the application of Nonaka's (1994) theory of organizational knowledge creation with its SECI elements, creates knowledge and quality performance improvements for firms (Anand et al., 2010; Linderman et al., 2004; Shan et al., 2013). This hypothesis test evaluates if a sustained KM/QM strategy application will reduce the number of quality related improvement activities. Restated, it is hypothesized that as quality improves due to the employment of a KM/QM strategy, with its dynamic spiral of organizational knowledge creation, the need for quality improvement activities subsides, due to the organization as a whole gaining quality related knowledge to avoid repeated occurrences and prevent new quality issues. Furthermore, the analysis of the third main research hypothesis test can validate the results of the first and second main research hypotheses, since all three hypothesize operational performance improvements as a result of implementing a KM/QM strategy.

The data set for the third main research hypothesis test consisted of n=60 data points and encompassed the monthly average number of quality improvement activities, a ratio scale variable, over a five year timespan from company B, after the KM/QM strategy was implemented. This timeframe coincides with year two through year six of the first and second main research hypotheses posttest timespan. The improvement activities were initiated because of internal quality findings reported by the internal customers within company B during the manufacturing operation or because of external quality findings reported by sources outside company B. The number of quality related improvement activities per day was compiled to monthly average quality related improvement activities per day for this research. The dependent variable for this third main research hypothesis test was the number of quality related improvement activities per day. The independent variable was the KM/QM strategy application time. A pretest could not be administered to determine if a relationship existed between time and the number of quality related improvement activities before the KM/QM strategy was implemented at company B since such data was not available for this research. It was also not possible to use company A, C, and D as control groups since data for the number of quality related improvement activities was not available from company A, C, and D for this research. This hypothesis test also used a quasi-experimental design since it allowed the evaluation of effects on variables associated with this hypothesis after the fact. The quasi-experimental design for the third hypothesis is shown in Table 3-3.

Table 3-3: Experimental Design for Hypothesis 3

Step 1	Step 2	Step 3
Company B is assigned to experimental group.	Treatment in form of a KM/QM strategy is induced.	Administer posttest. Method: Regression analysis, two-tail t test or alternatively F test.

A regression analysis with a two-tail t test was conducted to determine if a significant linear relationship existed between the KM/QM strategy application time and the number of quality related improvement activities after the KM/QM strategy was implemented at company B. The degree of freedom for the two-tail t test was n-2 and the level of significance used for this study was $\alpha = 0.05$. Correlation between the KM/QM strategy application time and the number of quality related improvement activities was measured by computing the sample correlation coefficient r. The square of r (coefficient of determination r^2) provided insights on how much variation in the dependent variable was explained by the linear relationship. The sample correlation coefficient r was calculated using equation (3.1) or (3.2) that was discussed in section 3.5.2. Equation 3.3 of section 3.5.2 describes the t-statistic for testing the existence of correlation, which was also used for this third hypothesis test. To evaluate the presence of a significant linear relationship between the KM/QM strategy application time and the number of quality related improvement activities, a hypothesis test was performed to see whether the population slope $ß_1$ of the linear regression line is equal to zero. The null and alternate sub-hypotheses for this inference test about the slope of the regression line are as follows:

H_0: $ß_1 = 0$

H_a: $ß_1 \neq 0$

In case the null hypothesis was rejected, it was concluded that there was evidence of a significant linear relationship between the KM/QM strategy application time and the number of quality related improvement activities. The following t-statistic for this third hypothesis test with degree of freedom n-2 and a 0.05 level of significance as defined by Levine et al. (2005) was applied:

$$t = \frac{b_1 - ß_1}{S_{b1}} \qquad with\ dof = n - 2 \tag{3.4}$$

Equation 3.4 generates the difference between the sample slope coefficient of the regression line (b_1) and the hypothesized value of the population slope ($ß_1 = 0$) over the standard error of the slope (S_{b1}) (Levine et al., 2005). The coefficient for the sample regression line slope and the standard error of the slope were obtained using Microsoft Excel. Levine et al. (2005) presents a second method for determining if there is a significant linear relationship between variables, namely the F test for the slope. The F statistic for the regression line slope equals the regression mean square (MSR) divided by the error mean square (MSE) with degree of freedom of 1 for the MSR and 58 for MSE as shown in equation 3.5. Both, MSR and MSE were obtained using Microsoft Excel.

$$F = \frac{MSR}{MSE} \qquad with\ dof = k\ for\ MSR\ and\ dof = n - k - 1\ for\ MSE \tag{3.5}$$

Based on the selected level of significance used for this hypothesis test of $\alpha = 0.05$ and the degree of freedom outlined in equation 3.4 and 3.5, the critical values (t_{CV} or alternatively the upper critical value F_{CVU}) and the p value were obtained from tables

such as Levine et al. (2005). The p value was also derived with Microsoft Excel. If the calculated t-test statistic or alternatively the F-test statistic was in the region of rejection, or the p value was smaller than the level of significance, the null hypothesis was rejected. In this case, it was concluded that the sample correlation was not due to chance and there was evidence of a significant linear relationship between the KM/QM strategy application time and the number of quality related improvement activities in the population. Microsoft Excel was used to perform regression analysis.

Correlation could have been produced by chance or by the effects of other variables that were possibly not considered in this research. To evaluate the causation of a relationship between the KM/QM strategy application time and the number of quality related improvement activities, it was investigated if any other changes or policy implementations took place at company B prior or during the KM/QM strategy implementation that could have affected the number of quality related improvement activities. Such changes include movements in product quality trends or changes in the company's quality targets. A company's decision to have more stringent product quality targets could lead to an increase in quality improvement activities to achieve the higher product quality goals. Contrary, lowering product quality targets could result in fewer quality related improvement activities since it is no longer necessary to achieve the high quality goals. The r^2 coefficient of determination, as described earlier in this section, provides insights in predictability of the relationship between variables. Section 4.6 of this dissertation offers a detailed evaluation of confounding effects and factor interactions that might have played a role while implementing a KM/QM strategy. The third hypothesis test can assist in validating the first and second hypothesis since similar

effects would support the causal assumptions, support and validate the results from the first two hypotheses tests, and address the basic research question of performance improvements through the employment of a KM/QM strategy.

3.5.4 Hypothesis 4

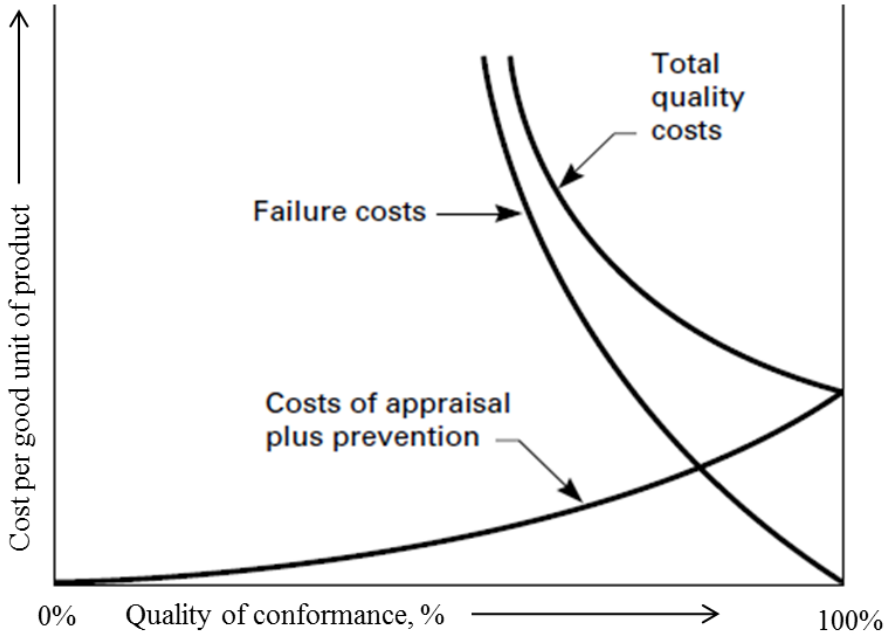
The fourth main research hypothesis evaluates the following sub-question: Does the employment of a KM/QM strategy explain the relationship between the KM/QM strategy application time and a company's cost of quality? The corresponding fourth set of null and alternate hypothesis is based on the conceptual framework of the KM/QM strategy shown in Figure 3-2 and this fourth research sub-question.

$H4_0$: There is no linear relationship between the KM/QM strategy application time and a company's cost of quality.

$H4_a$: A KM/QM strategy contributes significantly and negatively to cost of quality over time.

Juran & Gryna (1993) informed that the cost of poor quality is on average 15 percent of sales for manufacturing firms and can vary between 5% and 35% depending on the complexity of the product being manufactured. The three categories for COQ are prevention, appraisal and failure cost (Wortman et al., 2006). The later COQ category, namely failure cost, is typically the highest COQ component for companies. It is on average 70% of the total cost of quality (Campanella, 1999). Wortman et al. (2006) reports that failure cost ranges between 40% and 80% of total COQ with each of its two sub components, internal failure cost and external failure cost, individually contributing 20% to 40% to the total COQ for firms. In today's competitive business environment, a

trend towards 100% quality of conformance is becoming a major objective for firms (Juran & Godfrey, 1999). Figure 3-3 illustrates Juran et al.'s (1999) theoretical optimum quality costs model where the minimum level of the total COQ takes place when the quality of conformance reaches 100%. Empirical research in the manufacturing arena shows that with increased appraisal and prevention costs, product quality increased and failure costs decreased (Omachonu, Suthummanon, & Einspruch, 2004).



From Juran's Quality Handbook (Juran et al., 1999)
Reproduced with permission of McGraw-Hill Education LLC.

Figure 3-3: Juran et al.'s (1999) Optimum Quality Costs Model

The COQ element used in this research was the internal failure costs at company B and is shown as a normalized COQ score. The internal failure costs occurred before the products were shipped to the customer. The COQ score, a ratio scale variable, is a non-weighted performance metric and includes rework, repair, retesting, scrap and sorting costs. Higher numbers for the COQ score also represent higher COQ. The fourth

hypothesis test spanned over seven years and evaluated the relationship between time and COQ. Four research periods are analyzed for this hypothesis test. They are the pretest period, the KM/QM strategy implementation year, the posttest period, and the final posttest year as a subset of the posttest period. The pretest period consists of one year (n=12) of monthly COQ score samples before the KM/QM strategy was implemented at company B. The pretest was conducted to determine if a significant relationship already existed between time and cost of quality, before the KM/QM strategy was implementation at company B. The KM/QM strategy implementation year test consists of n=12 monthly COQ score samples from company B during the first year of KM/QM deployment. This investigation determined if there was a significant relationship or a change in the relationship between the KM/QM strategy application time and a company's cost of quality during the initial KM/QM strategy implementation period. The posttest period contained five years of monthly COQ data. At the end of each quarter, three month of data were used to calculate company B's average monthly COQ score, resulting in n=20 quarterly samples for the posttest period. The posttest research period started after the initial KM/QM strategy implementation period at company B, one year into the six year research period used for the first and second main research hypotheses test. It also coincided with the third main research hypothesis test period. The posttest determined if a significant relationship between the KM/QM strategy application time and the cost of quality score existed or if the relationship changed compared to the previous research periods. The dependent variable for this fourth main research hypothesis test was the cost of quality score and the independent variable was time. The last analysis for the fourth main research hypothesis test determines if there was a

significant difference in company B's COQ score before and after KM/QM implementation by comparing the pretest and final posttest year COQ score data. The final posttest year COQ score data contains n=12 monthly COQ scores from company B. This final study hypothesized that a company prior to KM/QM strategy implementation has a significantly higher mean COQ score than a company with an implemented KM/QM strategy. Since the COQ data were found not comparable between the four sites, company A, C, and D were not used as control groups for the fourth main research hypothesis test. A quasi-experimental design, as presented in Table 3-4, was used for this study.

Table 3-4: Experimental Design for Hypothesis 4

Step 1	Assign company B to experimental groups.
Step 2	Administer pretest before treatment (KM/QM strategy) is implemented. Method: Regression analysis, two-tail t test or F test.
Step 3	Treatment in form of a KM/QM strategy is administered.
Step 4	Administer test during implementation of treatment. Method: Regression analysis, two-tail t test or alternatively F test.
Step 5	Administer posttest. Method: Regression analysis, two-tail t test or alternatively F test.
Step 6	Administer test for difference before and after treatment. Method: Two sample t-test for difference between two means.

A regression analysis was conducted to determine the existence of a correlation and the significance of a linear relationship between time and the cost of quality score for three test periods: The pretest period, before the KM/QM strategy was implemented at company B, the initial KM/QM strategy implementation period, and the posttest period,

after the KM/QM strategy was implemented. Correlation between time and the COQ score for the three tests periods were measured by computing the sample correlation coefficient r using equations and procedures outlined in section 3.5.2 of this dissertation, in particular equation 3.1 and equation 3.2. The coefficient of determination r^2 was calculated to determine the variation in the COQ score as it was explained by the linear relationship. The t test statistic outlined in equation 3.3 was used to determine the existence of significant correlations between time and the COQ scores for the three test periods. The presence of significant linear relationships between time and the COQ score for the three test periods were evaluated with inference tests about the slopes of the regression lines. This test was defined in equation 3.4 and alternatively equation 3.5 of section 3.5.3 in this dissertation.

To determine if the mean COQ score prior to KM/QM strategy implementation is significantly higher than after KM/QM strategy implementation, a two sample t test was conducted. The mean COQ score prior to KM/QM strategy implementation is from the pretest period sample group. The mean COQ score after KM/QM strategy implementation is from the final posttest year sample group. Population means for the pretest period and the final posttest year are denoted by μ_1 and μ_2 respectively. The corresponding null and alternate sub-hypothesis for the two variable t test is as follows:

H_0: $\mu_1 \leq \mu_2$

H_a: $\mu_1 > \mu_2$

In case the null hypothesis was rejected, there was evidence to support the claim that a company prior to KM/QM strategy implementation has a significantly higher mean COQ score than after KM/QM strategy implementation. An F test for the difference

between two population variances was performed to determine if a pooled variance t test is appropriate (Levine et al., 2005). For normally distributed data with unknown but equal population variances, a two sample pooled-variance t test can be used (Levine et al., 2005). To corresponding null and alternate sub-hypotheses for the inference on the variance of two populations are as follows:

H_0: $\sigma_1^2 = \sigma_2^2$

H_a: $\sigma_1^2 \neq \sigma_2^2$

The following F test with degree of freedom n_1-1 and n_2-1 as defined by Levine et al. (2005) was applied:

$$F = \frac{S_1^2}{S_2^2} \quad with\ dof\ n_1 - 1\ and\ n_2 - 1 \qquad (3.6)$$

The F test for the difference between two population variances is based on the ratio of two sample variances from two independent and normally distributed populations. Based on the selected level of significance used for this test of $\alpha = 0.05$ and the degree of freedom outlined in equation 3.6, the upper and lower-tail critical values (F_{CVU} and F_{CVL}) were obtained from tables such as Levine et al. (2005). In case the computed F test statistic is not greater or less than the upper and lower-tail critical values, H_0 cannot be rejected and it was assumed that the two variances were equal. Consequently, the use of a two sample pooled-variance t test is appropriate. In case the two variances cannot be assumed equal, an alternate two variable t test statistic with different degrees of freedom has to be applied (Montgomery & Runger, 2002). The two sample pooled-variance t-test statistic as defined by Levine et al. (2005) is shown in equation 3.7 where the two sample

variances, S_1^2 and S_2^2, are combined to form the pooled sample variance S_p^2. Levine et al. (2005) also provide the general from for the pooled variance as presented in equation 3.8. Since the two sample group sizes, pretest group and the final posttest year group, are equal (n_1=n_2=12), a reduced and simplified statement for the pooled variance is expressed in equation 3.9.

$$t = \frac{(\bar{X}_1 - \bar{X}_2) - (\mu_1 - \mu_2)}{\sqrt{S_p{}^2 (\frac{1}{n_1} + \frac{1}{n_2})}} \quad with\ dof = n_1 + n_2 - 2 \tag{3.7}$$

$$S_p{}^2 = \frac{(n_1 - 1) S_1{}^2 + (n_2 - 1) S_2{}^2}{(n_1 - 1) + (n_2 - 1)} \tag{3.8}$$

$$S_p{}^2 = \frac{S_1{}^2 + S_2{}^2}{2} \quad applies\ only\ if\ n_1 = n_2 \tag{3.9}$$

Based on the selected level of significance of α= 0.05 and the degree of freedom outlined in equation 3.7, the critical values (t_{CV}) for a one sided t test were obtained from tables such as Levine et al. (2005). If the calculated t-test statistic was in the region of rejection marked by the critical value t_{CV}, the null hypothesis was rejected. In this case, it was concluded that there was evidence of a significantly higher mean COQ score prior to KM/QM strategy implementation than after KM/QM strategy implementation.

Correlation could have been produced by chance or by the effects of other variables that were possibly not considered in this research. For this reason, a pretest was performed to determine if a significant relationship or trend between time and the COQ score already existed before the treatment (KM/QM strategy) was administered at company B. After the KM/QM strategy was fully implemented at company B, a two

variable t test was performed to evaluate if there was in fact a significant difference in COQ compared to a time period just before the KM/QM strategy was implemented. To account for the effects of changes in production quantities and changes in operational costs on COQ, the performance metric was normalized to a COQ score. Possible other changes or policy implementations that took place at company B prior or during the KM/QM strategy employment were previously discussed in this chapter for the preceding three main research hypotheses tests and also apply to this fourth main research hypothesis test. Confounding effects and factor interactions that might have played a role while implementing a KM/QM strategy are examined in section 4.6 of this dissertation. The analysis from this fourth main research hypothesis test can validate the results from the previous three main research hypotheses tests, and addresses the basic research question by examining improvements in operational performance measures, such as COQ, through the employment of a KM/QM strategy. All four main research hypotheses check for operational performance improvements, as a result of implementing a KM/QM strategy.

Chapter 4. Data Analysis and Results

4.1 Hypotheses Summary

This dissertation analyzes four main research hypotheses. The first main research hypothesis proposes that there is a difference in product quality performance between a company that uses a KM/QM strategy and companies without a KM/QM strategy. The second main research hypothesis suggests that the use of a KM/QM strategy results in a significant linear relationship between the KM/QM strategy application time and a firm's product quality. The third main research hypothesis proposes a significant negative relationship between the KM/QM strategy application time and the number of quality related improvement activities. And the fourth main research hypothesis suggests that the employment of a KM/QM strategy explains the significant negative relationship between the KM/QM strategy application time and a company's cost of quality.

4.2 Hypothesis 1

4.2.1 Evaluation of Research Data: Hypothesis 1

The posttest samples for this first main research hypothesis test cover six-year average monthly quality performance results from four companies. Eight groups of data, consisting of two experimental groups and six control groups, of equal sample size ($n_{i=8}$=72) were collected. The posttest experimental groups include two sets of data from company B, consisting of 72 monthly average product quality score and quality issue rate results. The posttest control groups contain six sets of data from company A, C, and D, again with 72 monthly averages of product quality score and quality issue rate results. An

additional 36 month of quality performance data was analyzed for a pretest, before the KM/QM implementation at company B, and compared to the other sample groups to determine if there was a significant difference between the groups. To justify the use of parametric statistics for this research, and before proceeding with analysis of variance, the first main research hypothesis data were evaluated if it meets the underlying assumptions for a one-way ANOVA F test. The assumptions are randomness and independence, homogeneity of variance (or equal variances), and normality (Levine et al., 2005).

It was found that the datasets for the first main research hypothesis test meet the assumption of randomness and independence since the observations at one company were not related to the observations at the other companies. Stratified random sampling of various product model variations was applied at all four companies. This type of random sampling method ensured that the characteristic of the sample matched the characteristic of the population. Furthermore, the observations from the pretest period were independent to the observations from the posttest period.

Based on an analysis of residuals, the data for the first main research hypothesis test meets the homogeneity of variance assumption, since there is no observed major difference in the variability of the residuals against the independent variable and against the fitted values (Lattin, Carroll, & Green, 2003). The residuals fluctuate randomly around zero and there is no systematic pattern throughout the plots. The residual plots for the posttest product quality score and quality issue rate data sets from company A, B, C, and D are shown in Figure 4-3 and Figure 4-4 of section 4.3.1 respectively. The residual plots for the pretest product quality score and quality issue rate data sets are shown in

Figure 4-5 of section 4.3.1. Furthermore, since the sample size in each of the eight posttest groups are equal ($n_{i=8}$=72) for both metrics, product quality score and quality issue rate, an ANOVA is not critically affected by unequal variances (Levine et al., 2005).

The pretest and posttest research data for company A and B meet the assumption of normality based on the normal probability plots of residuals and the histograms of residuals shown in Figures 4-3 to 4-5. Skewed histograms of residuals indicate that the distributions for company C and D are different from normal. This is also confirmed by an Anderson-Darling (AD) test for normality of the original and residual data. A one-way ANOVA F test still works under such conditions given that the sample size is sufficiently large (Agresti & Franklin, 2009). Based on the central limit theorem, the pretest and posttest sample distributions of the means for the four companies in this first main research hypothesis test are approximately normal since the sample sets are sufficiently large. Authors of statistics books define this sufficiently large sample size with $n \geq 30$ (Levine et al., 2005). Nevertheless, non-parametric Kruskal-Wallis tests using Minitab 16 statistical software were performed to verify the normality assumptions applied for the parametric ANOVA tests.

4.2.2 Analysis: Hypothesis 1

A single factor ANOVA shows a significant difference between group means for both metrics; product quality score and quality issue rate (see Table 4-1 and Table 4-2). Since the p values (p=0.000) are less than the selected level of significance (α= 0.05), at least one mean for each quality performance metric is significantly different.

Table 4-1: ANOVA with Descriptive Statistics for Product Quality Score

Product quality score

Groups	*Count*	*Sum*	*Average*	*Variance*	*Std. Deviation*
Company A	72	474.8	6.594	0.064	0.253
Company B pretest	36	237.5	6.598	0.030	0.174
Company B posttest	72	487.3	6.768	0.021	0.146
Company C	72	479.6	6.661	0.087	0.295
Company D	72	481.0	6.680	0.094	0.307

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	*F crit*
Between Groups	1.300	4	0.325	5.179	0.000	2.400
Within Groups	20.01	319	0.063			
Total	21.31	323				

Table 4-2: ANOVA with Descriptive Statistics for Quality Issue Rate

Quality issue rate

Groups	*Count*	*Sum*	*Average*	*Variance*	*Std. Deviation*
Company A	72	13.32	0.185	0.014	0.119
Company B pretest	36	10.12	0.281	0.018	0.133
Company B posttest	72	9.252	0.128	0.009	0.093
Company C	72	19.94	0.277	0.055	0.233
Company D	72	13.21	0.183	0.042	0.205

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	*F crit*
Between Groups	1.064	4	0.266	9.321	0.000	2.400
Within Groups	9.099	319	0.029			
Total	10.16	323				

An analysis of means was performed to determine where the differences lie. Corresponding ANOM charts are shown in Figure 4-1 and Figure 4-2 which were generated using Minitab 16 statistical software. The horizontal center lines indicate the overall mean. The top and bottom horizontal lines represent the upper and lower critical limits respectively. Since the pretest sample sets for company B have smaller sample

sizes than the other sample groups, the acceptance limits for company B's pretest datasets are wider. The only mean product quality score that falls above the critical limit is company B's (B posttest), demonstrating that the site with a KM/QM strategy is significantly different in a positive way than the other three sites. To the contrary, company B prior to KM/QM strategy implementation (B pretest) shows the mean product quality score below the overall average in Figure 4-1, indicating an inferior product quality. The mean product quality score for company A falls below the critical limit and is therefore significantly different in a negative way than the mean product quality score for the other three sites. The reason for site A's inferior mean product quality score is not part of this research. In practical terms, the reader may ask what is the difference on having a mean product quality score of 6.77 (company B posttest) versus a score of 6.60 (company B pretest) as reported in Table 4-1? To illustrate the difference with an arbitrarily selected product such as a household appliance, the higher mean product quality score of 6.77 indicates that the customer can expect no functional defects upon installation of the product. The appliance should work as intended. However, the population with this score can still include a small number of appliances with minor defects that are not always noticed by the customer and do not affect the function of the appliance. Such minor defects can include scratch marks or small dents on surfaces not visible to the customer at first sight. The lower mean product quality score of 6.60 is an indication that the population can also have a small number of appliances that do not work upon installation and may require repair or a product exchange to resolve the quality problem for the customer, e.g., a washing machine spin cycle does not work upon

installation, a washing machine does not properly drain water in spite of being installed correctly, etc.

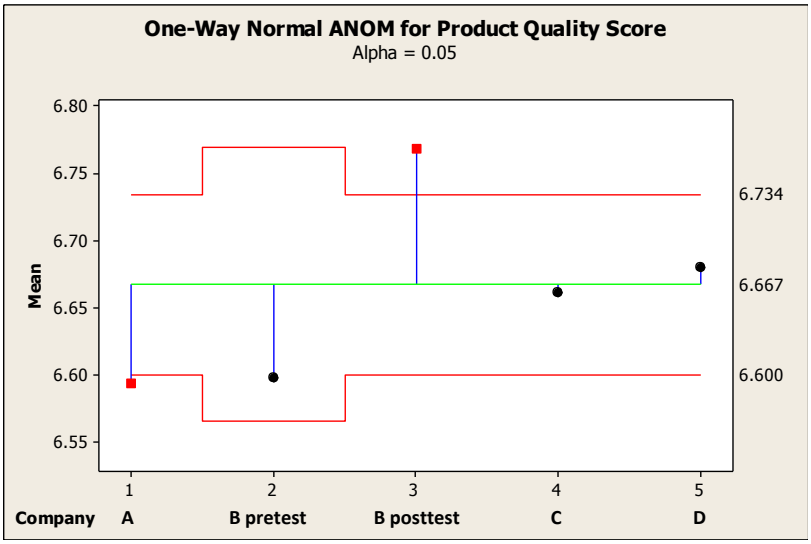


Figure 4-1: ANOM for Product Quality Score

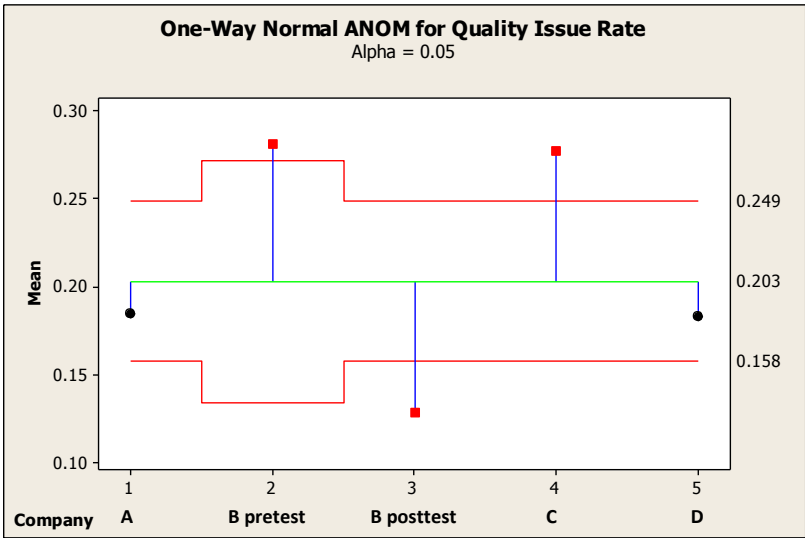


Figure 4-2: ANOM for Product for Quality Issue Rate

The only mean quality issue rate which falls below the critical limit is that of company B (B posttest), demonstrating again that the site with a KM/QM strategy is

significantly different in a positive way than the other three sites. We also observe that before the KM/QM strategy was implemented, the quality issue rate for company B (B pretest) is on the opposite side of the overall mean and outside the critical limit as shown in Figure 4-2, indicating a significantly inferior product quality. The mean quality issue rate for company C is above the critical limit and significantly different in a negative way than the other three companies. Analyzing the reason for company C's high quality issue rate is not part of this research.

Non-parametric Kruskal-Wallis tests confirm the results from parametric ANOVA. Because the Kruskal-Wallis test statistics H_{TV}=26.71 and H_{TV}=42.85 for the product quality scores and quality issue rates respectively are greater than the critical value H_{CV}=9.488, it is confirmed that there is evidence of a significant difference among the companies with respect to the median product quality score and median quality issue rate. The results from the Kruskal-Wallis test are shown in Table 4-3 and Table 4-4. The only median product quality score that falls above the critical Z-value is that of company B after KM/QM implementation (company B posttest). The only median quality issue rate that falls below the critical Z-value is also that of company B after KM/QM implementation. The non-parametric Kruskal-Wallis test confirms the ANOM results that the site with a KM/QM strategy is significantly different in a positive way.

Table 4-3: Non-Parametric ANOVA Verification with Kruskal-Wallis Test for Quality Score

	Kruskal-Wallis Rank Test Product Quality Score				
	N	Median	Ave Rank	Z_{TV}	Z_{CV}
Company A	72	6.616	132.1	-3.12	+/- 2.326
Company B pretest	36	6.629	118.1	-3.02	+/- 2.326
Company B posttest	72	6.797	196.5	3.49	+/- 2.326
Company C	72	6.703	169.4	0.71	+/- 2.326
Company D	72	6.752	174.2	1.2	+/- 2.326
Overall	324		162.5		
	$H_{TV} = 26.71$ DF = 4 P = 0.000 (adjusted for ties)				
	$H_{CV} = 9.488$ $\alpha = 0.05$				

Table 4-4: Non-Parametric ANOVA Verification with Kruskal-Wallis Test for Issue Rate

	Kruskal-Wallis Rank Test Product Issue Rate				
	N	Median	Ave Rank	Z_{TV}	Z_{CV}
Company A	72	0.1839	161.5	-0.10	+/- 2.326
Company B pretest	36	0.2581	224.9	4.24	+/- 2.326
Company B posttest	72	0.0968	120.1	-4.36	+/- 2.326
Company C	72	0.2452	195.0	3.34	+/- 2.326
Company D	72	0.1290	142.2	-2.08	+/- 2.326
Overall	324		162.5		
	$H_{TV} = 42.85$ DF = 4 P = 0.000 (adjusted for ties)				
	$H_{CV} = 9.488$ $\alpha = 0.05$				

The causal assumption that a KM/QM strategy at company B is responsible for the higher quality at company B than the three companies with a traditional QM system is based on the similar environment and uniform culture the companies operate in. The four large manufacturing companies operate under similar conditions, manufacture the same products, use the same manufacturing technologies, apply the same measuring methods and use the same quality metrics. Effects due to the four company's geographically

different locations and associated cultural differences can be discounted since there is a strong corporate culture among the companies in the organization. Frequent job rotations between the four companies, standardization of processes, and compliance audits are just a few of the measures that enable this strong corporate culture and uniform environmental condition. During the research period, there were no other changes or policy implementations found that impacted any of the four sites differently, with exception to the KM/QM strategy implementation at company B. A detailed discussion about all obtainable factors, confounding effects and factor interactions that might have played a role in the success at company B while implementing and employing a KM/QM strategy is offered in section 4.6 of this chapter. The causality assumption is further supported with the results of the pretest, which confirmed that company B did not have a significantly higher product quality than the other companies without a KM/QM strategy prior to KM/QM implementation at company B. The significantly superior product quality was only observed after the KM/QM strategy was implemented at company B.

4.2.3 Results of Analysis: Hypothesis 1

The result of this analysis supports the claim of the first main research hypothesis that companies which implement a KM/QM strategy, such as company B, have a significantly higher product quality than companies in the control groups without a KM/QM strategy such as companies A, C, and D. A pretest demonstrates that company B did not have superior product quality than companies A, C, and D prior to KM/QM strategy implementation. Furthermore, a comparison of the product quality performance before and after the KM/QM strategy was implemented at company B shows a positive change

with respect to product quality after implementing a KM/QM strategy. The results and the assumptions from the parametric ANOVA are confirmed by non-parametric Kruskal-Wallis tests. The causal assumption that a KM/QM strategy is responsible for significantly higher quality is based on the fact that the companies in this research operate under similar environmental and cultural conditions. There were no other changes or policy implementations found that impacted any of the sites differently during the research period, with exception to the KM/QM strategy implementation at company B.

4.3 Hypothesis 2

4.3.1 Evaluation of Research Data: Hypothesis 2

Pretest and posttest sample groups for the second main research hypothesis were analogous to the first main research hypothesis test. For the posttest, eight groups of equal sample size ($n_{i=8}$=72) were collected, containing the monthly average product quality score and the monthly average quality issue rate results for each of the four companies. The posttest experimental groups include two sets of data from company B, which are 72 monthly averages of product quality score and quality issue rate results. The posttest control groups contain six sets of data from companies A, C, and D, again with monthly averages of product quality score and quality issue rate results. An additional 36 month of quality performance data was analyzed for a pretest, before the KM/QM strategy implementation at company B, to determine if a significant relationship or trend existed between product quality performance characteristics and time before the KM/QM strategy was implemented at company B. Dependent variables for the regression analysis were the monthly average product quality score and the monthly average quality issue

rate. The independent variable was the KM/QM strategy application time (or just time for the pretest). The Pearson product-moment correlation coefficient r was determined via linear regression analysis. The correlation coefficient was previously described in equations 3.1 and 3.2 of section 3.5.2. It measures the strength of the relationship between the product quality score and KM/QM strategy application time as well as the strength of the relationship between the quality issue rate and KM/QM strategy application time. The coefficient of determination r^2 was calculated to measure the proportion of variation in product quality score and quality issue rate that is explained by the KM/QM strategy application time variable in the regression model.

To justify the use of parametric statistical methods such as linear regression analysis, a residual analysis was conducted using Minitab 16 statistical software to verify the assumptions necessary for linear regression analysis. The assumptions are homoscedasticity (also known as homogeneity of variance), normality of error and independence of error (Levine et al., 2005). Figure 4-3 shows the residual plots for the 72 month posttest product quality score vs. KM/QM strategy application time data from company A, B, C, and D. The posttest residual plots for the product quality issue rate vs. KM/QM strategy application time data are shown in Figure 4-4. Figure 4-5 displays the pretest residual plots from company B, before the KM/QM strategy was implemented.

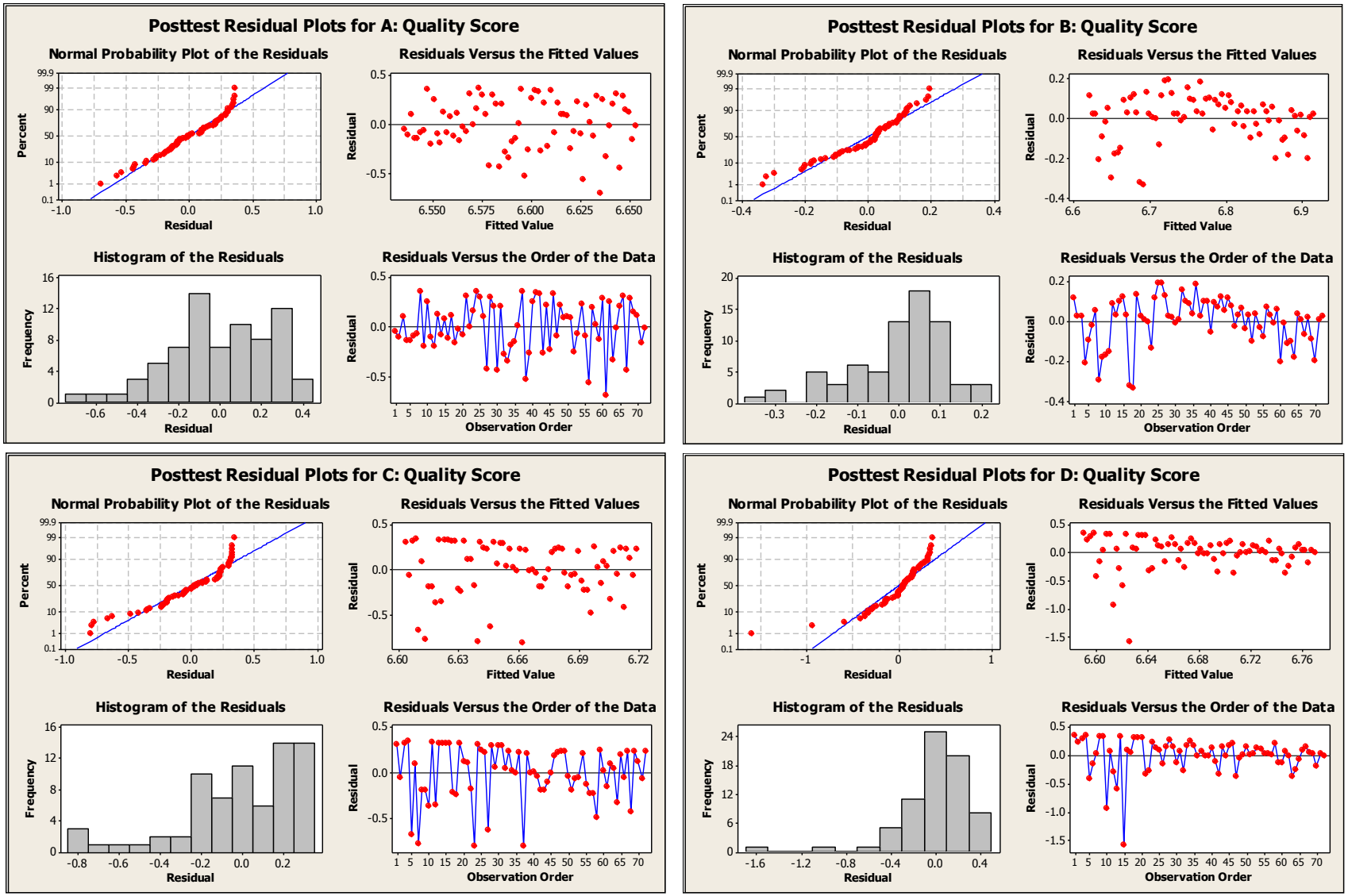


Figure 4-3: Posttest Residual Analysis of Quality Score vs. Time

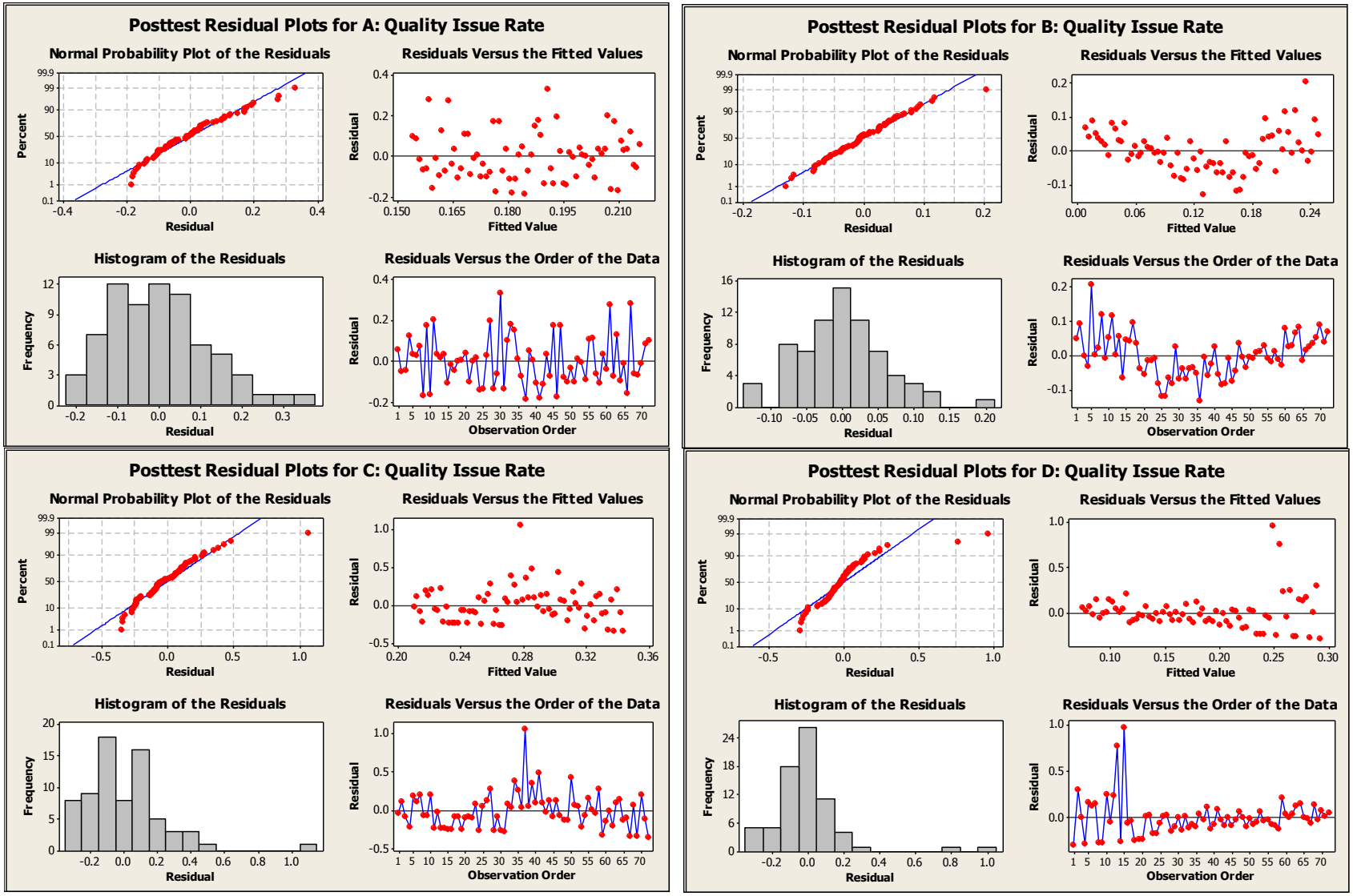


Figure 4-4: Posttest Residual Analysis of Quality Issue Rate vs. Time

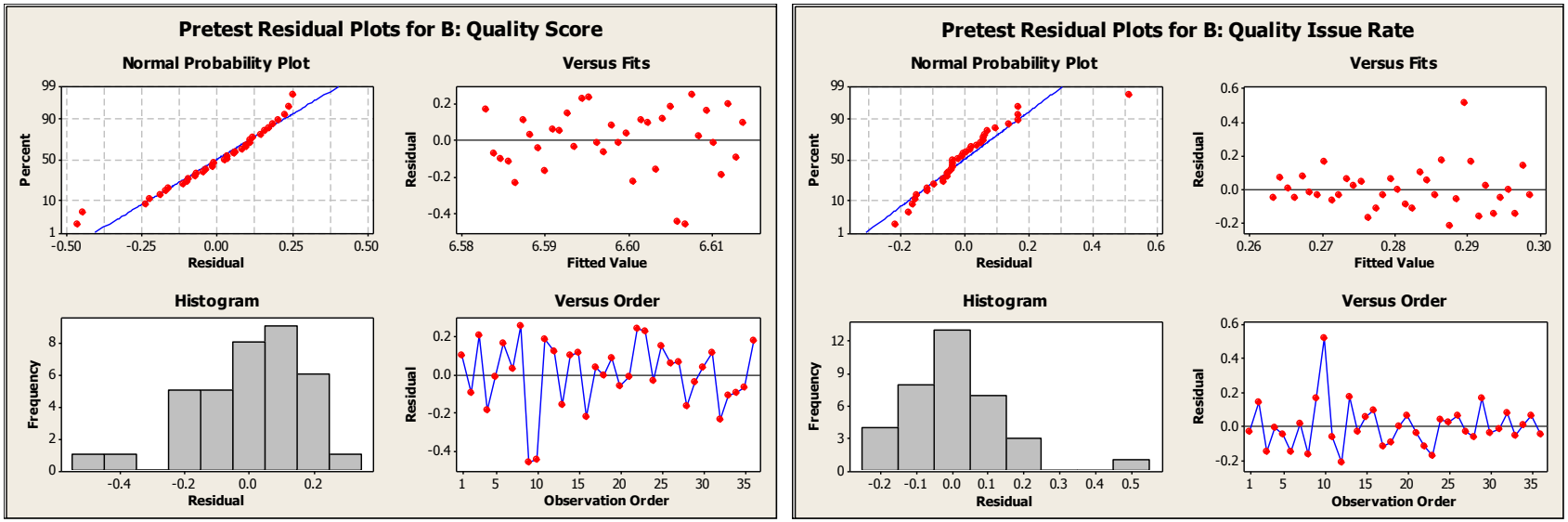


Figure 4-5: Pretest Residual Analysis of Quality Score & Issue Rate vs. Time

The residual analysis of the pretest and posttest research data for the second hypothesis test supports the assumption of homoscedasticity, since there is no observed major difference in the variability of the residuals against the independent variable and against the fitted values (Lattin et al., 2003). The residuals vary randomly and show no systematic pattern throughout the plot. The plots show no serious departures from the homoscedasticity assumption.

The pretest and posttest research data for company A and B meet the assumption for normality of error based on the normal probability plots of residuals and Anderson-Darling (AD) test for normality of residuals. Skewed histograms of residuals indicate that the distributions for the posttest data from company C and D are somewhat different from normal, which is also confirmed by an Anderson-Darling (AD) test for normality of the residuals. A regression analysis still works under such conditions given that the sample size is sufficiently large (Agresti & Franklin, 2009). Based on the central limit theorem, the sample distributions of the means for the companies in this hypothesis test are approximately normal since the sample sets are sufficiently large. Authors of statistics books define this sufficiently large sample size with $n \geq 30$ (Levine et al., 2005). Levine et al. (2005) also informs that similar to the ANOVA test, regression analysis exhibits robustness against certain departures from the normality assumptions. Nevertheless, non-parametric Spearman rank tests using Minitab 16 statistical software were performed to verify the assumptions of normality of error used in the parametric regression analysis for this second main research hypothesis test.

To meet the assumption of independence of errors for linear regression analysis, no apparent relationship between consecutive residuals versus time should be present

(Levine et al., 2005). In this research, the assumption of independence is supported since each of the four companies manufactures multiple different product models on separate production lines. Production lines within a company operate two or three shifts per day using different crews on each shift. It is assumed that an event affecting one production line crew, such as a particularly low quality score, only has short-term effects and is independent from the other production crews and production lines within a company. Drawing stratified random samples on a monthly basis contributes to the assumption of independence since the samples gathered one month were not influenced by any other sample collections in the experiment. However, since the KM/QM strategy at company B provides extensive knowledge creation and knowledge sharing opportunities between the production shift crews and departments to improve quality and performance throughout the company, the assumption of independence required for parametric statistical methods such as regression analysis might no longer be satisfied. Consequently, the Durbin-Watson statistic was calculated using Minitab 16 statistical software to evaluate if the assumption of independence for linear regression was met by testing for the presence of positive autocorrelation. The Durbin-Watson statistic D with its lower and upper critical values d_L and d_U are shown in Table 4-5. Company A, C, D, as well as the pretest sample group for company B met the criteria since the Durbin-Watson statistic D was above the upper critical limit d_U (Durbin & Watson, 1971; Durbin & Watson, 1951; Helsel & Hirsch, 1992). For the posttest sample group of Company B, a subsample approach as proposed by Helsel & Hirsch (1992) to reduce autocorrelation (also referred to as serial correlation) was applied by increasing the sample intervals from one month to two months. As a result, the subsampled posttest data sets for company B's product quality

score and quality issue rate were confirmed not to be positively autocorrelated, meeting the assumption of independence. Subsequently, the regression analysis was performed on company B's subsampled posttest data sets.

Table 4-5: Test for Independence for Quality Score and Issue Rate vs. Time

	Durbin-Watson statistic ($\alpha = 0.01$)				
	N	D Quality score vs. time	D Quality issue rate vs. time	d_L	d_U
Company A monthly sampling	72	2.51	2.53	1.43	1.49
Company B pretest monthly sampling	36	2.03	2.09	1.21	1.32
Company B posttest monthly sampling	72	1.29	1.24	1.43	1.49
Company B posttest subsample every 2nd month	36	2.17	1.52	1.21	1.32
Company C monthly sampling	72	2.20	1.74	1.43	1.49
Company D monthly sampling	72	2.13	2.18	1.43	1.49

4.3.2 Analysis: Hypothesis 2

In Figure 4-6 the linear trend lines from company B before and after KM/QM strategy implementation graphically indicate an increased strength in the relationship between KM/QM application time (x-axis) and the product quality performance characteristics (y-axis) when a KM/QM strategy is employed. To determine if there was a significant linear relationship, a regression analysis was conducted for company B with and without treatment (KM/QM strategy administered and not administered) as well as for the control groups which contain companies A, C, and D, all three operating without a treatment. For company B with a KM/QM strategy, 42.2% and 66.5% of total variation in product quality score and quality issue rate respectively can be explained by the variability in the KM/QM strategy application time, based on the coefficients of determination r^2 shown in

Figure 4-6 (r^2=0.4224 and r^2=0.6648). Prior KM/QM strategy implementation at company at B, it is less than 1% (r^2=0.0029 and r^2=0.0065).

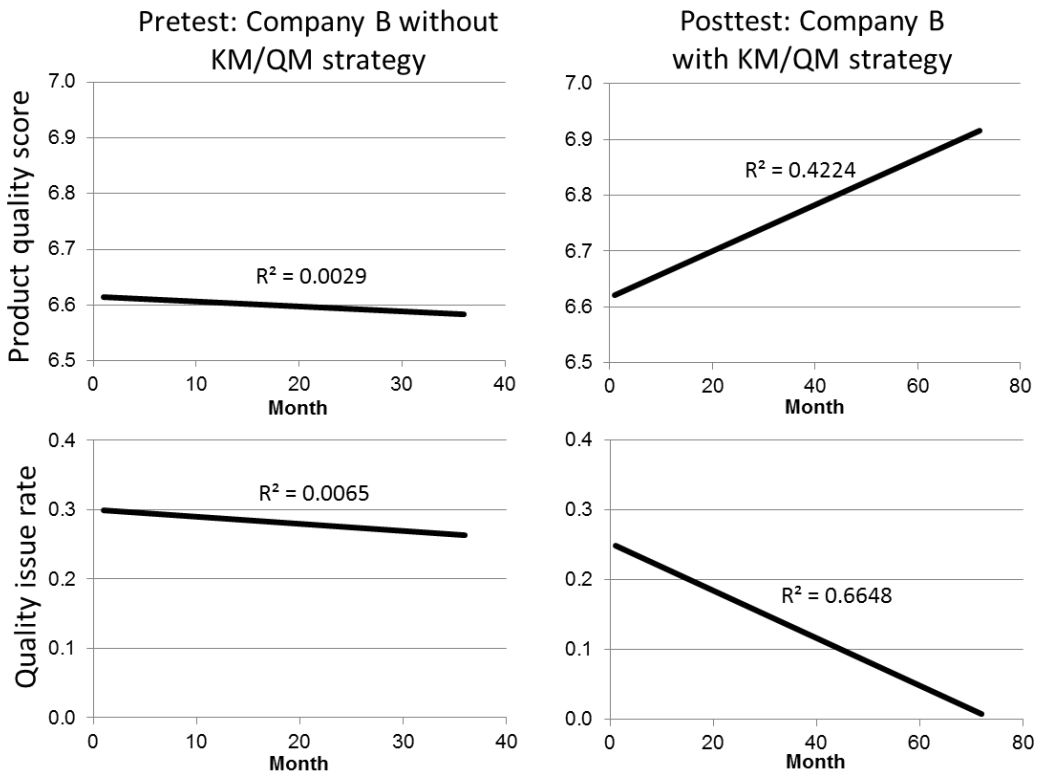


Figure 4-6: Quality Performance Trend at Company B

The results of the regression analysis are shown in Table 4-6 and Table 4-7. During the pretest period, the Pearson product-moment correlation coefficient for company B without a KM/QM strategy suggests no linear relationship between the product quality score and time as shown in Table 4-6 (r= -0.053 & p=0.757). The p value from a two tail t-test is clearly higher than the selected level of significance (α= 0.05) and the test values (t_{TV}) shown in Table 4-6 are not within the critical range marked by the critical value t_{CV}, indicating no correlation between variables prior to KM/QM deployment at company B. The pretest also provides insufficient evidence that would support a claim of a linear

relationship between quality issue rate and KM/QM strategy application time for company B without a KM/QM strategy (r= -0.080 & p=0.641) as shown in Table 4-7. The two results indicate no change in product quality performance during the pretest period for company B without the KM/QM strategy. Quite the opposite is the case in the posttest research time frame. The regression analysis for company B with an implemented KM/QM strategy shows that there is a significant strong positive linear relationship between the product quality score and the KM/QM strategy application time, as presented in Table 4-6 (r=0.650 & p=0.000). The positive slope for the product quality score indicates a quality improvement for company B. Likewise, the regression analysis for company B with an implemented KM/QM strategy shows a very strong significant negative linear relationship between quality issue rate and KM/QM strategy application time during the posttest research time frame (r= -0.815 & p=0.000) as shown in Table 4-7. The negative quality issue rate slope also indicates a quality improvement for company B. The regression analysis for the product quality scores of the control groups from company A, C, and D, all three operating without a KM/QM strategy, suggest no significant relationship between product quality score and time as shown in Table 4-6 (r=0.136 & p=0.253, r=0.115 & p=0.336, r=0.172 & p=0.148 respectively). Similarly, the regression analysis for the quality issue rates of company A and C indicate no significant relationship between quality issue rate and time as shown in in Table 4-7 (r= -0.152 & p=0.203, r=0.168 & p=0.157 respectively). The regression analysis for company D results in a significant weak negative linear relationship between quality issue rate and time as shown in Table 4-7 (r= -0.312 & p=0.008). Based on a non-parametric verification, which will be addressed later in this dissertation section, the Spearman rank

correlation test does not confirm a significant relationship between quality issue rate and time for company D.

Table 4-6: Regression Analysis of Product Quality Score vs. Time

	PPMCC & test statistics ($\alpha = 0.05$)			
	Product quality score vs. time			
	r	t_{TV}	t_{CV}	p
Company A	0.136	1.15	+/- 1.99	0.253
Company B pretest	-0.053	-0.312	+/- 2.03	0.757
Company B postest	0.650	4.99	+/- 2.03	0.000
Company C	0.115	0.97	+/- 1.99	0.336
Company D	0.172	1.46	+/- 1.99	0.148

Table 4-7: Regression Analysis of Quality Issue Rate vs. Time

	PPMCC & test statistics ($\alpha = 0.05$)			
	Quality issue rate vs. time			
	r	t_{TV}	t_{CV}	p
Company A	-0.152	-1.29	+/- 1.99	0.203
Company B pretest	-0.080	-0.470	+/- 2.03	0.641
Company B postest	-0.815	-8.21	+/- 2.03	0.000
Company C	0.168	1.43	+/- 1.99	0.157
Company D	-0.312	-2.74	+/- 1.99	0.008

The causal assumption that the KM/QM strategy at company B causes the significant relationship between product quality performance and KM/QM strategy application time is supported since a comparison with control groups from three similar companies without a KM/QM strategy do not show such a relationship. The causality assumptions for this hypothesis test are based on the similar environment and uniform culture the four companies operate in. The four companies manufacture the same products, use the same

manufacturing technologies, apply the same measuring methods, and quality metrics. Effects due to the four company's geographically different locations and associated cultural differences can be discounted since there is a strong corporate culture among the companies in the organization. Frequent job rotations between the four companies, standardization of processes, and compliance audits are just a few of the measures that enable this strong corporate culture and uniform environmental condition. During the research period, there were no other changes or policy implementations found that impacted any of the four sites differently, with exception to the KM/QM strategy implementation at company B. After the KM/QM strategy was implemented at company B, 42.2% and 66.5% of the variance in product quality score and quality issue rate respectively can be accounted for by the KM/QM strategy application time, as indicated by r^2 from Figure 4-6. Prior to KM/QM strategy implementation at company B, less than 1% of the variance in product quality score and quality issue rate respectively can be explained by the variation in time. The causality assumption is further supported with the results of the pretest. The pretest confirmed that prior to KM/QM strategy implementation at company B, no significant relationship between quality performance and time existed. Only after the KM/QM strategy was implemented did the product quality characteristics improve significantly at company B over KM/QM strategy application time while the control groups from similar companies without a KM/QM strategy did not change significantly with respect to product quality during the same research time period. Section 4.6 provides a detailed discussion about all obtainable factors, confounding effects and factor interactions that might have played a role in the success at company B while implementing and employing a KM/QM strategy.

Non-parametric Spearman rank tests confirm the results from the parametric regression analysis. For company B with an implemented KM/QM strategy (company B posttest), the non-parametric Spearman rank correlation test confirm the significant strong positive relationship between the product quality score and the KM/QM strategy application time (r_S=0.687 & p=0.000). The results from the Spearman rank test are shown in Table 4-8. The Spearman rank test for company B with an implemented KM/QM strategy also confirm the very strong significant negative linear relationship between quality issue rate and KM/QM strategy application time during the posttest research time frame (r_S= -0.816 & p=0.000). Both results confirm quality performance improvements over time at company B and are in line with the parametric Pearson product-moment correlation test results. The Spearman rank tests for company A, C, D, as well as the pretest for company B, all operating without a KM/QM strategy, indicate no relationship between quality performance characteristics and time. This is also in agreement with the parametric results with exception of the quality issue rate for company D. While the linear relationship between quality issue rate and time for company D was significant from the parametric Pearson product-moment correlation test, it does not result in a significant relationship from the non-parametric Spearman rank test. This is attributed to company D's data set that did not clearly meet the assumption of normality based on a normal probability plot. The parametric and non-parametric correlation results show larger differences for company C and D since the assumption of normality was not clearly satisfied. It is therefore recommend using the results from the non-parametric Spearman rank correlation test for company C and D.

Table 4-8: Non-Parametric Regression Analysis Verification with Spearman Rank T.

	Spearman Rank Correlation			
	Quality score vs. time		Quality issue rate vs. time	
	r_S	**p-value**	**r_S**	**p-value**
Company A	0.182	0.126	-0.166	0.164
Company B pretest	-0.142	0.408	-0.005	0.976
Company B posttest	0.687	0.000	-0.816	0.000
Company C	0.011	0.928	0.208	0.080
Company D	-0.028	0.819	-0.162	0.173

4.3.3 Results of Analysis: Hypothesis 2

The results of this research support the claim of the second main research hypotheses that a KM/QM strategy as implemented at company B contributes significantly and positively to product quality over KM/QM strategy application time. A regression analysis for a company with a KM/QM strategy (company B) showed that there was a significant strong positive relationship between the product quality score and the KM/QM strategy application time and a very strong significant negative relationship between quality issue rate and KM/QM strategy application time, both indicating substantial quality improvements over time. A comparison with control groups from three similar sites but without a KM/QM strategy showed no significant change in product quality characteristics during the same research time period for the three companies without the KM/QM strategy. A pretest showed that prior to KM/QM strategy implementation at company B, no relationship between product quality performance and time existed. The causal assumption that a KM/QM strategy causes a relationship between quality performance and KM/QM strategy application time is based on the fact that the companies in this research operate under similar environmental and cultural

conditions. There were no other changes or policy implementations found that impacted any of the sites differently during the research period, with exception to the KM/QM strategy implementation at company B. To verify the results of parametric statistics, the non-parametric Spearman rank correlation tests confirm the significant strong positive relationship between the product quality score and the KM/QM strategy application time for company B with a KM/QM strategy as well as a the very strong significant negative linear relationship between quality issue rate and KM/QM strategy application time during the posttest research time frame. The non-parametric Spearman rank correlation tests also confirms that there is no relationship between quality performance characteristics and time for companies in this research without a KM/QM strategy. While the assumption of independence necessary for regression analysis was supported for all companies without a KM/QM strategy, it was not satisfied for company B with a KM/QM strategy since the KM/QM strategy at company B provides extensive knowledge creation and knowledge sharing opportunities between the production shift crews and departments to improve quality and performance throughout the company. A subsample approach as proposed by Helsel & Hirsch (1992) to reduce serial correlation (also referred to as autocorrelation) was applied by increasing the sample intervals from one month to two months. The subsampled posttest data sets for company B's product quality score and quality issue rate were confirmed not to be serially correlated, meeting the assumption of independence.

4.4 Hypothesis 3

4.4.1 Evaluation of Research Data: Hypothesis 3

The sample group for the third main research hypothesis test consist of n=60 monthly average quality related improvement activities at company B that operates with a KM/QM strategy. The third main research hypothesis test period spanned over five years and coincided with year two through year six of the first and second main research hypotheses posttest period. To justify the use of parametric statistical methods, such as linear regression analysis, a residual analysis was conducted using Minitab 16 statistical software to verify the assumptions necessary for linear regression analysis. The assumptions are homoscedasticity, normality of error and independence of error (Levine et al., 2005). Figure 4-7 shows the residual plots for the 60 average number of quality related improvement activities vs. KM/QM strategy application time at company B. Based on these residual plots, the research data for the third main research hypothesis test meets the assumption of homoscedasticity, since there is no observed major difference in the variability of the residuals against the independent variable and against the fitted values (Lattin et al., 2003). The residuals fluctuate randomly around zero and there is no systematic pattern throughout the plot. The data also meets the assumption of normality of error based on the normal probability plots of residuals and Anderson-Darling (AD) test for normality of residuals ($p=0.610$, $\alpha= 0.05$). Based on the central limit theorem, the sample distributions of the means are approximately normal since the sample sets are sufficiently large. Authors of statistics books define this sufficiently large sample size with $n \geq 30$ (Levine et al., 2005).

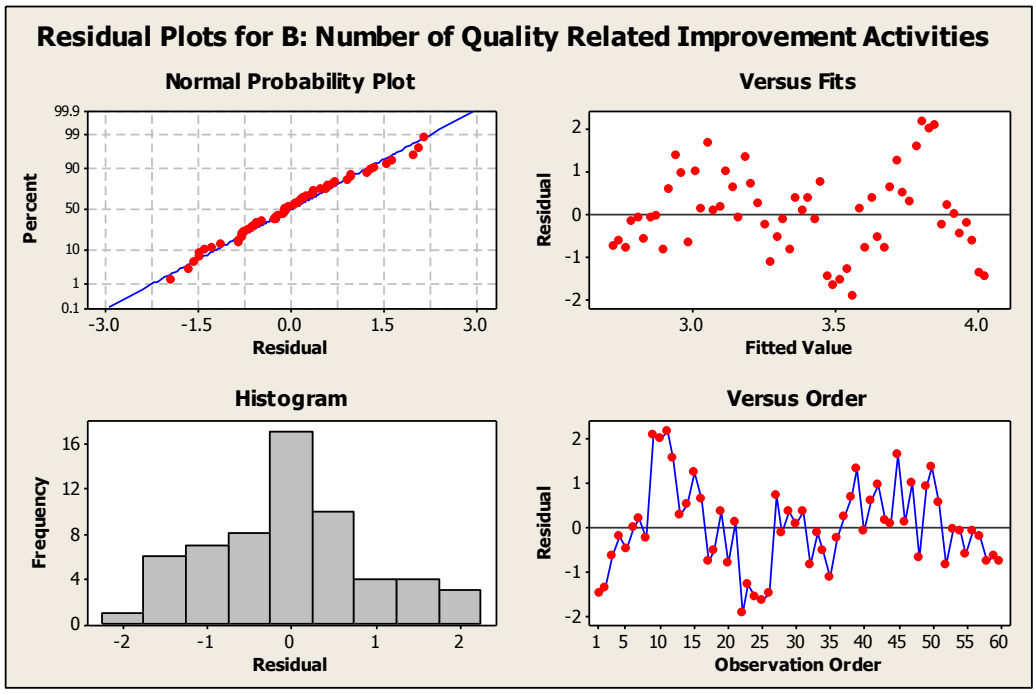


Figure 4-7: Residual Analysis of Quality Improvement Activities vs. Time

The assumption of independence of errors for regression analysis requires that no apparent relationship between consecutive residuals versus time are present (Levine et al., 2005). Since the KM/QM strategy implemented at company B provides extensive knowledge creation and knowledge sharing opportunities, consecutive measurements for the number of quality related improvement activities might be serially correlated and not meet the assumption of independence. Furthermore, the activities in a KM/QM strategy environment are well communicated, wide-ranging, sustained, and intended to be preventive, which can affect consecutive measurements for the number of quality related improvement events. In other words, as quality issues were solved throughout the company by means of extensive knowledge creation and knowledge sharing within an effective KM/QM strategy, quality issues captured once in the KM/QM system should no longer occur in the subsequent data collection periods throughout company B,

consequently reducing the number of improvement activities. Therefore, consecutive measurements could be affected and the assumption of independence for linear regression violated. The Durbin-Watson statistic was calculated using Minitab 16 statistical software to evaluate the assumption of independence of errors for linear regression and the presence of positive autocorrelation. The Durbin-Watson statistic D with its lower and upper critical values d_L and d_U are shown in Table 4-9. When sampling took place on a monthly basis, the Dublin-Watson statistic (D=0.89) was below the lower critical limit (d_L=1.55) indicating significant positive autocorrelation among the residuals, and therefore not meeting the assumption of independence for linear regression analysis. Helsel & Hirsch's (1992) subsample approach was applied to reduce the positive autocorrelation. Increasing the sample intervals to two months showed insufficient improvements, still indicating significant positive autocorrelation among the residuals because the Dublin-Watson statistic (D=1.15) was below the lower critical limit (d_L=1.35). By increasing the sample intervals to three months, the subsampled data for company B's number of quality related improvement activities was confirmed not to be positively autocorrelated because the Dublin-Watson statistic (D=1.66) was above the upper critical limit (d_U=1.41), meeting the assumption of independence as shown in Table 4-9. The dataset that was subsampled in three month intervals is used for the subsequent linear regression analysis.

Table 4-9: Test for Independence for Quality Improvement Activities vs. Time

	Durbin-Watson statistic: Quality related improvement activities vs. time ($\alpha = 0.05$)			
	N	D	d_L	d_U
Monthly sampling	60	0.89	1.55	1.62
Subsample every 2nd month	30	1.15	1.35	1.49
Subsample every 3rd month	20	1.66	1.20	1.41

Homoscedasticity and normality of errors assumptions were verified once more with a residual analysis for the dataset subsampled in three month intervals. Figure 4-8 shows the residual plots for the average number of quality related improvement activities vs. KM/QM strategy application time at company B with the 3 month subsample interval. Based on these residual plots, the subsampled data for the third main research hypothesis test also meets the assumption of homoscedasticity, since there is no observed major difference in the variability of the residuals against the independent variable and against the fitted values. The residuals fluctuate randomly around zero and there is no systematic pattern throughout the plot. The sample size of n=20 for the subsampled data is no longer sufficiently large to meet the central limit theorem criteria of sufficiently large sample sizes for assuming a normal distribution, which is frequently defined as $n \geq 30$ (Levine et al., 2005).

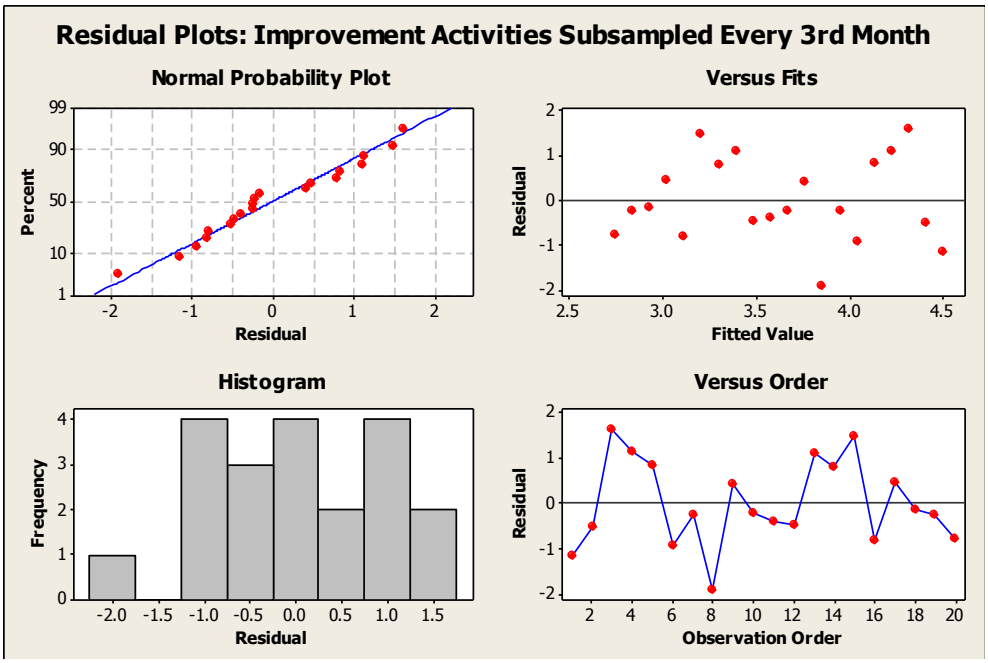


Figure 4-8: Residual Analysis of Improvement Activities with Subsampled Data

An Anderson-Darling (AD) test for normality was performed for residuals of the subsampled data using Minitab 16 statistical software. The AD test results are shown in the normal probability plot of Figure 4-9. The AD test provides an objective quantitative measure to determine if the empirical distribution function agrees with a hypothetical normal distribution function (Anderson & Darling, 1952, 1954). The AD test null sub-hypothesis claims that the data comes from a normal distribution while the alternate sub-hypothesis states that the data is not normally distributed (Ryan, Joiner, & Cryer, 2012). The p value from the AD normality test shown in Figure 4-9 is clearly above the selected level of significance ($p=0.487$, $\alpha= 0.05$). Therefore, the subsampled data meets the normality of error assumption required for linear regression analysis since the AD normality test provided insufficient evidence to suggest that the data are not from a normal distribution.

Figure 4-9: Normal Probability Plot with AD Test of Quality Improvement Activities Residuals

4.4.2 Analysis: Hypothesis 3

A trend line from the subsampled quality improvement data, which is shown in Figure 4-10, shows that the number of quality related improvement activities decreases the longer a KM/QM strategy was applied at company B. To determine the significance of the relationship between the KM/QM strategy application time and the number of quality related improvement activities after the KM/QM strategy was implemented at company B, a regression analysis was conducted. Results of the regression analysis are shown in Table 4-10.

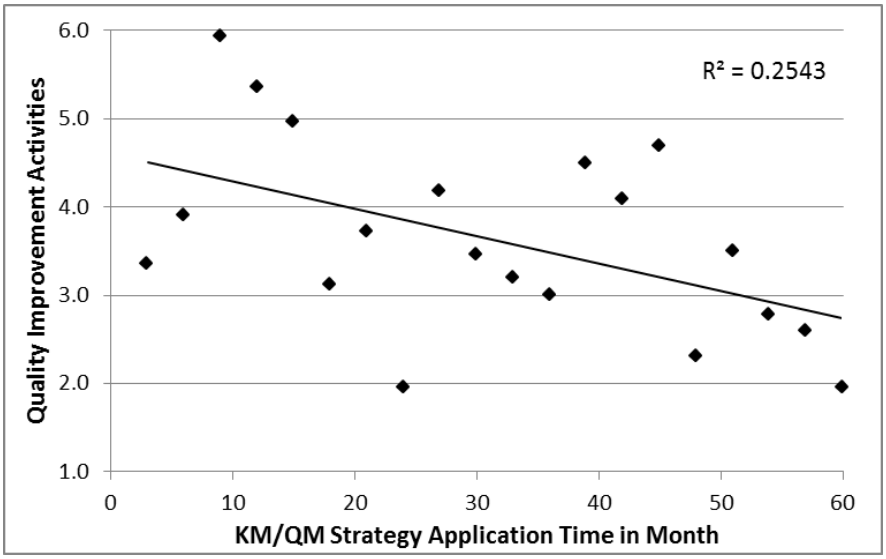


Figure 4-10: Quality Improvement Activity Trend at Company B

During the 5 year research period with subsampled data from company B, the Pearson product-moment correlation coefficient of r=-0.504 indicates a moderate negative relationship between the number of quality related improvement activities and the KM/QM strategy application time. Equation 3-4 was applied to calculate the t-statistic for this third hypothesis test with n-2 degrees of freedom. The corresponding test value (t_{TV} =-2.478) fell within the critical range marked by the critical value (t_{CV}=-2.101), and the p value (p=0.023) was below the selected level of significance (α= 0.05), representing a significant negative linear relationship. The F test statistic (F_{TV}=6.14) with 1 and 18 degrees of freedom as defined in equation 3-5 for the linear regression line slope falls in the region of rejection, marked as the critical F statistic (F_{CVU}=4.41) in Table 4-10. It confirms that the sample correlation was not due to chance and there was evidence of a significant negative linear relationship between the KM/QM strategy application time and the number of quality related improvement activities in the population. The null sub-hypothesis for the inference about the slope of the regression line (H_0: $ß_1$=0) was rejected

since there was evidence of a significant negative linear relationship between the KM/QM strategy application time and the number of quality related improvement activities. However, based on the coefficient of determination r^2 shown in Figure 4-10 (r^2=0.2543), only 25.4% of total variation in the number of quality related improvement activities can be explained by the variability in the KM/QM strategy application time.

Table 4-10: Regression Analysis of Quality Improvement Activities vs. Time

Regression analysis for improvement activities vs. time ($\alpha = 0.05$)	
N	20
r	-0.504
b_1	-0.031
Std. error of slope	0.013
MSR	5.761
MSE	0.938
F_{TV}	6.140
F_{CVU}	4.410
t_{TV}	-2.478
t_{CV}	+/- 2.101
p	0.023

The causal assumption that the employment of a KM/QM strategy at company B causes the significant negative linear relationship between the KM/QM strategy application time and the number of quality related improvement activities is supported since there were no other changes or policy implementations found at company B, with exception to the KM/QM strategy implementation at the onset of the research timeframe for this third main research hypothesis test. The effects of product quality changes on the number of quality related improvement activities were evaluated as a potential cause for

this relationship since a company's declining product quality or decision by a company to lower product quality targets could also result in fewer quality related improvement activities because of the subsiding need for high product quality. Conversely, high levels of product quality or a company's decision to increase product quality targets could lead to an increase in quality improvement activities to achieve higher product quality. To evaluate product quality as a cause, the results of the second hypothesis test were used. The second hypothesis test informed of significant product quality improvements over a coinciding KM/QM strategy application time frame than for the third hypothesis test. In other words, company B experienced significant quality improvements, while at the same time significantly reducing the number of quality related improvement activities. The significant decrease in the number of quality related improvement activities was therefore not caused by deteriorating product quality or a decision to lower product quality targets. The KM/QM strategy implementation was the single most important change found at company B. A more comprehensive assessment of obtainable factors, confounding effects and factor interactions associated with the KM/QM strategy employment at company B is conveyed in section 4.6 of this chapter. The three main research hypothesis tests analyzed so far in this dissertation address the basic research question by demonstrating that a KM/QM strategy improves an organization's performance.

4.4.3 Results of Analysis: Hypothesis 3

The results of this research support the claim of the third main research hypothesis that the employment of a KM/QM strategy contributes significantly and negatively to the number of quality related improvement activities over KM/QM strategy application time.

A regression analysis showed that there was a significant moderate negative linear relationship between the KM/QM strategy application time and the number of quality related improvement activities for the dataset from company B that was subsampled in three month intervals, indicating performance improvements over time. To meet the assumption of independence of errors for linear regression and to circumvent autocorrelation of the time series dataset, a subsample approach as proposed by Helsel & Hirsch (1992) was applied by increasing the sample intervals from one month to three months. A Dublin-Watson test confirmed that the subsampled data set for the third main research hypothesis test was not serially correlated, meeting the assumption of independence for linear regression. The causal assumption that the employment of a KM/QM strategy causes the relationship between the number of quality related improvement activities and KM/QM strategy application time is based on the fact that the KM/QM strategy implementation at company B was the single most important change found at the company, and all other available factors were found not to affect the number of quality related improvement activities. The first and second main research hypothesis showed that company B significantly improved product quality due to a KM/QM strategy implementation. During coinciding research timeframes with the first and second hypotheses test period, the third hypothesis test showed that company B also significantly reduced the number of quality related improvement activities because of an effective KM/QM strategy deployment. The third main research hypothesis test validates the first and second main research hypothesis' results and the basic research question by confirming operational performance improvements that are related to a KM/QM strategy implementation.

4.5 Hypothesis 4

4.5.1 Evaluation of Research Data: Hypothesis 4

The COQ data sets for the fourth main research hypothesis test stretch over seven years and consist of four groups of data from company B. They are the pretest sample group prior to KM/QM strategy implementation, a dataset from the KM/QM strategy implementation year during the first year of KM/QM strategy deployment, a posttest data set after the KM/QM strategy was implemented at company B, and the final posttest year group as a subset of the posttest. Linear regression analysis was used to evaluate the relationship between the COQ score and time for the pretest, KM/QM strategy implementation year and posttest sample groups. The difference between the COQ score pretest sample group and the final posttest year sample group was evaluated with a two sample t-test. To justify the use of parametric statistics and before proceeding with linear regression analysis and a two sample t-test for the difference between two means, an Anderson-Darling (AD) test for normality and a residual analysis was conducted using Minitab 16 statistical software. The COQ element used in this research was the internal failure cost and is shown as a normalized COQ score as discussed in section 3.5.4. External failure, appraisal and prevention costs are not included.

The pretest sample group for the fourth main research hypothesis test contains n=12 monthly COQ scores from company B before the KM/QM strategy was implemented. Figure 4-11 shows the normal probability plot with AD test results for the pretest COQ score. The null sub-hypothesis for the AD goodness of fit for normality test states that the data comes from a normal distribution while the alternate sub-hypothesis claims that the

data is not normally distributed. The AD test p value for the COQ pretest dataset is above the selected level of significance (p=0.313, α= 0.05) and the null sub-hypothesis cannot be rejected. There is insufficient evidence to support the claim that the COQ score pretest data are not from a normal distribution, which is in agreement with the normality assumption required for a two sample t-test that evaluates the difference between the mean pretest COQ score and the final posttest year COQ score. The pretest COQ score data and the final posttest year COQ score were independently collected for the two sample t-test. Testing for the assumption that the two population variances are equal to determine if a pooled-variance t test can be used will be performed in a later part of this section.

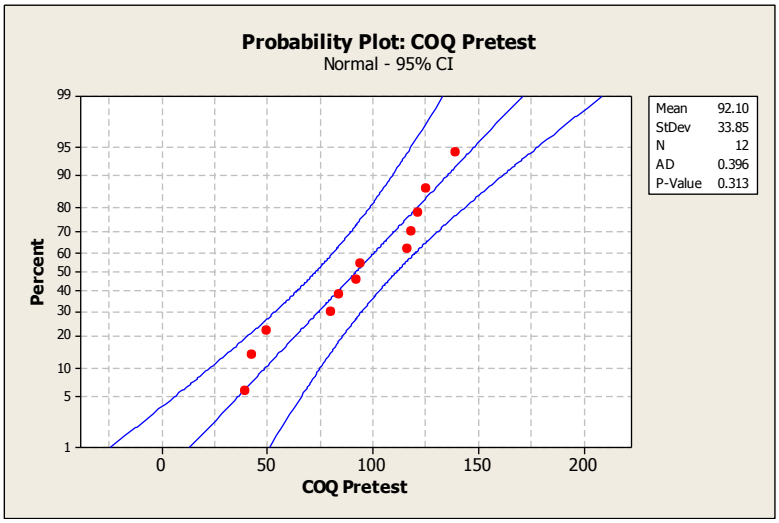


Figure 4-11: Normal Probability Plot with AD Test of Pretest COQ

The residual plots for the pretest COQ scores vs. time at company B are displayed in Figure 4-12. Based on these residual plots, the COQ pretest research data meets the assumption of homoscedasticity, since there is no observed major difference in the variability of the residuals against the independent variable and against the fitted values

(Lattin et al., 2003). The residuals fluctuate randomly around zero and there is no systematic pattern throughout the plot.

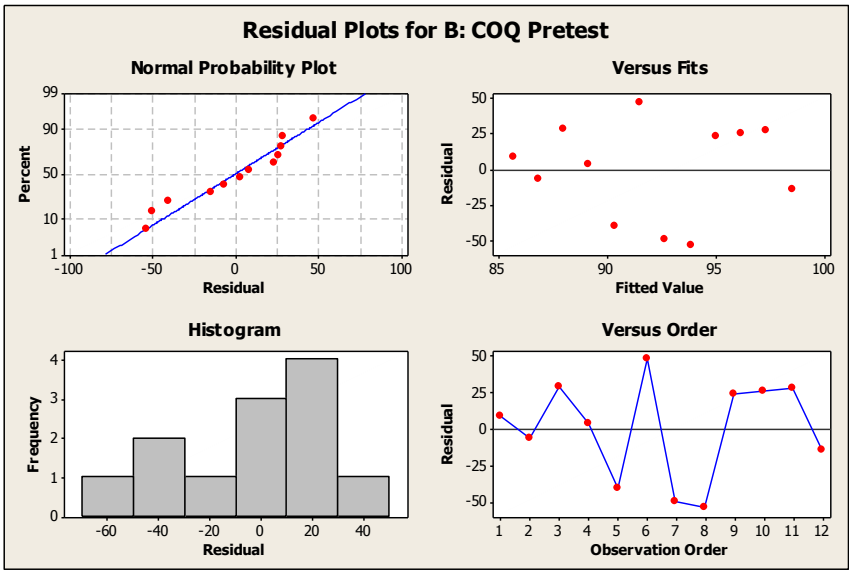


Figure 4-12: Residual Analysis of Pretest COQ Score vs. Time

An Anderson-Darling (AD) normality test was performed for residuals of the COQ pretest data using Minitab 16 statistical software to evaluate the normality of error assumption for linear regression analysis. The AD test results are shown in the normal probability plot of Figure 4-13. The COQ pretest data meets the normality of error assumption required for linear regression analysis since the AD normality test provided insufficient evidence to suggest that the data are not from a normal distribution ($p=0.281$, $\alpha= 0.05$).

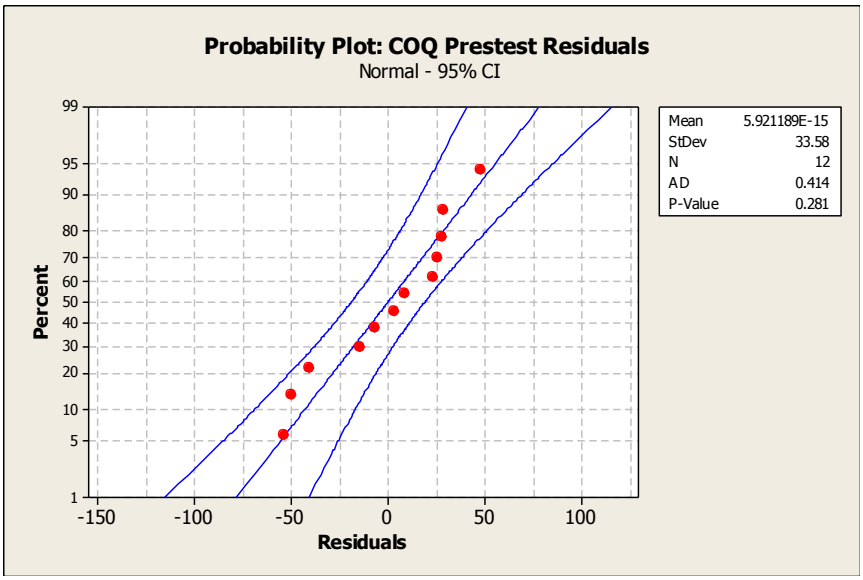


Figure 4-13: Normal Probability Plot with AD Test of Pretest COQ Residuals

To evaluate if the COQ time series research data meets the assumption of independence of errors for linear regression, the Durbin-Watson statistic was calculated using Minitab 16 statistical software. The Durbin-Watson test null sub-hypothesis states that there is no autocorrelation (or serial correlation) between the residuals while the alternate hypothesis claims that there is autocorrelation (Helsel & Hirsch, 1992). In case the Durbin-Watson statistic D is less than its lower critical limit d_L, the null hypothesis is rejected and it can be concluded that positive autocorrelation is statistically significant. On the other hand, if the Durbin-Watson statistic D is greater than its upper critical limit d_U, the null hypothesis cannot be rejected and there is no evidence of positive autocorrelation among the residuals, which is the case for the COQ pretest dataset in this research (D=2.34, d_U =1.33).When testing for negative autocorrelation, D is replaced by 4 – D (Durbin & Watson, 1951). If 4 - D is less than d_L, evidence of significant negative autocorrelation between residuals exists, which is not the case with the COQ pretest data.

Table 4-11 summarizes the Durbin-Watson statistics for three time periods of the fourth main research hypothesis test.

Table 4-11: Durbin-Watson Statistics for Fourth Hypothesis Test

	Durbin-Watson statistic: COQ score vs. time ($\alpha = 0.05$)			
	N	D	d_L	d_U
Pretest	12	2.34	0.97	1.33
10% trimmed KM/QM strategy implementation year	10	2.37	0.88	1.32
Posttest	20	2.55	1.20	1.41

The COQ score dataset for the KM/QM strategy implementation year consists of n=12 monthly COQ scores from company B during KM/QM strategy deployment. Residual plots for the COQ score vs. time data during the KM/QM strategy implementation year are presented in Figure 4-14. The data does not meet the normality of error assumption required for linear regression based on the normal probability plot of residuals and the AD test results displayed in Figure 4-15. The AD test null sub-hypothesis is rejected since there is sufficient evidence to support the claim that the COQ score data for the initial KM/QM strategy implementation year is not from a normal distribution ($p<0.005$, $\alpha= 0.05$). The sixth data point is particularly high and inconsistent with the rest of the data, necessitating further investigation since it is suspect for being an outlier. Potential sources for outliers can be transcription errors, missing data or process issues (Burke, 2001). Wilcox & Keselman (2003) recommend using boxplots for outlier detection to avoid masking. Boxplots generated in statistical software such as Minitab 16 identify outlier points if a data point exceeds the third quartile (top line in interquartile

range box) or if it falls below the second quartile (bottom line in Interquartile range box) by more than 1.5 times the interquartile range (Minitab, 2013). In a regression analysis, large standardized residuals are identified as outliers if the standardized residual is greater or less than ± 2 (Minitab, 2013). Agresti & Franklin (2009) define outliers in regression analysis when standardized residuals exceed 3 in absolute terms. Additional outlier detection methods reviewed during this dissertation work include the modified Thompson tau technique. This method is typically used for a sample of a single variable (Cimbala, 2011). It uses the sample mean and sample standard deviation, but this can result in masking and is therefore not used for this research (Wilcox & Keselman, 2003). Masking is a problem when the sample mean and sample standard deviations were calculated, with the outliers included, and used in the outlier detection process to detect the outliers. Such an approach can potentially affect the ability of the outlier detection method and can cause misleading interpretations (Wilcox & Keselman, 2003).

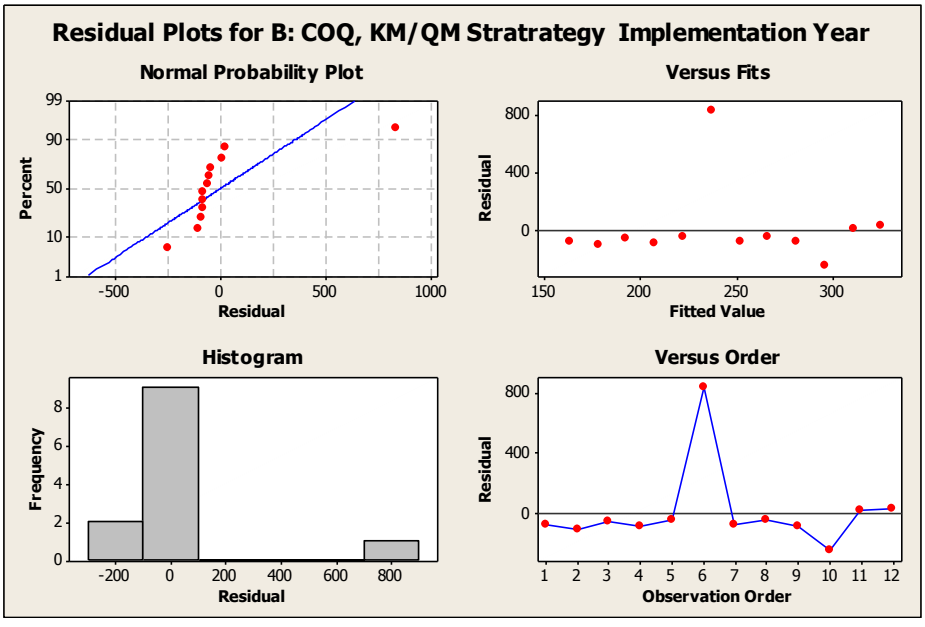


Figure 4-14: Residual Analysis of COQ vs. Time from KM/QM Strategy Implementation Year

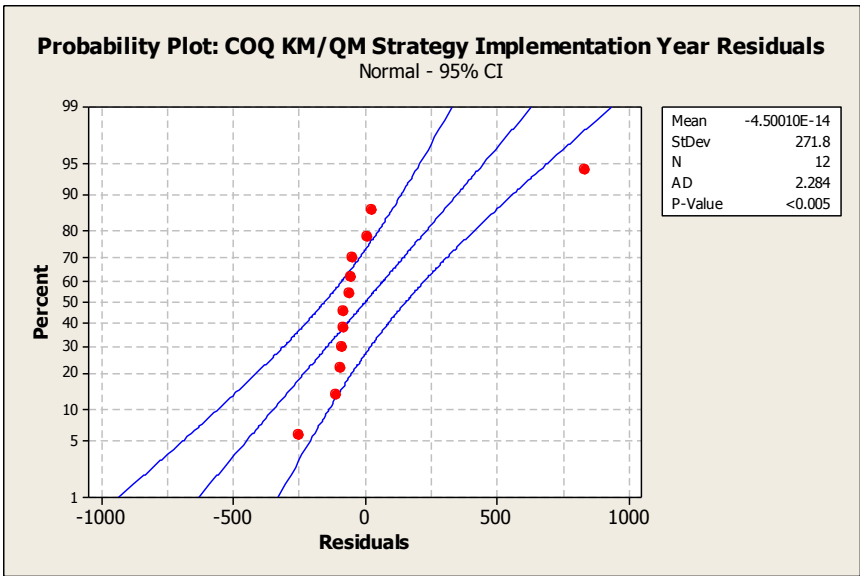


Figure 4-15: Normal Probability Plot with AD Test of COQ Residuals from KM/QM Strategy Implementation Year

The first boxplot of the COQ score data from the KM/QM implementation year of Figure 4-16 confirms that one outlier is present prior to any data cleaning. The outlier point is indicated by the asterisk (*) in Figure 4-16. This single outlier point is beyond the upper boxplot whisker, noticeably exceeding the third quartile (top line in interquartile range box) by more than 1.5 times the interquartile range. The standardized residual from the regression analysis for this data point is 3.07, above the $\pm$ 2 limit from Minitab (2013) as well as the $\pm$ 3 limit from Agresti & Franklin (2009), further confirming the outlier condition. Several methods exist to clean the data of outliers before estimating the parameters with regression analysis. Such data cleaning methods include trimming, winsorization, and dichotomization (Lien & Balakrishnan, 2005; Tukey & McLaughlin, 1963). Wilcox & Keselman (2003) describe trimming as a robust measure to address outliers. This method removes a proportion of the smallest and largest data points. Based on available literature, the optimum amount for trimming is unknown. But available

literature on this subject also informs that 20% trimming is seen as reasonable to still achieve a small standard error and to control the probability of a Type I error (Wilcox & Keselman, 2003). Data transformation methods such as the Johnson transformation and Box-Cox transformation can be used to convert non-normal data into a normally distributed data set. The Johnson transformation technique applies the best-fit Johnson distribution to the non-normal research data for transforming it to normality (Chou, Polansky, & Mason, 1998). Chou et al. (1998) inform that the Johnson transformation method is applicable for sample sizes of 10 and greater and is mainly used in statistical process control, which primarily relies on normal distributed data. The Box-Cox transformation method applies power transformations to enhance the ability of normalizing and variance reductions, but induces complexity in interpreting results of the analysis (Osborne, 2010).

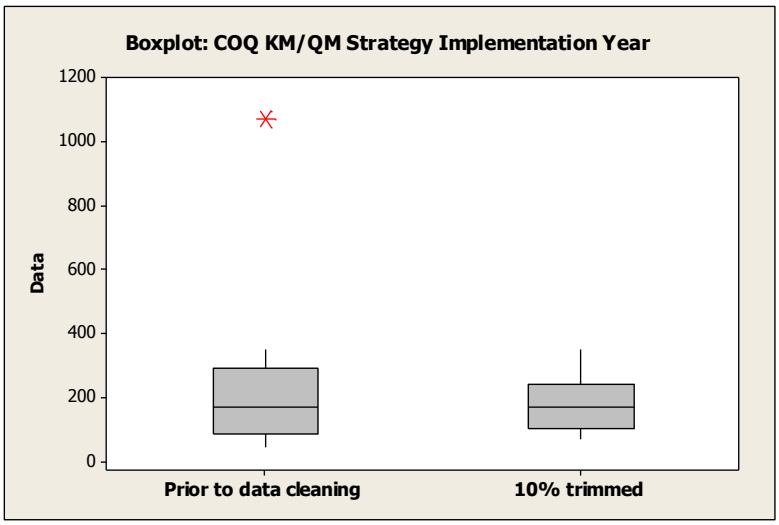


Figure 4-16: Boxplot of COQ from KM/QM Strategy Implementation Year

For the COQ score data from the KM/QM implementation year, 10% trimming was applied by removing the largest 10% and the smallest 10% of the COQ score data from

the KM/QM implementation year. The second boxplot in Figure 4-16 shows that 10% trimming was successful in removing all outliers from the dataset. The 10% trimmed COQ score data from the KM/QM implementation year meet the normality of error assumption required for linear regression. The Anderson-Darling test for normality provides insufficient evidence to suggest that the 10% trimmed data are not from a normal distribution, as shown in the normal probability plot of Figure 4-17 ($p=0.169$, $\alpha= 0.05$). Further data transformation to obtain a normal distribution, e.g., using Johnson transformation, is not required.

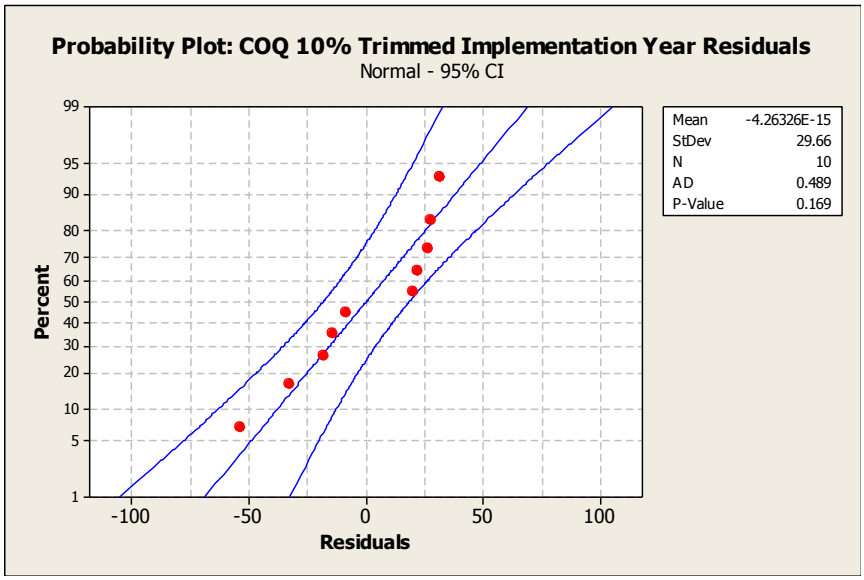


Figure 4-17: Normal Probability Plot with AD Test of 10%Trimmed COQ Residuals from KM/QM Strategy Implementation Year

The residual plots of Figure 4-18 show that the 10% trimmed COQ score data from the KM/QM implementation year vs. the KM/QM strategy application time meet the assumption of homoscedasticity. There is no observed major difference in the variability of the residuals against the independent variable and against the fitted values (Lattin et al., 2003). The 10% trimmed COQ score from the KM/QM implementation year vs. time

data also meet the assumption of independence of errors for linear regression since there is no evidence of autocorrelation among the residuals for this time series based data as shown in Dublin-Watson statistics of Table 4-11 (D=2.37, d_U=1.32). Consequently, the 10% trimmed KM/QM strategy implementation year COQ data is used during subsequent analysis.

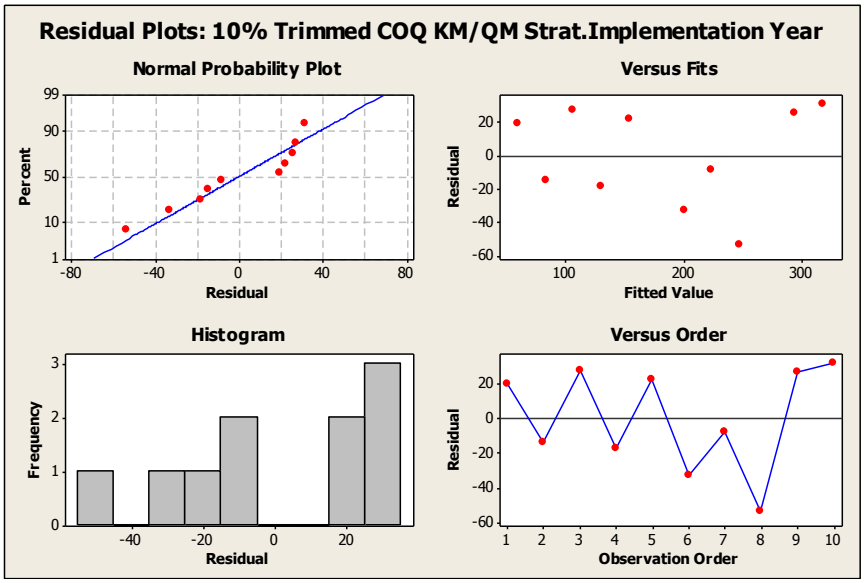


Figure 4-18: Residual Analysis of 10% Trimmed COQ vs. Time from KM/QM Strategy Implementation Year

The posttest data set contains five years of monthly COQ scores after the KM/QM strategy was implemented at company B. At the end of each quarter, three month of data were used to calculate company B's average monthly COQ score, resulting in n=20 quarterly samples for the posttest. The residual plots of Figure 4-19 show that the posttest COQ score vs. KM/QM strategy application time meet the assumption of homoscedasticity, since there is no observed major difference in the variability of the residuals against the independent variable and against the fitted values (Lattin et al., 2003). The posttest COQ score data meet the normality of error assumption required for

linear regression. The Anderson-Darling test for normality of residuals provides insufficient evidence to suggest that the data are not from a normal distribution, as shown in the normal probability plot of Figure 4-20 ($p=0.761$, $\alpha= 0.05$). The posttest COQ score vs. KM/QM strategy application time also meet the assumption of independence of errors for linear regression since there is no evidence of autocorrelation among the residuals of this time series based dataset, as shown in Dublin-Watson statistics of Table 4-11 ($D=2.55$, $d_U=1.41$).

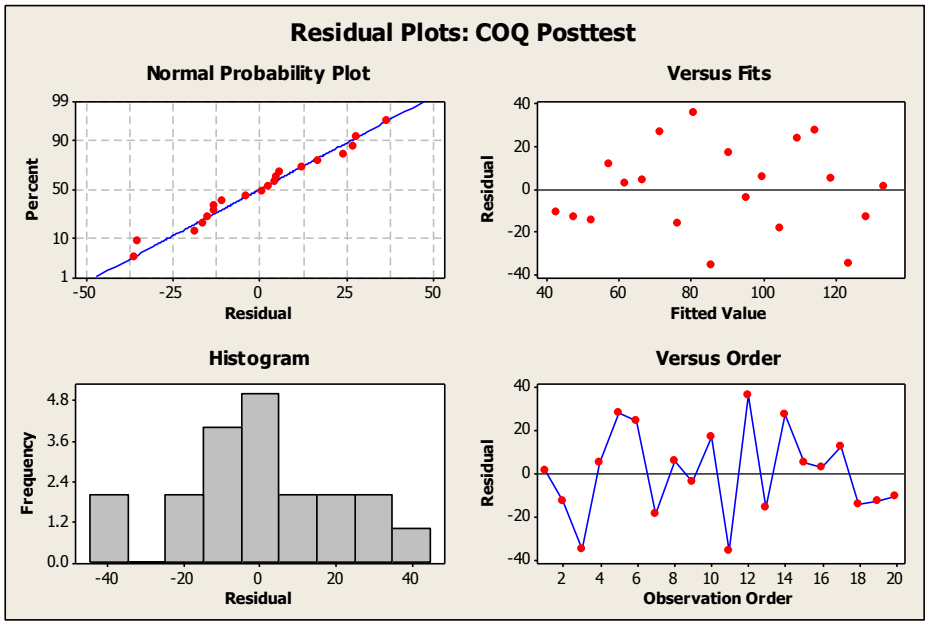


Figure 4-19: Residual Analysis of Posttest COQ Score vs. Time

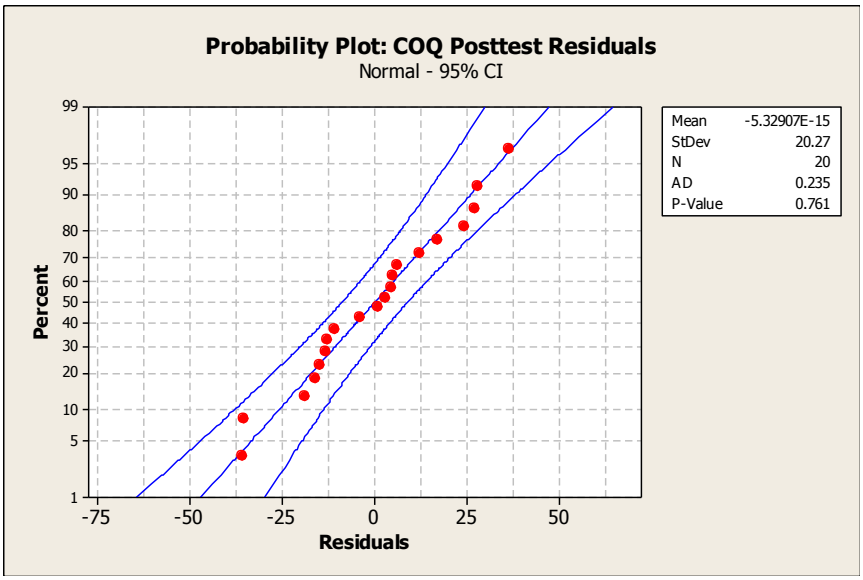


Figure 4-20: Normal Probability Plot with AD Test of Posttest COQ Residuals

The posttest COQ subset from the final posttest year contains n=12 monthly COQ scores from company B. This data set also meets the normality assumption required for a two sample t-test that evaluates the difference between the mean pretest COQ score and the final posttest year COQ score. The Anderson-Darling test for normality provides insufficient evidence to suggest that the final posttest year COQ score data are not from a normal distribution, as shown in the normal probability plot of Figure 4-21 ($p=0.393$, $\alpha=0.05$). The pretest COQ score data and the final posttest year COQ score data are from two independent populations, meeting the assumption of independence for a t test.

A test for the assumption of equal variances (also referred to as homogeneity of variance or homoscedasticity) between the two populations was performed by applying the F test for the difference between two variances as outlined by equation 3.6 of section 3.5.4 in this dissertation. The F test for the pretest COQ score and the final posttest year COQ score data results in the computed F test statistic of 2.63. Since this computed F

statistic is not greater or not less than its upper and lower-tail critical values of 3.47 and 0.288 respectively (used α=0.05, n_1=n_2=12), it can be assumed that the two variances are equal and the use of a two sample pooled-variance t test is appropriate.

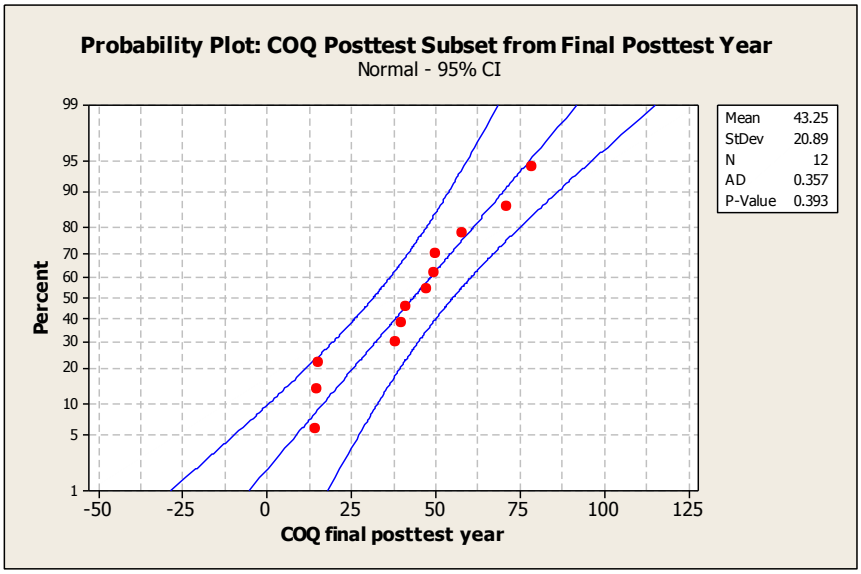


Figure 4-21: Normal Probability Plot with AD Test of Final Posttest Year COQ

4.5.2 Analysis: Hypothesis 4

To analyze if the employment of a KM/QM strategy explains the relationship between the KM/QM strategy application time and a company's cost of quality, COQ score trend lines from the four periods are first presented in Figure 4-22. To allow for a comparison between four time periods, the four graphs use identical scales for the dependent variable, the COQ score. The trend line for the pretest period, prior to KM/QM strategy implementation, indicates a slightly increasing but relatively stable COQ score, as shown in the upper left quadrant of Figure 4-21. During the first year of KM/QM strategy implantation, the slope of the linear COQ score trend line increases substantially over time compared to the pretest period without a KM/QM strategy, indicating a rising

cost for quality, as shown in the upper right quadrant of Figure 4-21. The opposite is the case for the following five year posttest period. The linear COQ score trend line now has a negative slope, which is displayed in the lower two quadrants of Figure 4-22. It represents a sustained decrease in the cost of quality over the five year posttest period.

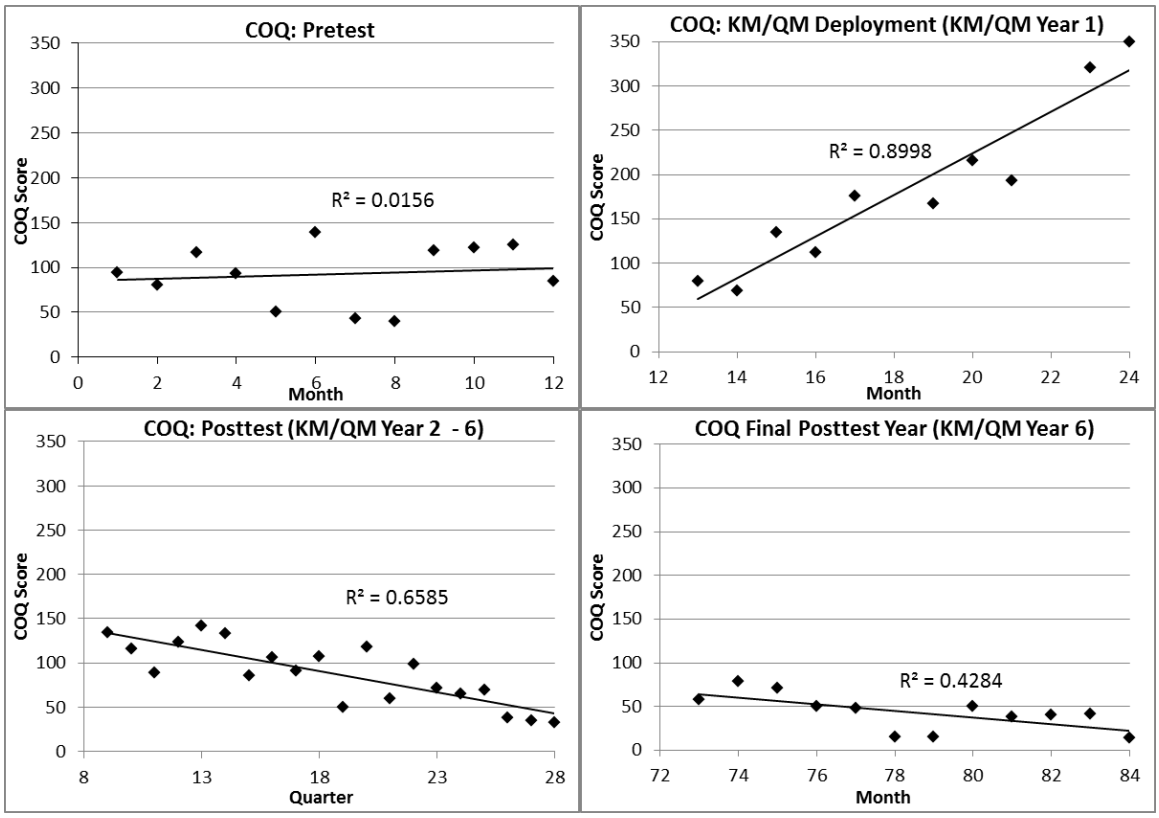


Figure 4-22: COQ Trend at Company B

To determine the significance of the relationships between COQ and the KM/QM strategy application time for the pretest period, KM/QM strategy implementation year and posttest period sample groups, a regression analysis was conducted. Results of the regression analysis are shown in Table 4-12. During the one year COQ pretest period, prior to KM/QM strategy implementation at company B, the PPMCC of r=0.125 indicates a very weak positive relationship between the COQ score and time. The p value

(p=0.699) from a two tail t-test is clearly higher than the selected level of significance (α= 0.05) and the test value (t_{TV} =0.398) shown in Table 4-12 is not within the critical range that is marked by the critical values (t_{CV}=+/-2.228), indicating no correlation and no significant linear relationship between the COQ score and time prior to KM/QM strategy implementation at company B. This result is also confirmed with an F test since the computed F statistic (F_{TV}=0.158) is less than the upper critical value (F_{CVU}=4.96). Only 1.56% of total variation in the COQ score during the pretest period can be explained by the variability in time, based on the coefficients of determination r^2 shown in Figure 4-22 (r^2=0.0156). The results of the pretest indicate no significant change in cost of quality during this period for company B prior to KM/QM strategy implementation.

During the first year of KM/QM strategy implantation at company B, the regression analysis results in a PPMCC of r=0.949, indicating a very strong positive linear relationship between the COQ score and the KM/QM strategy application time, as presented in Table 4-12. The p value (p=0.000) from a two tail t-test is clearly lower than the selected level of significance (α= 0.05) and the test value (t_{TV} = 8.476) is well within the critical range marked by the critical values (t_{CV}=+/-2.306), exposing the significance of this very strong positive linear relationship between the COQ score and KM/QM strategy application time during the first year of KM/QM strategy implementation at company B. The F test confirms this result since the computed F statistic (F_{TV}=71.836) is greater than the upper critical value (F_{CVU}=5.329), providing the evidence of a significant and very strong positive linear relationship in the population. Consequently, the null sub-hypothesis for the inference about the slope of the regression line (H_0: $ß_1$=0) was rejected. During the first year of KM/QM strategy implementation, 90% of total variation in the

COQ score can be explained by the variability in KM/QM strategy application time, based on the coefficients of determination r^2 shown in Figure 4-22 (r^2=0.8998). The results of this regression analysis indicate vastly increasing quality costs for company B during the first year of KM/QM strategy implementation.

The opposite is the case when analyzing the following five posttest years, starting one year after KM/QM strategy implementation at company B. During this five year posttest period, the PPMCC of r= -0.811 indicates a very strong negative relationship between the COQ score and KM/QM strategy application time. The p value (p=0.000) from a two tail t-test is below the selected level of significance (α= 0.05) and the test value (t_{TV} = -5.892) shown in Table 4-12 is within the critical range marked by the critical values (t_{CV}=+/- 2.101), revealing the significance of this very strong negative linear relationship between the COQ score and KM/QM strategy application time during the five year posttest period at company B. This result is also confirmed with an F test since the computed F statistic (F_{TV}=34.713) is greater than the upper critical value (F_{CVU}=4.41), providing evidence of a significant and very strong negative linear relationship between the KM/QM strategy application time and the COQ score in the population. The null sub-hypothesis for the inference about the slope of the regression line (H_0: ß$_1$=0) was rejected. 65.9% of the variance in COQ score during the posttest period can be accounted for by the KM/QM strategy application time, as indicated by r^2 from Figure 4-22 (r^2=0.6585). After the initial COQ increase during the KM/QM strategy implementation year, the results of this regression analysis indicate a sustained and significant decreased in quality costs for company B during the following five year KM/QM strategy posttest period.

Table 4-12: Regression Analysis of COQ vs. Time

Regression analysis for COQ score vs. time ($\alpha = 0.05$)			
	Pretest period	KM/QM strategy implementation year	Posttest period
N	12	10	20
r	0.125	0.949	-0.811
b_1	1.172	23.422	-4.758
Std. error of slope	2.946	2.764	0.808
MSR	196.338	71100.261	15057.572
MSE	1240.686	989.756	433.774
F_{TV}	0.158	71.836	34.713
F_{CVU}	4.960	5.320	4.410
t_{TV}	0.398	8.476	-5.892
t_{CV}	+/- 2.228	+/- 2.306	+/-2.101
p	0.699	0.000	0.000

F test results from section 4.5.1 of this dissertation chapter informed that the COQ variances from the pretest period, prior to KM/QM strategy implementation, and the final posttest year, after KM/QM strategy implementation, can be assumed equal. The use of a t test with pooled-variances is therefore appropriate. The results of a two sample pooled-variance t test are displayed in Table 4-13 and show that the mean COQ score from the pretest period was significantly higher than from the final posttest year. The p value (p=0.000) from the one sided t-test is lower than the selected level of significance (α= 0.05) and the test value (t_{TV} = 4.254) is higher than its critical value (t_{CV}= 1.717). The difference between the two sample groups is further exemplified with the boxplot of Figure 4-23. It graphically shows the significantly higher cost of quality during the pretest period, when company B operated without a KM/QM strategy, than during the final posttest year, when company B had an implemented KM/QM strategy.

Table 4-13: Two sample t Test with Descriptive Statistics for COQ Score

Two sample pooled-variance t test for COQ ($\alpha = 0.05$)		
	Pretest COQ	Final posttest year COQ
Mean	92.102	43.254
Variance	1145.746	436.225
N	12	12
Pooled-variance	790.985	
Hypothesized mean difference	0	
dof	22	
t_{TV}	4.254	
t_{CV} (one sided)	1.717	
p (one sided)	0.000	

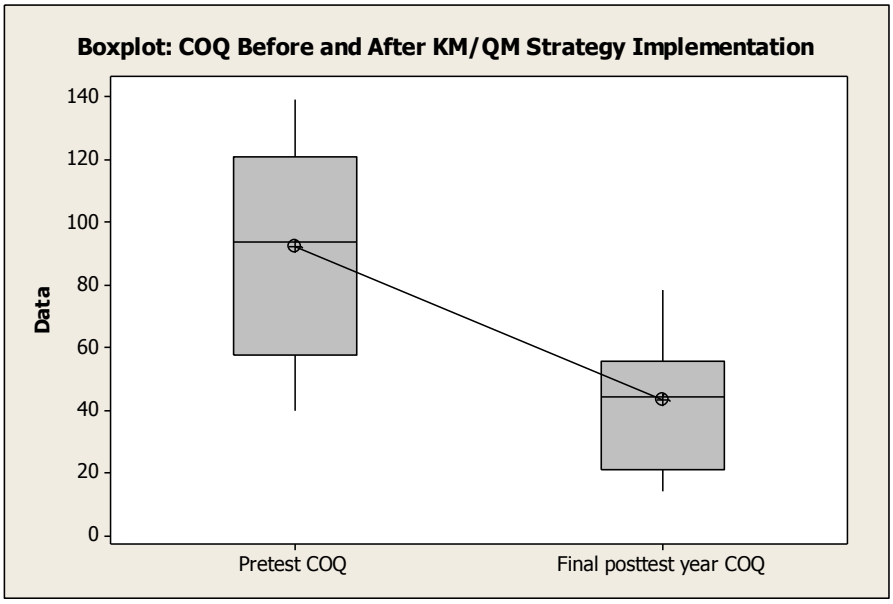


Figure 4-23: Boxplot of Pretest COQ and Final Posttest Year COQ

The causal assumption that the employment of a KM/QM strategy at company B causes the significant linear relationship between the KM/QM strategy application time and COQ is supported since there were no other changes or policy implementations found at company B, with exception to the KM/QM strategy. To account for changes in

production quantities, model mix, material cost, labor cost and other direct production costs over time, the COQ was normalized to a COQ score. Additional obtainable factors, confounding effects and factor interactions that might have influenced the results while implementing and employing a KM/QM strategy are analyzed in section 4.6 of this chapter. The causality assumption is further supported with the results of the pretest. The pretest confirmed that prior to KM/QM strategy implementation at company B, no significant relationship between COQ and time existed. Only after the KM/QM strategy was implemented did the product quality characteristics change significantly at company B over the KM/QM strategy application time. The initial very strong significant positive linear relationship between the COQ score and the KM/QM strategy application time during the first year of KM/QM implementation can be explained since the introduction of a KM/QM methodology with its dynamic spiral of organizational knowledge creation exposed issues at company B that resulted in early and short term COQ increases. This was followed with a significant and very strong negative linear relationship between the KM/QM strategy application time and the COQ score during the following five year posttest period, when the KM/QM strategy was implemented for more than one year. The significant decrease in COQ during the posttest period can also be attributed to the KM/QM strategy with its spiral of organizational knowledge creation and dynamic interaction of the SECI elements that result in sustained quality and COQ improvements. The KM/QM strategy implementation was the single most important change found at company B, and other factors such as policy changes or changes in the operational environment were found not to affect the COQ score or were accounted for through normalized data to allow a comparison over time. The results from the four hypotheses

tests outlined in the conceptual framework of Figure 3-2 are an indication of an effective quality management strategy. Results from this fourth main research hypothesis test validate the outcomes from the previous three main research hypotheses tests, and address the basic research question, since all four main research hypotheses tests demonstrate that a KM/QM strategy improves an organization's performance.

4.5.3 Results of Analysis: Hypothesis 4

The results of this analysis support the claim of the fourth main research hypotheses that the use of a KM/QM strategy contributes significantly and negatively to cost of quality over the KM/QM strategy application time, after the KM/QM strategy has been implemented for at least one year. A regression analysis showed that there was a significant and very strong negative linear relationship between the KM/QM strategy application time and the COQ score after the first year of KM/QM implementation, indicating sustained operational performance improvements through lower cost of quality. The opposite was the case during the first year of KM/QM strategy implementation. The claim of the fourth main research hypotheses is not supported when the KM/QM strategy was implemented for less than one year. The regression analysis showed a significant and very strong positive linear relationship between the COQ score and the KM/QM strategy application time, informing of a substantial COQ increase during this first year of KM/QM strategy implementation. An explanation for this increase is that the deployment of a new quality strategy exposed quality issues which were previously unidentified, necessitating corrective and preventive actions that resulted in short term COQ increases during the first year of the KM/QM strategy

implementation. These initial issues that caused short term COQ increases during the first year of KM/QM strategy implementation were successfully resolved with the KM/QM strategy approach presented in this dissertation, leading to sustained and continuous quality cost decreases during the following five year posttest research period. The results of a pretest showed no significant linear relationship between time and the COQ score for the year prior to KM/QM strategy implementation. A two sample t test showed that the mean COQ score after KM/QM strategy implementation was significantly lower than for the year prior to KM/QM strategy implementation.

The causal assumption that the employment of a KM/QM strategy causes the relationship between COQ and KM/QM strategy application time is based on the fact that the KM/QM strategy implementation at company B was the single most important change found at the company, and factors such as policy changes or changes in the operational environment were found not to affect the COQ score. A pretest confirmed that prior to KM/QM strategy implementation at company B, no significant correlation and no significant linear relationship between the COQ score and time was present. After the KM/QM strategy was rolled out at company B, the COQ score responded with significant changes over the KM/QM strategy application time. The fourth main research hypothesis test validates the three previous main research hypotheses' results and the basic research question by means of operational performance improvements through employment of a KM/QM strategy. The first and second main research hypothesis showed that company B significantly improved product quality due to a KM/QM strategy while the third main research hypothesis demonstrated that the number of quality related improvement activities was significantly reduced because of an effective KM/QM

strategy deployment. During a coinciding research timeframe with the first three research hypotheses, the fourth main research hypothesis test demonstrated that company B also significantly reduced the cost of quality because of an effective KM/QM strategy deployment, although showing short term COQ increases during the initial KM/QM strategy implementation year. The four main research hypotheses tests in this dissertation address the basic research question since all result in sustained operational performance improvements that are related to the deployment of the KM/QM strategy.

4.6 Discussion of Results: Factors, Confounding Effects and Interactions

Since this study includes only one company with a KM/QM strategy intervention, all obtainable factors, confounding effects and factor interactions that might have played a role in the success at company B while implementing a KM/QM strategy are being addressed in the final part of this chapter. Confounding variables and factor interactions are not measured or observed in the study, and its influence cannot be directly detected (Creswell, 2009).

This evaluation starts with factors not directly associated with the integration of knowledge management and quality management. From the supply chain side, we found that the organization used raw material and parts from their existing base of suppliers with no noticeable changes in supplier performance during the KM/QM strategy pretest and the posttest periods. All four sites purchased material and parts from the same sources and applied uniform supplier qualification criteria. There were no indications that supplier performance changes influenced the success at company B. Products manufactured at company B, as well as company A, C, and D, were in a mature product

life cycle stage with consistent low numbers of product engineering changes during the KM/QM strategy pretest and posttest periods. Product engineering changes, product specification changes, new product introductions, and other product innovations were not found as contributing factors for the superior results and the operational performance advances at company B that were observed in product quality, number of quality related improvement activities, and COQ improvements. Manufacturing technologies were standardized between all four sites, with the majority implemented prior to the KM/QM strategy pretest period. New or differentiating manufacturing technologies were not seen as a source for significant product quality advantages at company B, or significant improvement trends that are related to product quality, the number of quality related improvement activities, and COQ. Company B experienced productivity improvements during the posttest period, but the associated production increases and stable employment levels could not be linked to superior product quality, significant product quality improvements, significant decrease in the number of quality related improvement activities, and to a significant decline in COQ. The ratio between permanent and temporary employees, as well as the proportion of new inexperienced employees at company B, stayed consistent during KM/QM strategy pretest and posttest periods and did not provide an indication of influencing product quality characteristics, quality related improvement activities, or COQ. Quality measurement methodologies are standardized among the four sites and product audit criteria did not change during the KM/QM strategy pretest and posttest periods. Since incorrect or inconsistent product quality audit practices can influence the product quality score and quality issue rate results, product quality audit and measurement processes at the four companies were frequently audited

themselves by the corporate quality department to ensure compliance and uniformity in product audit performance between the four sites. The COQ performance metric was normalized to a cost of quality score to account for changes in production quantities, model mix, material cost, labor cost and other direct production costs over time.

Factors associated with the integration of knowledge management and quality management that potentially influenced the results of this research, but could not be measured or directly detected, are subject for the following review. In the socialization element of organizational knowledge creation, personal interaction between all stakeholders was increased at company B after KM/QM strategy implementation to foster a tacit to tacit knowledge transfer. After KM/QM strategy implementation, company B increased on-the-job training programs and job rotations for existing and new employees. Less experienced employees work hand-in-hand with their experienced colleagues for an extended period of time, allowing a rich tacit to tacit knowledge exchange. An increasing number of employees sought professional certifications after KM/QM strategy implementation. Preparation and training for the certification exam took place in groups of coworkers. Tacit knowledge was converted to new tacit knowledge while the cohort of candidates studied together and at the same time exchanged their knowledge and experience. After the KM/QM strategy was implemented, it was found that company B increased the number of short reoccurring daily and weekly meetings between stakeholders to allow the transfer of tacit to tacit knowledge and enable an almost instantaneous best practice replication process. In the stakeholder meetings, experienced attendees offer solutions to specific quality issues, on the spot, to their less experienced coworkers, avoiding "*reinventing the wheel*." In the externalization element of

organizational knowledge creation, it was found that after the KM/QM strategy was implemented, departments within company B started to develop and maintain operational handbooks that include work instructions and reference materials. Tacit knowledge housed in the minds of experienced employees was converted to clear explicit knowledge that can be used by others. Previously informal quality related corrective and preventive action processes were documented after KM/QM strategy implementation. It was found that after business related travel, company B started to ask employees to prepare trip reports to allow an exchange of the tacit knowledge acquired during the trip with other relevant stakeholders in an explicit (documented) format. Only one possible factor in the combination element of organizational knowledge creation was found, which could have played a role at company B while implementing the KM/QM strategy. On the onset of the KM/QM strategy posttest period, company B implemented a KM/QM enterprise system that manages quality data and generates reports, charts, and tables. The majority of other explicit to explicit knowledge transfer practices were already established within the traditional QM system at company B, before the KM/QM was implemented. Such established combination practices include statistical process control and process capability analysis, system audit and process audit reporting, and the analysis of information from manufacturing data acquisition systems. In the internalization element of organizational knowledge creation, it was found that after KM/QM strategy implementation, company B increasingly took advantage of their already existing quality data. Such data includes process capability analysis reports, corrective and preventive action reports, etc. Company B made the explicit data available to qualified employees at the manufacturing process so they can actually use the explicit data and convert it to tacit

knowledge by making process adjustments and process improvements. Explicit knowledge which was created in operational handbooks after KM/QM strategy implementation was converted to tacit knowledge when employees practiced it during work through "*learning by doing*."

The approach applied in this research of analyzing the KM/QM strategy as a holistic system includes the obtainable factors that influenced the results of this study, confounding effects, as well as the dynamic interaction of factors. The dynamic interaction of organizational knowledge creation factors, i.e., the spiral of organizational knowledge creation, is also accentuated in Nonaka's (1994) theory, which is the underlying principle of the KM/QM strategy analyzed in this dissertation. Determining the actual strength of the individual factors and the strength of factor interactions is not part of this research, but presents an opportunity for future studies. Since this research includes only one company with a KM/QM strategy intervention, an important opportunity for future research also lies in testing the effectiveness of a KM/QM strategy intervention at additional companies.

Chapter 5. Conclusions

This dissertation fills a gap in academic literature and contributes to the engineering management and systems engineering body of knowledge by analyzing the effects of integrating knowledge management and quality management on a firm's operational performance through quantitative empirical research. The KM/QM strategy presented in this dissertation resembles Nonaka's (1994) theory of organizational knowledge creation, integrated in a traditional QM system to form an enhanced quality management system. The analyses of four main research hypotheses demonstrate that a KM/QM strategy results in sustained operational performance improvements.

The first main research hypothesis' claim that a company using a KM/QM strategy has a significantly higher product quality than companies without a KM/QM strategy is supported with the results of an ANOVA and ANOM. The results of a pretest showed that before the KM/QM strategy was implemented, there was no significant difference in product quality.

A quantitative empirical study also supports the second main research hypothesis' claim that a KM/QM strategy contributes significantly and positively to product quality over the KM/QM strategy application time. A regression analysis for a company with a KM/QM strategy showed that there was a significant strong positive relationship between the product quality score and the KM/QM strategy application time and a very strong significant negative relationship between the quality issue rate and KM/QM strategy application time, both indicating substantial quality performance improvements. A comparison with control groups from three similar sites but without a KM/QM strategy

showed no significant change in product quality characteristics for those companies during the same research time period. A pretest showed that prior to KM/QM strategy implementation, no relationship between product quality and time existed.

The third main research hypothesis' claim that the employment of a KM/QM strategy contributes significantly and negatively to the number of quality related improvement activities over the KM/QM strategy application time is supported with the results of a regression analysis. The results show a significant moderate negative relationship between the KM/QM strategy application time and the number of quality related improvement activities. The decreasing numbers of quality related improvement activities are an indication for operational performance improvements.

The fourth and final main research hypothesis' claim that the use of a KM/QM strategy contributes significantly and negatively to cost of quality over KM/QM strategy application time is supported with the results of a regression analysis but only after the KM/QM strategy has already been implemented for one year. The results show a significant and very strong negative relationship between the KM/QM strategy application time and the COQ score after the first year of KM/QM implementation, indicating sustained performance improvements through a lower cost of quality. The claim of the fourth main research hypothesis is not supported when the KM/QM strategy was implemented for less than one year. During this period, the regression analysis shows a significant and very strong positive relationship between the COQ score and the KM/QM strategy application time. Prior to KM/QM strategy implementation, the results of a pretest showed no significant linear relationship between time and the COQ score. The results of a two sample t test showed that the mean COQ score after KM/QM

strategy implementation was significantly lower than before the KM/QM strategy was implemented, indicating operational performance improvements through a lower COQ.

The four main research hypotheses tests in this dissertation address the basic research question since all result in operational performance improvements that are related to the deployment of the KM/QM strategy. The causal assumption that a KM/QM strategy is responsible for significantly higher product quality than without one, or the causal assumption that a KM/QM strategy causes a significant relationship between a firm's operational performance characteristics and the KM/QM strategy application time is based on the fact that the companies in this research operate under similar environmental and cultural conditions. There were no other significant changes or policy implementations found that impacted any of the sites differently during the research period, with exception to the KM/QM strategy implementation. The KM/QM strategy was analyzed as one holistic system, including all obtainable factors that influenced the results of this study, confounding effects, as well as the dynamic interaction of factors. The dynamic interaction of organizational knowledge creation factors, i.e., the spiral of organizational knowledge creation, as accentuated in Nonaka's (1994) theory, is the underlying principle of the KM/QM strategy analyzed in this dissertation.

Chapter 6. Future Areas of Research

The work conducted for this dissertation offers the following opportunities for future engineering management and systems engineering research:

1. The strategy presented in this dissertation to integrate knowledge management into an existing management function is not isolated to quality management or the manufacturing sector. Many tracks of engineering management and systems engineering could benefit in a similar fashion as quality management by integrating a knowledge management strategy that has organizational knowledge creation at its core. Future research can evaluate the effects of integrating organizational knowledge creation in engineering management and systems engineering focus areas such as engineering project management, innovation management, new product development, engineering change management, operational efficiency improvement and system performance.
2. Additional opportunities for future research are to perform empirical research on the effects of a KM/QM strategy on knowledge creation to further explore Nonaka's (1994) theory in the QM arena.
3. Another interesting prospect lies by performing quantitative empirical research at different industry sectors such as healthcare, service, financial or governments, to determine the effectiveness of a KM/QM strategy outside the manufacturing industry.
4. By extending this research beyond the current research time frame, it can be analyzed how long the relationships between the KM/QM strategy application time and

operational performance characteristics maintains statistical significance. This will provide insights on the system life cycle stages of a KM/QM strategy (ISO, 2008).

5. An important opportunity for future research lies in testing the effectiveness of a KM/QM strategy intervention at additional manufacturing companies, since this research is limited to one company with a KM/QM strategy intervention and three similar companies without the intervention.
6. This dissertation analyzes the KM/QM strategy as a holistic system that includes the obtainable factors, confounding effects, and the dynamic interaction of factors, which influenced the results of this study. Determining the actual strength of the individual KM/QM strategy factors, factor interactions, as well as confounding effects, provides an opportunity for future research.
7. In the preceding literature review, collaborative industrial automation was found as a new evolutionary approach where manufacturing systems are never fully formed. Through direct collaboration between the component systems, system implementation time, investments, and system flexibility can outperform traditional industrial systems. This can further lead to a competitive advantage for firms (Colombo et al., 2013). An opportunity for future research is to study the effects of applying the dynamic interaction of the organizational knowledge creation elements, which were described in this dissertation, to system collaboration within collaborative industrial automation.

References

Agresti, A., & Franklin, C. (2009). *Statistics: The art and science of learning from data*. Upper Saddle River, NJ: Pearson Prentice Hall.

Akdere, M. (2009). The role of knowledge management in quality management practices: Achieving performance excellence in organizations. *Advances in Developing Human Resources, 11*(3), 349-361.

Anand, G., Ward, P. T., & Tatikonda, M. V. (2010). Role of explicit and tacit knowledge in Six Sigma projects: An empirical examination of differential project success. *Journal of Operations Management, 28*(4), 303-315.

Anand, G., Ward, P. T., Tatikonda, M. V., & Schilling, D. A. (2009). Dynamic capabilities through continuous improvement infrastructure. *Journal of Operations Management, 27*(6), 444-461.

Anderson, T. W., & Darling, D. A. (1952). Asymptotict theory of certain "goodness of fit" criteria based on stochastic processes. *The Annals of Mathematical Statistics, 23*(2), 193-212.

Anderson, T. W., & Darling, D. A. (1954). A test of goodness of fit. *Journal of the American Statistical Association, 49*(268), 765-769.

Ansari Ch, F., Khobreh, M., Nasiri, S., & Fathi, M. (2009). *Knowledge management support for quality management to achieve higher customer satisfaction.* Paper presented at the Electro/Information Technology, 2009. eit'09. IEEE International Conference on Electro/Information Technology, Windsor, ON, Canada.

Argote, L., & Miron-Spektor, E. (2011). Organizational learning: From experience to knowledge. *Organization Science, 22*(5), 1123-1137.

Armacost, R. L. (2011). Knowledge at KPMG Retrieved February 13, 2013, from http://www.irmac.ca/1112/KM%20overview%20IRMC%20v1.pdf

Bateson, G., & Bateson, M. C. (2000). *Steps to an ecology of mind: Collected essays in anthropology, psychiatry, evolution, and epistemology*. Chicago, IL: University of Chicago Press.

BEA. (2013). Gross domestic product: Fourth quarter and annual 2012. Retrieved September 1, 2013 http://www.bea.gov/newsreleases/national/gdp/2013/txt/gdp4q12_adv.txt

Behrens, B.-A., Wilde, I., & Hoffmann, M. (2007). Complaint management using the extended 8D-method along the automotive supply chain. *Production Engineering, 1*(1), 91-95.

Bergmann, C., Lindner, M., Zhang, W., Koczur, K., Kirsten, A., Telle, R., & Fischer, H. (2010). 3D printing of bone substitute implants using calcium phosphate and bioactive glasses. *Journal of the European Ceramic Society, 30*(12), 2563-2567.

Blessner, P., Mazzuchi, T. A., & Sarkani, S. (2013). ISO 9000 impact on product quality in a defense procurement environment. *The TQM Journal, 25*(3), 295-308.

BLS. (2014). Workforce statistics. Retrieved April 6, 2014, from United States Bureau of Labor Statistics http://www.bls.gov/webapps/legacy/cesbtab1.htm

BOC. (2013). North american industry classification system. Retrieved August 27, 2013, from United States Census Bureau http://www.census.gov/cgi-bin/sssd/naics/naicsrch?code=31&search=2012%20NAICS%20Search

BOC. (2014a). Trade in goods with China Retrieved April 6, 2014, from United States Census Bureau http://www.census.gov/foreign-trade/balance/c5700.html

BOC. (2014b). U.S. international trade in goods. Retrieved April 6, 2014 http://www.census.gov/foreign-trade/statistics/historical/

Bonvillian, W. B. (2012). Reinventing American manufacturing. *Innovations, 7*(3), 97.

Brady, J. E., & Allen, T. T. (2006). Six Sigma literature: a review and agenda for future research. *Quality and Reliability Engineering International, 22*(3), 335-367.

Breznitz, D., & Murphree, M. (2011). *Run of the red queen: Government, innovation, globalization, and economic growth in China*. New Haven, CT: Yale University Press.

Brown, J. S., & Duguid, P. (2000). *Social life of information*. Boston, MA: Harvard Business School Press.

Burke, S. (2001). Missing values, outliers, robust statistics & non-parametric methods. *LC-GC Europe Online Supplement, Statistics & Data Analysis, 2*, 19-24.

Campanella, J. (1999). *Principles of quality costs: Principles, implementation and sse*. Milwaukee, WI: ASQ Quality Press.

Castellacci, F. (2008). Technological paradigms, regimes and trajectories: Manufacturing and service industries in a new taxonomy of sectoral patterns of innovation. *Research Policy, 37*(6), 978-994.

Chao, G. H., Iravani, S. M., & Savaskan, R. C. (2009). Quality improvement incentives and product recall cost sharing contracts. *Management Science, 55*(7), 1122-1138.

Chin, K. S., Wang, Y. M., Yang, J. B., & Gary Poon, K. K. (2009). An evidential reasoning based approach for quality function deployment under uncertainty. *Expert Systems with Applications, 36*(3), 5684-5694.

Choo, A. S. (2011). Impact of a stretch strategy on knowledge creation in quality improvement projects. *Engineering Management, IEEE Transactions on, 58*(1), 87-96.

Choo, A. S., Linderman, K. W., & Schroeder, R. G. (2007a). Method and context perspectives on learning and knowledge creation in quality management. *Journal of Operations Management, 25*(4), 918-931.

Choo, A. S., Linderman, K. W., & Schroeder, R. G. (2007b). Method and psychological effects on learning behaviors and knowledge creation in quality improvement projects. *Management Science, 53*(3), 437-450.

Chou, Y.-M., Polansky, A. M., & Mason, R. L. (1998). Transforming non-normal data to normality in statistical process control. *Journal of Quality Technology, 30*(2), 133-141.

Cimbala, J. M. (2011). Outliers. *Penn State University lecture notes*. Retrieved from http://www.mne.psu.edu/me345/Lectures/Outliers.pdf

Cohen, M. D., March, J. G., & Olsen, J. P. (1972). A garbage can model of organizational choice. *Administrative Science Quarterly, 17*(1), 1-25.

Colombo, A. W., Bangemann, T., & Karnouskos, S. (2013). *A system of systems view on collaborative industrial automation.* Paper presented at the 2013 IEEE International Conference on Industrial Technology, Cape Town, Western Cape, South Africa.

Creswell, J. W. (2009). *Research design: Qualitative, Quantitative, and mixed methods approaches*. Thousand Oaks, CA: Sage.

Davenport, T. H., & Prusak, L. (2000). *Working knowledge: How organizations manage what they know*. Boston, MA: Harvard Business Press.

Deming, W. E. (2000a). *The new economics for industry, government, education*. Cambridge, MA: MIT Press.

Deming, W. E. (2000b). *Out of the crisis*. Cambridge, MA: MIT Press.

Douglas, T. J., & Judge, W. Q. (2001). Total quality management implementation and competitive advantage: The role of structural control and exploration. *Academy of Management Journal, 44*(1), 158-169.

Drucker, P. F. (1991). The new productivity challenge. *Harvard Business Review, 69*(6), 69-76.

Drucker, P. F. (1994). *Post-capitalist society*. New York, NY: HarperCollins.

Durbin, J., & Watson, G. (1971). Testing for serial correlation in least squares regression III. *Biometrika, 58*(1), 1-19.

Durbin, J., & Watson, G. S. (1951). Testing for serial correlation in least squares regression II. *Biometrika, 38*(1/2), 159-177.

Easton, G. S., & Jarrell, S. L. (1998). The effects of total quality management on corporate performance: An empirical investigation*. *The Journal of Business, 71*(2), 253-307.

Flynn, B. B., Schroeder, R. G., & Sakakibara, S. (1995). The impact of quality management practices on performance and competitive advantage. *Decision Sciences, 26*(5), 659-691.

Fredendall, L. D., Kovach, J. V., & LaGanga, L. (2010). Investigating quality management's link to performance in mental health outpatient services: A knowledge-based perspective: Mental Health Center of Denver.

Freeman, R. B., & Schettkat, R. (2005). Marketization of household production and the EU–US gap in work. *Economic Policy, 20*(41), 6-50.

Garstenauer, A., Blackburn, T. D., & Olson, B. A. (2013). *A knowledge management based approach to quality management for large manufacturing organizations*. Paper presented at the American Society for Engineering Management 2013 International Annual Conference, Minneapolis, MN.

Gee, G., Richardson, W. R., & Wortman, B. (2005). *The manager of quality organizational excelence primer*. West Terre Haute, IN: Quality Council of Indiana.

George, M. L., & George, M. (2003). *Lean six sigma for service*. New York, NY: McGraw-Hill.

Granovetter, M. S. (1973). The strength of weak ties. *American Journal of Sociology, 78*(6), 1360-1380.

Groover, M. P. (2001). *Automation, production systems, and computer-integrated manufacturing* (3 ed.). Upper Saddle River, NJ: Prentice Hall Press.

Hahn, G. J., Hill, W. J., Hoerl, R. W., & Zinkgraf, S. A. (1999). The impact of Six Sigma improvement - A glimpse into the future of statistics. *The American Statistician, 53*(3), 208-215.

Hart, D. M. (2012). The future of manufacturing: The United States stirs. *Innovations, 7*(3), 25-34.

Hays, J. M., & Hill, A. V. (2001). A preliminary investigation of the relationships between employee motivation/vision, service learning, and perceived service quality. *Journal of Operations Management, 19*(3), 335-349.

Helsel, D. R., & Hirsch, R. M. (1992). *Statistical methods in water resources*: Elsevier.

Hendricks, K. B., & Singhal, V. R. (1996). Quality awards and the market value of the firm: An empirical investigation. *Management Science, 42*(3), 415-436.

Hendricks, K. B., & Singhal, V. R. (1997). Does implementing an effective TQM program actually improve operating performance? Empirical evidence from firms that have won quality awards. *Management Science, 43*(9), 1258-1274.

Hendricks, K. B., & Singhal, V. R. (2001). Firm characteristics, total quality management, and financial performance. *Journal of Operations Management, 19*(3), 269-285.

Hilton, R. J., & Sohal, A. (2012). A conceptual model for the successful deployment of Lean Six Sigma. *International Journal of Quality & Reliability Management, 29*(1), 54-70.

Hoskisson, R. E., Hitt, M. A., Ireland, R. D., & Harrison, J. S. (2008). *Competing for advantage* (2 ed.). Mason, OH: Thomson/South-Western.

Inglehart, R. (1997). *Modernization and postmodernization: Cultural, economic, and political change in 43 societies* (Vol. 19). Princeton, NJ: Princeton University Press.

ISO. (2008) *System and software engineering - System life cycle processes*. ISO/IEC 15288:2008: ISO Standards Online. Retrieved from http://www.iso.org/

Ives, W., Torrey, B., & Gordon, C. (1997). Knowledge management: an emerging discipline with a long history. *Journal of Knowledge Management, 1*(4), 269-274.

Jayal, A., Badurdeen, F., Dillon Jr, O., & Jawahir, I. (2010). Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. *CIRP Journal of Manufacturing Science and Technology, 2*(3), 144-152.

Joiner, B. L. (1994). *Fourth generation management* (1 ed.). New York, NY: McGraw-Hill.

Juran, J. M., & Godfrey, A. B. (1999). *Juran's quality handbook* (5 ed.). New York, NY: McGraw-Hill.

Juran, J. M., & Gryna, F. M. (1993). *Quality planning and analysis* (3 ed.). New York, NY: McGraw-Hill.

Kakabadse, N. K., Kakabadse, A., & Kouzmin, A. (2003). Reviewing the knowledge management literature: Towards a taxonomy. *Journal of Knowledge Management, 7*(4), 75-91.

Kaynak, H. (2003). The relationship between total quality management practices and their effects on firm performance. *Journal of Operations Management, 21*(4), 405-435.

Kim, S.-S., Choi, H.-J., & Kwak, K.-C. (2012). Knowledge extraction and representation using quantum mechanics and intelligent models. *Expert Systems with Applications, 39*(3), 3572-3581.

Kogut, B., & Zander, U. (1992). Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science, 3*(3), 383-397.

Krajewski, L. J., Ritzman, L. P., & Malhotra, M. K. (2007). *Operations management: Processes and value chains*. Upper Saddle River, NJ: Pearson Prentice Hall.

Kull, T. J., & Wacker, J. G. (2010). Quality management effectiveness in Asia: The influence of culture. *Journal of Operations Management*, *28*(3), 223-239.

Lattin, J. M., Carroll, J. D., & Green, P. E. (2003). *Analyzing multivariate data*. Belmont, CA: Brooks/Cole Cengage Learning.

Levine, D. M., Berenson, M. L., Stephan, D., & Krehbiel, T. C. (2005). *Statistics for managers using Microsoft Excel* (4 ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Lien, D., & Balakrishnan, N. (2005). On regression analysis with data cleaning via trimming, winsorization, and dichotomization. *Communications in Statistics—Simulation and Computation®*, *34*(4), 839-849.

Linderman, K., Schroeder, R. G., Zaheer, S., Liedtke, C., & Choo, A. S. (2004). Integrating quality management practices with knowledge creation processes. *Journal of Operations Management*, *22*(6), 589-607.

Ma, Z., & Yu, K.-H. (2010). Research paradigms of contemporary knowledge management studies: 1998-2007. *Journal of Knowledge Management*, *14*(2), 175-189.

Manufacturing Institute, MAPI, National Association of Manufacturers. (2012). Facts about manufacturing. Retrieved from http://www.themanufacturinginstitute.org/Research/Facts-About-Manufacturing/Facts-2012.aspx

McFadden, K. L., Lee, J. Y., Gowen, C. R., & Sharp, B. M. (2014). Linking quality improvement practices to knowledge management capabilities. *Quality Management Journal, 21*(1), 17.

Mehrjerdi, Y. Z. (2010). Quality function deployment and its extensions. *International Journal of Quality & Reliability Management, 27*(6), 616-640.

Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., & Chryssolouris, G. (2010). Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach. *CIRP Journal of Manufacturing Science and Technology, 2*(2), 81-91.

Miller, G., Pawloski, J., & Standridge, C. R. (2010). A case study of lean, sustainable manufacturing. *Journal of Industrial Engineering and Management, 3*(1), 11-32.

Milton, N. (2009). Metrics in knowledge management. Retrieved from http://www.knoco.com/Knoco%20white%20paper%20-%20KM%20Metrics.pdf

Milton, N., Shadbolt, N., Cottam, H., & Hammersley, M. (1999). Towards a knowledge technology for knowledge management. *International Journal of Human-Computer Studies, 51*(3), 615-641.

Minitab. (2013). Minitab 16. Retrieved from Minitab 16 help file and http://it.minitab.com/en-us/support/answers/default.aspx

Montgomery, D. C., & Runger, G. C. (2002). *Applied statistics and probability for engineers* (3 ed.). New York, NY: Wiley.

Mukherjee, A. S., Lapré, M. A., & Van Wassenhove, L. N. (1998). Knowledge driven quality improvement. *Management Science, 44*(11), 35-49.

NIST. (2013). Malcolm Baldrige national quality award 2013–2014 criteria for performance excellence Retrieved August 17, 2013, from http://www.nist.gov/baldrige/publications/business_nonprofit_criteria.cfm

Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Organization Science, 5*(1), 14-37.

Nonaka, I. (1995). *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*. New York, NY: Oxford University Press.

Nonaka, I., & Konno, N. (1998). The concept of "ba": Building a foundation for knowledge creation. *California Management Review, 40*(3), 40-54.

Nonaka, I., & Toyama, R. (2003). The knowledge-creating theory revisited: Knowledge creation as a synthesizing process. *Knowledge Management Research & Practice, 1*(1), 2-10.

Nonaka, I., Toyama, R., & Konno, N. (2000). SECI, ba and leadership: A unified model of dynamic knowledge creation. *Long Range Planning, 33*(1), 5-34.

Nonaka, I., & Von Krogh, G. (2009). Perspective - Tacit knowledge and knowledge conversion: Controversy and advancement in organizational knowledge creation theory. *Organization Science, 20*(3), 635-652.

Omachonu, V. K., Suthummanon, S., & Einspruch, N. G. (2004). The relationship between quality and quality cost for a manufacturing company. *International Journal of Quality & Reliability Management, 21*(3), 277-290.

Osborne, J. W. (2010). Improving your data transformations: Applying the Box-Cox transformation. *Practical Assessment, Research & Evaluation, 15*(12), 1-9.

Pearson, K. (1895). Note on regression and inheritance in the case of two parents. *Proceedings of the Royal Society of London, 58*(347-352), 240-242.

Pearson, K. (1920). Notes on the history of correlation. *Biometrika, 13*(1), 25-45.

Pepper, M., & Spedding, T. A. (2010). The evolution of lean Six Sigma. *International Journal of Quality & Reliability Management, 27*(2), 138-155.

Polyani, M. (1966). *The tacit dimension*. Garden City, N.Y: Doubleday & Company.

Porter, M. E. (1985). *Competitive advantage*. New York, NY: The Free Press.

Powell, T. C. (1995). Total quality management as competitive advantage: A review and empirical study. *Strategic Management Journal, 16*(1), 15-37.

Rodchua, S. (2009). Comparative analysis of quality costs and organization sizes in the manufacturing environment. *Quality Management Journal, 16*(2), 34-43.

Rodgers, L. J., & Nicewander, W. A. (1988). Thirteen ways to look at the correlation coefficient. *The American Statistician, 42*(1), 59-66.

Ryan, B. F., Joiner, B. L., & Cryer, J. D. (2012). *Minitab handbook: Update for release 16* (6 ed.). Boston, MA: Cengage Learning.

Salkind, N. J. (2012). *Exploring Research* (8 ed.). Upper Saddle River, NJ: Pearson Education.

SBA. (2013). Small business size standards Retrieved February 4, 2013, 2013, from http://www.sba.gov/content/small-business-size-standards

Schell, W. J. P. E. (2008). Building a knowledge management framework to overcome the challenges of developing engineering teams in financial services. *Engineering Management Journal, 20*(1), 3-9.

Schettkat, R., & Yocarini, L. (2006). The shift to services employment: A review of the literature. *Structural Change and Economic Dynamics, 17*(2), 127-147.

Schroeder, R. G., Linderman, K., Liedtke, C., & Choo, A. S. (2008). Six Sigma: Definition and underlying theory. *Journal of Operations Management, 26*(4), 536-554.

Scott, R. E. (2012). The China toll *Briefing Paper No. 345*. Washington, DC: Economic Policy Institute.

Shan, S., Zhao, Q., & Hua, F. (2013). Impact of quality management practices on the knowledge creation process: The Chinese aviation firm perspective. *Computers & Industrial Engineering, 64*(1), 211-223.

Shewhart, W. A. (1980). *Economic control of quality of manufactured product*. Milwaukee, WI: American Society for Quality. (Original work published 1931)

Shipp, S. S., Gupta, N., Scott, J. A., Weber, C. L., Finnin, M. S., & Lal, B. (2012). Advancing manufacturing to new frontiers. *Innovations, 7*(3), 71.

Sitkin, S. B., & Sutcliffe, K. M. (1994). Distinguishing control from learning in total quality management: A contingency perspective. *Academy of Management Review, 19*(3), 537-564.

Smith, L., & Ball, P. (2012). Steps towards sustainable manufacturing through modelling material, energy and waste flows. *International Journal of Production Economics, 140*(1), 227-238.

Sousa, R., & Voss, C. A. (2002). Quality management re-visited: A reflective review and agenda for future research. *Journal of Operations Management, 20*(1), 91-109.

Stangler, D., & Maxwell, K. (2012). DIY producer society. *Innovations, 7*(3), 3.

Stankosky, M. (2005). *Creating the discipline of knowledge management*. Burlington, MA: Elsevier Butterworth–Heinemann.

Swezey, D., & McConaghy, R. (2011). Manufacturing Growth *Advanced Manufacturing and the Future of the American Economy*: The Schwartz Initiative on American Economic Policy, Third Way & The Breakthrough.

Taylor, F. W. (1911). *The principles of scientific management*. New York, NY: Harper & Brothers.

Tolk, A., & Aaron, R. D. (2010). Addressing challenges of transferring explicit knowledge, information, and data in large heterogeneous organizations: A case example from a data-rich integration project at the U.S. Army Test and Evaluation Command. *Engineering Management Journal, 22*(2), 44-55.

Trainor, T. E., Brazil, D. M., & Lindberg, T. (2008). Building knowledge from organizational experience: Approaches and lessons learned from US Army Base Camp Workshops. *Engineering Management Journal, 20*(2), 37-45.

Tukey, J. W., & McLaughlin, D. H. (1963). Less vulnerable confidence and significance procedures for location based on a single sample: Trimming/winsorization 1. *Sankhyā: The Indian Journal of Statistics, Series A, 25*(3), 331-352.

Von Krogh, G., Nonaka, I., & Rechsteiner, L. (2012). Leadership in organizational knowledge creation: A review and framework. *Journal of Management Studies, 49*(1), 240-277.

Waddell, D., & Stewart, D. (2008). Knowledge management as perceived by quality practitioners. *The TQM Journal, 20*(1), 31-44.

Waters, N. M., & Beruvides, M. G. P. E. (2012). An empirical study of large-sized companies with knowledge work teams and their impacts on project team performance. *Engineering Management Journal, 24*(2), 54-62.

Wenger, E. (2011). Communities of practice: A brief introduction. *University of Oregon Scholars' Bank*. Retrieved from https://scholarsbank.uoregon.edu/xmlui/handle/1794/11736

Wilcox, R. R., & Keselman, H. (2003). Modern robust data analysis methods: Measures of central tendency. *Psychological Methods, 8*(3), 254.

Winter, S. (1998). Knowledge and competence as strategic assets. In D. A. Klein (Ed.), *The strategic management of intellectual capital* (pp. 165-187). Woborn, MA: Butterworth-Heinemann.

Worldbank. (2012). Manufacturing, value added (% of GDP) Retrieved August 31, 2013, from The World Bank http://data.worldbank.org/indicator/NV.IND.MANF.ZS

Wortman, B., Carlson, D. R., & Richardson, W. R. (2006). *The quality engineer primer* (8 ed.). West Terre Haute, IN: Quality Council of Indiana.

Yong, J., & Wilkinson, A. (2002). The long and winding road: the evolution of quality management. *Total Quality Management, 13*(1), 101-121.