University of Arkansas, Fayetteville
ScholarWorks@UARK

Theses and Dissertations

8-2011

An Empirical Investigation of Supply Chain Excellence in Healthcare

Brian Keith Smith
University of Arkansas

AN EMPIRICAL INVESTIGATION OF
SUPPLY CHAIN EXCELLENCE IN HEALTHCARE

AN EMPIRICAL INVESTIGATION OF SUPPLY CHAIN EXCELLENCE IN HEALTHCARE

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Engineering

By

Brian K. Smith
Mississippi State University
Bachelor of Science in Industrial Engineering, 1997
University of Arkansas
Master of Science in Industrial Engineering, 2008

August 2011
University of Arkansas

ABSTRACT

This research is motivated by opportunities to improve the cost and quality of healthcare delivery through improved supply chain processes. This research assesses the quality of the healthcare supply chain and identifies factors that are driving supply chain excellence among organizations in the healthcare industry. The first objective of this research is to assess the state of quality measurement in the healthcare supply chain. The achievement of this first objective is presented in Chapter 3 of this dissertation in the form of a manuscript accepted for publication in *The Quality Management Journal.* The second research objective is to develop an optimization-based methodology to extract the maximum amount of survey data from a dataset containing missing responses. The work in support of the second objective is presented in Chapter 4 as a second revision of a manuscript under review by the *International Journal of Data Analysis Techniques & Strategies*. The third research objective is to identify the cost and quality factors that are driving supply chain excellence among organizations in the healthcare industry through empirical analysis. The achievement of the third objective is presented in Chapter 5. The contributions of this work can be used by healthcare supply chain researchers and practitioners to assess and improve their healthcare supply chain operations.

This dissertation is approved for recommendation
to the Graduate Council.

Dissertation Director:

____

Heather Nachtmann, Ph.D.

Dissertation Committee:

____

Justin R. Chimka, Ph.D.

____

Kim LaScola Needy, Ph.D.

____

Edward A. Pohl, Ph.D.

____

Matthew A. Waller, Ph.D.

DISSERTATION DUPLICATION RELEASE

I hereby authorize the University of Arkansas Libraries to duplicate this dissertation when needed for research and/or scholarship.

Agreed ____

Brian K. Smith

DEDICATION

This dissertation is dedicated to Tom and Colleen Smith for their strength, encouragement, and support and to Heather Dawn Smith for sticking with me through thick and thin.

I would like to thank my advisor and mentor, Heather Nachtmann, for her tremendous support throughout my graduate career at the University of Arkansas and preparing me for success in my future academic career; I cannot thank her enough. I would also like to thank my committee members: Kim LaScola Needy for her contribution to this work and support in starting my academic career; Justin Chimka for helping me develop the analytical tools necessary for this research and recognizing the potential value of my contribution; Edward A. Pohl for providing great ideas when I was drawing blanks; and Matthew A. Waller for his excellent advice and recommendations for completing and extending this work.

I would like to thank Richard Cassady and family for their friendship over the years. I would also like to thank Jen, Kellie, Rebekah, Hugh, Jared, and the Industrial Engineering Tailgating Scholars for all the fun and laughs, and thanks to the faculty and staff of the Department of Industrial Engineering at the University of Arkansas for their support and assistance.

I would like to acknowledge and give special thanks to the Center for Innovation in Healthcare Logistics at the University of Arkansas for providing funding and research opportunities for my graduate career.

TABLE OF CONTENTS

LIST OF PUBLISHED OR PUBLISHABLE PAPERS

Chapter 2

Smith, B.K., Nachtmann, H., and Pohl, E.A. (2011) An investigation of the healthcare supply chain: literature review, *Proceedings of the 2011 Industrial Engineering Research Conference*.

Chapter 3

Smith, B.K., Nachtmann, H., and Pohl, E.A., Quality measurement in the healthcare supply chain, to appear in *The Quality Management Journal*.

Chapter 4

Smith, B.K., Chimka, J.R., and Nachtmann, H., A 0-1 quadratic program for the case of missing data in regression, submitted to *International Journal of Data Analysis Techniques & Strategies* (under review).

Chapter 5

Smith, B.K., Nachtmann, H., Chimka, J.R. and Pohl, E.A., An empirical investigation of supply chain initiative effectiveness in healthcare providers (to be submitted).

1. INTRODUCTION

This research assesses the quality of the healthcare supply chain and identifies factors that are driving supply chain excellence among organizations in the healthcare industry. The contributions of this work can be used by healthcare supply chain researchers and practitioners to assess and improve their healthcare supply chain operations.

Research Objectives

The goal of this research is to improve the performance of the healthcare supply chain by identifying opportunities for cost reduction and quality improvement. This research goal is accomplished through achievement of three research objectives. The first research objective is to assess the state of quality measurement within the healthcare supply chain for the purpose of improving supply chain quality by increasing performance awareness. The second research objective is to develop an optimization-based methodology to extract the maximum amount of survey data from a data set containing missing responses. This research objective supports the third research objective as the conducted regression analysis requires a data set with no null values or missing data points. The third research objective supports improved healthcare supply chain performance by identifying factors that affect supply chain excellence via regression analysis of data from a survey of healthcare supply chain professionals.

Research Motivation

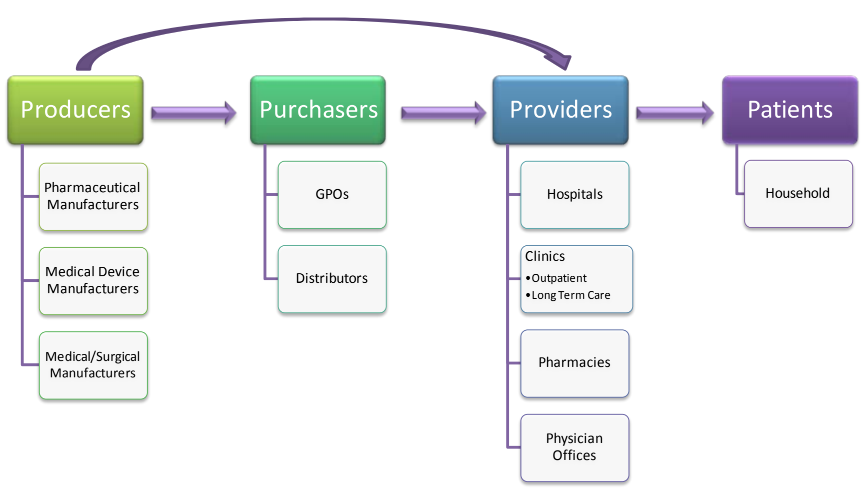
Companies in the manufacturing and retail industries continuously strive to increase revenue and reduce costs. The manufacturing and retail industries have made great improvements in product quality and process efficiency through the adoption of new technologies and automation. With the widespread adoption of automation and technology, increasing parity in terms of operational efficiency and product/service quality combined with economic globalization has led the manufacturing and retail industries to look to their supply chains for a competitive advantage. Efforts towards improved supply chain performance have led to increased profits and competitive advantage in the global marketplace. A focus on supply chain management is common at a strategic level in these industries.

The healthcare industry has not emphasized supply chain management to the extent that manufacturing and retail industries have. New technologies are continually developed that improve the delivery of healthcare services. These new technologies allow physicians to treat injuries and illnesses in more effective or less intrusive ways. Since the primary focus of healthcare providers is to provide the highest level of care possible, most of their budget is dedicated towards adopting new technologies and techniques directly associated with providing care to patients. Dedicating resources towards improving healthcare supply chain processes has not been a major priority for the healthcare industry. However, as the pressure to reduce healthcare cost currently increases, healthcare providers are seeking ways to reduce their costs without negatively impacting the quality of their healthcare services. The healthcare supply chain provides a great opportunity towards this initiative.

The cost and quality of healthcare are two of the most discussed and debated issues of our time. There is definitely reason for concern as healthcare costs account for more than 17% of the gross domestic product (GDP) of the United States. Healthcare costs are expected to grow at a rate greater than that of the GDP, reaching almost $4.6 trillion and accounting for 19.6% of the GDP by 2019 (Centers for Medicare and Medicaid Services, 2010). A 1996 healthcare industry study titled *Efficient Healthcare Consumer Response* (EHCR) concluded that 38% of the cost of goods sold in the healthcare industry can be attributed to supply chain related activities. The study noted that this percentage is much higher than the retail (6 to 8%) and grocery (3 to 6%) sector supply chains (EHCR, 1996; Burns, 2002).

The healthcare supply chain generally consists of four main components: producers, purchasers, providers, and patients (Burns, 2002). Producers produce products such as pharmaceuticals, medical devices and implants, and medical/surgical supplies that are necessary in the delivery of healthcare. Purchasers consist of group purchasing organizations (GPOs) and distributors who facilitate the payment for and shipment of goods from the producers to the providers. Providers may also purchase goods directly from the producers. Providers use the goods produced by producers to administer healthcare services to patients. An illustration of the healthcare supply chain is shown in Exhibit 1.

Exhibit 1. The healthcare supply chain (Smith, 2008)



The products used in the delivery of healthcare range from disposable gauze pads and bandages to state-of-the-art medical devices and implants. The frequency of utilization and cost of an item often determine how a product flows through the healthcare supply chain. Burns (2002) describes the typical distribution means and purchasing contract type of healthcare products as shown in Exhibit 2.

Exhibit 2. Product paths through the healthcare supply chain

	Purchasing Contract Type	
Distribution Means	**GPO Contract**	**No GPO Contract**
Distributor	Low cost/high volume products Medical-surgical products Generic drugs	Some name-brand specialty drugs Small volume items Generic drugs
Direct delivery	Less expensive medical devices and implants Name brand drugs	High-end medical devices and implants High cost/low volume specialty items

The healthcare supply chain is vast, diverse, and complex which presents many challenges to effective management. It is believed that opportunities exist to reduce costs and improve delivery of healthcare by improving the efficiency and quality of healthcare supply chain operations. In 1996, the EHCR identified $11 billion of potential savings through improved healthcare supply chain performance. According to the EHCR, these savings can be realized by improvements in physical distribution, transportation, order management, and inventory management. The estimated cost savings in these four areas are shown in Exhibit 3. The EHCR team determined that these savings could be realized through reducing material handling staff throughout the supply chain, improving invoice accuracy, increasing electronic transactions, and inventory reduction (EHCR, 1996).

Exhibit 3. EHCR supply chain costs and potential savings (billions)

Supply Chain Area	Cost	Estimated Savings	Cost After Savings
Physical Distribution	$3.2	$1.1	$2.1
Transportation	$5.5	$1.8	$3.7
Order Management	$8.5	$5.8	$2.7
Inventory Management	$5.8	$2.3	$3.5
Total	$23	**$11**	$12

In November 2008, researchers from the Center for Innovation in Healthcare Logistics (CIHL) at the University of Arkansas conducted an industry-wide survey of healthcare supply chain practitioners to assess the state of the healthcare supply chain. The web-based CIHL survey was completed by 1,381 healthcare supply chain professionals for a response rate of approximately 12% (Nachtmann and Pohl, 2009). The CIHL survey identifies several important characteristics of the healthcare supply chain and reveals that the healthcare supply chain has the following characteristics (Nachtmann and Pohl, 2009):

- Talent rich: The healthcare supply chain is rich in talent in terms of experience as 45% of the survey respondents have more than twenty years of experience in the healthcare industry.

- Information poor: Survey respondents often cite a lack of data and/or data of insufficient quality as a barrier to collaboration with supply chain partners and supply chain improvement.

- Strategic: The survey reveals that companies in the healthcare supply chain are actively implementing strategic initiatives aimed at improving supply chain operations.

- Collaborative: The survey respondents indicate that there is a high level of collaboration among partners in the healthcare supply chain. However, many barriers exist to improving the level of collaboration and realizing greater improvements in performance.

- Expensive: Supply chain costs account for more than one-third of the annual operating expense of the average organization in the healthcare supply chain according to the survey respondents.

- Immature: The CIHL survey reveals that the healthcare supply chain is immature. The healthcare supply chain lacks fundamental processes and controls necessary to reduce variability. The healthcare supply chain relies heavily on the daily manual actions of individuals to function (Nachtmann and Pohl, 2009).

The motivation for this dissertation is driven by the need to lower the cost of healthcare in the United States by identifying opportunities for organizations within the healthcare supply chain to improve their supply chain processes. The high cost and immaturity associated with the healthcare supply chain provides opportunities to make great strides towards supply chain excellence. The experience level of healthcare supply chain professionals and the collaborative nature of the industry are strong catalysts for improvement once the improvement opportunities and their associated barriers are revealed.

Research Approach

This research focuses on three primary research objectives: 1) assess the state of healthcare supply chain quality measurement, 2) develop a novel approach for extracting survey data from nonresponses, and 3) determine the factors that influence excellence in the healthcare supply chain through empirical analysis of industry data.

To support achievement of these objectives, a comprehensive literature review was conducted to investigate key attributes of today's healthcare supply chain. The literature review focused on the characteristics of the healthcare supply chain including its functional makeup, operational aspects, costs, and challenges. The literature review also explored how the healthcare supply chain is managed and what performance metrics are being used to assess the performance of the healthcare supply chain (Smith et al, 2011).

Phase 1 of this dissertation focuses on the first research objective. The first objective assesses the state of healthcare supply chain quality measurement through the completion of three main tasks:

1. Quality measure identification: Healthcare supply chain quality metrics published in the literature and collected from an industry-wide practitioner survey (Nachtmann and Pohl, 2009) were identified.

2. Quality measure taxonomy development: A taxonomy was developed based on Garvin's eight dimensions of quality (Garvin, 1984) to classify healthcare supply chain quality metrics identified in Task 1.

3. Quality measure assessment: The taxonomy from Task 2 was used to assess the coverage of quality measurement in the healthcare supply chain.

A manuscript on the work conducted in Phase 1 has been accepted for publication in *The Quality Management Journal*. A copy of this manuscript is found in Chapter 3 of this dissertation.

Phase 2 supports achievement of the second research objective by developing a method for extracting the maximum amount of data from a data set containing missing values. Much of this dissertation research is based on data from the survey of healthcare supply chain practitioners conducted by CIHL researchers in November 2008 (Nachtmann and Pohl, 2009). The survey data set contains responses from 1,381 healthcare supply chain professionals. Only surveys that were 80% complete are included in the data set. The data from this survey includes many nonresponses which are questions in which respondents did not provide a response. These nonresponses are essentially missing data in the data set. The valid data points from the survey must be extracted from the nonresponses before a statistical regression analysis of the survey data can be performed. Statistical methods like regression analysis require a complete data set void of missing or null values, and methodologies for resolving this issue have received much attention in the survey analysis literature. However, most of these methodologies are cumbersome and/or involve some form of imputation. Imputation is essentially making up data to fill in the nonresponses in the data set and is not a technique utilized in this research. In the second phase of this research, a novel approach utilizing quadratic programming is developed to automate the process of extracting the maximum amount of data from a data set containing nonresponses. A second revision of a manuscript under review by the *International Journal of Data Analysis Techniques & Strategies*, describing the efforts and findings of Phase 2 is presented in Chapter 4.

The third phase of this research seeks to achieve the third research objective through a comprehensive empirical investigation of supply chain excellence in healthcare supply chains. Phase 3 utilizes the data collected from the industry-wide CIHL survey (Nachtmann and Pohl, 2009). This data is used to develop an ordered regression model describing the factors that are driving supply chain excellence among organizations in the healthcare industry. A manuscript anticipated to be submitted to *IEEE Transactions on Engineering Management* describing the efforts and findings of Phase 3 of this research is provided in Chapter 5 of this dissertation.

Research Contributions

This research makes contributions that are applicable to healthcare supply chain researchers and practitioners, researchers that work with survey data, and individuals interested in the quality and performance of the healthcare supply chain. Affordable healthcare with high quality patient outcomes will be of concern to all Americans in the foreseeable future. Therefore, the quality of healthcare logistics is an area worthy of study. A survey of the related literature reveals that the surface has barely been scratched. The first phase of this research is an assessment of the state of quality measurement in the healthcare supply chain. The contribution of Phase 1 is improved knowledge of what quality management/measurement metrics are being utilized in the healthcare supply chain. Phase 1 also provides knowledge about the breadth of coverage provided by these metrics based on a taxonomy adapted from Garvin's eight dimensions of quality. This effort delivers an assessment of the current state of healthcare supply chain quality measurement which can help researchers and practitioners develop and improve quality measurement programs across the healthcare supply chain.

The second phase of this research develops a method for extracting the maximum amount of data from a data set containing missing responses. The contribution of Phase 2 is of interest to researchers analyzing survey data. Missing responses are common in survey data sets. The valid data must be extracted from the full data set before regression analysis can proceed. The contribution of Phase 2 is a novel method for eliminating missing responses while maximizing the amount of valid data preserved from a survey data set via a quadratic program.

The third phase of this research identifies factors that affect supply chain excellence via statistical analysis of data from a healthcare supply chain industry survey (Nachtmann and Pohl, 2009). For the healthcare supply chain researcher and practitioner, this is the first known, comprehensive empirical investigation of supply chain excellence in healthcare supply chains that is based on extensive industry input. The data from a vast industry-wide survey supports an ordinal regression analysis investigating what factors are driving supply chain excellence among healthcare organizations. The contribution of Phase 3 provides valuable knowledge to healthcare supply chain researchers and practitioners regarding the factors that drive supply chain performance so that they may support improved healthcare logistics performance.

Organization of Dissertation

This dissertation is formatted to follow the published or publishable papers dissertation model provided by the University of Arkansas Graduate School. Chapter 1 introduces the healthcare supply chain and describes the motivation and research objectives of this work. This chapter also describes the approach and methodology of the research and discusses the major contributions to the body of knowledge and healthcare community. Chapter 2 provides a review of the literature pertaining to the healthcare supply chain in the form of a paper published in the *Proceedings of the 2011 Industrial Engineering Research Conference*. Chapter 3 presents a journal paper accepted for publication by *The Quality Management Journal* titled “Quality Measurement in the Healthcare Supply Chain” that assesses the state of healthcare supply chain quality measurement. Chapter 4 is a second revision of a manuscript under review by the *International Journal of Data Analysis Techniques & Strategies* titled “A 0-1 Quadratic Program for the Case of Missing Data in Regression” that provides an approach for extracting valid survey data from missing responses. Chapter 5 presents a manuscript titled “An Empirical Investigation of Supply Chain Initiative Effectiveness in Healthcare Providers” aimed at presenting the findings from a regression analysis designed to identify the factors that are driving supply chain excellence among provider organizations in the healthcare industry. Chapter 6 provides an overall conclusion from this dissertation and opportunities for future work.

References

Burns, Lawton R., *The Health Care Value Chain: Producers, Purchasers, and Providers,* John Wiley & Sons (2002).

Centers for Medicare & Medicaid Services, Office of the Actuary, "National Health Expenditure Projections 2009-2019", September, 2010.

"Efficient Healthcare Consumer Response: Improving the Efficiency of the Healthcare Supply Chain," American Hospital Association/American Society for Healthcare Materials Management, (1996).

Nachtmann, Heather, and Edward A. Pohl, "The State of Healthcare Logistics: Cost and Quality Improvement Opportunities," Center for Innovation in Healthcare Logistics, University of Arkansas, July 2009.

Smith, Brian K., Heather Nachtmann, and Edward A. Pohl, "Quality Measures in the Healthcare Supply Chain," *Proceedings of the 2008 American Society for Engineering Management* (November, 2008).

Smith, Brian K., Heather Nachtmann, and Edward A. Pohl, "An Investigation of the Healthcare Supply Chain: Literature Review", *Proceedings of the 2011 Industrial Engineering Research Conference* (May, 2011).

2. AN INVESTIGATION OF THE HEALTHCARE SUPPLY CHAIN: LITERATURE REVIEW[1]

Brian K. Smith, M.S.

Heather Nachtmann, Ph.D.

Edward A. Pohl, Ph.D.

4207 Bell Engineering Center

University of Arkansas

Fayetteville, AR 72701

Abstract

A research effort is underway to improve the performance of the healthcare supply chain by identifying opportunities for cost reduction and quality improvement. This paper presents a review of the related literature focusing on management strategies, cost containment, information technology, and collaboration in the healthcare supply chain.

Introduction and Motivation

Companies in the manufacturing and retail industries continuously strive to increase revenue and reduce costs. These industries have made great improvements in product quality and process efficiency through the adoption of new technologies and automation. With the widespread adoption of automation and technology, increasing parity in terms of operational efficiency and product/service quality combined with

[1] Published in *Proceedings of the 2011 Industrial Engineering Research Conference*

economic globalization has led the manufacturing and retail industries to look to their supply chains for a competitive advantage. Efforts towards improved supply chain performance have led to increased profits and competitive advantage in the global marketplace. A focus on supply chain management is common at a strategic level in these industries.

The healthcare industry has not emphasized supply chain management to the extent that manufacturing and retail industries have. New technologies are continually developed that improve the delivery of healthcare services. These new technologies allow physicians to treat injuries and illnesses in more effective or less intrusive ways. Since the primary focus of healthcare providers is to provide the highest level of care possible, funds are typically invested towards adopting new technologies and techniques directly associated with providing care to patients. Dedicating resources towards improving healthcare supply chain processes has not been a major priority for the healthcare industry. However, as the pressure to reduce healthcare costs increases, healthcare providers are seeking ways to reduce their costs without negatively impacting the quality of their healthcare services. The healthcare supply chain provides a great opportunity towards this initiative.

The cost and quality of healthcare are two of the most discussed and debated issues of our time. There is definitely reason for concern as healthcare costs account for more than 17% of the gross domestic product (GDP) of the United States. Healthcare costs are expected to grow at a rate greater than that of the GDP, reaching almost $4.6 trillion and accounting for 19.6% of the GDP by 2019 [1]. A 1996 healthcare industry study titled *Efficient Healthcare Consumer Response* (EHCR) concluded that 38% of the cost of goods sold in the healthcare industry can be attributed to supply chain related activities. The study noted that this percentage is much higher than the retail (6% to 8%) and grocery (3 to 6%) sector supply chains [2,3].

The healthcare supply chain generally consists of four main components: producers, purchasers, providers, and patients [3]. Producers produce products such as pharmaceuticals, medical devices and implants, and medical/surgical supplies that are necessary in the delivery of healthcare. Purchasers consist of group purchasing organizations (GPOs) and distributors who facilitate the payment for and shipment of goods from the producers to the providers. Providers may also purchase goods directly from the producers. Providers use the goods produced by producers to administer healthcare services to patients. An illustration of the healthcare supply chain is shown in Figure 1.

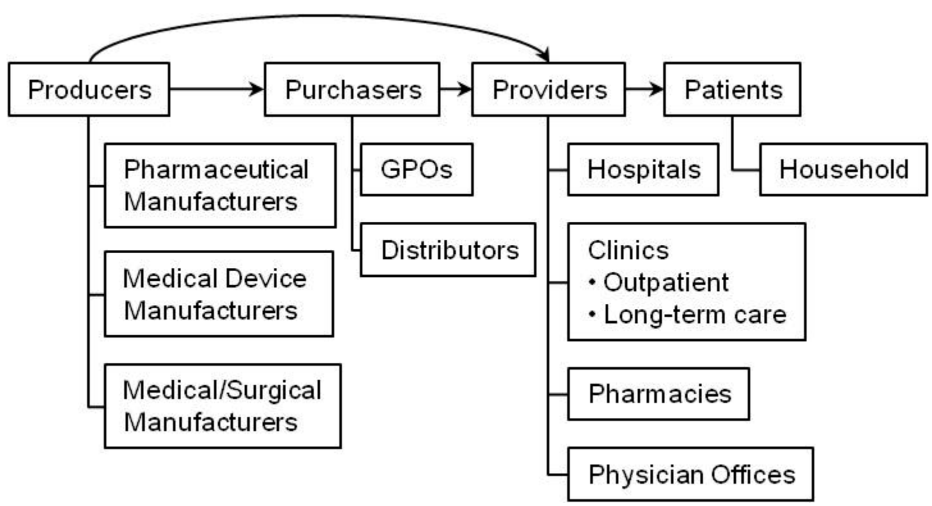


Figure 1: The healthcare supply chain [3,4]

The products flowing through the healthcare supply chain range from disposable gauze pads and bandages to state-of-the-art medical devices and implants. The frequency of utilization and cost of an item often determine how a product flows through the healthcare supply chain. Burns (2002) describes the typical distribution means and purchasing contract type of healthcare products as shown in Table 1.

	Purchasing Contract Type	
Distribution Means	**GPO Contract**	**No GPO Contract**
Distributor	Low cost/high volume products Medical-surgical products Generic drugs	Some name-brand specialty drugs Small volume items Generic drugs
Direct delivery	Less expensive medical devices and implants Name brand drugs	High-end medical devices and implants High cost/low volume specialty items

Table 1: Product paths through the healthcare supply chain [3]

The healthcare supply chain is vast, diverse, and complex which presents many challenges to effective management. It is believed that opportunities exist to reduce costs and improve delivery of healthcare by improving the efficiency and quality of healthcare supply chain operations. In 1996, the EHCR identified $11 billion of potential savings through improved healthcare supply chain performance. According to the EHCR, these savings can be realized by improvements in physical distribution, transportation, order management, and inventory management. The estimated cost savings in these four areas are shown in Exhibit 3. The EHCR team determined that these savings could be realized through reducing material handling staff throughout the supply chain, improving invoice accuracy, increasing electronic transactions, and inventory reduction [2].

Supply Chain Area	Cost	Estimated Savings	Cost After Savings
Physical Distribution	$3.2	$1.1	$2.1
Transportation	$5.5	$1.8	$3.7
Order Management	$8.5	$5.8	$2.7
Inventory Management	$5.8	$2.3	$3.5
Total	$23	$11	$12

Table 2: EHCR supply chain costs and potential savings (billions)

In November 2008, researchers from the Center for Innovation in Healthcare Logistics (CIHL) at the University of Arkansas conducted an industry-wide survey of healthcare supply chain practitioners to assess the state of the healthcare supply chain. The web-based CIHL survey was completed by 1,381 healthcare supply chain professionals for a response rate of approximately 12% [5]. The CIHL survey identifies several important characteristics of the healthcare supply chain and reveals that the healthcare supply chain has the following characteristics [5]:

- Talent rich: The healthcare supply chain is rich in talent in terms of experience as 45% of the survey respondents have more than twenty years of experience in the healthcare industry.
- Information poor: Survey respondents often cite a lack of data and/or data of insufficient quality as a barrier to collaboration with supply chain partners and supply chain improvement.
- Strategic: The survey reveals that companies in the healthcare supply chain are actively implementing strategic initiatives aimed at improving supply chain operations.
- Collaborative: The survey respondents indicate that there is a high level of collaboration among partners in the healthcare supply chain. However, many barriers exist to improving the level of collaboration and realizing greater improvements in performance.
- Expensive: Supply chain costs account for more than one-third of the annual operating expense of the average organization in the healthcare supply chain according to the survey respondents.
- Immature: The CIHL survey reveals that the healthcare supply chain is immature. The healthcare supply chain lacks fundamental processes and controls necessary

to reduce variability. The healthcare supply chain relies heavily on the daily manual actions of individuals to function.

Managing the Healthcare Supply Chain

A survey of the relevant literature reveals an abundance of supply chain management tools and techniques applicable to healthcare. However, without the use of performance measures, redesigning the healthcare supply chain may be ineffective [6]. Benchmarks are essential to establishing goals and measuring improvements [7]. Malin (2006) discusses the extensive use of internal and external performance measures, enabling the effective implementation of process improvement initiatives (another popular tool) [8]. After careful analysis of existing processes and appropriate redesign [9], the development of best practices for the various supply chain related functions within the organization can be achieved, driving down variation and increasing efficiency [10].

The establishment of accountability is an essential component of cost reduction initiatives; if there is no assignment of responsibility, unnecessary or ill-advised purchases will continue [11]. Combined with value analysis of the medical products being considered for procurement, accountability can provide the means of controlling the item file and prevent inattentive purchases [12]. Effective value analysis should be applied to physician's preference items [13] as well as items on a consignment policy [14].

The resistance of physicians to changes in the supply chain is a potential barrier commonly discussed in the literature [11, 15]; however, the obstacle may not be insurmountable. Physician buy-in is crucial to the success of supply chain improvement initiatives, as is executive support. A study conducted by McKone-Sweet et al. (2005) interviewed healthcare professionals from a variety of backgrounds; the lack of support at the executive level was labeled as a significant barrier to supply chain management initiatives. Successfully implementing changes in the healthcare supply chain requires cooperation across the organization [16].

Inventory Management in the Healthcare Supply Chain

Some of the most prevalent and significant problems facing the healthcare supply chain involve the area of inventory management. Despite this, it appears that few healthcare organizations allocate significant resources to improving inventory efficiency. Langabeer (2005) mentions a survey that found fewer than 10% of hospitals utilizing inventory optimization techniques to improve inventory practices; practices such as demand forecasting and replenishment planning generally remain rudimentary or non-existent [17]. As far back as the 1990s, observers of the healthcare sector have often suggested that supply chain practices such as just-in-time (JIT) or continuous replenishment be adopted from other industries in order to facilitate significant cost savings [18]. Practicing an adjusted version of JIT could aid in reducing chronically inflated inventory levels, alleviating problems such as product expiration or obsolescence, excessive capital tied up in inventory, high restocking costs, and distribution problems while maintaining practical levels of safety stock for emergencies [19]. Despite the fact that JIT has been prevalent in the literature for a considerable number of years, the process of adopting this supply chain practice continues. Purchasing items on consignment has become a more popular practice as it provides a method of reducing inventory cost [20].

A key aspect of a healthcare organization's supply chain complexity is the number of suppliers who are involved as well as the variety of products being sourced. Reducing the number of suppliers can lead to significant benefits, since prices tend to drop as volume is consolidated to a few main vendors [11]. Standardizing the medical products that are utilized by a provider further decreases the number of suppliers needed and contributes to the likelihood of volume discounts. One of the main contributors to supply costs is the number of physician preference items [15] in a provider's catalogue; standardization can relegate the cost associated with these traditionally high price items, particularly if accountability is enforced among purchasers within the organization. Careful evaluation of products on the basis of effectiveness and cost can lead to further savings.

Cost Containment in the Healthcare Supply Chain

Due to increasing focus on healthcare costs in recent years, a large section of the research literature is devoted to cost-reducing initiatives and practices. According to the Efficient Consumer Healthcare Consumer Response report, potential savings of over $11 billion dollars could be achieved within the healthcare supply chain [2]. Despite the fact that supply chain expenses are often a healthcare organization's second biggest expense, cost reduction efforts are often relegated to the price of materials alone [15]. In actuality, supply chain practices and initiatives can provide significant cost savings [11] throughout the organization.

One of the more widely applicable practices for streamlining the supply chain is process analysis. Efficient operation of a supply chain is directly dependent on the processes that drive product selection, sourcing, inventory management, transportation logistics, and transaction procedures [10]. Supply chain processes must be assessed periodically and compared to benchmarks in order to identify areas of opportunity; some processes may be integrated or automated [17]. Process evaluation can also reveal opportunities for collaboration with supply chain partners, further reducing costs and increasing efficiency.

Product selection can play a significant role in supply chain costs. Careful evaluation of products purchased by materials management can reduce costs through consolidating of functionally equivalent product types and decreasing the number of high-priced physician preference items [21]. Beyond simple pricing comparisons, it may be beneficial to evaluate suppliers to ensure quality and reliability, two vendor characteristics that may reverberate throughout a provider's operations [22].

Purchasing from fewer vendors can lead to volume discounts, and one of the common methods utilized by providers to decrease material costs is procuring products through a group purchasing organization (GPO). Maintaining a strong relationship with a single GPO can provide consistent price breaks [13], but the benefits derived from these memberships are still in question [16].

Quality Management in the Healthcare Supply Chain

The study of supply chain quality (not specific to healthcare) is relatively young as pointed out by [23]. However, the research that has been conducted in the area of supply chain quality often identifies the relationships between improved supply chain quality and lowered costs. Several examples of research focused on supply chain improvement view both cost and quality as key metrics. Sanchez-Rodriguez and Hemsworth (2005) found that applying Total Quality Management principles to supply chain purchasing operations had a significant impact on lowering purchasing costs and improving overall business performance [3]. One particular case of a large-scale supply chain reconfiguration occurred at IBM. IBM partnered with researchers from Arizona State University to overhaul their $39 billon supply chain operation with the aid of a decision support system considering cost, quality, and customer responsiveness as key metrics [25].

Other research has shown the importance of preventing quality problems in the supply chain and detecting problems as soon as possible in order to minimize the impact on cost. Value and cost is added to products as they move through the supply chain from the supplier to the end user much like value and cost is added to manufactured goods as they progress through successive steps of processing. Therefore, errors occurring or errors detected later in the supply chain are more costly than errors occurring or detected earlier [26]. Complimentary studies have also been recently published seeking to define and quantify the cost of quality in supply chains [27, 28].

Current research in the healthcare supply chain also takes into consideration the relationship between cost and quality. Schneller and Smeltzer (2006) identify the importance of cost and quality when they define the healthcare supply chain as “the information, supplies, and finances involved with the acquisition and movement of goods and services from the supplier to the end user in order to enhance clinical outcomes while controlling costs” [29]. This definition is supported by healthcare futurist Joe Flower who concludes that improving clinical outcomes while lowering costs should be the main goal of the healthcare supply chain [30].

Specific research applications related to improving the healthcare supply chain are beginning to appear in the literature. One study recognized that healthcare cost containment in Singapore focused primarily on reducing the purchase price of supplies, which often led to sacrifices in the quality of the supplies purchased. The researchers concluded that more effective cost reductions could occur without sacrificing quality by adopting a total delivered cost mentality and redesigning the supply chain to eliminate waste and improve efficiency [31]. Other research has focused on the roles of cost and quality in improving the internal supply chain of hospitals. Swinehart and Smith (2005) concluded that better satisfying the needs of internal customers (the actual recipients and users of products and data delivered by the healthcare supply chain) within a hospital could lead to better patient outcomes at a lower cost [6]. These internal customers of the supply chain within a hospital were categorized by cost center, and it was found that each had unique expectations from the supply chain. Although sometimes conflicting, thoroughly understanding the wants and needs of the internal customers in a hospital supply chain aids in identifying opportunities for cost and quality improvement. Smith et al identify existing metrics for healthcare supply chain quality and reveal that opportunities exist to develop quality metrics and management techniques that more broadly assess the performance of the healthcare supply chain [32].

Information Technology in the Healthcare Supply Chain

The effective utilization of IT plays a critical role in reducing costs within the healthcare supply chain. Resource planning, integrated purchasing catalogs, e-procurement transactions, and data collection are just a few of the information technology tools that enable increased supply chain performance [11]. Increased participation in e-commerce alone can have widespread effects on supply costs [33], reducing the number of labor hours required and decreasing rework, a problem rampant in manual purchasing processes. Information sharing between partners in the healthcare supply chain could provide the synchronization necessary for moving supplies efficiently and decreasing inventory costs [34], while the collection of supply utilization data enables organizations to more accurately forecast demand. Healthcare providers frequently struggle to maintain correct pricing for the thousands of items on their item files. IT resources could centralize purchasing information regarding contracts and prices, eliminating redundant or conflicting data. Coupled with the establishment and implementation of data standards, successful utilization of IT is a promising improvement to the healthcare supply chain [35]. Other potential benefits include standardized ordering processes, reduction in paperwork, order tracking, payment scheduling, and many others [36].

Although the necessary technological resources are available, effective implementation in a healthcare context is difficult. A study by McKone-Sweet et al. (2005) consisting of interviews conducted with healthcare supply chain experts indicated that even though the lack of information systems was often identified as a barrier against effective supply chain management, "most participants were more concerned with the effective use of the data that was available" [16]; this lack of IT systems maturity is prevalent among the majority of hospitals in the United States [17]. One of the essential requirements of information technology in healthcare is not only the ability to collect data, but the level of integration needed to create information flow within and across organizations [15]. Challenges to effective IT implementation continue to exist, but studies such as the Most Wired Survey [37] are supporting the continued struggle for information technology systems maturity.

Collaboration in the Healthcare Supply Chain

Operating a cost-efficient healthcare supply chain is dependent upon a number of factors; establishing cooperative relationships with other stakeholders and driving integration within the supply chain can contribute significantly to cost savings [36]. Opportunities for effective collaboration often exist within the organization itself. Ballard (2005) conveyed the importance of physician involvement in the effort to reduce the number of high cost physician preference items (PPI) [15]. Without physician buy-in, few cost reduction programs produce significant value to the organization. Additionally, integrating supply chain functions such as receiving, inventory, and distribution can lead to greater efficiencies [20]. Clear communication is essential to building trust between supply chain management personnel and healthcare professionals [12], as well as avoiding redundancies and other consequences of miscommunication.

In addition to building cooperation and integrating activities within an organization, collaboration with external partners in the healthcare supply chain can lead to significant cost savings. The ability to efficiently manage business processes with vendors or key suppliers is a characteristic of more mature supply chains [17]; e-procurement, collaborative planning, replenishment, and forecasting all become feasible. Brewer (2008) mentions a study in which organizations exhibiting best practices in supply chain management focused on vendor service rather than price alone [9]. Good vendor service can only be accomplished through maintaining healthy supplier relationships and clear communication. Likewise, a well maintained relationship with a single GPO rather than multiple memberships can lead to more consistent pricing and potentially longer term discounts [13].

Conclusion and Future Work

The motivation for this research is driven by the need to lower the cost of healthcare in the United States by identifying opportunities for organizations within the healthcare supply chain to improve their supply chain processes. The high cost and immaturity associated with the healthcare supply chain provides opportunities to make great strides towards supply chain excellence. The experience level of healthcare supply chain professionals and the collaborative nature of the industry are strong catalysts for improvement once the improvement opportunities and their associated barriers are revealed. Data from an industry-wide survey will support a rigorous regression analysis investigating what factors are driving supply chain excellence among healthcare organizations.

Acknowledgements

This research was supported by the Center for Innovation in Healthcare Logistics at the University of Arkansas and the Association for Healthcare Resource and Materials Management of the *American Hospital Association*. Any opinions, findings, conclusions, or recommendations in this document are those of the authors and do not necessarily reflect views of the sponsors.

References

1. Centers for Medicare & Medicaid Services, Office of the Actuary, September, 2010, "National Health Expenditure Projections 2009-2019".

2. "Efficient Healthcare Consumer Response: Improving the Efficiency of the Healthcare Supply Chain," 1996, American Hospital Association/American Society for Healthcare Materials Management.

3. Burns, L.R., 2002, The Health Care Value Chain: Producers, Purchasers, and Providers, 1st Edition, John Wiley & Sons, New York.

4. Smith, B. K., Nachtmann, H., Pohl, E.A., and Townsley, J.R., 2009, "Management Initiatives in Healthcare Logistics," Proceedings of the 2009 Industrial Engineering Research Conference.

5. Nachtmann, H., and Pohl, E.A., 2009, "The State of Healthcare Logistics: Cost and Quality Improvement Opportunities," Center for Innovation in Healthcare Logistics, University of Arkansas, July 2009.

6. Swinehart, K. D. & Smith, A. E., 2005, "Internal supply Chain Performance Measurement: A Health Care Continuous Improvement Implementation," International Journal of Health Care Quality Assurance, 18(7), 533-542.

7. Lauer, C., 2004, "Excellence in Supply Chain Management," Modern Healthcare, 34(50), 29-32.

8. Malin, J. H., 2006, "Knowing the SCOR: Using Business Metrics to Gain Measurable Improvements," Healthcare Financial Management, 60(7), 54-59.

9. Brewer, W., 2008, "How 'living lean' helped Denver health capture $11 million in cost savings," Healthcare Cost Containment. Web exclusive. Retrieved from http://www.hfma.org/publications/healthcarecost/exclusives/denver.htm

10. Davis, R. N., 2004, "No more chances for supply-chain savings? look again!," Healthcare Financial Management, 58(1), 68-75.

11. Neumann, L., 2003, "Streamlining the supply chain," Healthcare Financial Management, 57(7), 56-62.

12. McGinnis, M., Stark, E., & O'Leesky, K., 2005, "Supply and Conquer," Healthcare Financial Management, 59(3), 82-86.

13. Long, G., 2005, "Pursuing supply chain gains," Healthcare Financial Management, 59(9), 118-122.

14. Ricupito, G., 2006, “Consignment trays and the hidden costs of sterilization,” Materials Management in Health Care, 15(12), 32-36.

15. Ballard, R., 2005, “Strategic supply cost management: physician preference without deference,” Healthcare Financial Management, 59(4), 78-84.

16. McKone-Sweet, K. E., Hamilton, P., Willis, S. B., 2005, “The ailing healthcare supply chain: A prescription for change,” The Journal of Supply Chain Management, 41(1), 4-17.

17. Langabeer, J., 2005, “The evolving role of supply chain management technology in healthcare,” Journal of Healthcare Information Management, 19(2), 27-33.

18. Scanlin, T., 1997, “A case for “just in time”: could it be right,” Journal of Healthcare Resource Management, 15(8), 10-14.

19. Colletti, J. J., 1994, “Health care reform and the hospital supply chain,” Hospital Materiel Management Quarterly, 15(3), 28-35.

20. Compas, B. J., 2005, “Strengthening the links in the supply chain – some preventive medicine,” Journal of Healthcare Information, 19(2), 10-12.

21. Roark, D. C., 2005, “Managing the healthcare supply chain,” Nursing Management, 36(2), 36-40.

22. Neil, R., 2004, “The Ol’ Switcheroo,” Materials Management in Healthcare, 13(5), 14-18.

23. Batson, R. G., & McGough, K. D., 2006, “Quality planning for the manufacturing supply chain,” The Quality Management Journal, 13(1), 33.

24. Sanchez-Rodriguez, C., & Hemsworth, D., 2005, “A structural analysis of the impact of quality management practices in purchasing on purchasing and business performance,” Total Quality Management & Business Excellence, 16(2), 215.

25. Kirkwood, C. W., Slaven, M. P., & Maltz, A., 2005, “Improving supply-chain-reconfiguration decisions at IBM,” Interfaces, 35(6), 460.

26. Stokes, R., 2008, “Understanding supply chain risk,” Risk Management, 55(8), 54.

27. Srivastava, S., 2008, “Towards estimating cost of quality in supply chains,” Total Quality Management & Business Excellence, 19(3), 193.

28. Ramudhin, A., Alzaman, C., & Bulgak, A. A., 2008, "Incorporating the cost of quality in supply chain design," Journal of Quality in Maintenance Engineering, 14(1), 71.

29. Schneller, E. S., & Smeltzer, L. R., 2006, "Strategic management of the health care supply chain," San Francisco, CA: Jossey-Bass, p. 30.

30. Flower, J., 2005, "Mapping the future of health care," Physician Executive, 31(1), 60.

31. Kumar, A., Ozdamar, L., & Zhang, C. N., 2008, "Supply chain redesign in the healthcare industry of Singapore," Supply Chain Management, 13(2), 95.

32. Smith, B. K., Nachtmann, H., Pohl, E.A., to appear, "Quality management in the healthcare supply chain," *The Quality Management Journal*.

33. Holmes, S. C., & Miller, R. H., 2003, "The strategic role of e-commerce in the supply chain of the healthcare industry," International Journal of Services Technology and Management, 4, 507-517(11).

34. Kim, D., 2005, "An Integrated Supply Chain Management System: A Case Study in Healthcare Sector," Lecture Notes in Computer Science, 218-227.

35. Smith, A. D., & Flanegin, F. R., 2004, "E-procurement and automatic identification: Enhancing supply chain management in the healthcare industry," International Journal of Electronic Healthcare, 1, 176-198(23).

36. Brennan, C. D., 1998, "Integrating the healthcare supply chain," Healthcare Financial Management, 52(1), 31.

37. Solovy, A., 2004, A wired exchange. Materials Management in Health Care, 13(8), 27-31.

3. QUALITY MEASUREMENT IN THE HEALTHCARE SUPPLY CHAIN*

Brian K. Smith, M.S.

Heather Nachtmann, Ph.D.

Edward A. Pohl, Ph.D.

4207 Bell Engineering Center

University of Arkansas

Fayetteville, AR 72701

Abstract

The United States is actively attempting to reduce their national healthcare expenditures which account for more than sixteen percent of the Gross Domestic Product. A significant cost and quality driver of the healthcare industry is the universal complexity of its supply chain. It has been suggested that even small gains in supply chain quality can produce major, long-term cost savings. We are currently engaged in a research effort to identify opportunities for quality improvement in the healthcare supply chain. Expert testimony reveals that the concept of healthcare supply chain quality measurement can be difficult to grasp. However, almost ninety percent of the respondents to our recent survey of more than one thousand healthcare supply chain professionals indicate that their organizations are measuring the quality of their supply chains in some manner. Utilizing an adapted framework based on Garvin's eight dimensions of quality, we find that the quality metrics identified from the healthcare supply chain literature and our practitioner

* accepted for publication in *The Quality Management Journal*

survey are focused on measuring the performance, conformance, and features of healthcare supply chain performance.

Keywords

Quality measurement, Healthcare, Supply chain

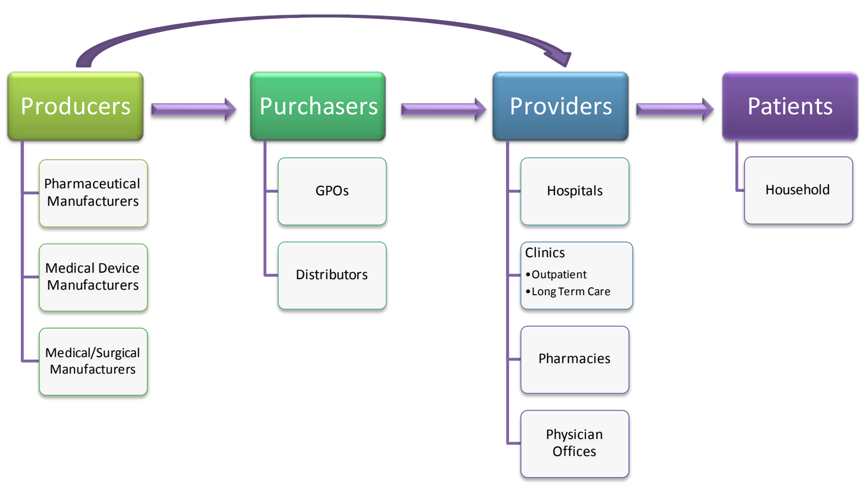
Introduction

In 2007, the United States' health expenditures exceeded two trillion dollars, accounting for more than sixteen percent of the nation's Gross Domestic Product (U.S. Department of Health & Human Services 2009). The nation's healthcare spending growth increased 6.1 percent at a slower rate than the previous year's increase of 6.7 percent. While this deceleration in healthcare spending may indicate a positive trend in controlling national healthcare costs, healthcare spending is still increasing at a rate higher than the nation's inflation rate. The increasing cost of providing healthcare services in the United States has created pressure to identify the root causes of increasing costs and to find ways to optimize the nation's healthcare resources. Today's hospital environments are characterized by higher overhead costs, increased complexity in product and service distribution, increased competition, and access to advanced information technologies.

In a recent industry-wide survey, the nation's healthcare supply chain is found to be immature, expensive, and information poor (Nachtmann and Pohl 2009). It has been recognized for more than a decade that the healthcare supply chain is inefficient and expensive when compared to supply chains from other sectors (Efficient Healthcare Consumer Response (EHCR) 1996). For example, the ratio of supply chain costs to cost of goods sold for the healthcare industry is estimated to be thirty-eight percent, while the retail sector has a ratio of six to eight percent and the grocery sector a ratio of three to six percent (EHCR 1996, Burns 2002). The nation's healthcare system is actually a complex system-of-systems that requires a supply chain very different from those of other industries.

The participants in the healthcare supply chain fall into four main categories; producers, purchasers, providers, and patients (Burns 2002) as depicted in Figure 1. Our research focuses on the producers, purchasers, and providers within the healthcare supply chain. Producers manufacture healthcare-related goods such as pharmaceuticals, medical devices, and medical-surgical supplies. Providers deliver healthcare services to patients. These providers (hospitals, clinics, pharmacies, and physician offices) acquire goods directly from the producer or through a purchaser such as a distributor or group purchasing organization (GPO).

Figure 1. The Healthcare Supply Chain.



While their overall goal of getting the right item in the right place at the right time is the same, how healthcare supply chain participants reach that goal and the environments in which they operate are significantly different. The issues unique to the healthcare supply chain include a lack of provider consolidation, regulatory issues, a lack of upstream or downstream planning in the supply chain, reactive rather than pro-active, tens of thousands of items in their item file with less than half ordered with regularity, the end customer is not the decision maker, a lack of visibility across the supply chain, and quality of care is the primary driver (not simply profit) (Nachtmann and Pohl 2009). While there are lessons to be learned, known supply chain practices and processes cannot simply be transferred from other industries into immediate practice in the healthcare industry due to these unique characteristics.

The National Coalition for Quality Assessment concluded that healthcare quality is always not equal, huge leaps in quality are possible, and even small gains in quality can produce major, long-term cost savings (Halverson 2005). The adoption of techniques such as process standardization, corrective/preventive action programs, and the establishment of performance metrics provide opportunities for adding value to the healthcare supply chain (Hutchins 2002). In a recent survey of healthcare supply chain professionals, we found that eleven percent of our more than one thousand respondents do not directly track supply chain quality within their organization (Nachtmann and Pohl 2009).

We are engaged in a research effort to identify the sources of inefficiency within the healthcare supply chain while simultaneously investigating opportunities for improving the quality of healthcare delivery. As part of this research, we are exploring quality measurement across the healthcare supply chain as well as opportunities for continuous process improvement in the design and operation of the healthcare supply chain. The focus of this paper is to report the state of healthcare supply chain quality measurement and provide insight into future improvements in this area which can support improved performance across the healthcare supply chain.

Background

Supply Chain Quality Measurement

A gap exists in the literature regarding supply chain quality metrics in general (Batson and McGough 2006). Wagner (2008) points out that there is no clear understanding of what supply chain quality means. This gap is even more prevalent when it pertains to the healthcare supply chain. Lessons learned from manufacturing and retail supply chains have been slow to find their way into healthcare. The literature pertaining to the healthcare supply chain primarily discusses supply chain management as it relates to reducing costs. Case studies have been conducted in specific hospitals attempting to address quality as it relates to customer satisfaction, but work addressing the need for quality management in the supply chain is lacking.

Healthcare Supply Chain Quality Measurement

The topics of quality measurement and management in the healthcare supply chain are receiving more attention in the recent literature. While many of the healthcare supply chain quality metrics that exist in the literature are only briefly mentioned in support of studies focused on other areas of healthcare performance improvement, the works of Blane (1990) and Kumar et al. (2005) offer two comprehensive lists of healthcare supply chain quality metrics. Nachtmann and Pohl (2009) provide a recent compilation of quality metrics that are currently employed in the healthcare supply chain.

Blane (1990) is one of the first to recognize the need for cost and quality performance measurement in the healthcare supply chain. He makes the case that cost and quality performance measurement is crucial to combating the rising cost of healthcare delivery in the United States and suggests several performance metrics. Poulin (2003) similarly recognizes the importance of supply chain performance measurement in healthcare and suggests performance metrics relating to ordering and inventory management, receiving, storage, and replenishment processes. Kumar et al. (2005) also offers several healthcare supply chain quality metrics in the context of a case study conducted at a hospital in Singapore.

Swinehart and Smith (2005) stress the importance of internal customer satisfaction within the healthcare supply chain. They note that tools such as internal customer satisfaction surveys can lead to healthcare delivery improvements that ultimately improve the quality of care that the end customer (the patient) receives. Compas (2005) shares this view and specifically points out that the time spent by physicians, nurses, and other clinicians searching for supplies rather than administering care should be measured and minimized.

The remainder of the healthcare supply chain quality metrics presented in the literature are related to very specific elements of healthcare delivery. Breen and Crawford (2005) suggest transcription errors as a quality metric for the pharmaceutical supply chain. Solovy et al. (2007) mention the hospital-internal metric “time to care” utilized by Denver Health to monitor the time between when an order is placed for an item and the time the item is actually used in the delivery of care. Operating room tray accuracy (having the correct items and instruments for a procedure) is noted by Carpenter

(2008) as another key hospital-internal supply chain metric. Fredendall et al. (2009) state that hospitals should track the availability and timeliness of vendor representatives for surgical procedures due to the fact that their presence is necessary before some medical devices and implants can be used.

The Leap from Healthcare Supply Chain Quality to Patient Safety

In our ongoing research, we conducted expert interviews with fourteen healthcare supply chain professionals that represent top producer, purchaser, and provider organizations in the healthcare industry. During these interviews, we searched for the most significant factor that influences the quality of the healthcare supply chain. It was during these expert interviews that we first learned about the leap from supply chain quality to patient safety. During our conversations, we asked the experts to tell us the most significant factor that they think influences quality of the healthcare supply chain. Unequivocally their responses were “patient safety.” In a manufacturing company, this would be analogous to saying “profit” in response to the same question. While it is clearly true that a perfectly executed supply chain contributes to patient safety, the healthcare industry’s overall goal, trying to manage and track the quality of day-to-day supply chain operations by simply tracking patient safety (or profit in a manufacturing setting) would be practically impossible. To better assess their supply chain quality measurement, we revised our question to ask them the most significant factor in addition to patient safety.

According to our experts, the most significant factors influencing the quality of the healthcare supply chain are:

- Availability of materials – "The provider's perspective is whether they have what they need to do their job at the time they need it."
- Data standards – "All the nomenclature is completely different, and it makes it virtually impossible to analyze across physicians and products."
- High volume of transactions - "In a typical healthcare inventory system, you would usually have 4000 or more transactions per month."
- Integrity of the supply chain - "Not knowing what happened to a product between the point of manufacture and the point of use leads to a decrease in quality."
- Poor product traceability – "Product recalls also present a problem because of poor product identification and tracking and finding a substitute."
- Process variation - "In the healthcare supply chain today, there are so many ways a product arrives at an organization that there is no consistent methodology of what gets it there."
- Quality of information and its exchange – "We have tremendous rework because we have data that is lacking integrity from manufacturer to bedside."

Their responses show that internal and external factors are influencing the quality of the healthcare supply chain and motivate the importance of tracking quality measures to improve healthcare supply chain performance.

Methodology

The goal of our research presented in this paper is to assess and report the state of healthcare supply chain quality measurement in support of increasing future quality performance across the healthcare supply chain. To accomplish this goal, we performed three primary research tasks: 1) Identify quality measures being utilized in the healthcare supply chain through reviewing the relevant literature and surveying healthcare supply chain practitioners, 2) Identify/develop a taxonomy to classify and report the coverage of healthcare supply chain quality measurement, and 3) Assess and report the coverage of current quality measurement practices within the healthcare supply chain through the application of the taxonomy resulting from Task 2 to the measures identified in Task 1.

Task 1: Quality Measure Identification

The first task we undertook to identify quality measures being utilized to assess healthcare supply chain performance was a thorough literature search and review in this area. We identified ten key papers that provided more than twenty-five distinct healthcare supply chain quality measures, as reported in Table 2 of the Results Section.

Table 2 also contains additional quality measures that were collected from healthcare supply chain practitioners through an industry-wide survey conducted in November 2008 (Nachtmann and Pohl 2009). As part of this survey, we investigated the quality improvement initiatives that the respondents engaged in and asked them to identify performance measures used within their organization to monitor quality of their supply chain performance. In response to our survey, more than one thousand healthcare supply professionals provided performance measures that their organization is currently using to monitor quality of their supply chain performance.

The survey instrument was developed with the assistance of the Survey Research Center (SRC) at the University of Arkansas. The survey was conducted online and was distributed to the membership of several healthcare supply chain related professional societies and member organizations of the Center for Innovation in Healthcare Logistics (Nachtmann and Pohl 2009). The SRC contacted each potential respondent via email and regular mail. Each potential respondent was given a unique identification code with which to access the survey. The survey instrument was designed to ensure the anonymity of any respondent.

We received 1,381 survey responses for a conservative response rate of approximately twelve percent. Seventy-seven percent of the respondents work for healthcare providers, six percent for manufacturers, five percent for GPOs, four percent for distributers and the remaining eight percent for other healthcare supply chain organizations. The majority of respondents (sixty-eight percent) have more than ten years of healthcare supply chain experience, with forty-five percent having more than twenty years of experience. Given the experience levels of the respondents, it is not surprising to find that forty-two percent of them hold director level positions, and thirty-one percent are classified as managers. Senior level participation includes approximately eight percent from the C-suite and eleven percent at the vice president level.

Task 2: Quality Measure Taxonomy Development

In order to assess and report the coverage of current healthcare supply chain quality measurement practices, we identified a taxonomy that could be used to classify the quality measures resulting from Task 1. Garvin (1984) defined quality by classifying the basic elements of product quality into eight dimensions. Garvin's eight dimensions are well known and continually used in guiding research in quality strategy (Sebastianelli and Tamimi 2002). A company may choose not to pursue all eight dimensions when defining their quality strategy (Garvin 1984). Studies have been conducted utilizing different subsets of the eight dimensions to evaluate the quality management strategy of companies, and surveys of quality managers reveal that each of the dimensions can have varying degrees of importance (Sebastianelli and Tamimi 2002).

Sousa and Voss (2002) note that most research focuses on one dimension of quality at a time. However, an organization competing in a diverse marketplace should have a multidimensional view of quality in order to achieve competitive advantage. Garvin's eight dimensions were initially developed to define "product quality" in a manufacturing setting. Applying the dimensions to a service or system may seem difficult to practitioners. However, the broad scope of the healthcare supply chain necessitates a multi-dimensional approach to quality management. Garvin's eight dimensions provide a good basis for this multidimensional approach. We adapted Garvin's original definitions (1984) to better describe quality dimensions of the healthcare supply chain as shown in Table 1. The resulting taxonomy provides a framework to assess the current coverage of healthcare supply chain quality measurement.

Table 1. Eight dimensions of healthcare supply chain quality (adapted from Garvin 1984)

Dimension	Definition
Performance	Primary operating characteristic of a healthcare supply chain
Features	Secondary characteristics that supplement the basic functioning of the healthcare supply chain
Reliability	Probability that a healthcare supply chain will function properly during a specified period of time
Conformance	Degree to which a healthcare supply chain's design and operating characteristics match established standards
Durability	Amount of service one gets from a healthcare supply chain before it breaks down to the point that alternative service is preferred over correction
Serviceability	Ease, courtesy, and competence of corrective action
Aesthetics	How the healthcare supply chain appears to a particular individual
Perceived Quality	Personal evaluation of quality based on secondary experiences

Task 3: Quality Measure Assessment

The adapted taxonomy presented in Table 1 was used as a framework to assess the coverage and applicability of the quality metrics identified in Task 1 according to an adaptation of Garvin's eight dimensions of quality (Garvin 1984). The results of this classification can guide future efforts in quality metric development for assessing healthcare supply chain performance. We believe one key to successful management of the healthcare supply chain is the development of quality metrics that can be used universally across the healthcare supply chain. Our long-term goal is to support the producers, purchasers, and providers of the healthcare industry as they work to improve the quality of their supply chain operations. Providing knowledge about current healthcare supply chain quality measurement practices can enable successful development and implementation of new quality measurement programs across the healthcare supply chain.

Results and Findings

The healthcare supply chain quality metrics collected from our literature review and practitioner survey conducted in Task 1 and their descriptions are provided in Table 2.

Table 2. Healthcare supply chain quality metrics

Metric	Description
Cost per order [K, B]	Total cost / Total number of receipts or purchase orders
Data integrity errors [N]	Number of errors in item file
Expenses per total purchases [B]	Total expenses / Total purchase amount
External customer satisfaction [N]	Satisfaction level of external customers
GPO participation rate [K, N]	Number of items under GPO / Total number of items
Instruments, equipment or supplies are not available [F]	Number of occurrences when all necessary material is not available for a procedure
Internal customer satisfaction [SS, N]	Satisfaction level of internal customers
Inventory days-supply [Ca, B]	Amount of inventory on hand / Amount used in one day
Inventory cost [B]	Total inventory dollars or holding cost
Inventory discrepancies [B, K, N, P]	Number of differences between the balance sheet and the physical count
Inventory dollars per adjusted daily census [B]	Total inventory dollars / Adjusted daily census
Inventory dollars per occupied bed [B]	Total inventory dollars / Number of inpatients
Inventory turnover [K8, P, B, N]	Rate at which inventory is sold and replenished
Invoice accuracy [N]	Percent of error-free invoice line items
Items and dollars excess [B]	Item and dollar amounts over the equivalent of a 12 month supply
Number of deliveries from receiving to storerooms [C]	Count of deliveries from receiving to storerooms
Number of emergency supply requests [C, P, N]	Count of emergency requests submitted when an item is out of stock at the point of use
Number of orders returned unused [N]	Count of items correctly ordered, received, and returned without being used
Number of POs issued after goods have arrived [N]	Number of times purchase orders (POs) are issued after receiving the goods
Obsolete inventory [N]	Amount of inventory that is obsolete or out of date
Operating room tray accuracy [Ca]	Percent of occurrences where the items on OR trays are incorrect
Overnight shipments [N]	Number of supply shipments requiring overnight delivery
Percentage of items on backorder [K, N]	Average number of items on backorder per month / Total number of items
Percentage of items purchased via EDI [N]	Percentage of items purchased via electronic data interchange (EDI)
Picking accuracy [N]	Rate at which internal supply requests are completed correctly
Purchase order accuracy [N]	Percent of error-free purchase order line items
Purchases per adjusted daily census [B]	Total purchase amount / Adjusted daily census
Purchases per occupied bed [B]	Total purchase amount / Number of inpatients
Quality of delivery [K, N]	Number of rejects, early or late shipments / Total number of items shipped or received
Requisition completion rate [K, K8, N]	Number of requests completed / Number of requests received
Requisitions processed [B]	Number of supply requisitions processed

Metric	Description
Rework rate [N]	Percent of transactions requiring rework
Slow moving inventory [B, N]	Inventory items that have been inactive for three months
Stock to non-stock percentage [B, N]	Percent of purchases on item file / Purchases for items not on item file
Stockout rate [P, B, N]	Number of requisition items for out-of-stock items / Number of requisitions
Storage area compactness [P]	Inventory value / Area of space occupied
Time spent by clinicians searching for supplies [C, N]	Time spent by physicians and nurses searching for supplies.
Time to care (order fulfillment cycle time)[S, N]	Time between when an item is ordered to when it is used in providing care
Utilization rate of primary vendor [N]	Number of primary vendor orders / Total number of orders
Vendor failed to arrive [F]	Occurrences where a vendor representative is needed for an item to be used but representative is not available

[B] (Blane 1990), [BC] (Breen and Crawford 2005), [Ca] (Carpenter 2008), [C] (Compas 2005), [F] (Fredendall et al 2009), [K] (Kumar 2005), [K8] (Kumar 2008), [N] (Nachtmann and Pohl 2009), [P] (Poulin 2003), [S] (Solovy et al 2007), [SS] (Swinehart and Smith 2005)

We utilized the adapted taxonomy presented in Table 1 as a framework for assessing the multidimensional view of quality metrics used in the healthcare supply chain. We examined the description of each healthcare supply chain quality metric presented in Table 2 and determined which quality dimension best fits each metric. The basis of these classifications was interpretation of the metric and dimension descriptions by the research team who has extensive experience in quality measurement. The resulting classifications are presented in Table 3.

Table 3. Healthcare supply chain quality metrics categorized by dimension

Metrics	Quality Dimensions							
	Performance	Features	Reliability	Conformance	Durability	Serviceability	Aesthetics	Perceived Quality
Cost per order [K, B]	X							
Data integrity errors [N]				X				
Expenses per total purchases [B]	X							
External customer satisfaction [N]							X	

Metrics	Quality Dimensions							
	Performance	Features	Reliability	Conformance	Durability	Serviceability	Aesthetics	Perceived Quality
GPO participation rate [K, N]				X				
Instruments, equipment or supplies are not available [F]	X							
Internal customer satisfaction [SS, N]							X	
Inventory days-supply [Ca, B]		X						
Inventory cost [B]	X							
Inventory discrepancies [B, K, N, P]				X				
Inventory dollars per adjusted daily census [B]	X							
Inventory dollars per occupied bed [B]	X							
Inventory turnover [K8, P, B, N]		X						
Invoice accuracy [N]				X				
Items and dollars excess [B]		X						
Number of deliveries from receiving to storerooms [C]		X						
Number of emergency supply requests [C, P, N]						X		
Number of orders returned unused [N]		X						
Number of POs issued after goods have arrived [N]						X		
Obsolete inventory [N]	X							
Operating room tray accuracy [Ca]				X				
Overnight shipments [N]						X		
Percentage of items on backorder [K, N]	X							
Percentage of items purchased via EDI [N]				X				
Picking accuracy [N]				X				
Purchase order accuracy [N]				X				
Purchases per adjusted daily census [B]	X							
Purchases per occupied bed [B]	X							
Quality of delivery [K, N]	X							
Requisition completion rate [K, K8, N]				X				
Requisitions processed [B]	X							
Rework rate [N]						X		
Slow moving inventory [B, N]		X						
Stock to non-stock percentage [B, N]				X				

Metrics	Quality Dimensions							
	Performance	Features	Reliability	Conformance	Durability	Serviceability	Aesthetics	Perceived Quality
Stockout rate [P, B, N]	X							
Storage area compactness [P]		X						
Time spent by clinicians searching for supplies [C, N]		X						
Time to care (order fulfillment cycle time)[S, N]	X							
Utilization rate of primary vendor [N]				X				
Vendor failed to arrive [F]		X						

Based on our framework analysis, the majority (eighty-five percent) of the forty healthcare supply chain quality metrics best fit into three of eight modified dimensions of quality: performance (fourteen), conformance (eleven), and features (nine). The quality dimensions of performance and conformance relate to how well the healthcare supply chain performs its essential functions and how often it fails to do so, so it is reasonable to find that many of the existing healthcare supply chain quality metrics address these two dimensions. Quality metrics falling under the conformance dimension such as inventory accuracy and GPO participation rate assess how well the healthcare supply chain conforms to internal or external specifications and requirements. Efficiency and effectiveness are features of a well-performing healthcare supply chain, and we found several metrics associated with the features of the healthcare supply chain. Four of the metrics deal with serviceability of the healthcare supply chain. These metrics are assessing the rework effort required to repair breakdowns in supply chain delivery. Aesthetics is assessed by two of the metrics, internal and external customer satisfaction, which have to do with how the healthcare supply chain appears to their customers. Our analysis of healthcare supply chain quality metrics shows that healthcare organizations are not assessing the reliability (how well their supply chain performs over time), durability (resiliency to a failure of the supply chain), or perceived quality of their supply chain performance.

In addition to identifying quality measures utilized within the healthcare supply chain, our survey also asked respondents to identify what quality improvement initiatives their organization engages in. We found that almost ninety percent of the 1,268 respondents to this question engage in two quality improvement initiatives related to their suppliers; emphasizing service as well as price in supplier relationships and communicating quality problems to suppliers. In addition, more than sixty percent of the respondents have a feedback system in place for internal customers to report supply chain errors/problems. We found that less than ten percent of the respondents formally define their external or internal customer expectations or have a formal corrective/preventative action program for external or internal issues. Only four percent of the respondents indicated that their organization does not engage in quality improvement initiatives of any type. These results are encouraging indicators that healthcare supply chain organizations are actively engaging in supply chain quality improvement initiatives.

Conclusions

We are engaged in a research effort to identify the sources of inefficiency within the healthcare supply chain while simultaneously investigating opportunities for improving the quality of healthcare delivery. As part of this work, we are exploring quality measurement across the healthcare supply chain as well as opportunities for continuous process improvement in healthcare supply chain performance. As a first step towards this long-term goal, we conducted a literature review, expert interviews, and an industry-wide survey to assess the current state of quality measurement in the healthcare supply chain. The results of which are discussed in this paper.

Our review of relevant literature indicates that the topics of quality measurement and management in the healthcare supply chain are receiving increased attention by practitioners and researchers. During our expert interviews, we learned about the leap from supply chain quality to patient safety and the need to overcome this leap by developing quality measures that can assist in day-to-day management of healthcare supply chain operations. According to the experts we interviewed, the most significant factors influencing the quality of the healthcare supply chain are availability of materials, data standardization, high volume of transactions, integrity of the supply chain, poor product traceability, process variation, and quality of information and its exchange. We identified forty quality measures currently utilized by healthcare organizations to assess their supply chain performance from a quality perspective.

We utilized our adapted dimensions of quality taxonomy as a framework for assessing the multidimensional view of quality metrics currently used in the healthcare supply chain. We determined which quality dimension best fits each metric and found that the vast majority of the identified healthcare supply chain quality metrics fell into three of eight modified dimensions of quality: performance, conformance, and features. This finding indicates that healthcare organizations are actively measuring the primary operating characteristics of their supply chain, the secondary operating characteristics that add value to the customer by enhancing the primary characteristics, and how well these characteristic of supply chain performance match established standards. Our analysis of healthcare supply chain quality metrics shows that healthcare organizations are not assessing the reliability, durability, or perceived quality of their supply chain quality. Clearly there is opportunity to improve quality measurement in the healthcare supply chain by developing metrics that assess how well their supply chain performs over time and the resiliency of their supply chain to failures. Additional opportunity lies in communicating the value of quality measurement and providing actionable quality management processes as we found that eleven percent of survey respondents do not directly track supply chain quality of their organization. This paper provides knowledge about current healthcare supply chain quality measurement practices which can help enable successful development and implementation of new quality measurement programs across the healthcare supply chain.

Acknowledgments

This research was supported by the *Center for Innovation in Healthcare Logistics* at the University of Arkansas and the *Association for Healthcare Resource and Materials Management* of the *American Hospital Association*. Any opinions, findings, conclusions, or recommendations in this document are those of the authors and do not necessarily reflect views of the sponsors.

References

Batson, Robert G., and Karen D. McGough. 2006. Quality Planning for the Manufacturing Supply Chain. *The Quality Management Journal* 13, (1): 33-41.

Blane, Donald J. 1990. Health care logistics: Back to the future. *Hospital Materiel Management Quarterly* 11, (4): 57.

Breen, L., and H. Crawford. 2005. Improving the pharmaceutical supply chain: Assessing the reality of e-quality through e-commerce application in hospital pharmacy. *International Journal of Quality Reliability Management* 22, (6): 572-90.

Burns, Lawton R. 2002. *The Health Care Value Chain: Producers, Purchasers, and Providers*. San Francisco: John Wiley & Sons.

Carpenter, Dave. 2008. Bringing discipline to your supply chain. *H&HN: Hospitals & Health Networks* 82, (5): 49-52.

Compas, Brian J. 2005. Strengthening the links in the supply chain-some preventive medicine. *Journal of Healthcare Information Management* 19, (2): 10-12.

Efficient healthcare consumer response: improving the efficiency of the healthcare supply chain. 1996. American Hospital Association/American Society for Healthcare Materials Management.

Fredendall, Lawrence D., Janet P. Craig, Pat J. Fowler, and Uzay Damali. 2009. Barriers to swift, even flow in the internal supply chain of perioperative surgical services department: A case study. *Decision Sciences* 40, (2): 327-349.

Garvin, David A. 1984. What does 'product quality' really mean? *Sloan Management Review* 26. (1): 25-43.

Halverson, George C. 2005. Healthcare tipping points: Two tipping points, cost and quality, promise to forever change the healthcare landscape as we know it. *Healthcare Financial Management* 59, (3): 74-80.

Hutchins, Greg. 2002. Supply chain management: A new opportunity. *Quality Progress* 35, (4) (April):111-113.

Kumar, Arun, Linet Ozdamar, and Chai Peng Ng. 2005. Procurement performance measurement system in the health care industry. *International Journal of Health Care Quality Assurance* 18, (2/3): 152.

Kumar, Arun, Linet Ozdamar, and Chun Ning Zhang. 2008. Supply chain redesign in the healthcare industry of Singapore. *Supply Chain Management* 13, (2): 95.

Nachtmann, Heather, and Edward A. Pohl. 2009. The state of healthcare logistics: cost and quality improvement opportunities. Center for Innovation in Healthcare Logistics, University of Arkansas.

Poulin, Etienne. 2003. Benchmarking the hospital logistics process: A potential cure for the ailing health care sector. *CMA Management* 77, (1) (Mar): 20.

Sebastianelli, Rose, and Nabil Tamimi. 2002. How product quality dimensions relate to defining quality. *The International Journal of Quality & Reliability Management* 19, (4): 442-453.

Solovy, A., S. Hoppszallern, and S. B. Brown. 2007. Ten lessons from the top 100. H&HN: Hospitals & Health Networks 81, (7) (07): 40.

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

Swinehart, Kerry D., and Allen E. Smith. 2005. Internal supply chain performance measurement: A health care continuous improvement implementation. *International Journal of Health Care Quality Assurance* 18, (6/7): 533.

U.S. Department of Health & Human Services, Centers for Medicare & Medicaid Services. 2007 National Health Expenditure Data. http://www.cms.hhs.gov/NationalHealthExpendData/

Wagner, Jeff. 2008. Fundamentals for quality management in materials management. *Supply Chain Strategies & Solutions* 2, (4): 1-5.

4. A 0-1 QUADRATIC PROGRAM FOR THE CASE OF MISSING DATA IN REGRESSION*

Brian K. Smith, M.S.

Justin R. Chimka, Ph.D.

Heather Nachtmann, Ph.D.

4207 Bell Engineering Center

University of Arkansas

Fayetteville, AR 72701

Abstract

Multivariate statistical analysis techniques including regression analysis compose a popular toolset for analyzing survey data, but the techniques require a complete dataset with no missing values. Unfortunately, most survey datasets contain missing values. These missing values must be resolved in some manner before regression analysis can take place. We present a quadratic programming methodology for eliminating nonresponses from a survey dataset.

Keywords: missing data, quadratic program, regression analysis, survey research

Introduction

The survey is a tool widely used by government, business, and academic researchers to gather information. Good surveys are developed so as to extract the most

---

* second revision under review by the *International Journal of Data Analysis Techniques & Strategies*

information from the target population as possible with minimal strain on the population. However, even the best surveys require some investment of time, thought, and research on the part of the respondents, and survey respondents are often unable or unwilling to answer all questions in a survey. Survey researchers realize that all respondents in the target population may not be able to answer all of the survey questions and therefore provide choices for waste answers to the respondents such as “do not know,” “prefer not to respond” or “not applicable.” However, the inclusion of waste answers does not guarantee that all respondents will provide answers to all questions. Also, these types of responses should be used with caution as they provide the respondents with an easy avenue to avoid thinking of a response and they should only be used when an answer such as “do not know” carries meaning to the researcher (de Leeuw, et al., 2003). Survey researchers are often faced with the problem of how to deal with incomplete survey data as a result.

Background / Literature

One problem with using the survey as a tool to gather data is missing data. Missing data occurs when a survey respondent does not provide a response to a question. This is referred to as a nonresponse. Troxel et al. (1997) categorizes nonresponses into two types: unavailability and refusal. An unavailability non-response is a case where the survey researcher is unsuccessful in the attempt to contact the potential respondent in order to administer the survey. The unavailability nonresponse is a problem common with telephone surveys. Peytchev et al. (2010) present a novel method for reducing the unavailability nonresponse by targeting likely non-respondents beforehand and allocating necessary resources to better the chance of obtaining a response. The refusal nonresponse occurs when a respondent does not answer specific questions in the survey. A respondent may refuse to answer individual questions or all questions of a particular type or category. Refusal nonresponse is more common than unavailability nonresponse in mail or email surveys (Troxel et al., 1997). Surveys can have both unavailability and refusal nonresponses with classic cases being the US Census and the Accuracy and Coverage Evaluation Survey conducted by the US Census Bureau (Cantwell and Ikeda, 2003). We limit the discussion in this paper to refusal nonresponse.

The problem of the missing data from nonresponses must be addressed before the data can be analyzed using popular techniques such as regression that requires a complete data set. The problem of missing data must generally be addressed before multivariate statistical analysis can take place (Pedreschi, et al., 2008). The techniques available to deal with missing data from nonresponses fall into two basic categories. One is to arbitrarily eliminate cases where missing data exists by either eliminating the associated respondent from the study or by eliminating the associated question from the study. The second category is imputation. Imputation is a set of techniques for estimating values for the missing responses in the data set (Little, 1988).

Much of the research on imputation focuses on developing better techniques or improving existing ones (Little and Rubin, 1987). A major weakness of imputation is that it creates estimated data from which additional estimates are made. This provides more opportunity for results to be questioned (especially when the results are used to allocate federal resources) as discussed by Davern, et al., (2004). Arbitrary elimination of missing responses from the data set also has a weakness. Bias can be introduced if there is a reason for the missing responses. However, Haitovsky (1968) concluded that for the case of random nonresponse, arbitrary elimination outperforms imputation except in the case where a large majority of the data set is incomplete.

For our purposes, we are not interested in imputation techniques. We are studying the case where a researcher is presented with a set of responses to survey questions that were administered to a group of respondents. The researcher has no preferences for certain columns (questions) or rows (respondents), and the data set includes observations missing at random. The researcher wishes to perform a series of regression analyses on the data. First, he/she must eliminate the missing observations by either removing the associated question or respondent from the dataset. The task of removing questions and/or respondents can be done arbitrarily by hand, but this would likely result in eliminating data unnecessarily.

Problem in Context

` The motivation for this work stems from ongoing research investigating opportunities for cost and quality improvements in the healthcare supply chain. The cost and quality of healthcare is one of the most discussed and debated issues of our time. There is definitely reason for concern as healthcare costs currently account for more than 17% of the gross domestic product (GDP) of the United States. Healthcare costs are expected to grow at a rate greater than that of the GDP reaching almost $4.6 trillion by 2019, accounting for 19.6% of the GDP (Centers for Medicare and Medicaid Services 2010). A 1996 healthcare industry study titled *Efficient Healthcare Consumer Response* (EHCR) concluded that 38% of the cost of goods sold in the healthcare industry can be attributed to supply chain related activities. The study noted that this percentage is much higher than the retail (6-8%) and grocery (3-6%) sector supply chains (EHCR 1996, Burns 2002).

In November 2008, researchers at Center for Innovation in Healthcare Logistics (CIHL) at the University of Arkansas administered a survey to practitioners in the healthcare supply chain in part to assess the state of healthcare logistics since the EHCR. Exactly 1381 respondents completed surveys for a response rate of approximately 12% (Nachtmann and Pohl, 2009). A survey was considered complete, if its respondent answered 80 percent of the questions. A grid of 74 columns (questions) and 1381 rows (respondents) can represent the resulting dataset. The dataset contains 25,392 missing data points or approximately 26% [25,392 empty cells / (74 questions x 1381 respondents) ≈ 0.26]. Of course, a researcher would hope to preserve as much data as possible while eliminating all of the nonresponses. The task of manually removing questions and respondents in order to eliminate 25,392 missing data points while trying to preserve as much data as possible from the dataset is daunting. The remainder of this paper presents an alternative method to imputation and arbitrary elimination that may unnecessarily eliminate useful data by taking advantage of mathematical programming. We begin by presenting a smaller, representative problem.

Representative Example

The example shown in Table 1 is a small scale, realistic representation of the actual problem faced in our research. The example consists of columns x_i representing survey questions and rows y_j representing individual respondents. A value of "1" in cell x_iy_j represents a valid response for question i from respondent j. A value of "0" in cell x_iy_j represents a missing or invalid response to question i from respondent j. Cells filled with

“0” in the example problem account for 24% of all cells. This is consistent with the percentage of missing or invalid responses in our survey data. The cells filled with “0” were generated randomly.

Table 1. Representative Example Problem

[6 randomly empty cells / (5 columns x 5 rows) = 0.24]

	x_1	x_2	x_3	x_4	x_5
y_1	1	1	0	1	1
y_2	0	1	1	1	1
y_3	0	1	0	1	1
y_4	1	0	1	0	1
y_5	1	1	1	1	1

Problem Formulation

A quadratic program (QP) is a nonlinear program with linear constraints and an objective function that is the product of terms with the following form (each term has a degree of 0, 1, or 2): $x_1^{k1}x_2^{k2} \ldots x_n^{kn}$. The problem of choosing what columns and rows with missing data should be discarded before regression analysis will be mathematically formulated and shown to fit the QP description with a caveat that every variable must equal 0 or 1. Therefore the problem of interest here is a 0-1 quadratic program for the case of missing data in regression. The general formulation for the quadratic program in the context of our work is as follows.

Parameter:

$a_{ij} = 1$ if valid data exists for Question i and Respondent j, 0 otherwise.

Decision variables:

$x_i = 1$ if Question i is preserved, 0 otherwise.

$y_j = 1$ if Respondent j is preserved, 0 otherwise.

Objective function:

Maximize $\sum a_{ij}x_iy_j$

Subject to:

1. $x_i + y_j \leq 1 \nabla a_{ij} = 0$
2. $x_i, y_j = 0{,}1$

The formulation to solve the representative example from Table 1 is as follows:

$$\max z = x_1y_1 + x_1y_4 + x_1y_5$$
$$+ x_2y_1 + x_2y_2 + x_2y_3 + x_2y_5$$
$$+ x_3y_2 + x_3y_4 + x_3y_5$$
$$+ x_4y_1 + x_4y_2 + x_4y_3 + x_4y_5$$
$$+ x_5y_1 + x_5y_2 + x_5y_3 + x_5y_4 + x_5y_5$$

s.t.

$$x_1 + y_2 \leq 1$$
$$x_1 + y_3 \leq 1$$
$$x_2 + y_4 \leq 1$$
$$x_3 + y_1 \leq 1$$
$$x_3 + y_3 \leq 1$$
$$x_4 + y_4 \leq 1$$
$$x_1, x_2, x_3, x_4, x_5, y_1, y_2, y_3, y_4, y_5 = 0 \text{ or } 1$$

Results

The representative example problem shown in Table 1 was formulated and coded into CPLEX 12.1.0 to solve on a Dell Latitude D620 laptop computer. The solution eliminates columns x_1 and x_3 and row y_4 from the dataset, preserving twelve of the nineteen valid data points in the representative problem. The solution to the representative example is shown in Table 2 with the eliminated columns and rows shaded.

Table 2. Solution to Representative Example

	x_1	x_2	x_3	x_4	x_5
y_1	1	1	0	1	1
y_2	0	1	1	1	1
y_3	0	1	0	1	1
y_4	1	0	1	0	1
y_5	1	1	1	1	1

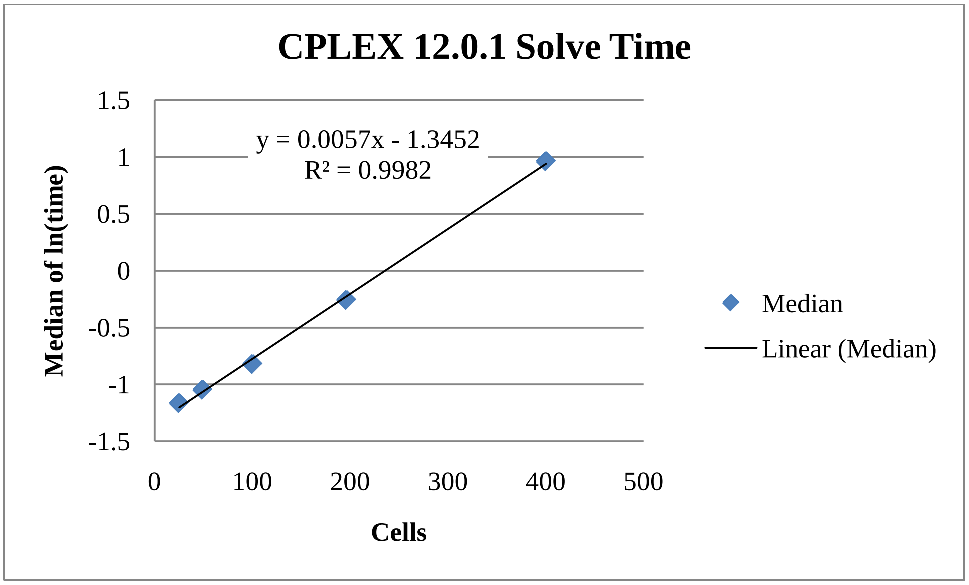
Larger representative problems were generated, each with 25% missing data points. Thirty examples each of problems with 25, 49, 100, 196, and 400 cells were generated. The example problems are square matrices with equal numbers of columns and rows. The location of missing data points in each problem was generated randomly. Each of the thirty example problems was individually solved thirty times. The median time to solve each representative problem is shown in Table 3.

Predictably, the time that it takes to solve a representative problem increases as the number of cells in the example problem increases. Figure 1 displays a plot of the median of the natural log of the 900 solve times for each representative problem size. This increase is exponential as evidenced by the correlation coefficient of 0.9982.

Table 3. Model Performance Using CPLEX 12.1.0

Example Problem Size (Column x Row)	CPLEX Solve Time (seconds): Median of 900 Solutions (30 Example Problems x 30 Solution Runs)
25 cells (5x5)	0.312
49 cells (7x7)	0.351
100 cells (10x10)	0.440
196 cells (14x14)	0.773
400 cells (20x20)	2.617

Figure 4. Example Problem Size Solve Time



The motivating problem is a survey of 74 questions with 1381 respondents. This problem can be viewed as a 74 x 1381 matrix of 102,194 cells. Extrapolating the exponential function reveals that solving a same-size square version of the motivating problem would take more than a lifetime using the same software and equipment. Table 4 illustrates the size of related problems that could be solved in common time frames.

Table 4. Maximum Problem Size for Common Time Frames

Time Frame	Maximum Problem Size Solvable in Time Frame
One day	2230
One week	2571
One month	2829
One year	3265

Discussion and Future Work

We have presented a novel method for extracting valid response data from a dataset containing missing responses for the purpose of enabling regression analysis. The major advantage of using the quadratic program to eliminate the missing values over arbitrary elimination is that the researcher can find comfort in the fact that the maximum amount of valid data is preserved.

To justify the benefits of using the quadratic program in terms of time and accuracy a larger scale example appears in appendices. We have created a sample from the famous Canadian lynx time series data (Elton and Nicholson, 1942). It began as the oldest complete set of twenty observations in time and the first nineteen lagged variables to constitute the 20 x 20 sheet shown in Appendix A. Next we randomly removed from the 20 x 20 sheet approximately one third of the observations that remain in Appendix B to create a problem without obvious solution. It is shown in Appendix C with eliminated columns and rows shaded. In this example, arbitrarily removing columns or rows to eliminate missing observations will eliminate the entire data set.

Here we have assumed that a question holds the same value as a respondent and that all questions and responses are equal. In other words we do not have a preference between whether a question or respondent is eliminated in order to resolve a missing data point. In the future we can modify the model presented here to include weights for questions and respondents according to the researcher’s preferences.

References

Burns, Lawton R. (2002). *The Health Care Value Chain: Producers, Purchasers, and Providers*. John Wiley & Sons

Cantwell, P. J., & Ikeda, M. (2003). Handling Missing Data in the 2000 Accuracy and Coverage Evaluation Survey. *Survey Methodology, 29*(2), 139-153

Centers for Medicare & Medicaid Services, Office of the Actuary. National Health Expenditure Projections 2009-2019. September, 2010

Davern, M., Blewett, L. A., Bershadsky, B., & Arnold, N. (2004). Missing the Mark? Imputation Bias in the Current Population Survey's State Income and Health Insurance Coverage Estimates. *Journal of Official Statistics, 20*(3), 519-549

de Leeuw, E. D., Hox, J., & Huisman, M. (2003). Prevention and Treatment of Item Nonresponse. *Journal of Official Statistics, 19*(2), 153-176

Elton, Charles and Mary Nicholson (1942), "The ten-year cycle in numbers of the lynx in Canada," *Journal of Animal Ecology* 11(2): 215-244

"Efficient Healthcare Consumer Response: Improving the Efficiency of the Healthcare Supply Chain," American Hospital Association/American Society for Healthcare Materials Management, (1996).

Haitovsky, Y. (1968). Missing data in regression analysis. *Journal of the Royal Statistical Society, Series B 30*(1), 67-82

Little, R. J. A. (1988). Missing-Data Adjustments in Large Surveys. *Journal of Business & Economic Statistics, 6*(1), 287-296

Little, R. J. A., & Rubin, D. B. (1987). *Statistical Analysis with Missing Data*. New York: Wiley

Nachtmann, H., & Pohl, E. A. (2009). The State of Healthcare Logistics: Cost and Quality Improvement Opportunities. Center for Innovation in Healthcare Logistics, University of Arkansas

Pedreschi, R., Maarten, L. A., Hertog, T.M., Carpenter, S.C., Lammertyn, J., Robben, J., Noben, J., Panis, B., Swennen, R., and Nicolai, B.M. (2008), Treatment of missing values for multivariate statistical analysis of gel-based proteomics data. *Proteomics 8* (7), 1371-1383.

Peytchev, A., Riley, S., Rosen, J., Murphy, J., & Lindblad, M. (2010). Reduction of Nonresponse Bias in Surveys through Case Prioritization. *Survey Research Methods, 4*(1), 21-29

Troxel, A. B., Lipsitz, S. R., & Brennan, T. A. (1997). Weighted Estimating Equations with Nonignorably Missing Response Data. *Biometrics, 53* (Sept.), 857-869

Appendix A.

Lagged Canadian Lynx Data

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}
y_1	409	1824	3409	2685	2285	409	279	184	98	523	2577	4950	5943	3928	2821	1475	871	585	321	269
y_2	151	409	1824	3409	2685	2285	409	279	184	98	523	2577	4950	5943	3928	2821	1475	871	585	321
y_3	45	151	409	1824	3409	2685	2285	409	279	184	98	523	2577	4950	5943	3928	2821	1475	871	585
y_4	68	45	151	409	1824	3409	2685	2285	409	279	184	98	523	2577	4950	5943	3928	2821	1475	871
y_5	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98	523	2577	4950	5943	3928	2821	1475
y_6	546	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98	523	2577	4950	5943	3928	2821
y_7	1033	546	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98	523	2577	4950	5943	3928
y_8	2129	1033	546	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98	523	2577	4950	5943
y_9	2536	2129	1033	546	213	68	45	151	409	1827	3409	2685	2285	409	279	184	98	523	2577	4950
y_{10}	957	2536	2129	1033	546	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98	523	2577
y_{11}	361	957	2536	2129	1033	546	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98	523
y_{12}	377	361	957	2536	2129	1033	546	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98
y_{13}	225	377	361	957	2536	2129	1033	546	213	68	45	151	409	1824	3409	2685	2285	409	279	184
y_{14}	360	225	377	361	957	2536	2129	1033	546	213	68	45	151	409	1824	3409	2685	2285	409	279
y_{15}	731	360	225	377	361	957	2536	2129	1033	546	213	68	45	151	409	1824	3409	2685	2285	409
y_{16}	1638	731	360	225	377	361	957	2536	2129	1033	546	213	68	45	151	409	1824	3409	2685	2285
y_{17}	2725	1638	731	360	225	377	361	957	2536	2129	1033	546	213	68	45	151	409	1824	3409	2685
y_{18}	2871	2725	1638	731	360	225	377	361	957	2536	2129	1033	546	213	68	45	151	409	1824	3409
y_{19}	2119	2871	2725	1638	731	360	225	377	361	957	2536	2129	1033	546	213	68	45	151	409	1824
y_{20}	684	2119	2871	2725	1638	731	360	225	377	361	957	2536	2129	1033	546	213	68	45	151	409

Appendix B.

Lagged Canadian Lynx Data with Random Missing Values

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}
y_1	409	1824	3409	2685	2285	409	279	184	98			4950	5943	3928	2821		871		321	269
y_2	151		1824	3409	2685	2285	409		184	98	523	2577	4950	5943	3928	2821			585	321
y_3	45	151	409		3409			409	279			523				3928		1475	871	585
y_4	68		151	409	1824	3409		2285	409	279		98	523		4950	5943		2821	1475	
y_5	213	68			409	1824		2685			279	184		523	2577	4950	5943	3928	2821	1475
y_6	546	213	68	45	151	409	1824	3409	2685	2285	409	279		98	523		4950		3928	2821
y_7		546		68		151	409	1824		2685	2285		279	184		523	2577	4950	5943	3928
y_8	2129	1033	546	213	68		151	409	1824	3409	2685	2285	409	279		98		2577		5943
y_9	2536	2129	1033	546		68	45				3409	2685			279	184	98			
y_{10}	957	2536	2129	1033	546		68		151	409	1824	3409	2685	2285	409	279	184	98	523	2577
y_{11}	361		2536	2129			213	68		151	409	1824	3409	2685	2285	409		184		523
y_{12}	377	361	957	2536			546	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98
y_{13}	225	377		957	2536	2129	1033		213	68				1824	3409	2685	2285	409		184
y_{14}	360	225	377		957	2536			546	213	68		151	409	1824	3409	2685	2285		
y_{15}	731	360	225	377	361	957			1033	546	213		45	151	409	1824	3409	2685	2285	409
y_{16}	1638		360	225	377	361		2536	2129	1033	546		68	45	151		1824	3409	2685	
y_{17}			731	360	225	377	361	957	2536	2129	1033		213	68	45	151	409	1824		2685
y_{18}	2871	2725	1638		360	225	377	361	957	2536	2129		546	213	68	45	151	409	1824	3409
y_{19}	2119	2871	2725	1638	731	360	225	377	361	957		2129	1033	546	213	68	45	151		
y_{20}	684	2119	2871		1638	731	360	225		361			2129	1033			68		151	409

Appendix C.

Lagged Canadian Lynx Data with Random Missing Values: Shaded Columns and Rows to Be Eliminated

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}
y_1	409	1824	3409	2685	2285	409	279	184	98			4950	5943	3928	2821		871		321	269
y_2	151		1824	3409	2685	2285	409		184	98	523	2577	4950	5943	3928	2821			585	321
y_3	45	151	409		3409			409	279			523				3928		1475	871	585
y_4	68		151	409	1824	3409		2285	409	279		98	523		4950	5943		2821	1475	
y_5	213	68			409	1824		2685			279	184		523	2577	4950	5943	3928	2821	1475
y_6	546	213	68	45	151	409	1824	3409	2685	2285	409	279		98	523		4950		3928	2821
y_7		546		68		151	409	1824		2685	2285		279	184		523	2577	4950	5943	3928
y_8	2129	1033	546	213	68		151	409	1824	3409	2685	2285	409	279		98		2577		5943
y_9	2536	2129	1033	546		68	45				3409	2685			279	184	98			
y_{10}	957	2536	2129	1033	546		68		151	409	1824	3409	2685	2285	409	279	184	98	523	2577
y_{11}	361		2536	2129			213	68		151	409	1824	3409	2685	2285	409		184		523
y_{12}	377	361	957	2536			546	213	68	45	151	409	1824	3409	2685	2285	409	279	184	98
y_{13}	225	377		957	2536	2129	1033		213	68				1824	3409	2685	2285	409		184
y_{14}	360	225	377		957	2536			546	213	68		151	409	1824	3409	2685	2285		
y_{15}	731	360	225	377	361	957			1033	546	213		45	151	409	1824	3409	2685	2285	409
y_{16}	1638		360	225	377	361		2536	2129	1033	546		68	45	151		1824	3409	2685	
y_{17}			731	360	225	377	361	957	2536	2129	1033		213	68	45	151	409	1824		2685
y_{18}	2871	2725	1638		360	225	377	361	957	2536	2129		546	213	68	45	151	409	1824	3409
y_{19}	2119	2871	2725	1638	731	360	225	377	361	957		2129	1033	546	213	68	45	151		
y_{20}	684	2119	2871		1638	731	360	225		361			2129	1033			68		151	409

5. AN EMPIRICAL INVESTIGATION OF SUPPLY CHAIN INITIATIVE EFFECTIVENESS IN HEALTHCARE PROVIDERS

Brian K. Smith, M.S.

Heather Nachtmann, Ph.D.

Justin R. Chimka, Ph.D.

Edward A. Pohl, Ph.D.

4207 Bell Engineering Center

University of Arkansas

Fayetteville, AR 72701

Abstract

The cost of healthcare is a major concern throughout the United States. The healthcare supply chain has been identified as an opportunity for improving the efficiency and reducing the cost of healthcare delivery. The 1996 *Efficient Healthcare Consumer Response* (EHCR) along with other sources recommend several strategic initiatives to improve the healthcare supply chain. This empirical research examines the impact of strategic supply chain initiatives on healthcare supply chain performance as measured by supply chain maturity and data standards readiness. Through an ordered logistic regression analysis of a nationwide survey of healthcare providers, we find that not all suggested initiatives have a significant influence. Specifically we find that healthcare provider organizations who collaborate with their suppliers, adopt automation in supply chain processes, engage in benchmarking, standardize purchasing procedures, involve

executives in improvement activities, and increase product traceability are more likely to have a mature supply chain. Similarly, collaborating with other healthcare providers, simplifying the rebate process, developing a total delivered cost mentality, and evaluating vendor performance positively impact the data standards readiness of a healthcare provider. The lack of end-to-end visibility of business processes is identified as a barrier to both supply chain maturity and data standards readiness. Interrupted information flows and limited management of product utilization are also found to be significant barriers to supply chain maturity.

Introduction

The cost of healthcare in the United States amounted to more than 17% of the gross domestic product (GDP) in 2009 and is expected to continue to grow at a rate faster than GDP, amounting to $4.6 trillion or 19.6% of GDP by 2019 (CMMS, 2010). The importance of supply chain management has increased in the healthcare industry as the cost of healthcare in the United States has risen. Nachtmann and Pohl (2009) found that 31% of the average healthcare provider's annual operating expense is spent on supply chain related activities. Another article provides a similar finding and puts the number in perspective; Grossman (2000) finds that the "moving and handling" of materials and supplies accounts for 38% of the cost of goods in an average hospital compared to less than 10% in other industries.

Companies in the retail and manufacturing sectors have realized for quite some time that effective and efficient supply chain operations is essential to overall business success. McKone-Sweet et al (2005) note that the healthcare industry has not yet adopted the supply chain improvement practices that have been successful in other industries; this is supported by our own discussions with healthcare supply chain professionals. Healthcare, like all industries, must determine how to allocate scarce resources to maintain and improve their operations. New technologies are being continually introduced to improve healthcare delivery, and implementing these new technologies often comes at a high cost. Since the primary role of healthcare providers is to provide the highest level of medical care possible, resources are often dedicated to procuring and implementing new technologies for delivering care, according to one healthcare expert we interviewed. Dedicating resources to supply chain improvement activities has not been a high priority in healthcare with most supply-related efforts being dedicated to negotiating reductions in the cost of materials (Ballard, 2005).

Our research objective is to conduct an empirical investigation of strategic supply chain initiative effectiveness in healthcare providers by examining initiatives impacting current performance as measured by supply chain maturity and future potential as measured by data standards readiness. The data for this study was collected through a nationwide survey of 1,056 supply chain professionals employed by healthcare provider organizations. Our methodology is similar to recent work by Hill et al (2009) investigating electronic data interchange and performance improvement in the food supply chain.

About the Healthcare Supply Chain

The Efficient Healthcare Consumer Response (EHCR) is still discussed today by healthcare supply chain professionals seeking to improve their supply chain performance. The key item reported by the EHCR was that over $11 billion of supply chain costs in healthcare were avoidable in 1995 (EHCR, 1996). The EHCR proposed a set of strategic initiatives to improve the cost and effectiveness of the healthcare supply chain. These EHCR strategic initiatives are an important component of this research and are discussed in further detail later in the paper.

The literature reveals that the healthcare supply chain is receiving increasing attention, and highlights are discussed here. Additional discussion of the relevant literature can be found in Smith et al (2011). Much of the attention in the literature has been focused on identifying general supply chain management tools applicable to healthcare. Swinehart and Smith (2005) suggest that performance measures should be developed and adopted as a first step. In addition, benchmarking is recommending as a good tool to set goals and gauge levels of improvement (Lauer, 2004). Performance measurement and benchmarking can then lead to the development of practices that reduce variation and increase efficiency in the healthcare supply chain (Davis, 2004).

Management of purchasing processes and procedures is an issue in healthcare. Purchases are often made outside of normal procurement channels that are unnecessary or overly costly (Neumann, 2003). Careful attention to policies and procedures relating to physician preference items (Long, 2005) and items on consignment (Ricupito, 2006) are specific areas where improvements are needed. Physician preference items in particular have been associated with excessive numbers of suppliers for the same category of product and increased supply costs due to a lack of volume-buying discounts (Ballard, 2005; Roark, 2005). Inventory management in general is not as sophisticated in healthcare as in other industries with less than 10% of hospitals making use of inventory optimization techniques (Langabeer, 2005).

The study of healthcare supply chain quality management is also beginning to be addressed in the literature as current research in the healthcare supply chain takes into consideration the relationship between cost and quality. Schneller and Smeltzer (2006) identify the importance of cost and quality when they define the healthcare supply chain as "the information, supplies, and finances involved with the acquisition and movement of goods and services from the supplier to the end user in order to enhance clinical outcomes while controlling costs." This definition is supported by healthcare futurist Joe Flower who concludes that improving clinical outcomes while lowering costs should be the main goal of the healthcare supply chain (Flower, 2005). Smith et al (to appear) identify existing metrics for healthcare supply chain quality and reveal that opportunities exist to develop quality metrics and management techniques that more broadly assess the performance of the healthcare supply chain.

Collaboration is another area explored in the healthcare supply chain literature. Brennan (1998) identifies the opportunity for healthcare supply chain participants to engage in mutually beneficial partnerships by sharing in the cost savings that result from eliminating redundancies. Common supply chain processes resulting from collaboration will likely result in reduced purchasing, transportation, and distribution costs that benefit all participants in the supply chain. Shifting focus from price alone toward details such as delivery schedules, payment procedures, and delivery methods can result in improved internal operations, ultimately reducing total cost of materials (Compas, 2005) for both suppliers and healthcare providers. Additionally, healthcare can be described as a cottage industry, lacking a clear leader with market leverage (Ford and Hughes, 2007). If supply chain partners collaborated more effectively, greater efficiencies could be achieved.

Another area discussed often in the healthcare supply chain literature is the immaturity of information technology (IT) systems. Although the necessary technological resources are available, effective implementation in a healthcare context is difficult. A study by McKone-Sweet et al. (2005) consisting of interviews conducted with healthcare supply chain experts indicated that even though the lack of information systems was often identified as a barrier against effective supply chain management, “most participants were more concerned with the effective use of the data that was available,” This lack of IT systems maturity is prevalent among the majority of hospitals in the United States (Langabeer, 2005). One of the essential requirements of information technology in healthcare is not only the ability to collect data, but the level of integration needed to create information flow within and across organizations (Ballard, 2005). Challenges to effective IT implementation continue to exist, but studies such as the Most Wired Survey (Solovy, 2004) are supporting the continued work towards information technology systems maturity.

With regards to performance and compared to other industries, the healthcare supply chain is thought to be immature. We utilize the supply chain maturity model of Lockamy III and McCormack (2004) as a measure of current supply chain performance. The survey respondents were asked to assess the maturity of their healthcare provider organization’s supply chain as one of five levels of supply chain maturity: Ad Hoc, Defined, Linked, Integrated, and Extended. This metric is further described in the methodology section. Another major difference between the healthcare supply chain and the retail supply chain is in the traceability and identification of products. The familiar Universal Product Code (UPC) barcode that is present on almost all products in retail stores has been in use for over 35 years. UPC barcodes were initially developed to improve the efficiency of retail check-out lines; however, many other benefits were realized. UPC barcodes allowed retailers to improve operations by simplifying and improving inventory, rebate, and return processes. Savings just in the grocery sector from UPCs were estimated at $17 billion (Vineet et al, 1999). No data standards system such as the UPC has been adopted by the healthcare industry as a whole. Members of the healthcare supply chain believe there are potential benefits to data standards adoption, and there has been a strong push for data standards adoption led by the Association for Healthcare Resource and Materials Management (AHRMM) and GS1 (AHRMM, 2011). The Food and Drug Administration (FDA) is also encouraging the adoption of a data standards system, but has so far stopped short of issuing a mandate through regulation (Barlow, 2010). While the possibility of a future FDA mandate is one driver, Smith et al (2011b) provide a full look into the data standards readiness of healthcare providers and finds the possibility of efficiency increases and cost reductions to be more important drivers of data standards adoption. To assess factors influencing supply chain performance, we examine the supply chain maturity and data standards readiness of healthcare providers and determine which supply chain strategic initiatives are effectively influential.

Data Collection and Analysis

In 2008, we began an empirical study to assess the state of healthcare logistics. This was the first industry-wide empirical study of the healthcare supply chain since the EHCR report was published in 1996. The EHCR identified opportunities for cost savings in the healthcare supply chain and proposed strategic initiatives that would facilitate cost improvements. Our survey questions were constructed using the EHCR as a starting point. Additional questions were developed through literature review and comprehensive interviews with twelve experts representing the four major sectors of the healthcare supply chain including three healthcare product manufacturers, two large healthcare distributors, one group purchasing organization, two hospitals, and two healthcare delivery networks.

Pilot studies were conducted on initial drafts of the questionnaire to validate the content. The initial questionnaire was distributed to five of our healthcare supply chain experts who completed the survey and provided feedback. This information was used to ensure that the final questionnaire contained terminology and content that is understandable and valuable to the survey respondent pool and to confirm the estimated survey completion time of 20 minutes.

With assistance from the University of Arkansas Survey Research Center, the questionnaire was conducted in November and December 2008 through an internet-based survey instrument. Potential respondents were collected from the membership lists of AHRMM, GS1 Healthcare US, the Strategic Marketplace Initiative (SMI), and subscribers to Materials Management in Healthcare magazine. Notification of the upcoming survey was advertised in member communications by AHRMM and SMI. Potential respondents were mailed letters inviting them to participate in the survey. The pre-survey notices informed potential respondents of the general content of the questionnaire and of its importance to the healthcare industry. The questionnaire was deployed via email to potential respondents requesting their participation. Each respondent was given a unique identifier that was used to gain access to the online questionnaire and allow for confidential and anonymous data collection. Three follow-up requests were sent to non-respondents during the four weeks that the survey was open. With an approximate response rate of 12%, the survey received responses from 1,381 healthcare supply chain professionals, 1,056 (77%) of whom are employed by healthcare provider organizations and are the respondent pool for this paper (Nachtmann and Pohl, 2009). Two-thirds of the healthcare provider respondents have more than ten years of employment experience in the healthcare supply chain with over half holding senior management job titles including director, vice president, or executive. More than three-quarters of the healthcare provider respondents identified themselves as being employed by a hospital with more than a third responding that their employer was part of a health system or health network.

The two dependent variables of interest in this study include the performance measures of supply chain maturity and data standards readiness of the respondent's organization. The respondents were asked to assess the supply chain maturity of their organization on a five-point ordinal scale based on the supply chain maturity model developed by Lockamy III and McCormack (2004). Their supply chain maturity model provides five levels of increasing maturity: Ad Hoc, Defined, Linked, Integrated, and Extended. The definitions provided to the respondents are shown in Figure 1.

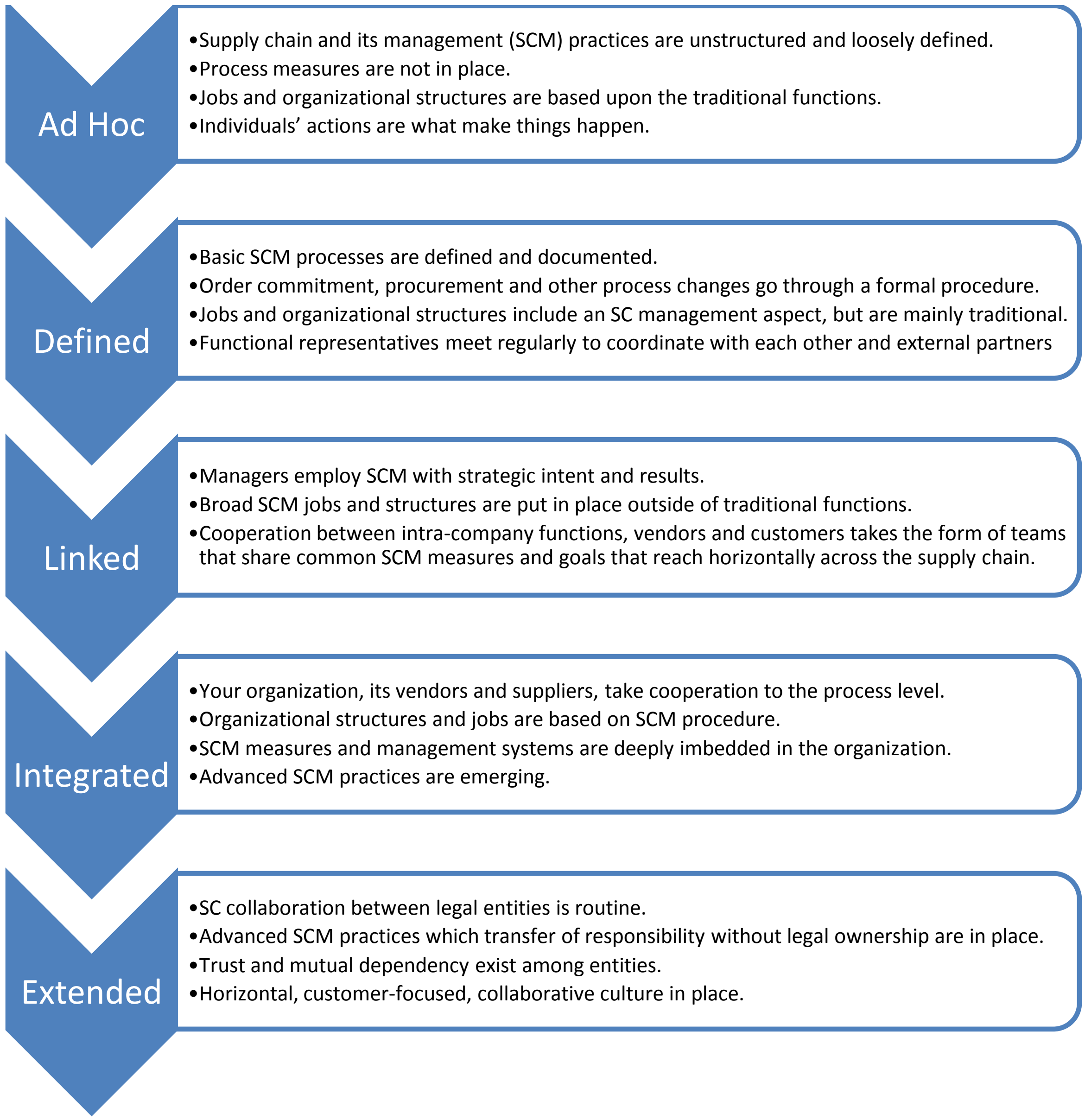


Figure 1: Supply Chain Maturity Levels

As shown in Figure 2, over half (57%) of the respondents indicate that their healthcare provider organization has an immature supply chain (described as Ad Hoc or Defined). Less than one quarter of the respondents indicate that their healthcare provider organization has a mature supply chain (described as Integrated or Extended). The remaining respondents fall into the Linked maturity category.

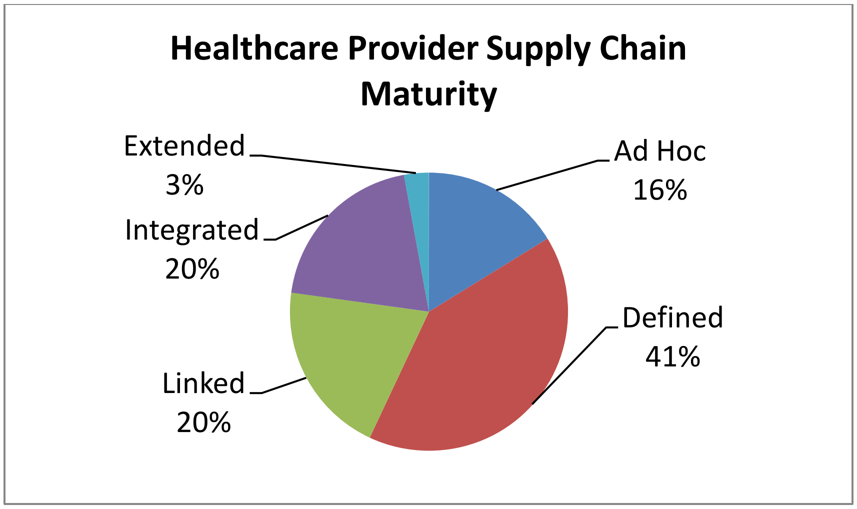


Figure 2: Healthcare Provider Supply Chain Maturity

The second dependent variable of interest is the level of readiness for data standards adoption. The respondents were asked to assess their organization's level of readiness as follows: Very Ready, Ready, Both Ready and Marginally Ready, Marginally Ready, and Not at All Ready. Just over one quarter (26%) of the respondents indicate that their healthcare provider organization is at least ready to adopt a system of data standards. Almost half (49%) indicate that their organization is marginally ready, at best. The results are shown in Figure 3.

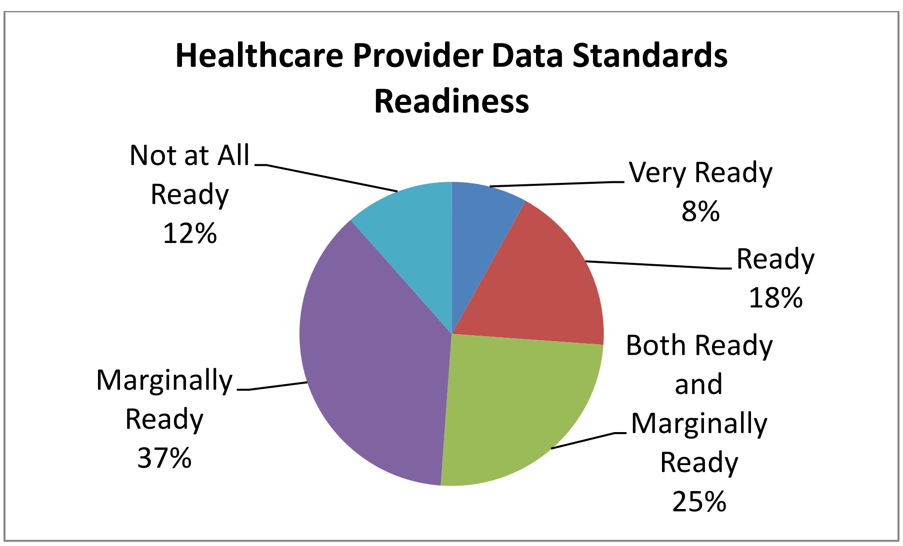


Figure 3: Healthcare Provider Data Standards Readiness

The survey results were presented to the group of healthcare supply chain experts to gauge their reaction to the findings. None of the experts found the results presented in Figures 2 and 3 to be unreasonable.

The strategic supply chain initiatives examined in this study and modeled as independent variables can be grouped as collaboration practices, strategic supply chain initiatives recommended by the EHCR, strategic supply chain improvement initiatives identified outside the EHCR, executive and clinician/physician participation in supply chain improvement, barriers to supply chain improvement, and supply chain quality assessment. There are also two organization-level demographic variables, Provider Type and Size of Organization. A summary of the independent variables is shown in Table 1. With the exception of provider size (open response as number of beds), all variables are binary (Yes - this is applicable to my organization or No - this is not applicable to my organization).

Category	Independent Variables
Collaboration practices	• Collaborate with our o Suppliers o Distributors o GPOs o Providers o Professional associations o Academic institutions • No barriers exist to collaboration
EHCR strategic initiatives	• Increase E-commerce transactions • Adopt automation for common supply chain processes • Actively encourage supply chain certifications for suppliers • Implement net billing (discounts/rebates deducted at the point of sale) • Simplify rebate process • Cost containment/collection of outcomes data • Apply activity based costing • Develop a total delivered cost mentality

Category	Independent Variables
	• Improve the receiving function • Industry-wide freight consolidation • Inventory management/reduction programs • Clearly define the role of your organization in healthcare • Participate in industry “best practice” teams • Outsource services
Non-EHCR strategic supply chain initiatives	• Centralize/consolidate supply chain data • Improve invoice accuracy • Standardize internal purchasing procedures • Evaluate vendor performance • Improve service levels/fill rates • Increase product traceability • Reduce number of product stop points (tiers) • Defined procedures specifically for handling physician preference items (PPI) • Establish strategic partnerships and alliances • Benchmark your supply chain against other supply chains • Develop a contingency plan for supply chain disruptions such as supplier product shortages
Participants in supply chain improvement initiatives	• Stakeholders who participate o Executives (CEO, CFO, CIO, President) o Clinicians/Physicians
Barriers to supply chain improvement	• No visibility of end-to-end performance of business processes • Low product traceability throughout the supply chain • Information flows interrupted at each point in the supply chain • Duplication of core activities • Extended information lead times • Extensive rework to correct and recover from data inaccuracy • High variation in customer/client preferences • Low ability to match cost to specific output • Separation between procurement, clinicians and payers • Low ability to manage product utilization • Regulatory compliance • Lack of data standards • Amount of transactions handled electronically [*#] • Amount of PPI in item file [*#]

Category	Independent Variables
Supply chain quality assessment	• Do not directly track supply chain quality #
Demographics	• Type of healthcare provider o Hospital o Ambulatory care center o Long-term care facility o Health system/Network (IDS/IDN) o For-profit o Non-profit o Military/government affiliated o University affiliated
	• Size of organization (number of beds) • Size of organization (number of facilities) *#

Variable was eliminated by quadratic program selection for Supply Chain Maturity Model.

* Variable was eliminated by quadratic program selection for both Data Standards Readiness models.

Table 1. Summary of Independent Variables

The measures of current (Supply Chain Maturity) and future (Data Standards Readiness) supply chain performance are ordinal dependent variables. Ordered logistic regression is conducted here because it is statistically appropriate due to the use of ordinal response variables. Some authors suggest interpreting the coefficients of independent variables in ordered logistic regression models in terms of the effect they have on the dependent variable (Hoffman, 2004); this is how results are discussed here.

Ordered logistic regression, like other regression modeling, requires a complete data set with no “blanks” or missing values. There are two data sets used in this analysis, one for the Supply Chain Maturity model (n=750) and one for the Data Standards Readiness model (n=268). The Supply Chain Maturity model has more data points because the related question was open to all survey respondents, whereas the question related to Data Standards Readiness was only available to those respondents who first responded that their organization was moving towards adopting a system of data standards. Both data sets consist of all survey respondents from healthcare provider organizations who responded to each dependent variable respectively. Empty data cells exist in both data sets. The empty data cells result from a respondent providing a non-response such as “Do not know,” “Prefer not to respond,” or where no response at all was recorded. The amount of valid and missing data for each data set is summarized in Table 2.

Data Set	n	# of Independent Variables	# of Possible Data Points	# of Actual Valid Data Points	# of Missing Data Points
Supply Chain Maturity	750	59	44,250	43,950	300
Data Standards Readiness	268	59	15,812	15,752	60

Table 2. Data Set Summary

The missing data for both data sets must be resolved before ordered logistic regression analysis can be conducted. One method for dealing with missing data is imputation, which consists of a variety of techniques for estimating values for the missing responses (Little, 1988) and is not desirable in this study. Another method is to arbitrarily eliminate respondents and/or questions (independent variables) that contain missing data. A paper by Smith et al (2011c) presents a 0-1 quadratic program solution for eliminating missing data from a data set. The solution involves the use of a quadratic program to prescribe which respondents and/or independent variables should be eliminated such that the maximum amount of valid data is preserved while eliminating all missing data values (Smith et al, 2011c). This method is used to eliminate the missing data from both data sets. The general formulation is as follows:

Parameter:

$a_{ij} =$
1 if valid data exists for independent variable i and respondent j, 0 otherwise.

Decision variables:

$x_i = 1$ if independent variable i is preserved, 0 otherwise.

$y_j = 1$ if respondent j is preserved, 0 otherwise.

Objective function:

Maximize $\sum a_{ij} x_i y_j$

Subject to:

1. $x_i + y_j \leq 1 \;\nabla\; a_{ij} = 0$
2. $x_i, y_j = 0,1$

For the Supply Chain Maturity data set, 91.1% of the data was preserved when eliminating the respondents and independent variables prescribed by the quadratic program solution. The solution resulted in twenty-two respondents and four independent variables being excluded from the analysis. The independent variables eliminated are indicated in Table 1 above. The quadratic program solution preserves 18.3% more of the total valid data available than eliminating all respondents that contain missing data, and it preserves 0.7% more of the total valid data available than eliminating all independent variables containing missing data. A comparison of the data preserved from the quadratic program solution for the Supply Chain Maturity data set to the data preserved by eliminating all independent variables or respondents that contain missing data is shown in Table 3.

	# of Respondents Preserved	# of Independent Variables Preserved	Valid Data Cells Preserved	Valid Data Cells Lost	% of Valid Data Cells Preserved
Eliminating Respondents	542	59	31,978	11,972	72.8%
Eliminating Independent Variables	750	53	39,750	4,200	90.4%
Quadratic Program Solution	728	55	40,040	3,910	91.1%

Table 3. Data Set Preservation Summary: Supply Chain Maturity

Utilizing the quadratic program, 93.5% of the data was preserved for the Data Standards Readiness data set. The solution resulted in eight respondents and three independent variables being excluded from the analysis. The independent variables eliminated are indicated in Table 1. The quadratic program solution preserves 8.6% and 2.3% of the total valid data available than eliminating all respondents that contain missing data and eliminating all independent variables containing missing data, respectively. A comparison of the data preserved from the quadratic program solution for the Data Standards Readiness data set to the data preserved by eliminating all independent variables or respondents that contain missing data is shown in Table 4 below.

	# of Respondents Preserved	# of Independent Variables Preserved	Valid Data Cells Preserved	Valid Data Cells Lost	% of Valid Data Cells Preserved
Eliminating Respondents	224	59	13,216	2,536	84.9%
Eliminating Independent Variables	268	53	14,204	1,548	91.2%
Quadratic Program Solution	260	56	14,560	1,192	93.5%

Table 4. Data Set Preservation Summary: Data Standards Readiness

Identification of Impact Factors

Ordered logistic regression was utilized to develop the models for supply chain maturity and data standards readiness using Stata/SE 10.1. A description of ordered logistic regression is provided in Appendix A. The full ordered logistic regression results for supply chain maturity and data standards readiness are presented in Appendix B and Appendix C as well.

We asked respondents to identify the level of supply chain maturity within their organization to gain some insight into the current state of the healthcare supply chain. Table 5 contains the supply chain initiatives and organizational characteristics found to have a significant ($p < 0.05$) effect on supply chain maturity. The size of the healthcare provider organization was not found to have a significant impact on supply chain maturity. Our model shows that respondents belonging to a healthcare system or network are more likely to report a more mature supply chain in their organization as opposed to those who do not.

While collaboration with supply chain partners is believed to be important, our model finds that only collaboration with their suppliers has a significant effect on increasing the maturity of a healthcare provider's supply chain. We asked survey respondents to identify which supply chain stakeholders participated in their supply chain improvement initiatives including participation of executives and physicians/clinicians. The results show that executive involvement in supply chain improvement activities has a significant and positive impact on healthcare provider supply chain maturity. This finding is consistent with healthcare supply chain professionals we have spoken with who have stressed the importance of senior management support for supply chain improvement initiatives.

The survey respondents were presented with fourteen strategic initiatives recommended by the 1996 EHCR. Only one of the EHCR strategic initiatives is found to have a significant effect on supply chain maturity. Our model shows that those healthcare providers who have adopted automation for common supply chain processes in their organization are more likely to report having a more mature supply chain than those who did not. Eleven additional supply chain improvement activities found in the literature were also examined. Three of the eleven were found to have a significant positive impact on healthcare provider supply chain maturity, specifically standardizing purchasing procedures, increasing product traceability, and benchmarking supply chain operations against other supply chains. The literature identifies benchmarking as an important strategic initiative for the healthcare supply chain (Swinehart and Smith, 2004; Lauer, 2004; Davis, 2004); our model further supports this claim. In addition, the EHCR (1996), Langabeer (2005), and several experts we interviewed emphasize the importance of inventory management/reduction programs to the healthcare supply chain. However, the adoption of inventory management/reduction programs was not found to have a significant impact on supply chain maturity.

The survey respondents were asked to identify any perceived "barriers to supply chain excellence" within their organization. Of the twelve barriers presented, our model suggests that three have a significant negative effect on supply chain maturity. The model suggests that no visibility of end-to-end performance of business processes, interrupted information flow, and low ability to manage product utilization all have a negative impact on supply chain maturity. The three barriers are possible consequences of the lack of IT system maturity in healthcare as identified by Langabeer (2005).

Dependent Variable Category	Independent Variable	β	*p*-value
Collaboration	Collaborate with suppliers	0.457	0.018
EHCR Strategic Initiatives	Adopt automation	0.714	0.000
Other Supply Chain Improvement Initiatives	Standardize purchasing procedures	0.503	0.014
	Increase product traceability	0.539	0.002
	Benchmarking supply chain	0.566	0.001
Participation in Supply Chain Improvement Initiatives	Executives involved in improvement activities	0.357	0.027
Barriers to Supply Chain Improvement	No visibility of business processes	-0.524	0.003
	Interrupted information flow	-0.375	0.047
	Low product utilization management	-0.470	0.003
Demographics	Health System/Network	0.686	0.000

Table 5. Significant Independent Variables for Supply Chain Maturity

Table 6 displays the dependent variables found to have a significant ($p < 0.05$) effect on data standards readiness. Recall that respondents were asked to rate the level of data standards readiness in their organization on a scale from “very ready” to “not at all ready.” Negative model coefficients are to be interpreted as having a positive impact on the data standards readiness in a healthcare provider organization. The type of healthcare provider was not significant in the model for data standards readiness. However, the healthcare provider size, measured in number of beds, was found to be significant for the data standards readiness model. The coefficient for healthcare provider size is relatively small because it is measured in units of hospital beds, and some respondents employed by large IDNs reported the size of their organization as over ten thousand beds. Our results show that larger healthcare providers are more likely to be ready for data standards adoption.

Respondents reporting that their organization actively collaborates with other healthcare providers are more likely to be ready for data standards adoption. The results of the data standards readiness model show that physician/clinician involvement in improvement activities has a negative impact on the readiness of a healthcare provider organization to adopt data standards. Interestingly this means that organizations that actively engage with physicians/clinicians in their supply chain initiatives are less prepared for data standardization that those organizations who do not engage these professionals.

Two of the EHCR initiatives were found to have a significant impact on the data standards readiness of a healthcare provider organization. Healthcare providers that have simplified the rebate process and developed a total delivered cost mentality are more likely to be ready for data standards adoption. Only one of the eleven supply chain improvement initiatives not explicitly suggested by the EHCR, evaluate vendor performance, was found to have a significant positive effect on data standards readiness.

Multiple healthcare supply chain experts we interviewed believe that the adoption of data standards will require some modification and/or enhancement of IT infrastructure. Yet none of the IT related strategic initiatives such as increasing e-commerce transactions, implementing net billing, or increasing product traceability were found to have a significant impact on data standards readiness. Similarly, none of the IT related barriers such as no visibility of end-to-end performance of business processes, interrupted information flow, extended information lead times, and low ability to manage product utilization were found to have a significant impact on data standards readiness. The only barrier found to have a significant impact on data standards readiness was no visibility of end-to-end performance of business processes; this barrier has a negative impact on readiness.

Dependent Variable Category	Dependent Variable	β	*p*-value
Collaboration	Collaborate with other providers	-0.900	0.005
EHCR Strategic Initiatives	Simplify rebate process	-0.715	0.022
	Develop a total delivered cost mentality	-0.700	0.020
Other Supply Chain Improvement Initiatives	Evaluate vendor performance	-0.602	0.049
Participation in Supply Chain Improvement Initiatives	Physicians involved in improvement activities	0.747	0.040

Dependent Variable Category	Dependent Variable	β	*p*-value
Barriers to Supply Chain Improvement	No visibility of business processes	0.914	0.003
Demographics	Organization size (number of beds)	-2.6×10^{-4}	0.000

Table 6. Significant Dependent Variables for Data Standards Readiness

Conclusions and Future Work

The healthcare supply chain has been identified as an important area for reducing cost and improving the efficiency of healthcare delivery in the United States. However, the healthcare supply chain is not considered to be as mature or advanced as the supply chains of other industries. The 1996 EHCR, along with other studies, identified strategic initiatives that improve the healthcare supply chain. We have examined those initiatives and investigated their impact on the current maturity of healthcare providers' supply chains and the readiness of healthcare providers to adopt data standards in the future.

We identify several strategic initiatives and barriers that are important to the supply chain maturity of healthcare providers. While collaboration is believed to be important, collaboration with suppliers is identified as having a significant impact on healthcare supply chain maturity. Of the 25 specific strategic initiatives we studied, standardizing purchasing procedures, increasing product traceability, and benchmarking the supply chain are identified as having a significant impact on supply chain maturity. Healthcare providers should also note that specific IT related barriers are found to have a negative effect on supply chain maturity; our model suggests that healthcare providers should examine their operations and determine the level of visibility in their business processes, the continuity of information flow, and the level of product utilization management as these barriers are indicated to have a negative impact on supply chain maturity.

In examining the impact of strategic supply chain initiatives and barriers to the future of the healthcare supply chain as measured by readiness to adopt data standards, we again see that collaboration with one supply chain partner is perhaps more important than collaboration with others. We find that healthcare providers that collaborate with other healthcare providers are more likely to report that their organization is ready to adopt data standards. Three supply chain initiatives are found to positively affect the data standards readiness of a healthcare provider: two initiatives suggested by the EHCR, simplifying the rebate process and developing a total delivered cost mentality, and one other, evaluating vendor performance. The only barrier to supply chain improvement that is found to have a significant impact on the data standards readiness is that organizations having no visibility of business processes are less likely to be ready for data standards adoption. Curiously, having physicians involved with supply chain improvement activities in the organization is found to have a significant negative effect on data standards readiness. Finally, organization size measured in number of beds is found to have a significant effect on data standards readiness indicating that larger healthcare providers are more likely to be ready to adopt data standards.

Several opportunities exist to expand this work. The first priority would be to discuss these findings with healthcare supply chain professionals to obtain their reactions. Our research indicates that physician/clinician involvement in supply chain improvement activities has a negative effect on data standards readiness; this is a curious result, and it presents an opportunity for a separate study to further investigate the role that physicians/clinicians should play in supply chain management of healthcare providers. In addition, physician preference items (PPI) are often mentioned as a barrier to supply chain performance by several of the healthcare supply chain professionals we interviewed. Neither of our models indicate that PPI is having a significant negative impact on supply chain performance. A more in-depth study focused on the impact of PPI on healthcare provider supply chains is of interest. An opportunity exists to compare the supply chain initiative impacts factors identified here for healthcare providers with other healthcare organizations, such as industry manufacturers, distributors, and group purchasing organizations. Our current sample did not allow us to thoroughly study this comparison. As a long term goal, we plan to repeat the study in a few years to examine how the healthcare supply chain has changed over time and how data standards adoption has progressed.

Acknowledgements

This research was supported by the Center for Innovation in Healthcare Logistics at the University of Arkansas and the Association for Healthcare Resource and Materials Management of the American Hospital Association. Any opinions, findings, conclusions, or recommendations in this document are those of the authors and do not necessarily reflect views of the sponsors.

References

AHRMM, accessed June, 2011, "Are you ready?: What are data standards, and why are they important in the healthcare supply chain industry?," http://www.ahrmm.org/ahrmm_app/ext/standards/

Ballard, R., 2005, "Strategic supply cost management: physician preference without deference," Healthcare Financial Management, 59(4), 78-84.

Barlow, R.D., 2010, "FDA negotiates through device data standards stalemate," Healthcare Purchasing News, 34(2), 14-16.

Brennan, C. D., 1998, "Integrating the healthcare supply chain," Healthcare Financial Management, 52(1), 31.

Centers for Medicare and Medicaid Services, Office of the Actuary, "National Health Expenditure Projections 2009-2019", (September 2010).

Compas, B. J., 2005, "Strengthening the links in the supply chain – some preventive medicine," Journal of Healthcare Information, 19(2), 10-12.

Davis, R. N., 2004, "No more chances for supply-chain savings? look again!," Healthcare Financial Management, 58(1), 68-75.

"Efficient Healthcare Consumer Response: Improving the Efficiency of the Healthcare Supply Chain," 1996, American Hospital Association/American Society for Healthcare Materials Management.

Flower, J., 2005, "Mapping the future of health care," Physician Executive, 31(1), 60.

Ford, E. W., & Hughes, J. A., 2007, A collaborative product commerce approach to value-based health plan purchasing. Supply Chain Management, 12(1), 32-41.

Grossman, Robert J., "The Battle to Control Online Purchasing," *Materials Management in Health Care*, 9:3 (March 2000), pp. 22-27.

Hill, C. A., Zhang, G.P., Scudder, G.D., 2008 "An empirical investigation of EDI usage and performance improvement in food supply chains," IEEE Transactions on Engineering Management, 56(1), 61-75.

Langabeer, J., 2005, "The evolving role of supply chain management technology in healthcare," Journal of Healthcare Information Management, 19(2), 27-33.

Lauer, C., 2004, "Excellence in Supply Chain Management," Modern Healthcare, 34(50), 29-32.

Lockamy III, A., and McCormack, K., 2004, "The development of a supply chain management process maturity model using the concepts of business process orientation," Supply Chain Management: An International Journal, 9(4), 272-278.

Long, G., 2005, "Pursuing supply chain gains," Healthcare Financial Management, 59(9), 118-122.

McCullagh, P., 1980, "Regression models for ordinal data (with discussion)," Journal of the Royal Statistical Society, Series B, 42(2), 109-142.

McKone-Sweet, K. E., Hamilton, P., Willis, S. B., 2005, "The ailing healthcare supply chain: A prescription for change," The Journal of Supply Chain Management, 41(1), 4-17.

Nachtmann, Heather and Edward A. Pohl, "The State of Healthcare Logistics: Cost and Quality Improvement Opportunities," Center for Innovation in Healthcare Logistics, University of Arkansas, (July 2009).

Neumann, L., 2003, "Streamlining the supply chain," Healthcare Financial Management, 57(7), 56-62.

Ricupito, G., 2006, "Consignment trays and the hidden costs of sterilization," Materials Management in Health Care, 15(12), 32-36.

Roark, D. C., 2005, "Managing the healthcare supply chain," Nursing Management, 36(2), 36-40.

Schneller, E. S., & Smeltzer, L. R., 2006, "Strategic management of the health care supply chain," San Francisco, CA: Jossey-Bass, p. 30.

Smith, B.K., Nachtmann, H., Pohl, E.A., (2011a) "An investigation of the healthcare supply chain: literature review," Proceedings of the 2011 Industrial Engineering Research Conference.

Smith, B.K., Nachtmann, H., and Pohl, E.A., Quality measurement in the healthcare supply chain, to appear in The Quality Management Journal.

Smith, B.K., Nachtmann, H., and Pohl, E.A., (2011b) Improving healthcare supply chain processes via data standardization, submitted to the Engineering Management Journal (second revision under review by Engineering Management Journal).

Smith, B.K., Chimka, J.R., and Nachtmann, H., (2011c) A 0-1 quadratic program for the case of missing data in regression, submitted to International Journal of Data Analysis Techniques & Strategies (second revision under review by International Journal of Data Analysis Techniques & Strategies).

Solovy, A., 2004, A wired exchange. Materials Management in Health Care, 13(8), 27-31.

Swinehart, K. D. & Smith, A. E., 2005, "Internal supply Chain Performance Measurement: A Health Care Continuous Improvement Implementation," International Journal of Health Care Quality Assurance, 18(7), 533-542.

Vineet, Garg, Charles Jones, and Christopher Sheedy, 1999, "17 Billion Reasons to Say Thanks: The 25th Anniversary of the U.P.C. and Its Impact on the Grocery Industry," PricewaterhouseCoopers.

Appendix A

The models presented here rely on respondents reporting dependent variables, the level of Supply Chain Maturity and Data Standards Readiness in their organization, based on five-point, ordinal scales. We use ordered logistic regression for the analysis of these models as it is the most theoretically appropriate technique for estimating the relationships between ordered dependent variables and other independent variables (McCullagh, 1980).

The dependent variables are categorical and ordered. The ordered categories for Supply Chain Maturity are Ad Hoc, Defined, Linked, Integrated, and Extended, and the ordered categories for Data Standards Readiness are Very Ready, Ready, Both Ready and Marginally Ready, Marginally Ready, and Not at All Ready. We include fifty-five independent variables in the model of Supply Chain Maturity and fifty-six independent variables in the model of Data Standards Readiness. We chose to include these large numbers of independent variables to investigate the impact of strategic initiatives in as much detail as possible. Controlling for so many variables makes the models somewhat cumbersome but lowers the potential for confounding.

Ordered logistic regression in our models uses maximum likelihood to estimate coefficients β_j, four cutpoints κ_1, κ_2, κ_3, and κ_4, and a value for a linear function of independent variables x_j plus random error u. For the model of Supply Chain Maturity, let $N = 1$ if the respondent chooses Ad Hoc, let $N = 2$ if the respondent chooses Defined, let $N = 3$ if the respondent chooses Linked, let $N = 4$ if the respondent chooses Integrated, and let $N = 5$ if the respondent chooses Extended. For the model of Data Standards Readiness, let $N = 1$ if the respondent chooses Very Ready, let $N = 2$ if the respondent chooses Ready, let N = 3 if the respondent chooses Both Ready and Marginally Ready, let N = 4 if the respondent chooses Marginally Ready, and let N = 5 if the respondent chooses Not at All Ready. The probability of a respondent choosing a certain level of Supply Chain Maturity is equal to the probability that the function value is within a range of cutpoints as follows:

$$\Pr(N = 1) = \Pr(-\infty < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55} + u_1 \leq \kappa_1)$$

$$\Pr(N = 2) = \Pr(\kappa_1 < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55} + u_2 \leq \kappa_2)$$

$$\Pr(N = 3) = \Pr(\kappa_2 < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55} + u_3 \leq \kappa_3)$$

$$\Pr(N = 4) = \Pr(\kappa_3 < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55} + u_4 \leq \kappa_4)$$

$$\Pr(N = 5) = \Pr(\kappa_4 < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55} + u_5 \leq \infty)$$

The probability of a respondent choosing a certain level of Data Standards Readiness is equal to the probability that the function value is within a range of cutpoints as follows:

$$\Pr(N = 1) = \Pr(-\infty < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56} + u_1 \leq \kappa_1)$$

$$\Pr(N = 2) = \Pr(\kappa_1 < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56} + u_2 \leq \kappa_2)$$

$$\Pr(N = 3) = \Pr(\kappa_2 < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56} + u_3 \leq \kappa_3)$$

$$\Pr(N = 4) = \Pr(\kappa_3 < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56} + u_4 \leq \kappa_4)$$

$$\Pr(N = 5) = \Pr(\kappa_4 < \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56} + u_5 \leq \infty)$$

It is assumed that $u_{1\text{-}5}$ is logistically distributed as in logistic regression. The probability of a respondent choosing a certain level of Supply Chain Maturity is found as follows:

$$\Pr(N = 1) = \left(1 + \exp(-\kappa_1 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55})\right)^{-1}$$

$$\Pr(N = 2) = \left(1 + \exp(-\kappa_2 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55})\right)^{-1} - \left(1 + \exp(-\kappa_1 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55})\right)^{-1}$$

$$\Pr(N = 3) = \left(1 + \exp(-\kappa_3 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55})\right)^{-1} - \left(1 + \exp(-\kappa_2 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55})\right)^{-1}$$

$$\Pr(N = 4) = \left(1 + \exp(-\kappa_4 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55})\right)^{-1} - \left(1 + \exp(-\kappa_3 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55})\right)^{-1}$$

$$\Pr(N = 5) = \left(1 + \exp(-\kappa_4 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{55} x_{55})\right)^{-1}$$

The probability of a respondent choosing a certain level of Data Standards Readiness is found as follows:

$$\Pr(N = 1) = \left(1 + \exp(-\kappa_1 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56})\right)^{-1}$$

$$\Pr(N = 2) = \left(1 + \exp(-\kappa_2 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56})\right)^{-1} - \left(1 + \exp(-\kappa_1 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56})\right)^{-1}$$

$$\Pr(N = 3) = \left(1 + \exp(-\kappa_3 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56})\right)^{-1} - \left(1 + \exp(-\kappa_2 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56})\right)^{-1}$$

$$\Pr(N = 4) = \left(1 + \exp(-\kappa_4 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56})\right)^{-1} - \left(1 + \exp(-\kappa_3 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56})\right)^{-1}$$

$$\Pr(N = 5) = \left(1 + \exp(-\kappa_4 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{56} x_{56})\right)^{-1}$$

The maximum likelihood estimates of β_j are assumed to be normally distributed in ordered logistic regression. Ten independent variables were found to be significant with *p*-values less than 0.05 for the model of Supply Chain Maturity and are shaded in Appendix B. The cutpoints for the Supply Chain Maturity model are estimated to be κ_1 = 0.145, κ_2 = 2.813, κ_3 = 4.078, and κ_4 = 6.752. The chi-square goodness-of-fit statistic for the model of Supply Chain Maturity with fifty-five degrees of freedom is 333.8 (*p*-value approximately zero), therefore we reject the assumption of independence between the supply chain maturity of a healthcare provider organization and the independent variables.

Seven independent variables were found to be significant with *p*-values less than 0.05 for the model of Data Standards Readiness and are shaded in Appendix C. The cutpoints for the Data Standards Readiness model are estimated to be κ_1 = -2.104, κ_2 = -0.382, κ_3 = 1.085, and κ_4 = 3.617. The chi-square goodness-of-fit statistic for the model of Data Standards Readiness with fifty-six degrees of freedom is 104.7 (p-value approximately 0.0001), therefore we reject the assumption of independence between the data standards readiness of a healthcare provider organization and the independent variables.

Appendix B

Supply Chain Maturity	Number of observations	728				
	LR chi2(55)	333.8				
	Prob > chi2	0				
Log likelihood	Pseudo R2	0.163				
-857.703		Coef (β)	Std. Err	P>z	95% CI	
Collaboration	Collaborate suppliers*	0.457	0.193	0.018	0.078	0.836
	Collaborate distributors	-0.135	0.256	0.598	-0.636	0.366
	Collaborate GPOs	-0.083	0.294	0.779	-0.658	0.493
	Collaborate providers	-0.047	0.168	0.779	-0.375	0.281
	Collaborate prof. assns.	-0.159	0.163	0.327	-0.478	0.159
	Collaborate academic inst.	0.174	0.242	0.471	-0.299	0.648
	No barriers to collaboration	0.386	0.277	0.164	-0.157	0.929
EHCR Strategic Initiatives	Increase e-commerce	0.228	0.189	0.227	-0.142	0.598
	Adopt automation*	0.714	0.198	0.000	0.326	1.102
	Supplier certification	0.275	0.210	0.190	-0.136	0.687
	Net billing	-0.319	0.182	0.080	-0.676	0.038
	Simplify rebate process	0.027	0.180	0.882	-0.325	0.378
	Collection of outcomes data	0.311	0.160	0.052	-0.002	0.624
	Activity based costing	0.126	0.183	0.489	-0.232	0.485
	Total delivered cost mentality	0.004	0.177	0.984	-0.344	0.351
	Improve receiving function	0.042	0.168	0.803	-0.288	0.372
	Freight consolidation	0.055	0.163	0.737	-0.265	0.375
	Inventory mgmt./reduction	-0.272	0.204	0.182	-0.671	0.127
	Defining role of organization	0.032	0.179	0.858	-0.319	0.383
	Best practice teams	0.009	0.165	0.958	-0.314	0.331
	Outsource services	0.260	0.174	0.134	-0.080	0.601
Other Supply Chain Improvement Initiatives	Centralize/consolidate data	0.335	0.185	0.070	-0.028	0.697
	Improve invoice accuracy	0.296	0.168	0.078	-0.033	0.625
	Standardize purch. procedures*	0.503	0.205	0.014	0.100	0.906
	Evaluate vendor performance	-0.017	0.171	0.922	-0.352	0.318
	Improve services levels/fill rates	0.266	0.171	0.120	-0.070	0.601
	Increase product traceability*	0.539	0.177	0.002	0.192	0.886
	Reduce product stop points	0.165	0.173	0.338	-0.173	0.504
	Define procedures for PPI	0.259	0.171	0.130	-0.076	0.595
	Establish strategic partnerships	0.318	0.167	0.056	-0.009	0.644
	Benchmarking supply chain*	0.566	0.168	0.001	0.236	0.896
	Plan for supply disruptions	0.013	0.164	0.938	-0.309	0.335

Participation in Supply	Executives involved in imp.*	0.357	0.162	0.027	0.040	0.674
	Physicians involved in imp.	0.063	0.186	0.736	-0.303	0.428
Barriers to Supply Chain Improvement	No vis. of business processes*	-0.524	0.177	0.003	-0.871	-0.177
	Low product traceability	-0.205	0.167	0.220	-0.532	0.123
	Interrupted information flow*	-0.375	0.188	0.047	-0.744	-0.006
	Duplication of activities	-0.121	0.170	0.475	-0.454	0.211
	Long information lead times	-0.265	0.187	0.156	-0.632	0.101
	High rework due to bad data	-0.252	0.178	0.157	-0.601	0.097
	High customer variation	-0.010	0.157	0.951	-0.317	0.298
	Inability to match cost to output	0.104	0.179	0.560	-0.246	0.454
	Separation of provider and payer	-0.165	0.156	0.290	-0.472	0.141
	Low product utilization mgmt.*	-0.470	0.161	0.003	-0.785	-0.155
	Regulatory compliance	-0.054	0.244	0.825	-0.532	0.424
	Lack of data standards	-0.171	0.162	0.290	-0.488	0.146
Demographics	Hospital	0.107	0.215	0.620	-0.315	0.529
	Ambulatory care center	0.126	0.230	0.584	-0.324	0.575
	Long-term care facility	-0.418	0.289	0.148	-0.984	0.148
	Health System/Network*	0.686	0.195	0.000	0.304	1.068
	For-profit	0.244	0.305	0.425	-0.355	0.843
	Non-profit	0.054	0.169	0.751	-0.278	0.386
	Military/government	-0.456	0.322	0.156	-1.087	0.174
	University affiliated	-0.203	0.237	0.392	-0.666	0.261
	Organization size	1.150E-05	1.880E-05	0.541	-2.530E-05	4.830E-05
	Cut 1	0.145	0.445		-0.728	1.017
	Cut 2	2.813	0.463		1.905	3.720
	Cut 3	4.078	0.472		3.152	5.003
	Cut 4	6.752	0.524		5.725	7.780

Appendix C

Data Standards Readiness	Number of observations	260				
	LR chi2(56)	104.7				
	Prob > chi2	1.000E-04				
Log likelihood	Pseudo R2	0.136				
-331.417		Coef (β)	Std. Err	P>z	95% CI	
Collaboration	Collaborate suppliers	-0.157	0.338	0.643	-0.820	0.507
	Collaborate distributors	0.655	0.525	0.213	-0.375	1.685
	Collaborate GPOs	0.331	0.495	0.503	-0.639	1.302
	Collaborate providers*	-0.900	0.321	0.005	-1.528	-0.271
	Collaborate prof. assns.	-0.255	0.276	0.356	-0.795	0.286
	Collaborate academic inst.	0.589	0.419	0.159	-0.232	1.410
	No barriers to collaboration	-0.960	0.568	0.091	-2.073	0.154
EHCR Strategic Initiatives	Increase e-commerce	-0.273	0.414	0.510	-1.085	0.539
	Adopt automation	0.083	0.454	0.855	-0.806	0.973
	Supplier certification	-0.201	0.333	0.545	-0.853	0.450
	Net billing	0.024	0.286	0.933	-0.537	0.584
	Simplify rebate process*	-0.715	0.313	0.022	-1.330	-0.101
	Collection of outcomes data	0.205	0.273	0.453	-0.330	0.741
	Activity based costing	0.233	0.297	0.434	-0.350	0.816
	Total delivered cost mentality*	-0.700	0.302	0.020	-1.293	-0.108
	Improve receiving function	-0.142	0.315	0.652	-0.759	0.475
	Freight consolidation	-0.086	0.292	0.769	-0.658	0.486
	Inventory mgmt./reduction	0.172	0.391	0.660	-0.594	0.938
	Defining role of organization	0.405	0.306	0.185	-0.194	1.004
	Best practice teams	-0.286	0.318	0.367	-0.909	0.336
	Outsource services	0.100	0.301	0.739	-0.489	0.690
Other Supply Chain Improvement Initiatives	Centralize/consolidate data	-0.565	0.374	0.131	-1.298	0.169
	Improve invoice accuracy	0.168	0.316	0.595	-0.452	0.788
	Standardize purch. procedures	0.347	0.399	0.384	-0.434	1.128
	Evaluate vendor performance*	-0.602	0.306	0.049	-1.201	-0.003
	Improve services levels/fill rates	0.161	0.357	0.651	-0.538	0.861
	Increase product traceability	0.313	0.297	0.292	-0.269	0.895
	Reduce product stop points	-0.148	0.280	0.598	-0.697	0.402
	Define procedures for PPI	0.208	0.315	0.508	-0.409	0.826
	Establish strategic partnerships	-0.104	0.296	0.726	-0.683	0.476
	Benchmarking supply chain	-0.476	0.282	0.091	-1.029	0.076
	Plan for supply disruptions	-0.424	0.327	0.195	-1.064	0.217

Participation in Supply	Executives involved in imp.	0.068	0.287	0.814	-0.495	0.630
	Physicians involved in imp.*	0.747	0.364	0.040	0.033	1.461
Barriers to Supply Chain Improvement	No vis. of business processes*	0.914	0.308	0.003	0.311	1.517
	Low product traceability	0.548	0.280	0.051	-0.001	1.097
	Interrupted information flow	0.085	0.340	0.802	-0.581	0.751
	Duplication of activities	-0.004	0.320	0.991	-0.630	0.623
	Long information lead times	-0.311	0.329	0.345	-0.956	0.334
	High rework due to bad data	0.041	0.295	0.889	-0.538	0.621
	High customer variation	0.462	0.298	0.120	-0.121	1.046
	Inability to match cost to output	0.110	0.303	0.716	-0.484	0.704
	Separation of provider and payer	-0.399	0.281	0.156	-0.950	0.152
	Low product utilization mgmt.	-0.063	0.286	0.826	-0.623	0.497
	Regulatory compliance	0.115	0.421	0.785	-0.710	0.939
	Lack of data standards	0.508	0.297	0.088	-0.075	1.091
Supply Chain Quality	Do not track supply chain quality	0.821	0.611	0.179	-0.378	2.019
Demographics	Hospital	0.545	0.359	0.129	-0.158	1.248
	Ambulatory care center	-0.339	0.486	0.486	-1.292	0.615
	Long-term care facility	0.582	0.570	0.308	-0.536	1.699
	Health System/Network*	0.375	0.378	0.321	-0.366	1.115
	For-profit	0.377	0.623	0.545	-0.845	1.599
	Non-profit	0.173	0.325	0.594	-0.464	0.810
	Military/government	-0.523	0.532	0.325	-1.565	0.519
	University affiliated	-0.121	0.363	0.739	-0.833	0.591
	Organization size*	-2.582E-04	6.980E-05	0.000	-3.951E-04	-1.214E-04
	Cut 1	-2.104	0.967		-3.999	-0.208
	Cut 2	-0.382	0.949		-2.242	1.478
	Cut 3	1.085	0.955		-0.786	2.956
	Cut 4	3.617	0.982		1.692	5.542

6. CONCLUSIONS AND FUTURE WORK

This section reviews the conclusions of the three research contributions presented in this dissertation. In addition to these three contributions, the research conducted in support of this dissertation has resulted in six additional publications not included in this document. Smith et al (2008) presents an initial investigation of healthcare supply chain quality. Smith et al (2010a) provides a framework for using the balanced scorecard (Kaplan and Norton, 1992) to measure healthcare supply chain performance. An exploration of the potential synergy between kaizen events and data standards in healthcare is presented in Smith et al (2010b). The benefits of and barriers to data standardization and how engineering managers can support progress towards data standardization in an improved healthcare supply chain are presented and discussed in Smith et al (2009a) and in a second revision of a manuscript under review by the Engineering Management Journal (Smith et al, 2011c). Smith et al (2009b) offers data-driven insights into the adoption and success of strategic supply chain initiatives in healthcare. The literature review presented in Chapter 2 was published in the Proceedings of the 2011 Industrial Engineering Research Conference (Smith et al, 2011b).

In the first research contribution of this dissertation presented in Chapter 3, our review of relevant literature indicates that the topics of quality measurement and management in the healthcare supply chain are receiving increased attention by practitioners and researchers. During our expert interviews, we learned about the leap from supply chain quality to patient safety and the need to overcome this leap by developing quality measures that can assist in day-to-day management of healthcare supply chain operations. According to the experts we interviewed, the most significant factors influencing the quality of the healthcare supply chain are availability of materials, data standardization, high volume of transactions, integrity of the supply chain, poor product traceability, process variation, and quality of information and its exchange. We identify forty quality measures currently utilized by healthcare organizations to assess their supply chain performance from a quality perspective.

We utilize our adapted dimensions of quality taxonomy as a framework for assessing the multidimensional view of quality metrics currently used in the healthcare supply chain. We then determine which quality dimension best fits each metric and found that the vast majority of the identified healthcare supply chain quality metrics fell into three of eight modified dimensions of quality: performance, conformance, and features. This finding indicates that healthcare organizations are actively measuring the primary operating characteristics of their supply chain, the secondary operating characteristics that add value to the customer by enhancing the primary characteristics, and how well these characteristic of supply chain performance match established standards. Our analysis of healthcare supply chain quality metrics shows that healthcare organizations are not assessing the reliability, durability, or perceived quality of their supply chain quality. Clearly there is opportunity to improve quality measurement in the healthcare supply chain by developing metrics that assess how well their supply chain performs over time and the resiliency of their supply chain to failures. Additional opportunity lies in communicating the value of quality measurement and providing actionable quality management processes as we found that eleven percent of survey respondents do not directly track supply chain quality of their organization. Accepted for publication in the Quality Management Journal, this paper provides knowledge about current healthcare supply chain quality measurement practices which can help enable successful development and implementation of new quality measurement programs across the healthcare supply chain (Smith et al, 2011a).

Chapter 4 contains the second research contribution of this dissertation, a novel method for extracting valid response data from a dataset containing missing responses for the purpose of enabling regression analysis is presented. This method was used to develop data sets for analysis in Chapter 5. The major advantage of using the quadratic program to eliminate the missing values over arbitrary elimination is that the researcher can find comfort in the fact that the maximum amount of valid data is preserved. To justify the benefits of using the quadratic program in terms of time and accuracy a larger scale example appears in appendices of Chapter 4. We have created a sample from the famous Canadian lynx time series data (Elton and Nicholson, 1942). It began as the oldest complete set of twenty observations in time and the first nineteen lagged variables to constitute the 20 x 20 sheet shown in Appendix A of Chapter 4. Next we randomly removed from the 20 x 20 sheet approximately one third of the observations that remain in Appendix B of Chapter 4 to create a problem without obvious solution. It is shown in Appendix C of Chapter 4 with eliminated columns and rows shaded. In this example, arbitrarily removing columns or rows to eliminate missing observations will eliminate the entire data set. Here we have assumed that a question holds the same value as a respondent and that all questions and responses are equal. In other words we do not have a preference between whether a question or respondent is eliminated in order to resolve a missing data point. In the future we can modify the model presented here to include weights for questions and respondents according to the researcher’s preferences.

In Chapter 5, the final research contribution of this dissertation, it is noted that the healthcare supply chain has been identified as an important area for reducing cost and improving the efficiency of healthcare delivery in the United States. However, the healthcare supply chain is not considered to be as mature or advanced as the supply chains of other industries. The 1996 EHCR, along with other studies, have identified strategic initiatives that improve the healthcare supply chain. We have examined those initiatives and investigated their impact on the current maturity of healthcare providers' supply chains and the readiness of healthcare providers to adopt data standards in the future. We identify several strategic initiatives and barriers that are important to the supply chain maturity of healthcare providers. While collaboration is believed to be important, collaboration with suppliers is identified as having a significant impact on healthcare supply chain maturity. Of the twenty-five specific supply chain initiatives we studied, standardizing purchasing procedures, increasing product traceability, and benchmarking the supply chain are identified as having a significant impact on supply chain maturity. Healthcare providers should also note that specific IT related barriers are found to have a negative effect on supply chain maturity; our model suggests that healthcare providers should examine their operations and determine the level of visibility in their business processes, the continuity of information flow, and the level of product utilization management as these barriers are indicated to have a negative impact on supply chain maturity. In examining the impact of strategic supply chain initiatives and barriers to the future of the healthcare supply chain as measured by readiness to adopt data standards, we again see that collaboration with one supply chain partner is perhaps more important than collaboration with others. We find that healthcare providers that collaborate with other healthcare providers are more likely to report that their organization is ready to adopt data standards. Three supply chain initiatives are found to positively affect the data standards readiness of a healthcare provider: two initiatives suggested by the EHCR, simplifying the rebate process and developing a total delivered cost mentality, and one other, evaluating vendor performance. The only barrier to supply chain improvement that is found to have a significant impact on the data standards readiness is that organizations having no visibility of business processes are less likely to be ready for data standards adoption. Curiously, having physicians involved with supply chain improvement activities in the organization is found to have a significant negative effect on data standards readiness. Finally, organization size measured in number of beds is found to have a significant effect on data standards readiness indicating that larger healthcare providers are more likely to be ready to adopt data standards. Several opportunities exist to expand this work. The first priority would be to discuss these findings with healthcare supply chain professionals to obtain their reactions. Our research indicates that physician/clinician involvement in supply chain improvement activities has a negative effect on data standards readiness; this is a curious result, and it presents an opportunity for a separate study to further investigate the role that physicians/clinicians should play in supply chain management of healthcare providers. In addition, physician preference items (PPI) are often mentioned as a barrier to supply chain performance by several of the healthcare supply chain professionals we interviewed. Neither of our models indicate that PPI is having a significant negative impact on supply chain performance. A more in-depth study focused on the impact of PPI on healthcare provider supply chains is of interest. An opportunity exists to compare the supply chain initiative impacts factors identified here for healthcare providers with other healthcare organizations, such as industry manufacturers, distributors, and group purchasing organizations. Our current sample did not allow us to thoroughly study this comparison. As a long term goal, we plan to repeat the study in a few years to examine how the healthcare supply chain has changed over time and how data standards adoption has progressed.

This dissertation relies heavily on survey data, and the effects of nonresponses to survey questions had a large impact on conducting this research. An opportunity for expanding this work is to study the factors influencing the occurrence of nonresponses. It would be of benefit to future survey research if commonalities could be identified within the population of respondents that did not complete the survey entirely or supplied nonresponses; it may be possible to address those issues and decrease the amount of nonresponses in future data sets. Also, the time required to solve the 0-1 quadratic program eliminating missing data in Chapter 4 was shown to increase exponentially when approximately 24% of the data set is missing and randomly dispersed. However, the original data sets for the Supply Chain Maturity and Data Standards Readiness models in Chapter 5 contained only 0.7% and 0.4% missing data respectively, and the missing data was not randomly dispersed. The quadratic program was able to provide a solution to eliminate the missing data within a few seconds. The Supply Chain Maturity model contains 40,040 data cells, and the Data Standards Readiness model contains 14,560 cells; the quadratic program would not have been able to provide a solution if 24% of the data had been missing and randomly dispersed. Future work could explore the performance of the quadratic program solution for eliminating missing data in data sets with varying amounts of random and non-random missing data to better identify its applicability and limitations.

References

Elton, Charles and Mary Nicholson (1942), "The ten-year cycle in numbers of the lynx in Canada," Journal of Animal Ecology 11(2): 215-244

Kaplan, Robert S., and David P. Norton, "The Balanced Scorecard-Measures That Drive Performance," Harvard Business Review 70:1 (January/February 1992), pp. 71-79.

Smith, B.K., Nachtmann, H., and Pohl, E.A., (2011a) Quality measurement in the healthcare supply chain, to appear in *The Quality Management Journal*.

Smith, B.K., Nachtmann, H., and Pohl, E.A. (2011b) An investigation of the healthcare supply chain: literature review, *Proceedings of the 2011 Industrial Engineering Research Conference*.

Smith, B.K., Nachtmann, H., and Pohl, E.A., (2011c) Improving healthcare supply chain processes via data standardization, submitted to the Engineering Management Journal (second revision under review by Engineering Management Journal).

Smith, B.K., Nachtmann, H., and Pohl, E.A. (2010a) A balanced scorecard approach to measuring healthcare supply chain performance, American Society for Engineering Management Conference Proceedings.

Smith, B.K., Nachtmann, H., and Pohl, E.A. (2010b) Kaizen event effectiveness via healthcare logistics data standardization, Proceedings of the 2010 Industrial Engineering Research Conference.

Smith, B.K., Nachtmann, H., and Pohl, E.A. (2009a) Improving healthcare supply chain processes via data standardization, *American Society for Engineering Management Conference Proceedings*.

Smith, B.K., Nachtmann, H., Pohl, E.A., and Townsley, J.R. (2009b) Management initiatives in healthcare logistics, Proceedings of the 2009 Industrial Engineering Research Conference.

Smith, B.K., Nachtmann, H., and Pohl, E.A. (2008) Quality measures in the healthcare supply chain, *American Society for Engineering Management Conference Proceedings*.