# An Analytical Approach to Lean Six Sigma Deployment Strategies:

## Project Identification and Prioritization

by

Brett Duarte

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved November 2011 by the
Graduate Supervisory Committee:

John Fowler, Co-Chair
Douglas Montgomery, Co-Chair
Dan Shunk
Connie Borror
John Konopka

ARIZONA STATE UNIVERSITY

December 2011

# ABSTRACT

The ever-changing economic landscape has forced many companies to re-examine their supply chains. Global resourcing and outsourcing of processes has been a strategy many organizations have adopted to reduce cost and to increase their global footprint. This has, however, resulted in increased process complexity and reduced customer satisfaction. In order to meet and exceed customer expectations, many companies are forced to improve quality and on-time delivery, and have looked towards Lean Six Sigma as an approach to enable process improvement. The Lean Six Sigma literature is rich in deployment strategies; however, there is a general lack of a mathematical approach to deploy Lean Six Sigma in a global enterprise. This includes both project identification and prioritization. The research presented here is two-fold. Firstly, a process characterization framework is presented to evaluate processes based on eight characteristics. An unsupervised learning technique, using clustering algorithms, is then utilized to group processes that are Lean Six Sigma conducive. The approach helps Lean Six Sigma deployment champions to identify key areas within the business to focus a Lean Six Sigma deployment. A case study is presented and 33% of the processes were found to be Lean Six Sigma conducive.

Secondly, having identified parts of the business that are lean Six Sigma conducive, the next steps are to formulate and prioritize a portfolio of projects. Very often the deployment champion is faced with the decision of selecting a portfolio of Lean Six Sigma projects that meet multiple objectives which could include: maximizing productivity, customer satisfaction or return on investment, while meeting certain budgetary constraints. A multi-period 0-1 knapsack problem is presented that maximizes the expected net savings of the Lean Six Sigma portfolio over the life cycle of the deployment. Finally, a case study is presented that demonstrates the application of the model in a large multinational company.

Traditionally, Lean Six Sigma found its roots in manufacturing. The research presented in this dissertation also emphasizes the applicability of the methodology to the non-manufacturing space. Additionally, a comparison is conducted between manufacturing and non-manufacturing processes to highlight the challenges in deploying the methodology in both spaces.

# DEDICATION

To my Mother and Father who have encouraged, supported and motivated me through this entire process!

# ACKNOWLEDGMENTS

I would firstly like to thank my Co-Chairs, Dr. Fowler and Dr. Montgomery for the time and effort they have devoted to this research. Their guidance and counsel have been immeasurable through the course of this dissertation. I would also like to thank my committee members Dr. Shunk and Dr. Borror for their participation in this research, their insight and knowledge in the area is much appreciated.

I would also like to thank Dr. Konopka, my mentor at IBM, and a committee member on my research panel. His guidance, support, encouragement and motivation through this long are arduous process has been invaluable. Additionally, I would like to thank my manager Mr. Daniel Lofaro (IBM) for his encouragement and flexibility in what seemed an impossible task as I attempted to juggle school and work for last few years.

Finally, I would like to thank my friends at Paradise Bakery for the free coffee and cookies every evening for the last year. It certainly helped make the long hours less painful. And last but not the least; I would like to thank my girl friend Meghan Bullock for encouraging and supporting me through this entire process.

# TABLE OF CONTENTS

Page

CHAPTER

APPENDIX

# LIST OF TABLES

Table Page

# LIST OF FIGURES

Chapter 1

# INTRODUCTION

## 1. Overview

With the global nature of the world’s economy, the pressure to make and deliver the right product in a timely and cost effective manner is more important than ever. The pressure to meet and beat the competition has led many companies to re-examine their end to end supply chains and focus on improving the efficiency and effectiveness of their business. Manufacturing organizations frequently focus on producing defect free products in a timely manner while striving to maintain zero inventory levels. The service sector on the other hand focuses on providing the customer timely and accurate services around the clock. To compete in this economy, companies should not only focus on product differentiation, but also have to focus on cost. This has forced many organizations to resort to outsourcing and global resourcing.

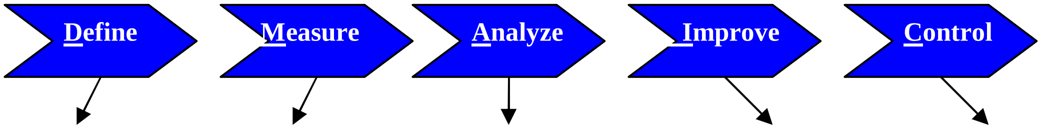
The advantage is clearly cost and expense reduction, in addition it provides the opportunity to tap into growth markets. The term “Multinational” company is passé; a “Global” company is truly one that utilizes the right resources in the right place to deliver the right products and services to the end customer in a timely and cost effective manner. This global nature of enterprises not only enables companies to take advantage of lower cost jurisdictions, but it also enables them to execute processes twenty-four-seven.

It isn’t hard to imagine that an order generated in the US could be processed by a center in New Delhi, India and finally fulfilled by operations in Shanghai, China. Follow-the-Sun isn’t just a business paradigm, it’s a competitive advantage and companies are beginning to leverage their world wide presence to stay ahead of the competition. There is a flip side! More hand-offs result in complicated processes with larger cycle times and more opportunity for defects to occur. Many companies have realized that outsourcing to lower cost jurisdictions comes with a price!

Over the years many organizations have resorted to quality improvement initiatives to streamline their processes and circumvent defects caused by increased process complexity. The history of quality improvement dates back to the early 1920’s with quality icons like Walter Shewhart, W. Edwards Deming, J.M. Juran and Feigenbaum. The history of quality initiatives has been well documented in the literature. For a comprehensive view, refer to (Montgomery and Woodall, 2008), (Montgomery, 2010), (Hahn *et al*., 2000), (Harry, 1998), and (Zua *et al.*, 2008). Ever since Shewhart, quality engineers have used a variety of tools to achieve process improvement. The fundamentals established by these early practitioners were the building blocks for improvement efforts in Japan. Toyota Production Systems, Lean thinking, Just In Time (JIT), Total Preventive Maintenance (TPM), Quality Function Deployment (QFD), Poka-Yoke, and Kaizen to name a few, were outcomes of work efforts conducted by Shingo and Ohno (Bodek, 2004). Toyota was responsible for propagating Lean thinking

(Spear and Brown, 1999). In the 1980's Motorola introduced Six Sigma. The methodology was a spin-off of the original Plan-Do-Study-Act (PDSA) cycle established by Deming. The DMAIC cycle (Define, Measure, Analyze, Improve and Control) was born, and it used a rigorous project management approach to process transformation. The approach used statistical tools and methodologies to drive fact based decision making. This quality improvement method was first crafted by Bill Smith at Motorola. By the late 80's Motorola had achieved unprecedented growth and sales and was recognized with the Malcolm Baldrige National Quality Award (Schroeder, 2008). Thereafter, it was popularized by Jack Welch the CEO of General Electric at the time. In 1995 Jack Welch initiated the Six Sigma program that aligned quality improvement efforts with the companies strategic and business goals. In the first five years of its Six Sigma campaign, General Electric estimated benefits in the billions, and since have managed to drive the methodology into the DNA of the organization (Snee and Hoerl, 2003). As is usually the case, one approach doesn't fit all situations and various programs have emerged over the years including the Malcolm Baldrige Award, ISO 9000, Total Quality Management (TQM), and TPM to name a few (http://www.quality.nist.gov/).

Today many companies have integrated the Lean focus of Toyota Production Systems, with the variance reduction focus of Six Sigma to create a hybrid process improvement approach (Thomas *et al*., 2008). With Lean focusing on the "speed" of the process and Six Sigma focusing on the accuracy, the combination has proven to be a powerful tool in driving efficiencies and effectiveness of processes. Figure 1 illustrates how Lean tools can be incorporated into the Six Sigma DMAIC (Define, Measure, Analyze, Improve, and Control) cycle.



| Define | Measure | Analyze | Improve | Control |
|---|---|---|---|---|
| **Objective**<br>To define a clear business problem, to identify the objective of the project and establish a team to address the issue. To understand the AS-IS process | **Objective**<br>Establish a baseline for the current state (AS-IS) based on an appropriate sample size and to ensure that the operational metric are correct | **Objective**<br>To stratify, analyze and identify root causes for a the business problem | **Objective**<br>To identify, evaluate, and implement solutions. To validate the changes through a pilot. To improve the existing process | **Objective**<br>Process Monitoring and control, validate recommendations. Statistical Process Control and monitoring. |
| **Lean Tools**<br>• Value Stream Mapping (VSM)<br>• Kaizen Events | **Lean Tools**<br>• Value Stream Mapping (VSM)<br>• Takt Time/and Demand Management<br>• Kaizen Events | **Lean Tools**<br>• Value Stream Mapping (VSM)<br>• Takt Time/and Demand Management<br>• Jidoka<br>• Kaizen Events | **Lean Tools**<br>• Just in Time, Pull Systems & Kanban<br>• Continuous Flow and Set up reduction<br>• SMED<br>• Poke Yoke<br>• Visual Management<br>• The 5S Method<br>• Kaizen Events<br>• Heijunka<br>• Jidoka | **Lean Tools**<br>• Takt Time/and Demand Management<br>• Visual Management<br>• Andon<br>• The 5S Method (Process documentation)<br>• Kaizen Events (Not as intensive) |

**Fig. 1.** Integrating Lean and Six Sigma

Lean Six Sigma has become a widely recognized process improvement methodology and has been adopted by many companies like Ford, DuPont, 3M, Dow Chemicals, and Honeywell. At present, the methodology has been carried out in 35 percent of companies listed in the Forbes top 500 (Ren and Zhang, 2008). In addition, Lean Six Sigma has found its place in many healthcare related companies (Atallah and Ramudhin 2010) and in finance and banking (Zhang and Liu 2007), highlighting its applicability to not just manufacturing processes and new product introduction, but also to the transactional space and business/administrative processes.

## 2. Motivation

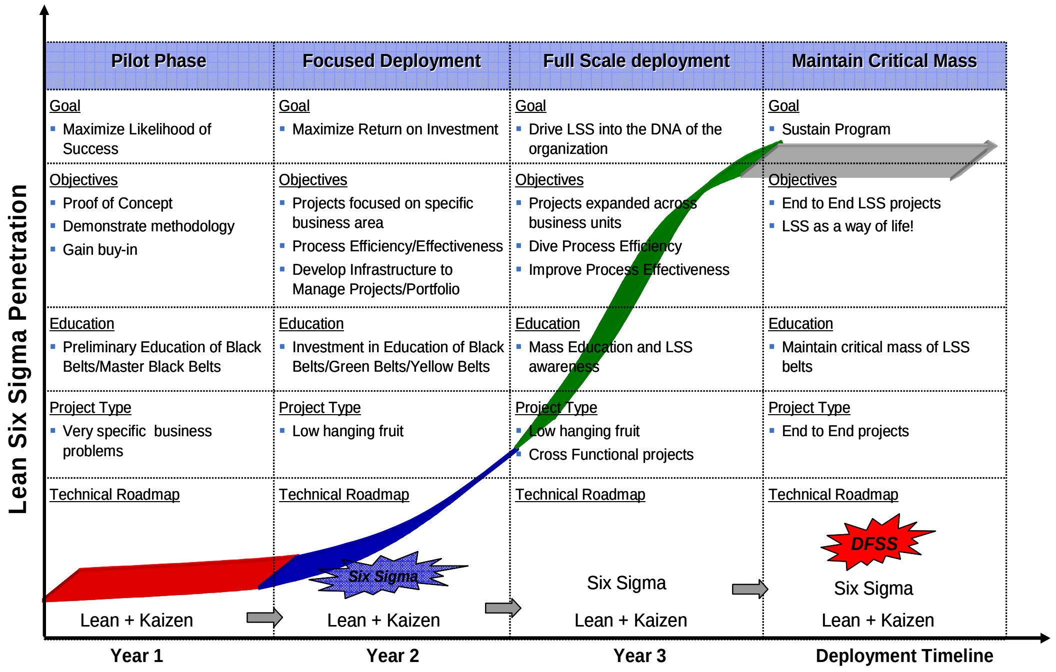
Lean Six Sigma has been around for over thirty years. Many companies have utilized the methodology with great success. In general the approach has been to align Lean Six Sigma deployments with the strategy of the organization (Snee and Rodebaugh, 2002) and (Linderman *et al.*, 2003). The strategy typically includes a plan that addresses the high level goals of the organization be it: Sales growth, earnings per share, profit, or return on invested capital, each of which drives at satisfying the share holder (Banuelas *et al.*, 2006). The strategic objectives are then broken down into performance metrics at the operational level. In classic Six Sigma terminology the “Big Y” is broken into “smaller y’s” and plans are put in place to address each “small y” at the operational level. Most companies use this approach to create a Six Sigma portfolio that helps meet the strategic goals of the organization. The reasons for deploying Lean Six Sigma often include poor financial performance, diminishing customer satisfaction, increased competition or the existence of a burning platform/problem area. There are multiple deployment models that are widely used in the industry today. There isn’t a single recipe that fits all Lean Six Sigma deployments. Clearly, a number of factors govern which approach might work best for an organization. The trick, however, is to adapt these approaches to fit the culture of the organization.

Many companies have employed the Lean Six Sigma approach. For these companies the question is typically not whether to implement Lean Six Sigma but how. Not all companies have experienced the same level of success deploying Lean Six Sigma. It is as much a culture change as a strategic initiative and many companies have struggled to adopt and sustain their programs. Part of the lack of success is based on a weak project identification and selection process (Mader, 2007). Selecting six sigma projects is one of the most frequently discussed issues in the six sigma literature today (Kumar and Anthony, 2009). Ever since Lean Six Sigma gained its reputation as a methodology that drives bottom line results, researchers have studied the field. A survey conducted by the Aviation Week magazine reported that less than 50 percent of the companies expressed satisfaction with results from six sigma projects. Nearly 30 percent were dissatisfied and around 20 percent were somewhat satisfied (Zimmerman and Weiss, 2005). The article noted that one of the major reasons for this lack of success was an ad hoc approach to project selection, and that approximately 60 percent of the companies did not have a formal project selection and identification approach. This has lead to a lot of research in the area of project selection and prioritization. Banuelas *et al.* (2006) conducted a survey of companies in the United Kingdom to understand their Lean Six Sigma project identification and selection process. The results of the survey indicated that the majority of the companies used brainstorming techniques, Critical-to-Quality (CTQ) trees, focus groups, interviews, customer visits, Quality Function Deployment (QFD), Kano analysis, and surveys. A small number of respondents implement value stream mapping, and balance scorecards as an aid in the identification of projects. Identifying the right project is crucial, since Lean Six Sigma works best for a specific type of business problems. Very little work has been done to evaluate parts of an organization that are Lean Six Sigma conducive. Identifying Lean Six Sigma opportunities is a crucial step, as the success of a Lean Six Sigma deployment depends on how and where it is applied. The subsequent sections in this dissertation describe various approaches to deploy Lean Six Sigma in a global enterprise. The critical success factors are highlighted, and a model to aid in project identification and selection is described. The model establishes the evaluation criterion that enables six sigma practitioners to identify parts of the business that are Lean Six Sigma conducive, a topic that is typically not addressed in the literature today. A mathematical approach is presented that attempts to bridge this gap in the literature by using an unsupervised learning approach, using a clustering algorithm, to group processes based on eight process characteristics. The cluster evaluation helps the deployment champion identify key areas within the business to focus a Lean Six Sigma deployment. The clustering approach can be applied to any industry segment, including non-manufacturing, healthcare and financial based organizations.

Identifying parts of the business that are Lean Six Sigma conducive is the first step in a deployment, however, once a given set of projects have been identified, it becomes exceedingly important to formulate and prioritize a portfolio of Lean Six Sigma projects that meets the strategic direction of the organization. Many Lean Six Sigma practitioners use cost-benefit analysis, Pareto charts, un-weighted scoring models, and non-numerical models as a prioritization approaches. Lean Six Sigma portfolio optimization is a critical element in the overall deployment. Having identified a number of potential Lean Six Sigma projects, deployment champions are often faced with the following questions: How many projects can be executed given a limited number of resources? What is the ideal project mix? How do you maximize your return on investment? How quickly do you deploy the methodology for the program to be sustainable? For a portfolio of projects, the process of identifying a subset of priority projects to execute given a set of multiple objectives is a non-trivial decision. As the portfolio grows in size this decision becomes significantly more difficult. The problem of achieving the most desirable outcome by allocating limited resources to competing activities is perhaps the most common application of operations research. The literature on portfolio optimization is rich. Traditionally, Six Sigma project selection uses impact versus effort to prioritize project. Kumar and Anthony, (2009c) proposed a hybrid methodology using an Analytic Hierarchy Process (AHP) and a Project Desirability Matrix (PDM) for project prioritization. Su and Choua, (2008) developed a very similar approach using Analytic

Hierarchy Process (AHP) models in conjunction with Failure Mode Effects Analysis (FMEA) to evaluate the risk of each project in a semiconductor company. Ren and Zhang, (2008) proposed an evaluation method for project selection based on a multi-criteria decision-making method that uses fuzzy set theory and Kumar *et al.,* (2007a, 2008b) describe a method to prioritize Lean Six Sigma projects using data envelopment techniques. In their research a mathematical model is used to select one or more Six Sigma projects that will result in the maximum benefit to the organization. Yang and Hsieh, (2008) also use a hierarchical criteria evaluation process for project selection using a fuzzy multi-criteria decision-making method. The approach is demonstrated through a case study of a component manufacturer. Kahraman (2008) have presented a combined fuzzy Analytic Hierarchy Process (AHP) and fuzzy goal programming approach to determine the preferred compromise solution for a six-sigma project selection problem with multiple objectives. In the paper, the author considers several factors including the maximization of financial benefits of the projects, maximization of process capability, maximization of customer satisfaction, minimization of cost, minimization of project completion time and the minimization of risk. A fuzzy Analytic Hierarchy Process (AHP) is then used to specify judgment about the relative importance of each goal in terms of its contribution to the achievement of the overall goal. Stewart (1991) discusses a multi-criteria decision support system for research and development (R&D) project selection carried out in a large electric utility corporation. He proposes a non-linear knapsack problem. Sowlati *et al.*, (2005) presents a model using a data envelopment analysis framework for prioritizing information system based projects. A set of sample/artificial projects is created for which the criteria and priority scores are defined by decision makers. Each project is compared to the set of defined projects and receives a score. The model is tested on a real case of prioritizing information system based projects at a large financial institution. De Lima and De Sousa (2009) use a Multi-criteria Decision Aid (MDA) approach to support the decision-making process for research and development project for the Brazilian aerospace sector. The proposed method makes use of existing methods and techniques found in the literature, such as cognitive mapping and Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) to prioritize projects. Manalo (2010) use an Analytic Hierarchy Process (AHP) to optimize capital investment decision. The model developed used performance measurements like service cost, support cost and social cost in addition to more traditional methods like net present value to prioritize their project portfolio. Kendrick (2002) also suggests the use of an Analytic Hierarchy Process (AHP) method in Lean Six Sigma prioritization decisions. Dickinson *et al*., (2001) developed a dependency matrix approach for project prioritization at Boeing Corporation. The authors use a dependency matrix, which quantifies the interdependencies between projects. A nonlinear, integer program model was then developed to optimize project selection. The model also balances risk, overall objectives, and the cost and benefit of the entire portfolio. Abe (2007) propose a two-stage methodology based on (1) correlation analytics for identifying key drivers of business performance and (2) advanced portfolio optimization techniques for selecting optimal business-transformation portfolios given a set of budget constraints. Hu *et al.*, (2008) presents a multi-objective formulation for project portfolio selection problem in manufacturing companies. The model presented is a multi-objective formulation where the benefit objective function is novel and the weights of the multiple objectives can be flexibly determined by the corporate management team. The output is a Pareto frontier chart that allows decision makers to have the flexibility of choosing the optimal decision based on the specific focus which may change over time. The two objectives considered in the research are to minimize the cost of implementing the portfolio while maximizing the return on investment. In their objective function, Hu *et al.,* have gone beyond the simple summation of the benefit from each project chosen, they have also considered the interactions that may exist among projects during implementation. The model proposed considers three constraints. 1) The available number of Black Belt resources to execute projects. 2) A diversity constraint is included to diversify the portfolio and 3) A constraint on the number of projects that can be executed is also imposed. Kumar *et al.*, (2008b) present two optimization models that can assist management in choosing process improvement opportunities. The first model maximizes the quality level of a process under cost constraint, while the second model maximizes returns.

Typically the literature shows that companies tend to achieve a better result when applying a portfolio based approach to project selection. As described in the preceding paragraph, a significant amount of work has been done in the area of Lean Six Sigma project prioritization and portfolio optimization. The research presented in this dissertation, however, considers portfolio optimization across the lifecycle of a Lean Six Sigma deployment. Most companies will go through an evolutionary Lean Six Sigma deployment, which consists of multiple phases like; 1) A Pilot or Proof of Concept phase, 2) A Focused Deployment within a specific area of the business 3) A Full-Scale Deployment resulting in mass education across the organization and finally 4) Maintain and Sustain Lean Six Sigma program. Figure 2 describes this process.



| Pilot Phase | Focused Deployment | Full Scale deployment | Maintain Critical Mass |
|---|---|---|---|
| Goal<br>▪ Maximize Likelihood of Success | Goal<br>▪ Maximize Return on Investment | Goal<br>▪ Drive LSS into the DNA of the organization | Goal<br>▪ Sustain Program |
| Objectives<br>▪ Proof of Concept<br>▪ Demonstrate methodology<br>▪ Gain buy-in | Objectives<br>▪ Projects focused on specific business area<br>▪ Process Efficiency/Effectiveness<br>▪ Develop Infrastructure to Manage Projects/Portfolio | Objectives<br>▪ Projects expanded across business units<br>▪ Dive Process Efficiency<br>▪ Improve Process Effectiveness | Objectives<br>▪ End to End LSS projects<br>▪ LSS as a way of life! |
| Education<br>▪ Preliminary Education of Black Belts/Master Black Belts | Education<br>▪ Investment in Education of Black Belts/Green Belts/Yellow Belts | Education<br>▪ Mass Education and LSS awareness | Education<br>▪ Maintain critical mass of LSS belts |
| Project Type<br>▪ Very specific business problems | Project Type<br>▪ Low hanging fruit | Project Type<br>▪ Low hanging fruit<br>▪ Cross Functional projects | Project Type<br>▪ End to End projects |
| Technical Roadmap<br>Lean + Kaizen | Technical Roadmap<br>Six Sigma<br>Lean + Kaizen | Technical Roadmap<br>Six Sigma<br>Lean + Kaizen | Technical Roadmap<br>DFSS<br>Six Sigma<br>Lean + Kaizen |

**Fig. 2**. Lean Six Sigma Deployment Wave

In each of these phases, the deployment champion could have multiple objectives which vary from maximizing the likelihood of success and cost reduction to minimizing the investment required to sustain the program. A multi-period, 0-1 knapsack problem is presented, where the value of each potential project considered in the portfolio is phase dependent. A case study is then presented to demonstrate the application of the model in a large multi-national organization.

Additionally, the research presented in this dissertation discusses the differences in deploying Lean Six Sigma in the manufacturing space versus the non-manufacturing space by highlighting the differences in some key process characteristics like process structure, data availability and metric. An analysis is provided that evaluates the compatibility of various business functions including areas like Sales and Marketing, which traditionally have not been common grounds for Lean Six Sigma

## 3. Organization of Dissertation

This dissertation is organized into five chapters. The first chapter provides and overview of Lean Six Sigma as a quality improvement initiative and highlights the motivation behind the research conducted in this dissertation. Chapter two, three and four are meant to be stand alone journal articles. Additionally, Chapter two and three focus on the first element of this dissertation: Project Identification.

Chapter four discuss Lean Six Sigma portfolio optimization and Chapter five provides a summary and conclusion of the research carried out, and presents future opportunities for research in the area of Lean Six Sigma project identification and prioritization. Please note that the organization of this dissertation leads to some redundant content between chapters.

## Chapter 2

# DEPLOYING LEAN SIX SIGMA IN A GLOBAL ENTERPRISE: PROJECT IDENTIFICATION

## 1. Abstract

The purpose of this paper is to provide Lean Six Sigma deployment champions with a structured approach to identify and prioritize parts of their business that are conducive to the Lean Six Sigma methodology. A five step approach to Lean Six Sigma project identification is presented in this paper. The approach utilizes a clustering technique to group similar processes based on eight process characteristics. The clusters formed are then evaluated and prioritized for their compatibility to Lean Six Sigma. The clustering approach can be applied to any industry segment, including non-manufacturing, healthcare and financial based organizations. A case study is presented in this paper in which the approach is applied to an IT based company, 30 processes were found to be Lean Six Sigma conducive. There is a general lack of a mathematical approach to enable Lean Six Sigma practitioners to identify parts of their business that are conducive to the methodology. This research attempts to bridge this gap in the literature by using an unsupervised learning approach, using a clustering algorithm, to group processes based on eight process characteristics. The cluster evaluation helps the deployment champion identify key areas within the business to focus an LSS deployment.

***Key Words –*** Lean Six Sigma, Project Identification, Clustering, deployment Strategy

## 2. Introduction

With the global nature of the world's economy, the pressure to make and deliver the right product in a timely and cost effective manner is more important than ever. The pressure to meet and beat the competition has led many companies to examine their end to end supply chains and focus on improving the efficiency and effectiveness of their business. Manufacturing organizations frequently focus on producing defect free products in a timely manner while striving to maintain zero inventory levels. The service sector on the other hand focuses on providing the customer timely and accurate services around the clock. To compete in this economy, companies should not only focus on product differentiation, but also have to focus on cost. This has forced many organizations to resort to outsourcing and global resourcing. The advantage is not only cost reduction. It also provides the opportunity to tap into growth markets. The term "Multinational" company is passé; a "Global" company is truly one that utilizes the right resources in the right place to deliver the right product and services to the end customer in a timely and cost effective manner. This global nature of enterprises not only enables companies to take advantage of lower cost jurisdictions, but it also enables them to execute processes twenty-four-seven.

It isn’t hard to imagine that an order generated in the US, could be processed by a center in New Delhi, India and finally fulfilled by operations in Shanghai, China. Follow-the-Sun isn’t just a business paradigm, it’s a competitive advantage and companies are beginning to leverage their world wide presence to stay ahead of the competition. There is a flip side! More hand-offs result in complicated processes with larger cycle times and more opportunity for defects to occur. Many companies have realized that outsourcing to lower cost jurisdictions comes with a price!

Over the years many organizations have resorted to quality management initiatives to streamline their processes and circumvent defects caused by increased complexity. The history of quality management dates back to the early 1920’s with quality icons like Walter Shewhart, W. Edwards Deming, J.M. Juran and Feigenbaum. The history of quality initiatives has been well documented in the literature. For a comprehensive view, refer to (Montgomery and Woodall, 2008), (Montgomery, 2010), (Hahn *et al*., 2000), (Harry, 1998), and (Zua *et al.*, 2008). Ever since Shewhart, quality engineers have used a variety of tools to achieve process improvement. The fundamentals established by these early practitioners were the building blocks for improvement efforts in Japan. Toyota Production Systems, Lean thinking, JIT, TPM, QFD, Poka-Yoke, and Kaizen to name a few, were outcomes of work efforts conducted by Shingo and Ohno (Bodek, 2004). Toyota was responsible for propagating Lean thinking (Spear and Brown, 1999). In the 1980’s Motorola introduced Six Sigma. The methodology was a spin-off of the original Plan-Do-Study-Act (PDSA) cycle established by Deming. The DMAIC cycle (Define, Measure, Analyze, Improve and Control) was born, and it used a rigorous project management approach to process transformation. The approach used statistical tools and methodologies to drive fact based decision making. This quality improvement method was first crafted by Bill Smith at Motorola. By the late 80’s Motorola had achieved unprecedented growth and sales and was recognized with the Malcolm Baldrige National Quality Award (Schroeder *et al.*, 2008). Thereafter, it was popularized by Jack Welch the CEO of General Electric at the time. In 1995 Jack Welch initiated the Six Sigma program that aligned quality improvement efforts with the companies strategic and business goals. In the first five years of its Six Sigma campaign, General Electric estimated benefits in the billions, and since have managed to drive the methodology into the DNA of the organization (Snee and Hoerl, 2003). As is usually the case, one approach doesn’t fit all situations and various programs have emerged over the years including the Malcolm Baldrige Award, ISO 9000, TQM, and TPM to name a few (http://www.quality.nist.gov/).

Today many companies have integrated the lean focus of Toyota Production Systems, with the variance reduction focus of Six Sigma, to create a hybrid process improvement approach (Thomas *et al*., 2008). With Lean focusing on the “speed” of the process and Six Sigma focusing on the accuracy, the combination has proven to be a powerful tool in driving efficiencies and effectiveness. Lean Six Sigma has become a widely recognized process improvement methodology and has been adopted by many companies like Ford, DuPont, 3M, Dow Chemicals, and Honeywell. At present, the methodology has been carried out in 35 percent of companies listed in Forbes top 500 (Ren and Zhang, 2008). In addition, Lean Six Sigma has found its place in many healthcare related companies (Atallah and Ramudhin 2010) and in finance and banking (Zhang and Liu 2007), highlighting its applicability to not just manufacturing processes and new product introduction, but also to the transactional space and business/administrative processes.

Many companies have employed the Lean Six Sigma approach. For these companies the question is typically not whether to implement Lean Six Sigma but how. Not all companies have experienced the same level of success deploying Lean Six Sigma. It is as much a culture change as a strategic initiative and many companies have struggled to adopt and sustain their programs. Part of the lack of success is based on a weak project identification and selection process (Mader, 2007). Selecting six sigma projects is one of the most frequently discussed issues in the six sigma literature today (Kumar and Anthony, 2009). Ever since Lean Six Sigma gained its reputation as a methodology that drives bottom line results, researchers have studied the field. A survey conducted by the Aviation Week magazine reported that less than 50 percent of the companies expressed satisfaction with results from six sigma projects. Nearly 30 percent were dissatisfied and around 20 percent were somewhat satisfied (Zimmerman and Weiss, 2005). The article noted that one of the major reasons for this lack of success was an ad hoc approach to project selection, and that approximately 60 percent of the companies did not have a formal project selection and identification approach. This has lead to a lot of research in the area of project selection and prioritization. Banuelas *et al.* (2006) conducted a survey of companies in the United Kingdom to understand their Lean Six Sigma project identification and selection process. The results of the survey indicated that the majority of the companies used brainstorming techniques, Critical-to-Quality (CTQ) trees, focus groups, interviews, customer visits, Quality Function Deployment (QFD), Kano analysis, and surveys. A small number of respondents implement value stream mapping, and balance scorecards as an aid in the identification of projects. The study also indicated that cost-benefit analysis, Pareto charts, un-weighted scoring models, and non-numerical models were the most popular prioritization approaches.  Kumar and Anthony (2009) proposed a hybrid methodology using an Analytical Hierarchy Process (AHP) and a project desirability matrix (PDM) for project selection. The approach was applied to a die-casting company. Su and Choua (2008) developed a very similar approach using an analytical hierarchy process models in conjunction with failure mode effects analysis (FMEA) to evaluate the risk of each project. They present a case study and demonstrate the use of the approach in a semiconductor company. Ren and Zhang (2008) proposed an evaluation method for project selection based on a multiple criteria decision-making method based on fuzzy set theory. Kumar *et al.* (2007, 2008) describe a method to prioritize Six Sigma projects using data envelopment techniques. In their research a mathematical model is used to select one or more Six Sigma projects that will result in the maximum benefit to the organization. Traditionally, Six Sigma project selection uses impact versus effort to find out desirable Six Sigma project. Yang and Hsieh (2008) propose a hierarchical criteria evaluation process for project selection using a fuzzy multiple criteria decision-making method. The approach is demonstrated through a case study applied to a component manufacturer. Hu *et al.* (2008) present a decision support system that utilizes a multi-objective formulation for project portfolio selection problem in manufacturing companies. Kumar *et al.* (2008) present two optimization models that can assist management in choosing process improvement opportunities. The first model maximizes the quality level of a process under a total cost constraint while the second model maximizes returns. Typically the literature shows that companies tend to achieve a better result when applying a portfolio based approach to project selection.

Selecting Six Sigma projects is one of the most frequently discussed issues in the literature today. Most of the literature, as described above, speaks through project prioritization. Very little work has been done to evaluate parts of an organization that are Lean Six Sigma conducive. Identifying Lean Six Sigma opportunities is a crucial step, as the success of a Lean Six Sigma deployment depends on how and where it is applied. The subsequent sections in this paper describe various approaches to deploy Lean Six Sigma in a global enterprise. The critical success factors are highlighted, and a model to aid in project identification and selection is described. The model establishes the evaluation criterion that enables six sigma practitioners to identify parts of the business that are Six Sigma conducive, a topic that is typically not addressed in the literature today. In addition, a case study is presented that demonstrates the use of the model in a large global company. Finally, future research in this area is highlighted.

## 3. Lean Six Sigma Deployment Strategy

Lean Six Sigma has been around for over thirty years. Many companies have utilized the methodology with great success. In general the approach has been to align Lean Six Sigma deployments with the strategy of the organization (Snee and Rodebaugh, 2002) and (Linderman *et al.*, 2003). The strategy typically includes a plan that addresses the high level goals of the organization be it: Sales growth, earnings per share, profit, or return on invested capital, each of which drives at satisfying the share holder (Banuelas *et al.*, 2006). The strategic objectives are then broken down into performance metrics at the operational level. In classic Six Sigma terminology the "Big Y" is broken into "smaller y's" and plans are put in place to address each "small y" at the operational level.  Most companies use this approach in creating a Six Sigma portfolio that helps meet the strategic goals of the organization.

The reasons for deploying Lean Six Sigma often include poor financial performance, diminishing customer satisfaction, increased competition or the existence of a burning platform/problem area. There are multiple deployment models that are widely used in the industry today. Table 1 illustrates various deployment approaches that are used along with some of the pros and cons of using the approach.

**Table 1.** Lean Six Sigma Deployment Strategies

| Deployment Strategy | Pros | Cons |
|---|---|---|
| Tops-Down Approach (Company Wide) | • Quick dissemination of knowledge<br>• End to End projects<br>• Large ROI | • Large initial Investment required<br>• Higher Risk<br>• Large Scope and Complexity |
| Partial Deployment | • Narrow Scope<br>• Reduced Complexity<br>• Easier to Navigate through organization – Change Management | • Narrow scope potentially sub-optimizes supply chain<br>• Longer time to deploy<br>• Smaller ROI |
| Focused Deployment | • Quick Wins<br>• Address burning platforms | • Narrow scope potentially sub-optimizes supply chain<br>• Smaller ROI |

Some companies use a top-down organization wide approach, which is driven by strong governance (Gates, 2007). General Electric is a classical example of a top-down Lean Six Sigma deployment approach. This approach is characterized by a quick dissemination of knowledge resulting in end to end projects with large results. This approach requires strong executive commitment and company wide acceptance to change. The initial investment of starting the deployment can be high, and hence this approach comes with a higher risk attached. In addition to the company wide holistic approach, some companies focus their Lean Six Sigma deployments on specific functional areas or business units. This is often referred to as a partial deployment. The advantage to this approach lies in its scale, with a narrower scope the deployment can focus on specific business issues while taking advantage of reduced complexity. The smaller focus helps establish a proof of concept and with navigating through a skeptical organization that may not be ready for change. There are disadvantages with this approach: the narrower focus prevents end to end process improvement, thus potentially sub-optimizing the supply chain. This “silo based” approach, while effective, can add to the overall timeline for Lean Six Sigma deployment across the organization. Some companies deploy Lean Six Sigma by focusing on specific business problems. This targeted approach can yield quick wins while demonstrating the use of the methodology very effectively; unfortunately it shares the same disadvantages of the approach which focuses on a specific business unit including a lack of a change in the organizational mindset and a more localized form of process improvement. There isn’t a single recipe that fits all Lean Six Sigma deployments. Clearly, a number of factors govern which approach might work best for an organization. The trick, however, is to adapt these approaches to fit the culture of the organization. Gates (2007) and De Mast (2004) describe various deployment models that companies use and they discuss the pros and cons of each approach. Figure 3 illustrates a deployment strategy that incorporates a few concepts presented above.

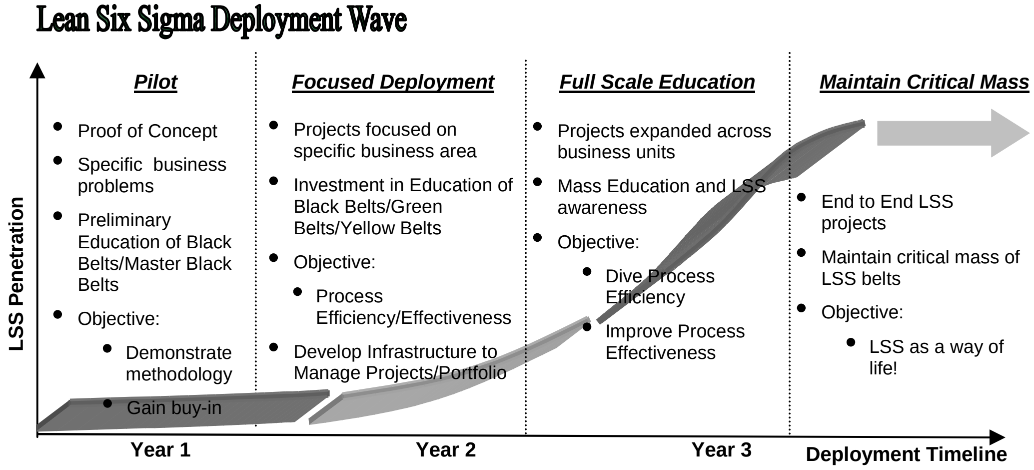


**Fig. 3.** Strategic Goals and Objectives in Deployment Wave

The strategy includes a pilot or proof of concept phase and ends with a company wide Lean Six Sigma deployment. Very specific business problems are addressed in the pilot phase to demonstrate the usefulness of the methodology and to gain buy-in. As the deployment progresses, larger investments are made in infrastructure, education and training of yellow belts, green belts, black belts and master black belts. In addition, as the deployment progresses, the compositions of the projects tend to change, and the focus is more end-to-end (Mader, 2008). Eventually, Lean Six Sigma becomes a way of life as the organization reaches critical mass with its training. As the scope and complexity of projects increase, so does the need for appropriate tools. Process re-engineering through DMAIC can help squeeze out the variability in a process, and lean concepts can help eliminate waste and speed up a process but eventually the entitlement of a process prevents further improvement. At this stage, it is important to re-design processes to achieve further improvements. DFSS is typically a tool set that is introduced both in the area of new product development and in process re-design to get beyond the 4.5 sigma wall (Montgomery, 2009). As part of a Lean Six Sigma deployment, organizations must be continuously aware of their toolset and enhancements needed to move forward. Many organizations train their Black belts on the theory of constraints and agile techniques to keep their tool set honed with an end goal of incorporating various industrial engineering methodologies.

The success achieved by deploying Six Sigma is well documented in the literature (Breyfogle, 2003). Many companies have received unprecedented bottom line savings and revenue generation within the first few years of their deployments. However, the companies that have been able to sustain their Lean Six Sigma initiatives over an extended period of time are few and far between. Like most initiatives, Lean Six Sigma tends to die out after the first five or six years, ROI tends to dwindle as most of the low hanging fruit have been addressed. Most companies endeavor to sustain their program by exploring new areas of the business but with little success. The key to maintaining the program is to embed it into the DNA of the organization, Lean Six Sigma as a way of life! Many companies extend their scope of work to include their suppliers and customers. Improving the supplier’s processes inadvertently benefits both the supplier and the company. Various phases in a Lean Six Sigma deployment have been described in the section above. The recipe, however, for a successful Six Sigma deployment seems to be common across various companies: commitment from executive leadership; a strategy for aligning Lean Six Sigma with company goals;

strong project review and selection process and the use of top talent in Black Belt roles (Szeto and Tsang, 2005). While most of the literature speaks through this consistently, what is lacking is an approach for Lean Six Sigma practitioners to be able to identify focus areas in the supply chain which are Lean Six Sigma conducive. The consulting Black Belt's often rely on their subject matter experts for project identification and hence project success. There is a lack of quantifiable/scientific way to highlight focus areas in the supply chain. Often project selection in large organizations tends to be ad hoc. For Lean Six Sigma to be truly successful, the deployment must be tied into the strategy and be focused on the right parts of the business. The emphasis should be on proactive process improvement as opposed to reactive fire-fighting. The Lean Six Sigma portfolio should be strategic as opposed to projects which are aimed at providing incremental benefit and for the most part temporary relief. Traditionally, the more successful companies have used a balanced scorecard technique as the basis to establish their Lean Six Sigma portfolios. The following section describes a model that can be used in project identification.

## 4. Lean Six Sigma Project Identification Model

The success of a Lean Six Sigma deployment is governed by a company's ability to identify and select the right projects. Most companies have a fairly robust project prioritization process, but are light on project identification techniques (Mader, 2008).

In the early phases of a Lean Six Sigma deployment, project identification and selection are important to demonstrate the methodology and to gain buy-in. Factors that typically dictate project selection and identification are often more political in nature. An executive champion, a persistent business problem, and an opportunity to demonstrate quick wins are probably the three most important ingredients of project identification and selection. As the deployment matures, it is imperative to align project selection and identification with the strategy. The focus now is on understanding the strategy, and aligning improvement efforts to meet the objectives of the organization. The model described here addresses the project identification and selection requirements of a company that is considering deploying Lean Six Sigma and acts as a decision support tool for companies to choose processes that are Lean Six Sigma conducive. Figure 4 is an illustration of our proposed 4 step approach to identifying parts of a business that are Lean Six Sigma conducive. Each of these steps is described below.

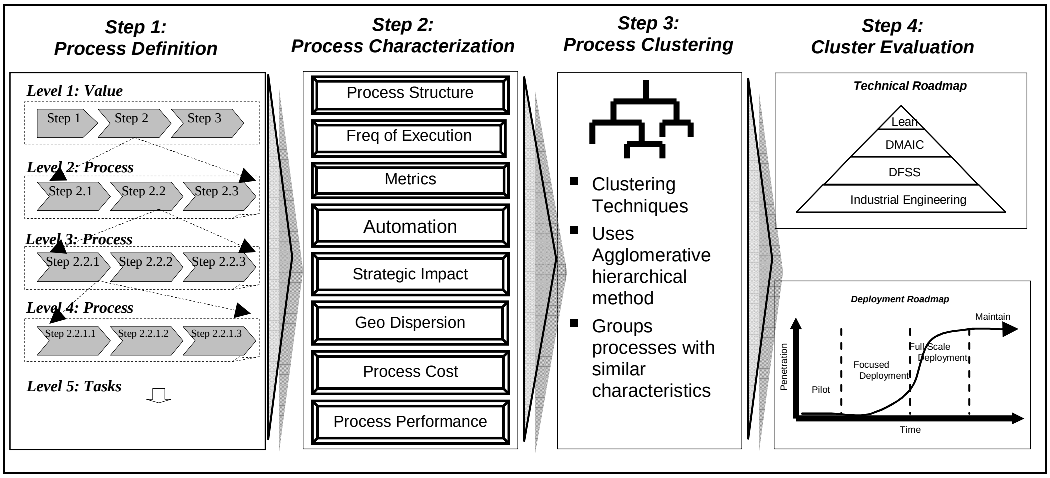


**Fig. 4.** Lean Six Sigma Project Identification Model

## 4.1. *Step 1: Process Definition*

Lean Six Sigma is about process and the first step of the project identification model described in Figure 3 is to create a process framework to enable end to end value chain definition and characterization. The existing literature is rich in process reference models. The Supply-Chain Operations Reference-model (SCOR) for instance, based on the Plan-Make-Source-Deliver-Return processes, is a product of the Supply Chain Council (SCC), and provides a unique framework that links business process, metrics, best practices and technology features into a unified structure to support communication among supply chain partners and to improve the effectiveness of supply chain management. This model can be used as the basis for process characterization. A point of note is that the SCOR model does not include sales and marketing related processes and post delivery customer support. The complete SCOR-model and other related models of the Supply Chain Council (SCC) are accessible through www.supply-chain.org website. Process reference models integrate business process reengineering, benchmarking, and process measurement into a framework that drives standard process descriptions with relationships among processes and metrics that measure process performance. Additionally, the Value Chain Operations Reference model (VCOR) can also be used as a process decomposition framework. A detailed description of this model can be found at http://www.value-chain.org.

For the purpose of this research a Classic Process Decomposition Model with its hierarchical structure will suffice. Figure 5 is an example of one such model.

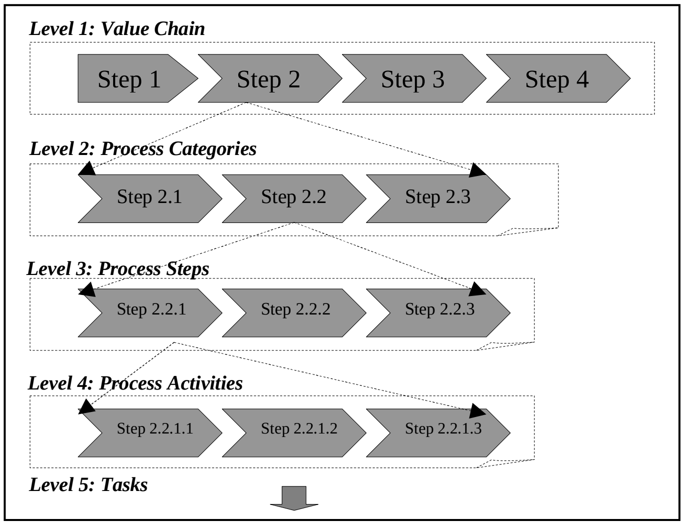


**Fig. 5.** Process Decomposition Model

The American Productivity and Quality Center (APQC) also introduced the Process Classification Framework (PCF) in 1992 (http://www.apqc.org/process-classification-framework), and a similar framework is used in this paper. The processes used include order entry to invoicing, including demand supply planning process, procurement and sourcing related processes for an IT company. Extensions into other areas of the business are fairly easy to do.

The data set considered in our model includes 4 processes at level 1, 35 processes at level 2 and 151 processes at level 3. For purpose of confidentiality, the process documentation is not provided in this paper. Also, level 3 process decomposition was chosen as the lowest level of decomposition for the identification model.

A Level 3 of process decomposition was chosen because any further decomposition of process will result in projects being identified at the activity and task level instead of the process functional level resulting in projects with a very narrow scope. As an example: If we pick a level 4 decomposition, we might land up considering a credit check task as a potential project instead of the level 3 billing process. Alternatively, a level 2 of process decomposition does not provide an appropriate level of process granularity. Processes like strategic sourcing may be confounded with tactical sourcing under a level 2 procurement process, resulting in projects that may not be Lean Six Sigma conducive. Further process decomposition (level 4 and 5) is more pertinent at the project execution stage as it aids in root cause analysis.

### 4.2. *Step 2: Process Characterization*

The process definition framework described in the prior sections enables end to end value chain definition. The next step is to characterize each process based on eight different parameters:

1. *Strategic Impact (risk)/VOC:*

   Processes in general can be categorized based on the value they drive for their stakeholders. Some processes drive revenue for the organization while others are customer facing and impact customer satisfaction if not executed correctly.

Other processes are supporting processes which enable organizations to operate (HR, Finance). The strategic impact of a process is a key factor in determining where an organization deploys Lean Six Sigma. Typically processes that impact the Voice of the Customer (VOC) are candidates for Lean Six Sigma

2. *Performance Factor:*

   The gap between how a process is currently performing and how it should be performing is an important element that a Lean Six Sigma practitioner should utilize in deciding the project portfolio mix. Most companies use a balanced scorecard approach to ascertain the "health" of the organization by monitoring the key performance indicators. This factor essentially utilizes the same concepts as a balanced scorecard by evaluating the difference between the current performance of a process and its targeted performance. Processes that are not performing well at the operational level are good candidates for Lean Six Sigma.

3. *Process Structure*:

   This parameter describes how processes are executed. Processes can vary from being extremely structured and repeatable with clearly defined rules, inputs, outputs, controls, and mechanisms; to being contextual in nature and highly dependent on the condition at the time of execution. These "contextual" processes require tacit knowledge by the executing agent. Typically, processes that are more structured are lean six sigma conducive.

4. *Process Cost:*

   This parameter classifies processes based on their operating costs. This includes headcount that support processes as well as IT infrastructure. Processes that have a high cost factor are opportunities for cost reduction using Lean Six Sigma.

5. *Level of Process Automation:*

   This parameter describes the level of people-to-people and people-to-IT interactions. Processes can vary from being extremely manual to being completely automated. Lean Six Sigma aims at addressing non-value added process steps and elimination of waste in processes. Processes that are manual in nature are opportunities for productivity improvements using Lean Six Sigma.

6. *Frequency of Execution:*

   This parameter describes how often a process is executed. This can include processes that are executed multiple times a day, to processes that are executed as infrequently as once a year. Again, the higher the frequency of execution, the more likely is the processes a candidate for Lean Six Sigma consideration.

7. *Process Measurement/Metric:*

   It is difficult to improve a process that can’t be measured! Process Improvement begins with process measurement and this parameter is used to characterize processes that vary from ones that have an established measurement system that is monitored regularly, to processes that are difficult to measure. Processes with established measurement systems that are monitored regularly are lean Six Sigma conducive.

8. *Geographical Dispersion:*

   This parameter classifies processes by their geographical dispersion. Processes can be localized, standardized and executed the same way (tools) or can span multiple geographies and can be executed with dissimilar tools. Processes that are localized have the advantage of being candidates for Kaizen events. Incidentally, this factor doesn't negate the selection of a global process spread across multiple geographies from being considered for a six sigma project.

A rating system on a scale of 1 to 5 was developed for each of the eight process characterization parameters mentioned above. Table 2 has the definition and criteria for a particular rating/score. Once again, the data set used in this case study is for an IT company and includes processes from order entry to invoicing, including demand supply planning, procurement and sourcing related processes. In total, 151 processes at level 3 were characterized and scored by subject matter experts based on the definition and scoring system in Table 2.

**Table 2.** Process Characterization and Rating System

| Category | Score | Definition |
|---|---|---|
| Strategic Impact (risk) VOC | 1 | Process is purely customer facing, impacts customer satisfaction – quality, revenue, litigation |
| | 2 | Process may indirectly impact customer satisfaction/revenue/litigation |
| | 3 | Process enables execution of the value chain |
| | 4 | Process supports execution of value chain |
| | 5 | Supporting processes that enable org to operate (HR, Finance) |
| Process Performance | 1 | Very Large gap between current performance and target (greater than 60%) |
| | 2 | Large gap between current performance and target (greater than 40%) |
| | 3 | Medium gap between current performance and target (greater than 20%) |
| | 4 | Small gap between current performance and target (greater than 10%) |
| | 5 | No gap between current performance and target |
| Process Structure | 1 | Process is structured with clearly defined rules clear inputs, outputs, controls and mechanism and documented processes |
| | 2 | Process is semi-structured with clearly defined rules clear inputs, outputs, controls and mechanism |
| | 3 | Process is semi-structured and is partially dependent on the conditions at the time of execution |
| | 4 | Process is unstructured and is partially dependent on the conditions at the time of execution |
| | 5 | Process is contextual/highly dependent on conditions. Judgment based |
| Process Cost | 1 | Very high operating cost, with headcount > 200 Full Time Equivalents |
| | 2 | High operating cost, with headcount < 200 Full Time Equivalents |
| | 3 | Medium operating cost, with headcount < 100 Full Time Equivalents |
| | 4 | Low operating cost, with headcount < 50 Full Time Equivalents |
| | 5 | Very low operating cost, with headcount < 10 Full Time Equivalents |
| Process Automation | 1 | Process is extremely manual |
| | 2 | Process is somewhat manual |
| | 3 | Process is semi-manual and requires people to IT interactions |
| | 4 | Process is mostly automated |
| | 5 | Process is automated |
| Frequency of execution | 1 | High frequency of execution-daily |
| | 2 | Process is executed on a weekly basis |
| | 3 | Process is executed monthly |
| | 4 | Process is executed with a low frequency – quarterly |
| | 5 | Process is executed once a year |
| Metric/Process measurement | 1 | Established measurement system monitored regularly |
| | 2 | Established measurement system monitored infrequently |
| | 3 | Available measurement system not monitored but can be collected |
| | 4 | No metric in place, but can be established and collected |
| | 5 | Process is difficult to measure |
| Geographical Dispersion | 1 | Process is localized, standardized and executed the same way (tools) |
| | 2 | Process spans more that one location and is executed the same way (tools) |
| | 3 | Process spans more that one location but is executed similarly with standard tools |
| | 4 | Process spans multiple geographies with similar tools |
| | 5 | Process is world wide with dissimilar tools |

### 4.3. *Step 3: Process Clustering*

Clustering is a process of organizing objects into groups whose members are similar in some way. The thought is that objects that are classified in the same group should display similar properties based on some criteria. For detailed review on clustering approaches refer to (Xu and Wunsch II, 2009). Clustering algorithms often provide the advantage of extracting valid, previously unknown, patterns in large datasets above and beyond what would be considered pure unstructured noise. The approach enables the user to either predefine the number of clusters into which the data is grouped or to establish a decision rule that determines the number of clusters based on the homogeneity/similarity of the objects in the cluster. The similarity index is a proximity measure of the data objects and can be defined as the distance between the objects in *p*-dimensional space (Xu and Wunsch II, 2009). There are various methods to calculate the distance between data objects, and Xu and Wunsch II (2009) describe various approaches. As pointed out by Backer and Jain (1981), clustering splits a group of objects into more or less homogeneous subgroups on the basis of their similarity such that the similarity between objects within a subgroup is larger than the similarity between objects belonging to different subgroups. Therefore, minimizing the distance of points within a cluster inadvertently maximizes the distances of points between clusters (Banks *et al.*, 2004).

The data collected in the previous step was sanitized and validated to ensure that the scoring process was consistently applied to all processes. Since scaling is an important parameter to consider for many dissimilarity/distance measures, each parameter in the model is scored on a likert scale of 1-5. This would essentially, circumvent any issues relative to scaling. An unsupervised learning approach using an agglomerative hierarchical clustering algorithm was then used to group candidate processes based on common process characteristics (Xu and Wunsch II, 2009). Minitab 14 was used to conduct the analysis. The algorithm begins with each observation in its own cluster. In the first step, the two clusters closest together are joined to form *n*-1 clusters. In the next step, either a third observation joins the first two in a new cluster, or two other observations join together into a different cluster. This process will continue until all clusters are joined into one. The squared Euclidean distances of a point from the centroid of the cluster is used as the decision criteria to join a particular cluster. Other linkage approaches including single, average, complete, ward and geometric methods exist (Abonyi and Feil 2007), but for the purpose of this research the squared Euclidian distance was used.

Mathematically, the objective can be demonstrated as follows: Consider a data set $D = \{x_1, x_2, x_3, ...x_n\}$ of objects in *p*-dimensional space; we look for a partition $P = \{C_1, C_2, C_3, ...C_K\}$ of *D* that minimizes the intra-cluster distance '*W*'.

The clustering approach can then be represented as:

$$\text{Minimize}(W) = \sum_{k=1}^{K} \sum_{x_i \in C_k} d(x_i, x_j)$$

Where,

$K$ – Number of clusters

$d(x_i, x_j) = \left\| x_i - x_j \right\|^2$ is the squared Euclidean distance between two points.

$W$ - Is the within cluster distances summed over all clusters

Figure 6 shows the dendogram that was created using Minitab 14. The dendrogram or tree diagram shows the amalgamation process of the hierarchical clustering algorithm. At each iteration, the dendogram indicates which clusters were combined. The y-axis is the similarity index of the clusters and Figure 6 shows how the similarity index degrades as clusters are joined together at each iteration.

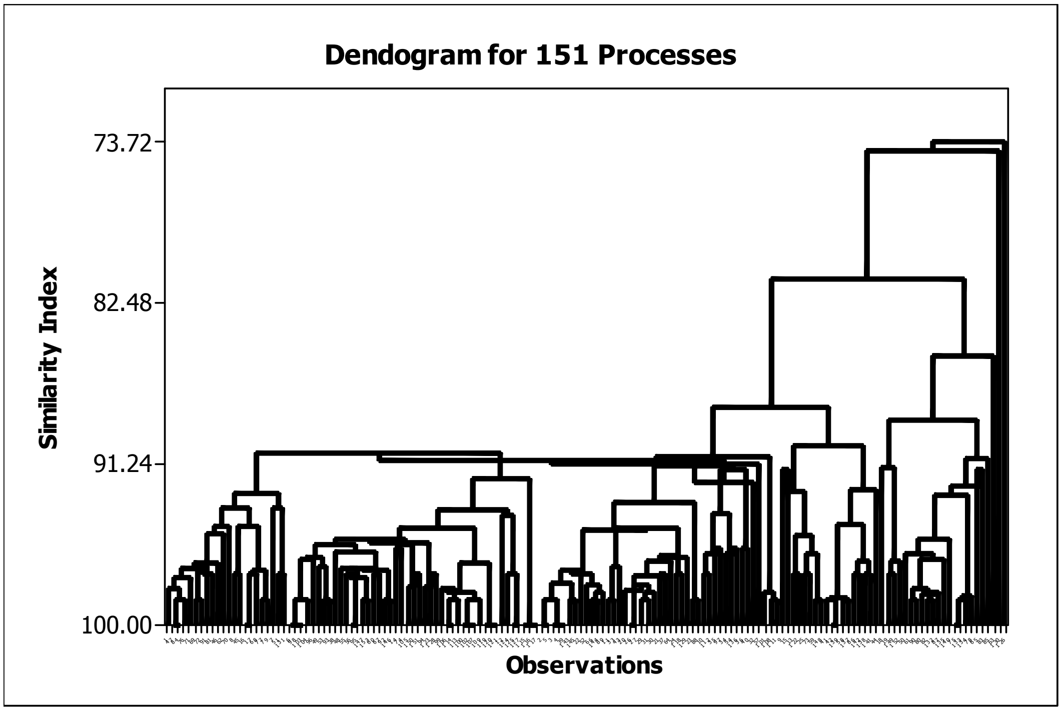


**Fig. 6.** Dendogram for 151 Processes

Typically, a decision on the number of clusters needs to be made. Examining the similarity index and distance levels between/within clusters can aid in the decision. Figure 7 shows the similarity index for the data set through the evolution of the algorithm.

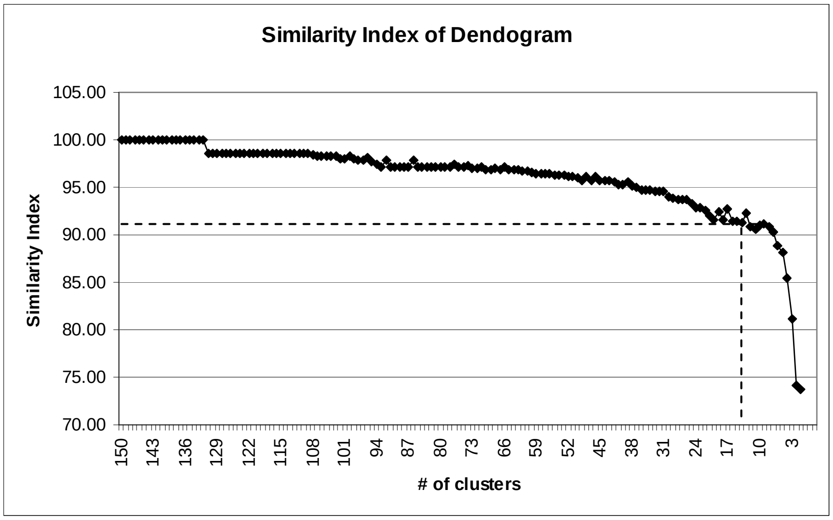


**Fig. 7.** Similarity Index for Data Set

Based on the similarity index, 15 clusters were picked at a similarity index of 91%. Figure 7 shows a steep decline in the similarity index beyond 10 clusters, indicating the degradation in the homogeneity of each cluster. In addition, the index is fairly flat (~91%) between 21 and 15 clusters. For the purpose of simplicity, 15 clusters were chosen. Figure 8 shows the dendogram for 15 clusters, and Figure 9 shows the count of processes in each of the 15 clusters.

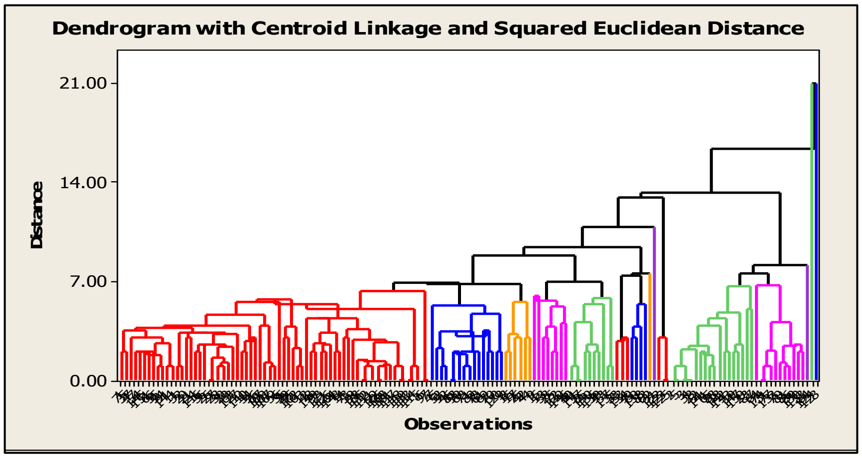


**Fig. 8**. Dendogram for 15 Clusters

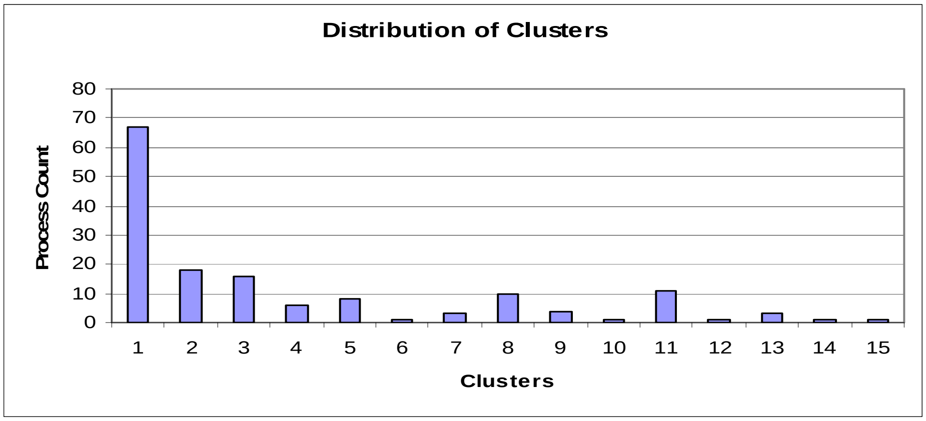


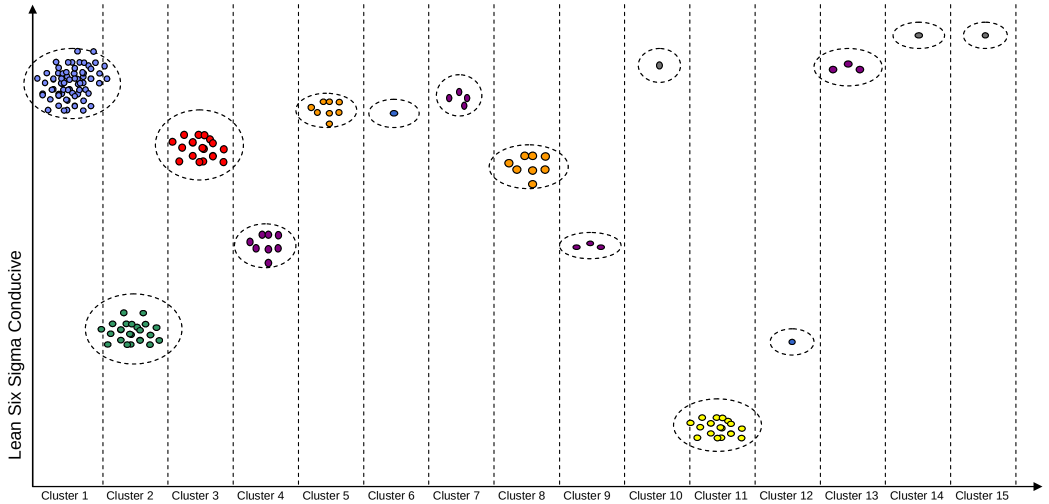
**Fig. 9.** Count of Processes in Each Cluster

The clustering approach described above is a hierarchical clustering algorithm, which essentially means that once two observations are joined in a cluster, they are not separated. Other clustering approaches like K-means clustering, which are not hierarchical, do not have this constraint. Observation/Processes move into a cluster based on their squared Euclidean distance from the centroid. In this case the centroid is recalculated when an observation moves in or out of the cluster.

### 4.4. *Step 4: Cluster Evaluation*

The section above describes the clustering algorithm used to group processes which have similar characteristics. Based on the scoring criteria, processes that score a “1” on all seven parameters are the best candidates for Lean Six Sigma projects since these processes are structured with clearly defined rules, inputs, outputs, controls and mechanisms. In addition, these processes are data driven with established measurement systems and are executed several times a day. These processes tend to directly impact the end customer and stakeholders and present an opportunity for improved quality, delivery and revenue generation. By observing the centroid of the clusters a determination can be made on whether a particular cluster of processes is a suitable candidate for Lean Six Sigma. A point of note is that processes that are localized are good candidates for Lean Kaizen events and processes that are extremely manual are potential opportunities for productivity type improvements. Typically, while deploying Lean Six Sigma in an organization; the deployment champions look for a large return on investment. The overall operating cost including the headcount of a process is an appropriate parameter to help with process prioritization from a stand point of return on investment. Figure 10 is a pictorial representation of the 15 clusters along with their centroids.

Based on the centroids of the 15 clusters, Clusters #11, #12 and #2 seem to have the best attributes for Lean Six Sigma projects. Cluster #11 has eleven processes which includes processes like manufacturing, procurement, order management processes, billing, and client services to name a few. The centroid of this cluster (1.9, 1.4, 1.3, 1.2, 1.6, 1.5, 1.5 and 2.4) indicates that these processes are the best candidates for Lean Six Sigma projects. Cluster #12 and Cluster #2, have nineteen processes between them. Albeit it’s low operating cost Cluster #2 has a strategic value, and performance parameter that indicates that these processes drive business value to the end customer and stakeholders and could negatively impact customer satisfaction if not executed efficiently and effectively. Cluster # 9 has three processes; however, they are currently performing fairly well.



| Variable | Clusters | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| **Strategic Impact** | 3.9 | 2.2 | 2.9 | 2.0 | 2.3 | 3.0 | 4.3 | 2.4 | 2.8 | 4.0 | 1.9 | 2.0 | 4.7 | 5.0 | 5.0 |
| **Process Performance** | 3.6 | 2.3 | 3.9 | 2.2 | 3.5 | 4.0 | 4.0 | 3.6 | 4.0 | 4.0 | 1.4 | 2.0 | 2.3 | 5.0 | 5.0 |
| **Process Structure** | 3.2 | 2.0 | 3.6 | 3.5 | 4.8 | 2.0 | 2.3 | 4.3 | 1.8 | 2.0 | 1.3 | 3.0 | 5.0 | 2.0 | 3.0 |
| **Process Cost** | 4.1 | 3.5 | 1.9 | 3.7 | 3.8 | 4.0 | 1.7 | 1.4 | 1.0 | 1.0 | 1.2 | 1.0 | 5.0 | 5.0 | 5.0 |
| **Process Automation** | 2.3 | 2.0 | 2.1 | 2.8 | 1.1 | 3.0 | 3.0 | 1.2 | 2.0 | 4.0 | 1.6 | 3.0 | 1.0 | 3.0 | 1.0 |
| **Frequency of execution** | 3.4 | 1.8 | 3.9 | 4.3 | 2.6 | 4.0 | 3.7 | 1.9 | 2.5 | 2.0 | 1.5 | 3.0 | 5.0 | 5.0 | 1.0 |
| **Process Metric** | 3.3 | 1.8 | 3.4 | 3.0 | 4.4 | 2.0 | 2.7 | 3.6 | 2.3 | 1.0 | 1.5 | 1.0 | 3.3 | 4.0 | 4.0 |
| **Geographical Spread** | 2.7 | 2.8 | 2.2 | 1.8 | 3.3 | 5.0 | 4.0 | 3.5 | 2.8 | 2.0 | 2.4 | 2.0 | 3.0 | 5.0 | 5.0 |

**Fig. 10.** Cluster Analysis and Evaluation

Figure 10 can be viewed as a roadmap for a Lean Six Sigma deployment champion as it indicates parts of the business that are most in need of Lean Six Sigma, given their strategic value and current performance. As each cluster is worked on, its score can be updated making the map a live document. Clusters #8, and #3 lack the process structure and clusters above these groups tend to not have the best characteristics for Lean Six Sigma engagements. For these processes, alternate transformation options could include a change in the business model, policy or even IT based infrastructure changes. Of the 151 processes that were evaluated, approximately 30 (clusters 11, 12 and 2) were Lean Six Sigma conducive. For the 30 processes that are Lean Six Sigma conducive, the next step is to identify specific projects which address the key performance indicators, process metric, strategic impact, process cost, and geographical spread. Specific project could additionally address process simplification, process standardization, product quality, and process lead time. As a result, there could be multiple projects for each process that are Lean Six Sigma conducive.

## 5. Conclusions and Future Work

The ever changing nature of the global economy has forced many organizations to outsource parts of their business that are either not their core competence or that can be executed in a lower cost jurisdiction. Products and services traditionally executed in-house are now being delivered by contractors, vendors and suppliers half way across the globe. This continuous pressure to compete on price has led to increased process complexity, resulting in longer lead times and increased product and process defects. Many companies have embraced these challenges to compete in this complex environment, and have resorted to quality improvement programs to deliver efficient and effective processes. The most popular of these quality initiatives, Six Sigma, dates back to the 80's.

The success that companies have had with Six Sigma is well documented. The literature is rich in describing the success criteria for deploying Six Sigma in an organization and speaks to the importance of aligning the program with the organizations strategic goals (Coronado and Anthony, 2002). Many companies, however, have struggled with adopting and sustaining their programs and much of this lack of success can be attributed to weak project identification and selection processes (Mader, 2007). While most of the literature speaks to this consistently, there is a lack of quantifiable/scientific way to highlight focus areas in the supply chain that are Lean Six Sigma conducive. The research presented in this paper enables an organization to use a systematic, holistic, data driven approach to deploy Lean Six Sigma. An unsupervised learning approach using a clustering algorithm is employed to group processes with similar characteristics. The agglomerative hierarchical clustering approach groups processes based on eight characteristics: strategic impact, process performance, process structure, process cost, level of automation, frequency of execution, existence of metric/process measurement, and geographical dispersion. This approach enables deployment champions to perform a readiness assessment prior to deploying Lean Six Sigma, bridging the gap in the literature relative to process identification. The research can be used to set the roadmap for process led transformation. A case study is presented using data from large global company and the use of the methodology is demonstrated in the business process space. Lean Six Sigma found its roots in manufacturing, this research, however, demonstrates the use of the deployment model in the transactional space as well.

A point to note is that the model described in this paper is a decision support tool, and cannot be used in a vacuum. With Lean Six Sigma’s strong focus on Voice of the Customer (VOC), it isn’t uncommon that a burning platform or a specific business problem highlighted by management might be a priority. Hence, while deploying Lean Six Sigma provision must be made to incorporate management input. The model currently does not have the capability to link processes/clusters that are a part of a specific product line or market segment. Future research will need to address this gap by ensuring that processes within a cluster are more horizontally integrated across the supply chain.

The process characterization process also provides executives with an assessment of the maturity of their processes. The evaluation criterion highlights parts of the business that are manual, unstructured and lack process metric. Future research in this space will include a comparison of manufacturing based processes with processes that are more services oriented. This will enable Six Sigma practitioners, in the future, to baseline various industries based on the nature of business and services they provide. In this research, eight parameters are used to characterize processes. Processes with similar characteristics are grouped in a cluster. The decision on the transformation lever to apply to a particular cluster is based on the centroid of the cluster as shown in Figure 10. Future research will include the prioritization of these factors, perhaps the utilization of weights, and the development of an automated approach to help practitioners with this decision. For instance, "Process Metric" may not always be present; this however, should not negate a process from being conducive to Lean Six Sigma. It would require the practitioner to spend the upfront work establishing and collecting data to baseline the process in question. The model described in this paper uses a hierarchical clustering approach based on squared Euclidean distances. Consequently, processes which are joined in a clustering step can never be separated. A *K*-means clustering approach, which is not hierarchical, doesn't have this constraint, and could also be considered. In addition to the squared Euclidean distance from the centroid, a sensitivity analysis could be performed based on other linkage and distance base alternatives to evaluate the impact on process clustering.

Having identified processes that are Lean Six Sigma conducive, future work in this area will be aimed at portfolio optimization. Considerations could be made to optimize the Lean Six Sigma portfolio across its life cycle considering multiple objectives like: Return on investment, Lean Six Sigma penetration into the DNA of the organization, and improved customer satisfaction.

**Reference:**

Abonyi, J. and Feil, B. (2007) *Cluster Analysis for Data Mining and System Identification*, Birkhauser Verlag, Germany.

Atallah, B. and Ramudhin, A. (2010) Improving Healthcare Reliability by Integrating Six-Sigma in a Business Process Modeling and Analysis Strategy. *IEEE International Conference on Industrial Engineering and Engineering Management (IE&EM 2010),* 2234-2238.

Backer, E. & Jain, A. (1981) A Clustering Performance Measure Based on Fuzzy Set Decomposition. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *PAMI*, 3(1), 66-75.

Banks, D., House, L., McMorris, F., Arabie, P., Gaul, W. (2004) Classification, Clustering, and Data Mining Applications. *Proceedings of the meeting of International Federation of Classification Societies (IFCS),* 25-32.

Banuelas, R., Tennant, C., Tuersley, I. and Tang, S. (2006) Selection Of Six Sigma Projects In UK. *The TQM Magazine*, 18(5), 514-527.

Bodek, N. (2004) *Kaikaku: The Power and Magic of Lean - A study in knowledge transfer*, PCS Press, Vancouver, WA.

Breyfogle, F.W. (2003) *Implementing Six Sigma*, Wiley, Hoboken, New Jersey.

Coronado, R.B. and Antony, J. (2002) Critical Success Factors For the Successful Implementation of Six Sigma Projects in Organizations. *TQM Magazine*, 14, 92–99.

De Mast, J. (2004) A Methodological Comparison of Three Strategies for Quality Improvement. *International Journal of Quality & Reliability Management,* 21(2), 198-213.

Gates, R. (2007) Deployment: Start Off on The Right Foot. *Quality Progress*, 40(8), 51-58.

Hahn, G.J., Doganaksoy, N. and Hoerl, R. (2000) The Evolution of Six Sigma. *Quality Engineering*, 12(2), 317-326.

Harry, M.J. (1998) Six Sigma: A Breakthrough Strategy for Profitability. *Quality Progress,* 31(5), 60–64.

Hu, G., Wang, L., Fetch, S., and Bidanda, B. (2008) A Multi-Objective Model for Project Portfolio Selection to Implement Lean and Six Sigma Concepts. *International Journal of Production Research*, 46(23), 6611–6625.

Kumar, U.D., Saranga, H., Ramirez-Marquez, J. and Nowicki, D. (2007) Six Sigma Project Selection Using Data Envelopment Analysis. *The TQM Magazine*, 19(5), 419-441.

Kumar, D., Nowickib, D., Ramirez, J., and Verma, D. (2008) On the Optimal Selection of Process Alternatives in a Six Sigma Implementation. *International Journal of Production Economics*, 111, 456–467.

Kumar, M. and Antony, J. (2009) Project Selection and Its Impact on the Successful Deployment of Six Sigma. *Business Process Management Journal*, 15(5), 669-686.

Linderman, K., Schroeder, R., Zaheer, S., and Choo, A. (2003) Six Sigma: A Goal-Theoretic Perspective. *Journal of Operations Management*, 21, 193–203.

Mader, D.P. (2007) How to Identify and Select Lean Six Sigma Projects. *Quality Progress*, 40(7), 58-62.

Mader, D.P. (2008) What comes after the low-hanging fruit?. *Quality Progress*, Vol. 41, No. 8, pp. 58-61.

Montgomery, D.C. (2009) *Introduction to Statistical Quality Control*, 6th edition, Wiley, Hoboken, NJ.

Montgomery, D.C. and Woodall, W.H. (2008) An Overview of Six Sigma. *International Statistical Review*, 76(3), 329-346.

Montgomery, D.C, (2010) A Modern Framework For Achieving Enterprise Excellence. *International Journal of Lean Six Sigma*, 1(1), 56-65.

Ren, X. and Zhang, G, (2008) Research on Decision Support for Six Sigma Project Selection Based On Fuzzy Evaluation. *4th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM)*, 11, 1-11.

Schroeder, R.G., Linderman, K., Liedtke, C., and Choo, A. (2008) Six Sigma: Definition and Underlying. *Journal of Operations Management, 536-554*.

Snee, R.D and Rodebaugh (2002) Project Selection Process. *Quality Progress*, pp. 78-90.

Snee, R. and Hoerl, R. (2003) *Leading Six Sigma*, Prentice Hall, Upper Saddle River, NJ.

Spear, S. and Brown, K. (1999) Decoding the DNA of the Toyota Production System. *Harvard Business Review*, 96-106.

Su, Chao-Ton. and Choua, Chia-Jen. (2008) A Systematic Methodology For The Creation Of Six Sigma Projects: A Case Study of Semiconductor Foundry. *Expert Systems with Applications*, 34(4), 2693-2703.

Szeto, A.Y.T. and Tsang, A.H.C. (2005) Antecedents to Successful Implementation of Six Sigma. *International Journal of Six Sigma and Competitive Advantage*, 1(3), 307-322.

Thomas, A.J., Rowlands, H., Byard, P., and Rowland-Jones, R. (2008) Lean Six Sigma: An Integrated Strategy for Manufacturing Sustainability. *International Journal of Six Sigma and Competitive Advantage*, 4(4), 333-354.

Xu Rui, and Wunsch II, D.C. (2009) *Clustering*, Wiley, Hoboken, NJ.

Yang, Taho., and Hsieh, Chiung-His. (2008) Six-Sigma Project Selection Using National Quality Award Criteria and Fuzzy Multiple Criteria Decision-Making Method. *Wireless Communications, Networking and Mobile Computing, WiCOM '08. 4th International Conference on 12-14 Oct. 2008*, 1 – 4.

Zhang J., and Liu Wenchi. (2007) A study on implementing six-sigma in banking service. *3rd International Conference on Wireless Communications, Networking, and Mobile Computing - WiCOM '07*, 3246-3249.

Zimmerman, J.P. and Weiss, J. (2005) Six Sigma's Seven Deadly Sins. *Quality*, 44(1), 62-66.

Zua Xingxing, Fredendallb, L. D., and Douglas, T. J. (2008) The Evolving Theory of Quality Management: The Role of Six Sigma. *Journal of Operations Management*, 26(5), 630-650.

## Chapter 3

# LEAN SIX SIGMA PROJECT IDENTIFICATION USING HIERARCHICAL CLUSTERING

## 1. Abstract

The ever-changing economic landscape has forced many companies to re-examine their end-to-end supply chains. Global resourcing and outsourcing of processes has been a strategy many organizations have adopted to reduce cost and to increase their global footprint. This has, however, resulted in increased process complexity and reduced customer satisfaction. In order to meet and exceed customer expectations, many companies are forced to improve quality and on-time delivery, and have looked towards Lean Six Sigma (LSS) as an approach to enable process improvement. The LSS literature is rich in deployment strategies and project prioritization; however, we present a project identification model that will aid Lean Six Sigma (LSS) deployment champions to identify parts of their business that are conducive to the methodology. The model utilizes an unsupervised learning technique to cluster processes based on their similarity. In addition, the paper highlights some of the major differences, challenges and considerations in applying LSS in a non-manufacturing environment. Finally, a case study is presented, which demonstrates the application of the model in a global company.

## 2. Managerial Relevance Statement

The purpose of this paper is to provide Lean Six Sigma deployment champions with a structured approach to identify and prioritize parts of their business that are conducive to the Lean Six Sigma methodology. Various deployment strategies are discussed and an eight step approach to identify Lean Six Sigma, conducive processes is presented. The model can be applied to any industry segment, including non-manufacturing, healthcare and financial based organizations. Additionally, this paper discusses the differences in deploying Lean Six Sigma in the manufacturing space versus the non-manufacturing space by highlighting the differences in some key process characteristics like process structure, data availability and metric. The model presented provides the Lean Six Sigma deployment champion with an approach to indentify processes that are Lean Six Sigma conducive.

## 3. Introduction

The literature on the history of quality management and quality improvement is rich (Evans and Lindsay, 2008; Montgomery and Woodall, 2008; Montgomery, 2010; Hahn, *et al.* 2000; Harry, 1998; Zua *et al.* 2008). Over the years manufacturing, services, healthcare, education and government organizations have all found the need to focus on quality improvement and performance excellence efforts.

These organizations have invested in many initiatives like the Malcolm Baldridge Criteria for Performance Excellence, ISO 9000, Total Quality Management (TQM), Total Productive Maintenance (TPM), and Six Sigma. Productivity, cost and quality have been at the forefront of many a manager's priority list, and rightfully so! To compete in today's global economy organizations are forced to produce high quality products and services that exceed customer expectations in a timely and cost effective manner. Global resourcing and outsourcing has been a strategy that many companies have adopted to leverage the advantages of a lower cost jurisdiction. Apart from the lower operating cost, this strategy enables organizations to broaden their world wide footprint and get closer to their shifting customer base. With a world wide presence, processes can now be executed around the clock, providing organizations with the capability to execute on business paradigms like "Follow-the-Sun". Clearly, there is a competitive advantage in being globally dispersed. There is, however, a downside! Geographically dispersed business functions (both manufacturing and services) lead to increased process complexity, and with it the added pressure of process performance.

The focus on quality improvement has been ongoing for a number of years. The early work carried out by Walter Shewhart in the 20's set the foundation for quality improvement efforts carried out by engineers today. Toyota Production Systems and Lean thinking found its roots in Japan and were quickly embraced by many companies world wide (Spear and Brown, 1999). Bodek (2004) details the evolution of Lean concepts and discusses various efforts including Just in Time (JIT), Poke Yoke, Quality Function Deployment (QFD), and Kaizen that spun off from the original lean concepts. In the 1980's Motorola introduced Six Sigma. The DMAIC cycle (Define, Measure, Analyze, Improve and Control) was established and its project management and statistical assumptions were formalized (Montgomery, 2009). In the mid 90's Six Sigma was popularized by Jack Welch, the CEO of General Electric. Within the first five years of its deployment, the company claimed benefits in the billions (Snee and Hoerl, 2003). The history of Six Sigma is well documented. Many companies have deployed the approach and reaped its benefits. Schroeder *et al.* (2008) describes the importance of Lean Six Sigma and some of the implications of deploying the methodology. Over the years many companies have merged Lean approaches developed by Toyota and Six Sigma principals established by Motorola to create a hybrid process improvement methodology, Lean Six Sigma (Thomas *et al.,* 2008). Today many companies like Ford, DuPont, 3M, Dow Chemicals and Honeywell have integrated the lean focus of Toyota Production Systems, with the variance reduction focus of Six Sigma to create a hybrid process improvement approach (Ren and Zhang, 2008), It is estimated that 35% of companies in the Forbes top 500 list have embraced the methodology (Ren and Zhang, 2008). The genesis of Lean Six Sigma is in manufacturing; however, more recently Lean Six Sigma has also found many applications in the financial sector and in healthcare highlighting its applicability to the non-manufacturing space (Atallah and Ramudhin, 2010).

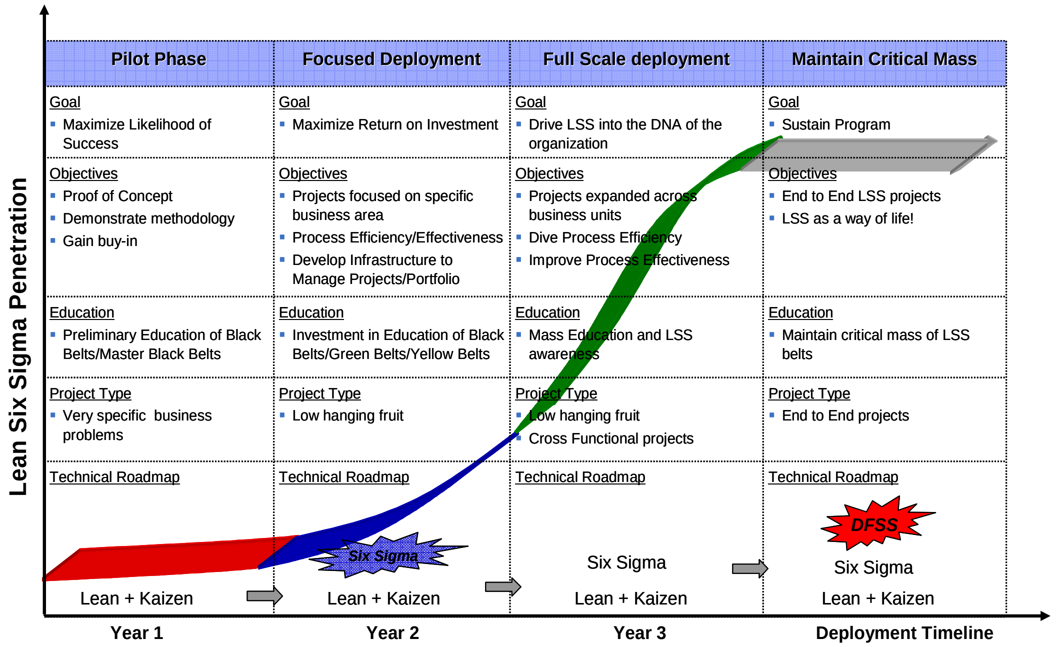
Selecting a six sigma projects is one of the most frequently discussed issues in the literature today (Kumar and Antony, 2009). Many companies have deployed Lean Six Sigma with varied degrees of success. One of the biggest factors that inhibit the success off a Lean Six Sigma deployment is the lack of a structured approach to identifying the right projects. Zimmerman and Weiss (2005) noted that approximately 60% of the companies that were surveyed did not have a formal project identification and selection process for Lean Six Sigma projects. They concluded that this lack of a formal approach to identify projects was a significant factor that contributed to an unsuccessful Lean Six Sigma program. This notion is supported by many researchers in the area of Lean Six Sigma (Mader, 2007; Banuelas *et al*., 2006).

As a result a significant amount of work has been done in the area of project identification and prioritization. Most companies use brainstorming techniques, Critical-to-quality (CTQ) trees, focus groups, interviews, customer visits, Quality Function Deployment (QFD), Kano analysis, and surveys to identify projects. In addition, Value Stream Mapping, balance scorecards, cost-benefit analysis, Pareto chart, and scoring models seem to be popular prioritization approaches (Banuelas *et al.,* 2006). Many practitioners have used Analytical Hierarchy Process (AHP), project desirability matrix (PDM) and Failure Mode and Effect Analysis for project selection (Kumar and Antony, 2009; Su and Choua, 2008). Some research has also been done in prioritization of Lean Six Sigma projects. For the most part this involves some form of impact versus effort analysis. Ren and Zhang (2008) have proposed an evaluation method for project selection that utilizes a multi-criteria decision-making method based on fuzzy set theory. Yang and Hsieh (2008) also use a process based on fuzzy mult-criteria decision-making methods. Kumar and Ramirez-Marquez (2008) describe a method to prioritize Six Sigma projects using data envelopment techniques. Multi-objective optimization models have also been used to prioritize a Lean Six Sigma portfolio based on various criteria (Hu *et al.,* 2008; Kumar *et al.,* 2007). Shunk (2010) have developed an evaluation model that Pareto ranks processes based on the product of their strategic value and the difference between its current performance and an established target. An 18 month time window is used to view this distribution of process scores.

Regardless of the project prioritization method, the Lean Six Sigma project identification approach is typically aligned with the strategy of the organization (Snee and Rodebaugh, 2002; De Mast, 2004; Linderman, *et al.,* 2003). This entails understanding the high level goals of the organization, be in sales growth, earning per share, increased profit or return on invested capital. The high level goals are then broken down into key performance indicators which intern are impacted by operational metric. The Lean Six Sigma portfolio is selected to address these Key Performance Indicators (KPI). Balanced scorecards have been used for a number of years as a dashboard that enables executives to view the performance of their organization by monitoring the key performance indicators of the business. A balanced scorecard can be viewed as a strategic planning tool and a management system that aligns business operations with the overall strategy of a company (Gonzalez-Padron, 2010). Recently, balanced scorecards have incorporated more than just the financial metrics and performance of an organization, they include metric related to internal business processes and customer satisfaction related metric. Additionally, some balanced score cards capture the learning and growth perspective of an organization. This score card enables executives to get a glimpse of the health of the overall business and make informed decisions on improvement areas that need attention. The literature is rich with examples of balanced score cards (Cheng-Ru *et al.*, 2010; Kraus, 2010). Clearly, the value of a balanced scorecard is in its ability to help executives define a strategy and a set business priorities to address. Lean Six Sigma practitioners have used balanced scorecards to help identify areas of opportunity and to focus process improvement efforts on specific business problems by viewing key performance indicator in a scorecard. Most companies use this approach to create a Six Sigma portfolio that helps meet the strategic goals of the organization.

For many companies looking to embark on a Lean Six Sigma journey, the decision doesn’t stop at how to select a Six Sigma project. The organization’s strategy and dashboard may provide the impetus to utilize Lean Six Sigma; however its adoption, acceptance, and success are heavily dependent on executive commitment and support. The use of top talent in Black Belt roles, and a company wide acceptance to change are equally important (Szeto and Tsang, 2005). A lean

Six Sigma deployment is bigger than establishing a portfolio of projects to address; it involves the development of a strategic roadmap that aims at infusing the methodology into the DNA of the organization. There are multiple deployment approaches that companies use today. A top-down organization wide deployment, much like the GE model is characterized by mass education and projects that run across the end to end supply chain (Gates, 2007). Typically, the return on investment for this approach is large. The approach requires strong executive commitment to ensure that there is an appropriate level of buy-in across the organization. Intuitively, the investment required for this approach is large, and with it the risk of success. The role of an executive champion can not be overemphasized for this model to be a success. Some companies focus their Lean Six Sigma deployments on specific business function. This targeted deployment approach offers a narrower scope with the opportunity to focus on specific business issues. The narrower scope has the advantaged of reduced complexity. It offers a proof of concept phase which can circumvent some of the issues faced with a company wide deployment i.e. navigating through a skeptical organization that may not be ready for change. The flip side is that the narrower focus prevents end to end process improvement, thus potentially sub-optimizing the supply chain. Some companies deploy Lean Six Sigma by focusing on specific business problems. This targeted approach can yield quick wins while demonstrating the use of the methodology very effectively; unfortunately it shares the same disadvantages of the approach which focuses on a specific business unit. A description of various deployment strategies and the pros and cons of each approach are well documented in the literature (Gates, 2007). Clearly one size doesn’t fit all, and most deployment champions will use a combination of these strategies that best fit the culture of their organization. Figure 11 has been adapted from Duarte *et al.* (2011). The pictorial depicts a phased approach to deploy Lean Six Sigma in a global enterprise, starting with a pilot phase. It highlights some of the goals, objectives, and considerations that need to be made at each phase. A technical roadmap is also established that includes lean, Kaizen Events, Six Sigma and Design for Six Sigma. Various maturity models exist that provide a formal description of the evolution of Lean Six Sigma in an organization. A description of some of these models can be found at www.isixsigma.com.



| Pilot Phase | Focused Deployment | Full Scale deployment | Maintain Critical Mass |
|---|---|---|---|
| Goal<br>- Maximize Likelihood of Success | Goal<br>- Maximize Return on Investment | Goal<br>- Drive LSS into the DNA of the organization | Goal<br>- Sustain Program |
| Objectives<br>- Proof of Concept<br>- Demonstrate methodology<br>- Gain buy-in | Objectives<br>- Projects focused on specific business area<br>- Process Efficiency/Effectiveness<br>- Develop Infrastructure to Manage Projects/Portfolio | Objectives<br>- Projects expanded across business units<br>- Dive Process Efficiency<br>- Improve Process Effectiveness | Objectives<br>- End to End LSS projects<br>- LSS as a way of life! |
| Education<br>- Preliminary Education of Black Belts/Master Black Belts | Education<br>- Investment in Education of Black Belts/Green Belts/Yellow Belts | Education<br>- Mass Education and LSS awareness | Education<br>- Maintain critical mass of LSS belts |
| Project Type<br>- Very specific business problems | Project Type<br>- Low hanging fruit | Project Type<br>- Low hanging fruit<br>- Cross Functional projects | Project Type<br>- End to End projects |
| Technical Roadmap<br>Lean + Kaizen | Technical Roadmap<br>Six Sigma<br>Lean + Kaizen | Technical Roadmap<br>Six Sigma<br>Lean + Kaizen | Technical Roadmap<br>DFSS<br>Six Sigma<br>Lean + Kaizen |

**Fig. 11.** Lean Six Sigma Deployment Wave – Adapted from Duarte *et al.* (2011)

A Lean Six Sigma deployment involves a step by step process to infuse the methodology into the DNA of the organization. The end goal is to drive a mindset of process led transformation with focus on quality and data driven decision making. Deploying Lean Six Sigma in an organization is typically a phased approach. Most companies will go through an evolutionary deployment over a prolonged period. The roadmap typically includes a pilot or proof of concept phase, where very specific business problems are addressed. This is the most important phase as success in resolving an age old problem can demonstrate the usefulness of the methodology and help gain buy-in. Most companies focus on efficiency and cost reduction, with the intention of sparking an interest through pilot projects that demonstrate the power of Lean Six Sigma. Investments are made on education to train Business Leaders, Champions, Black Belts, and Master Black Belts. The pilot phase can typically take a year and the Return on Investment (ROI) can be negative due to the initial investment in training. The second phase tends to be a Focused deployment. It is in this phase that most companies achieve an accelerated Return on Investment (ROI) as projects tend to focus on addressing the low hanging fruit. Green belt and Yellow belt training is typically carried out in this phase in an attempt to drive Lean Six Sigma into the DNA of the organization. Most successful companies have used this approach to accelerate Lean Six Sigma awareness. It isn’t uncommon to see a 300% ROI in this phase as in the case of GE (Snee and Hoerl, 2003). Kaizen events tend to be very successful in this phase as projects tend to be localized and small in scope.

With a growing portfolio of projects, it is important to establish a crisp reporting and tracking system. This enables management and master black belts to review and track projects. Best practices can be shared, and project financials can be documented and traced.

A Full Scale Deployment is accompanied by mass education. Many companies limit this phase to manufacturing and supply chain supporting processes; however, it isn’t uncommon to extend the scope of the deployment to Finance, Sales and Marketing. More recently, the healthcare industry has been a fertile ground for Lean Six Sigma practitioners as is the banking industry. In 1999, four years into their deployment, General Electric, initiated Six Sigma projects in Finance, Ecommerce and Digitization (Snee and Hoerl, 2003),  a classic example of non manufacturing related applications. As the organization tends to move into the full scale deployment phase, project identification, selection and prioritization become exceedingly important. As the scope and complexity of projects increase, so does the need for appropriate tools. Process re-engineering through DMAIC can help squeeze out the variability in a process, and lean concepts can help eliminate waste and speed up a process but eventually the entitlement of a process prevents further improvement. At this stage, it is important to re-design processes to achieve further improvements. DFSS is typically a tool set that is introduced both in the area of new product development and in process re-design to get passed the 4.5 sigma wall (Montgomery, 2009). As part of a Lean Six Sigma deployment, organizations must be continuously aware of their toolset and enhancements needed to move forward. Many organizations train their Black belts on the theory of constraints and agile techniques to keep their tool set honed with an end goal of incorporating various Industrial engineering methodologies. The success achieved by deploying Six Sigma is well documented in the literature (Breyfogle, 2003; Coronado and Antony, 2002). Many companies have received unprecedented bottom line savings and revenue generation within the first few years of their deployments. However, the trick is to sustain a Lean Six Sigma program over an extended period of time by imbedding it into the DNA of the organization. Most companies endeavor to sustain their program by exploring new areas of the business and executive continue to invest in education to ensure that the company maintains its critical mass of Lean Six Sigma practitioners. Many companies extend their scope of work to include their suppliers and customers. Improving the supplier's processes inadvertently benefits both the supplier and the company.

Various phases in a Lean Six Sigma deployment have been described in the section above. The recipe, however, for a successful Six Sigma deployment seems to be common across various companies: commitment from executive leadership; a strategy for aligning Lean Six Sigma with company goals; strong project review and selection process and the use of top talent in Black Belt roles (Szeto and Tsang, 2005). While most of the literature described above speaks through the prioritization of Lean Six Sigma projects, deployment strategies, and critical success criteria, what is missing, is a quantifiable way to evaluate if Lean

Six Sigma is the right transformation mechanism to apply to a particular process, business function or problem. The methodology works well for specific business problems that are process based, data rich, and where the root causes of problems may not already be known. There is a strong dependency on the repeatability and frequency of execution of the process, ensuring that the Black belts can characterize and baseline the process. Clearly, every business problem may not fit the mold! Very often the solution may be known and might require IT infrastructure and investment, or perhaps a change in the business model and policies that constrains the performance of the business unit. In these situations, Lean Six Sigma may not be the right transformational lever. There isn't a quantifiable/scientific way for Lean Six Sigma deployment champions to identify parts of their business that are Lean Six Sigma conducive. As a result deployment champions have a strong dependency on subject matter experts that very often are not attuned to the Lean Six Sigma methodology. This often results in the application of the wrong tools/methodology to fix a particular problem. The literature consistently speaks about the importance of project selection, and a number of companies have failed at Lean Six Sigma primarily because of poor project selection models. Very little work has been done to evaluate parts of an organization that are Lean Six Sigma conducive. Identifying Lean Six Sigma opportunities is a crucial step, as the success of a Lean Six Sigma deployment depends on how and where it is applied. The subsequent sections in this paper describe a model to aid in project identification and selection. The model establishes the evaluation criterion that enables six sigma practitioners to identify parts of the business that are Six Sigma conducive, a topic that is typically not addressed in the literature today. In addition, a case study is presented that demonstrates the use of the model in a large global company. Finally, future research in this area is highlighted

## 4. Project Identification Model

As described in the previous section, many companies have a fairly robust Lean Six Sigma project prioritizing approach, however, their ability to identify parts of the business that are conducive to the approach is light (Mader, 2007). Regardless of the deployment strategy, as discussed in the previous section, the message in the literature is consistent with regard to project selection being tied to the overall strategy of the organization. Figure 12 is an illustration of the proposed project identification and prioritization model. The figure is an adaptation and extension of the work carried out by Duarte *et al.* (2011). The model consists of an eleven step approach to identify Lean Six Sigma projects and thereafter the optimization of a portfolio over the life cycle of the deployment. This paper discusses the first half of the model beginning with the formalization of the organization’s strategy and leading on to the Lean Six Sigma project identification model. Subsequent work will address the Lean Six Sigma portfolio optimization model.

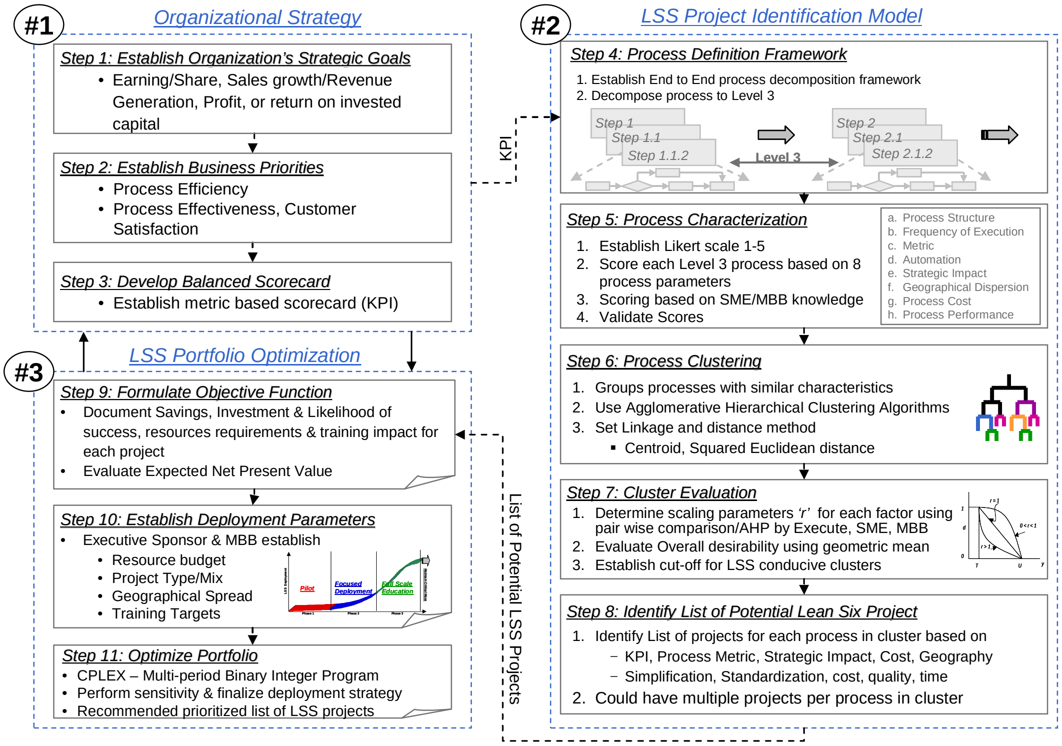


**Fig. 12.** Lean Six Sigma Project Identification and Prioritization Model

## 4.1. *Step 1: Formalization of Organizational Goals and Objectives*

Many companies typically have a long term strategic roadmap which includes the strategic direction the organization is taking. For many companies this might be sales growth, earnings per share, maximizing profit, or return on invested capital. Its important to establish this strategic roadmap and more importantly for the Lean Six Sigma deployment champion to align Lean Six Sigma with the strategic direction of the company.

### 4.2. *Step 2: Establish Business Priorities*

The second step involves breaking down of the organization strategy into clear business priorities. In Lean Six Sigma terminology, this would involve establishing the “Big Ys” and subsequently breaking down the “Big Y’s” into “smaller y’s”. This would provide the Lean Six Sigma deployment champion a view of which parts of the business to focus on and to ensure that the Lean Six Sigma portfolio is addressing the strategic objectives of the organization. As mentioned before, most companies are fairly good at aligning their Lean Six Sigma portfolios with the overall strategy.

### 4.3. *Step 3: Develop a Balanced Scorecard*

Balanced scorecards are invaluable is assessing the health of the business. Key Performance Indicators (KPIs) are established and monitored. The scorecard ensures that the projects that are selected are addressing the weaknesses in the performance of the organization. It is important to establish a balanced scorecard to ensure that Lean Six Sigma project selection is tied into performance of the organization and is focused on projects that impact the end customer.

### 4.4. *Step 4: Process Definition Framework*

The first three steps described above are common strategic considerations that many organizations make while identifying Lean Six Sigma projects. The next four steps collectively characterize and assess the applicability of Lean Six Sigma to various business functions based on the structure and characteristics of the processes they execute. The approach begins with the establishment of a process framework to enable end to end value chain definition and characterization. The existing literature is rich in process reference models. As an example American Productivity and Quality Center (APQC) introduced the Process Classification Framework (PCF) in 1992 that helps create a high-level, generic enterprise model. This framework enables organizations to document processes hierarchically, starting with the value chain, and ending with process tasks and activities. The Supply Chain Council (SCC) also has a reference model; The SCOR model can be accessed at http://supply-chain.org/ and is based on the Plan-Make-Source-Deliver-Return cycle and provides a unique framework that links business processes and metric. For the purpose of this research, a hierarchical approach similar to the APQC process taxonomy was utilized. Figure 13 is a schematic representation of the process definition framework and taxonomy.

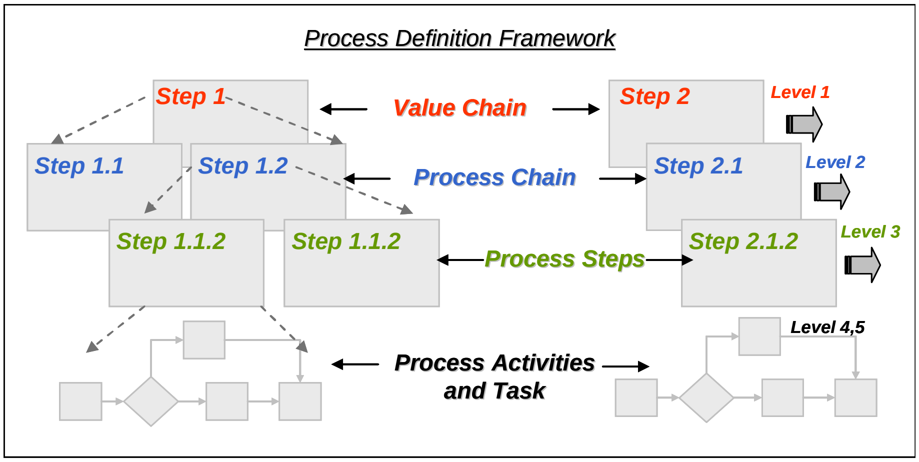


Fig. 13. **Process Definition Framework**

Additionally, the Value Chain Operations Reference model (VCOR) can also be used as a process decomposition framework. A detailed description of this model can be found at http://www.value-chain.org. The processes documented in this research were supply chain supporting processes that included order management, procurement, sourcing, invoicing, demand management, and some manufacturing and assembly processes. The data set considered in our model includes 4 processes at level 1, 35 processes at level 2 and 151 processes at level 3. For purpose of confidentiality, the process documentation is not provided in this paper. Also, level 3 process decomposition was chosen as the lowest level of decomposition for the identification model. A Level 3 of process decomposition was chosen because any further decomposition of process will result in projects being identified at the activity and task level instead of the process functional level resulting in projects with a very narrow scope. As an example: If we pick a level 4 decomposition, we might land up considering a credit check task as a potential project instead of the level 3 billing process. Alternatively, a level 2 of process decomposition does not provide an appropriate level of process granularity. Processes like strategic sourcing may be confounded with tactical sourcing under a level 2 procurement process, resulting in projects that may not be Lean Six Sigma conducive. Further process decomposition (level 4 and 5) is not required for this assessment, but perhaps is more relevant when a Lean Six Sigma project is kicked-off and a detailed investigation of process is required.

### 4.5. *Step 5: Process Characterization*

Lean Six Sigma is a process improvement methodology that has a strong statistical undertone. The methods and tools used are data driven, and work best on structured repeatable process that are not performing relative to customer expectations. Incidentally, Lean Six Sigma isn't the only transformational approach to improve the efficiency and effectiveness of a process! Many situations call for IT development and investments in infrastructure to enable business capabilities. Very often the constraint might be in the form of policy that inhibits business flexibility, while in other situations the solutions to the problem may be know and could just require project management. Consequently, knowing the right approach to use to solve a particular business problem is paramount. The process characterization approach described in this section helps evaluate the applicability of Lean Six Sigma to a business process.

Eight factors are considered while evaluating a process and a likert scale of 1-5 is used to score each process based on these eight factors. The process definition framework described in the previous sections sets the landscape of processes that will evaluated based on eight factors described below. As mentioned before, 151 processes at level 3 will be considered for this evaluation. A description of the eight factors follows:

1. *Strategic Impact (risk)/VOC:*

   Processes that impact the strategic priorities of an organization are critical while considering a Lean Six Sigma deployment. These processes drive value to their stakeholders as well as the end customer. If not executed well, they will directly impact customer satisfaction and ultimately revenue. Other processes are supporting processes which may not impact the end customer directly; however, they enable organizations to operate on a day to day basis. Examples of such processes could be HR based process like payrolls and employee re-imbursements. These processes on the other hand may not be a priority for Lean Six Sigma. The strategic impact of a process is a key factor in determining where and organization deploys Lean Six Sigma. Typically processes that impact the Voice of the Customer (VOC) are candidates for Lean Six Sigma

*2. Performance Factor:*

The gap between how a process is currently performing and how it should be performing is an important element that Lean Six Sigma practitioners should utilize in deciding the project portfolio mix. The balanced scorecard described earlier in this paper is one way to ascertain the “health” of an organization by monitoring the key performance indicators. Processes that are not performing well at the operational level are good candidates for Lean Six Sigma.

*3. Process Structure:*

Lean Six Sigma works well on processes that are structured! Structured processes can be described as processes that are repeatable with clearly defined rules, inputs, outputs, controls, and mechanism. Such processes tend to be well documented with a clear description on how they are executed at the activity and task level (level 4, 5 in Figure 4). These structured processes enable Lean Six Sigma practitioners to utilize Lean Six Sigma tools to identify bottlenecks and root causes of problems by isolating each process step and evaluating value-add and non value-added activities. On the other hand, processes that are contextual in nature and highly dependent on the condition at the time of execution are not the best candidates for Lean Six Sigma. Typically, processes that are more structured are Lean Six Sigma conducive.

*4. Process Cost:*

Apart from improving the effectiveness of a process, very often Lean Six Sigma projects are aimed at improving the efficiency of a process. With continued pressure to produce more with less, many projects are focused on operational cost. This parameter classifies processes based on their operating cost. The operating cost includes both the supporting headcount as well as IT and infrastructure cost. Processes that have a high operating cost are good candidates for Lean Six Sigma.

*5. Level of Process Automation:*

This parameter measures the level of automation of the processes. Processes in general can be very manual in nature or on the other hand can be automated. Processes that are manual are prone to human error and in general may be more susceptible to quality issues. In addition, process variability tends to be amplified in manual processes. The Lean Six Sigma focuses on improving the quality of a process by reducing the variability and eliminating waste in the process. Processes that are manual are good candidates for Lean Six Sigma projects.

6. *Frequency of Execution:*

This parameter describes how often a process is being executed. Structured processes that are executed often enable the Black Belt to map and baseline the process. Sufficient data can then be collected to characterize and trend the behavior of the process. In addition, it also presents the opportunity to statistically verify improvements made to the process, as sufficient data can be collected to compare the "before" and "after". This parameter helps distinguish between processes that are executed multiple times a day, to processes that are executed as infrequently as once a year. Again, the higher the frequency of execution, the more likely is the process conducive to Lean Six Sigma.

7. *Process Measurement/Metric:*

It is difficult to improve a process that can't be measured! Lean Six Sigma has a strong dependency on data as most of the tools and techniques used to improve processes have a statistical underpinning. The availability of an established process metric is an added bonus, on the other hand, the lack of a process metric or supporting data makes it difficult to measure the current performance of a process or even improvements that can be made to the process. In certain scenarios a metric may be established when the Six Sigma project is kicked off. This factor helps the Lean Six Sigma deployment champion distinguish between processes that have a metric from ones that are difficult to quantify and measure.

### *8. <u>Geographical Dispersion:</u>*

This parameter classifies processes by their geographical dispersion. Processes can be localized, standardized and executed the same way (tools) or can spans multiple geographies and can be executed with dissimilar tools. Processes that are localized have the advantage of being candidates for Kaizen events. Incidentally, this factor doesn't negate the selection of a global process (spread across multiple geographies) from being considered for a six sigma project, its geographical spread merely adds to the complexity of executing the project.

**Table 3.** Process Characterization Factors and Rating Criterion

| Category | Score | Definition |
|---|---|---|
| Strategic Impact (risk) VOC | 1 | Process is purely customer facing, impacts customer satisfaction – quality, revenue, litigation |
| | 2 | Process may indirectly impact customer satisfaction/revenue/litigation |
| | 3 | Process enables execution of the value chain |
| | 4 | Process supports execution of value chain |
| | 5 | Supporting processes that enable org to operate (HR, Finance) |
| Process Performance | 1 | Very Large gap between current performance and target (greater than 60%) |
| | 2 | Large gap between current performance and target (greater than 40%) |
| | 3 | Medium gap between current performance and target (greater than 20%) |
| | 4 | Small gap between current performance and target (greater than 10%) |
| | 5 | No gap between current performance and target |
| Process Structure | 1 | Process is structured with clearly defined rules clear inputs, outputs, controls and mechanism and documented processes |
| | 2 | Process is semi-structured with clearly defined rules clear inputs, outputs, controls and mechanism |
| | 3 | Process is semi-structured and is partially dependent on the conditions at the time of execution |
| | 4 | Process is unstructured and is partially dependent on the conditions at the time of execution |
| | 5 | Process is contextual/highly dependent on conditions. Judgment based |
| Process Cost | 1 | Very high operating cost, with headcount > 200 Full Time Equivalents |
| | 2 | High operating cost, with headcount < 200 Full Time Equivalents |
| | 3 | Medium operating cost, with headcount < 100 Full Time Equivalents |
| | 4 | Low operating cost, with headcount < 50 Full Time Equivalents |
| | 5 | Very low operating cost, with headcount < 10 Full Time Equivalents |
| Process Automation | 1 | Process is extremely manual |
| | 2 | Process is somewhat manual |
| | 3 | Process is semi-manual and requires people to IT interactions |
| | 4 | Process is mostly automated |
| | 5 | Process is automated |
| Frequency of execution | 1 | High frequency of execution-daily |
| | 2 | Process is executed on a weekly basis |
| | 3 | Process is executed monthly |
| | 4 | Process is executed with a low frequency – quarterly |
| | 5 | Process is executed once a year |
| Metric/Process measurement | 1 | Established measurement system monitored regularly |
| | 2 | Established measurement system monitored infrequently |
| | 3 | Available measurement system not monitored but can be collected |
| | 4 | No metric in place, but can be established and collected |
| | 5 | Process is difficult to measure |
| Geographical Dispersion | 1 | Process is localized, standardized and executed the same way (tools) |
| | 2 | Process spans more that one location and is executed the same way (tools) |
| | 3 | Process spans more that one location but is executed similarly with standard tools |
| | 4 | Process spans multiple geographies with similar tools |
| | 5 | Process is world wide with dissimilar tools |

For each of the eight factors described above a likert scale was developed from 1 - 5 with definitions for the criteria for each score. Table 3 has the definitions and criterion used. As described in step 4 of the process identification model, 151 processes at a level 3 (refer to Figure 13) were evaluated. Each process was scored relative to the eight factors. These processes represent supply chain execution processes ranging from order entry and procurement of raw materials to manufacturing and billing processes

## 4.6. *Step 6: Process Clustering*

Clustering is a process of organizing objects into groups whose members have similar attributes. Clustering can be classified as hierarchical clustering or non hierarchical clustering methods depending on the algorithm used to form the clusters. The data collected in the previous step consists of 151 processes that were scored based on eight factors using the criteria defined in Table 3. A hierarchical clustering algorithm was then used to group these processes based on the commonality of their characteristics. Minitab 14 was used to conduct the analysis. The clustering algorithm uses an agglomerative hierarchical method that begins with all observations being separate in their own cluster. In the first step, the two clusters closest together are joined to form $n$-1 clusters. In the next step, either a third observation joins the first two in a new cluster, or two other observations join together into a different cluster. This process will continue until all clusters are joined into one cluster. Note the approach described above is a hierarchical clustering method.

This means that that once an observation is assigned a cluster, it cannot be removed from the cluster; the cluster can join another cluster to form a new one. There also exists non-hierarchical clustering algorithms like the K-mean clustering algorithm which doesn't have this limitation. In general clustering algorithms are based off of a distance matrix/proximity measure that considers various linkage options in deciding if a particular data point joins a cluster or not. Various distance measures (Euclidean, Manhattan, Pearson to name a few) and linkage methods (Average, Centroid, Complete, McQuitty, Median, Single, Ward etc.) exists (Xu Rui and Wunsch, 2009). The clusters formed are sensitive to both the distance and the linkage methods and the composition of the clusters can change depending on the method used. In this model the squared Euclidean distance from the centroid of the cluster was used as the distance and linkage methods for the data set. For a detailed review of clustering approaches refer to Xu Rui and Wunsch, (2009). Figure 14 shows the dendogram that was created using Minitab 14.

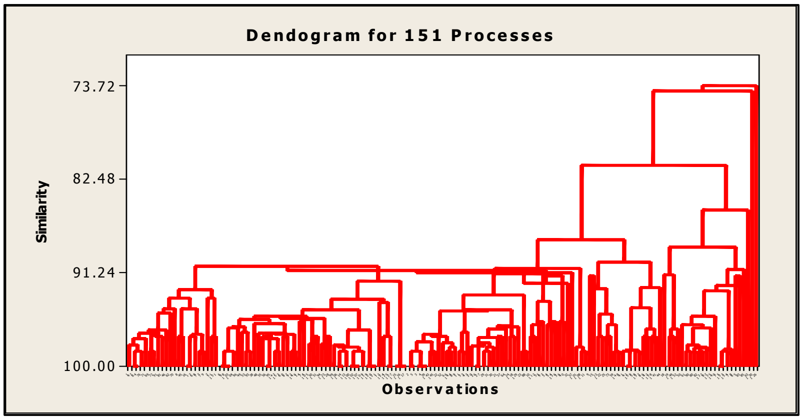


**Fig. 14.** Dendogram for 151 processes and Similarity Index

The dendrogram or tree diagram shows the amalgamation process of the hierarchical clustering algorithm. At each iteration, the dendogram indicates which clusters were combined. The y-axis is the similarity index of the clusters and Figure 15 shows how the similarity index degrades as clusters are joined together at each iteration.

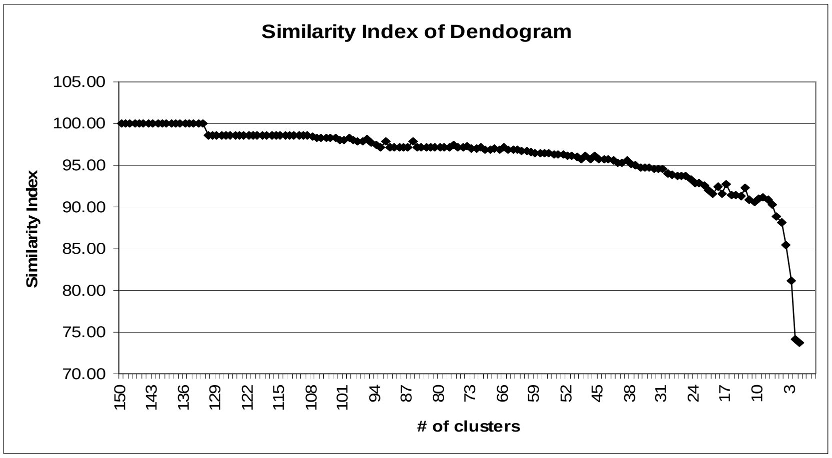


**Fig. 15.** Similarity Index at Each Clustering Step

Mathematically, the objective can be demonstrated as follows: Consider a data set $D = \{x_1, x_2, x_3, ...x_n\}$ of objects in *p*-dimensional space; we look for a partition $P = \{C_1, C_2, C_3, ...C_K\}$ of *D* that minimizes the intra-cluster distance '*W*'. The clustering approach can then be represented as:

$$\text{Minimize}(W) = \sum_{k=1}^{K} \sum_{x_i \in C_k} d(x_i, x_j)$$

Where,

$K$ – Number of clusters

$d(x_i, x_j) = \left\| x_i - x_j \right\|^2$ is the squared Euclidean distance between two points.

$W$ - Is the within cluster distances summed over all clusters

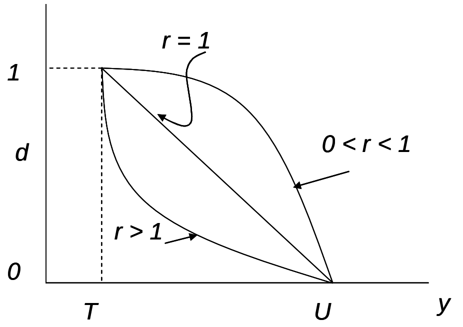
The hierarchical, agglomerative clustering method eventually groups all processes into one cluster. Figure 14 shows the iterative process beginning with a 151 clusters and eventually ending with one cluster. As each cluster is formed/combined, the homogeneity of the cluster is impacted by the joining object. The similarity index gives an indication of the deterioration in homogeneity of a cluster with each subsequent iteration. Therefore, examining the similarity index at each iteration helps adjudicate stopping rules for the algorithm. Based on the similarity index, 15 clusters were picked at a similarity index of 91%. Further consolidation of clusters impacts the similarity index as indicated by Figure 15.

### 4.7. *Step 7: Cluster Evaluation*

Lean Six Sigma is a process improvement methodology that works well for a very specific type of business problem. Its dependence on data and its focus on statistical analysis to drive process transformation make processes with established metrics that are structured with clearly defined rules, inputs, outputs, controls and mechanism especially attractive. Processes that are manual in nature and that are executed frequently present the best attributes for a Lean Six Sigma project. The geographic factor described in Table 3 impacts the complexity and ease of execution of the project but doesn’t necessarily prevent the application of Lean Six Sigma to the process. Traditionally, kaizen events and Lean workshops work best on processes that are co-located and the geographical spread only adds complexity to the project.

The clustering algorithm described above groups processes that have similar scores for each of the eight factors described in Table 3. The centroid of the cluster gives an indication of the overall characteristics of the processes within the cluster. The desirability of the cluster from a Lean Six Sigma perspective can be evaluated using an index that is a function of the relative importance of the eight factors. Clearly, a cluster with a score of “1” in each of the eight factors would be the best candidates for a Lean Six Sigma projects as it would represent a group of processes that are strategic, non-performing, structured processes with a high operating cost. Additionally, these processes are manual, executed often, and have an established measurement system. Geographically, these processes are co-located making it relatively easy to investigate and analyze. Any departures from this target value “1” would make the process less desirable from a Lean Six Sigma perspective.

In situations where the output of a process could have multiple responses, desirability functions can be used to determine an overall desirability based on the weighted product of the individual desirability indices (Myers, 2009). This enables decision makers to optimize multiple objectives simultaneously. A requirement in such situations (multiple responses) is to be able to ascertain the relative importance of each response through a desirability function. Derringer and Suich, (1980) were responsible for popularizing desirability functions. Since their first paper in 1980, there has been a lot of work in this area (Jeong and Kim, 2009). For the data set at hand, the next step is to ascertain the individual desirability functions for each process characteristic ($d_i$). This is approximating the shape of the function relative to the importance of the factor. Based on the scoring system used, the model fits the *"Minimum Value Case"* since a lower score on the likert scale is more desirable. Figure 16 illustrates the profiles of a desirability function for the minimum value case.



$$d = \begin{cases} 1 & y < T \\ \left( \dfrac{U - y}{U - T} \right)^{r} & T \leq y \leq U \\ 0 & y > U \end{cases}$$

**Fig. 16.** Minimum Value Case - Desirability Function

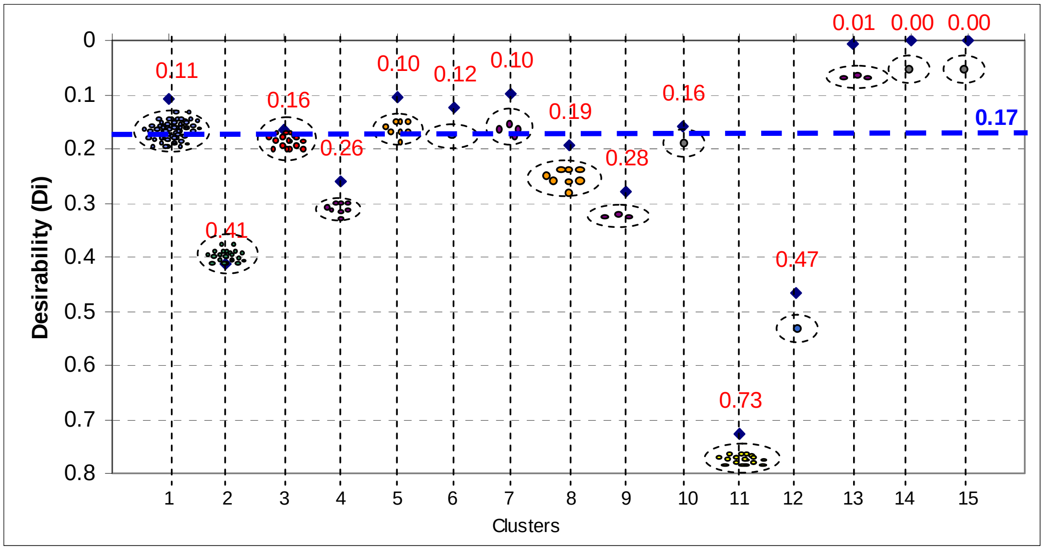
Note the shape parameter '*r*' dictates the shape of the desirability function. For '*r*'=1 the function is linear. For '*r*' > 1, the function is convex and places more importance on the parameter being closer to the target value. When *0 < r < 1,* the function is concave, with smaller values of '*r*' denoting that the factor is less important as far as meeting the target. The shape parameter *'r'* can be set by the deployment champion. For this data set, assumptions were made to determine the shape parameters for each of the eight factors. Table 4 highlights the parameters chosen and elaborates on the assumptions made. The shape parameters were chosen based on a pair wise comparison of each factor. This activity was performed by a group of subject matter experts in conjunction with the deployment champion and the executive sponsor. Parameters with the highest importance were scored ‘5’ while factors with the least importance were scored ‘0.5’. Table 4 has the rational behind the scoring used while conducting the pair wise comparisons. The process of selecting the shape parameters could be done by an Analytical Hierarchy Process (AHP) as described by Saaty (2008). The value of the shape parameter ‘r’ significantly impacts the overall desirability score of a cluster, and hence care must be taken to ensure that the values are chosen appropriately. A sensitivity analysis of the scaling parameters in conjunction with the analytical hierarchy process described above could also aid in addressing this issue.

**Table 4.** Shape Parameters for desirability Function

| Factor | Importance | Shape Parameter | Comment |
|---|---|---|---|
| Strategic Impact | Most Importance | *r = 5 (Convex)* | Impacts the end customer |
| Performance Factor | Very Importance | *r = 4 (Convex)* | Links to balance Score card |
| Process Structure: | Very Importance | *r = 3 (Convex)* | Process structure is an important factor for LSS projects |
| Process Cost | Very Important | *r = 2 (Convex)* | LSS aims at driving bottom line savings |
| Level of Automation | Important | *r = 1 (Linear)* | LSS works best for manual process |
| Frequency of Execution | Important | *r = 1 (Linear)* | Processes executed often are good candidates for LSS |
| Process Metric | Not Very Important | *r = 0.8 (Concave)* | Metric can be established and collected |
| Geographical Dispersion | Not Very Important | *r = 0.5 (Concave)* | Its an inhibitor but can be circumvented |

In addition target value ‘*T*’ = 1, the Upper Limit ‘*U*’ = 5.05 to ensure non-zero desirability values (Each process is scored on a scale of 1-5). Overall Desirability ($D_i$) is the geometric mean of the individual desirability indices $D = \left(d_1 d_2 d_3 \ldots d_m\right)^{1/m}$

Figure 17 is a pictorial representation of the 15 clusters along with their centroids. Clusters #11, #12 and #2 have the highest desirability scores. Cluster #11 has eleven processes with the highest desirability index of 0.73. It includes processes like manufacturing, procurement, order management processes, billing, and client services to name a few.



| Variable | Clusters | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Strategic Impact | 3.9 | 2.2 | 2.9 | 2.0 | 2.3 | 3.0 | 4.3 | 2.4 | 2.8 | 4.0 | 1.9 | 2.0 | 4.7 | 5.0 | 5.0 |
| Process Performance | 3.6 | 2.3 | 3.9 | 2.2 | 3.5 | 4.0 | 4.0 | 3.6 | 4.0 | 4.0 | 1.4 | 2.0 | 2.3 | 5.0 | 5.0 |
| Process Structure | 3.2 | 2.0 | 3.6 | 3.5 | 4.8 | 2.0 | 2.3 | 4.3 | 1.8 | 2.0 | 1.3 | 3.0 | 5.0 | 2.0 | 3.0 |
| Process Cost | 4.1 | 3.5 | 1.9 | 3.7 | 3.8 | 4.0 | 1.7 | 1.4 | 1.0 | 1.0 | 1.2 | 1.0 | 5.0 | 5.0 | 5.0 |
| Process Automation | 2.3 | 2.0 | 2.1 | 2.8 | 1.1 | 3.0 | 3.0 | 1.2 | 2.0 | 4.0 | 1.6 | 3.0 | 1.0 | 3.0 | 1.0 |
| Frequency of execution | 3.4 | 1.8 | 3.9 | 4.3 | 2.6 | 4.0 | 3.7 | 1.9 | 2.5 | 2.0 | 1.5 | 3.0 | 5.0 | 5.0 | 1.0 |
| Process Metric | 3.3 | 1.8 | 3.4 | 3.0 | 4.4 | 2.0 | 2.7 | 3.6 | 2.3 | 1.0 | 1.5 | 1.0 | 3.3 | 4.0 | 4.0 |
| Geographical Spread | 2.7 | 2.8 | 2.2 | 1.8 | 3.3 | 5.0 | 4.0 | 3.5 | 2.8 | 2.0 | 2.4 | 2.0 | 3.0 | 5.0 | 5.0 |

**Fig. 17.** Clusters with Desirability Scores

The centroid of this cluster (1.9, 1.4, 1.3, 1.2, 1.6, 1.5, 1.5 and 2.4) indicates that these processes are the best candidates for Lean Six Sigma projects. Cluster #12 and Cluster #2, have nineteen processes between them and also have a relatively high desirability index (0.47, 0.41).

Albeit it's low operating cost Cluster #2 has a strategic value, and performance parameter that indicates that these processes drive business value to the end customer and stakeholders and could negatively impact customer satisfaction if not executed efficiently and effectively. Cluster # 9 has a desirability index of 0.28. This cluster has four processes; however, they are currently performing fairly well. Figure 17 can be viewed as a roadmap for a Lean Six Sigma deployment champion as it indicates parts of the business that are most in need of Lean Six Sigma, given their strategic value and current performance. As each cluster is worked on, its score can be updated making the map a live document.

Clusters #8, has ten processes and while it lacks the process structure, it has processes that are strategic and have a high operating cost. A cut-off point is established in Figure 17 to aid the deployment champion in deciding which clusters are Lean Six Sigma conducive and which are not. The cut-off is at an overall desirability of 0.17 and is a function of the scaling parameter *'r'* used in the desirability indices. This cut was set based on clusters that scored at least '3' on Strategic Impact, Performance Factor, Process Structure, Process Cost, Level of Automation, and Frequency of Execution, and a '4' or better on process metric.

The score on the geographical parameter didn't impact the cut-off since this parameter primarily impacts the complexity of the project. Clusters above the cut-off tend to not have the best characteristics for Lean Six Sigma engagements. For these processes, alternate transformation options could include a change in the business model, policy or even IT based infrastructure changes. Of the 151 processes that were evaluated, approximately 33% were Lean Six Sigma conducive. For the processes that are Lean Six Sigma conducive, the next step is to identify specific projects which address the key performance indicators, process metric, strategic impact, process cost, and geographical spread. Specific project could additionally address process simplification, process standardization, product quality, and process lead time. As a result, there could be multiple projects for each process that are Lean Six Sigma conducive.

## 5. A Comparison of Manufacturing and Non-Manufacturing Processes

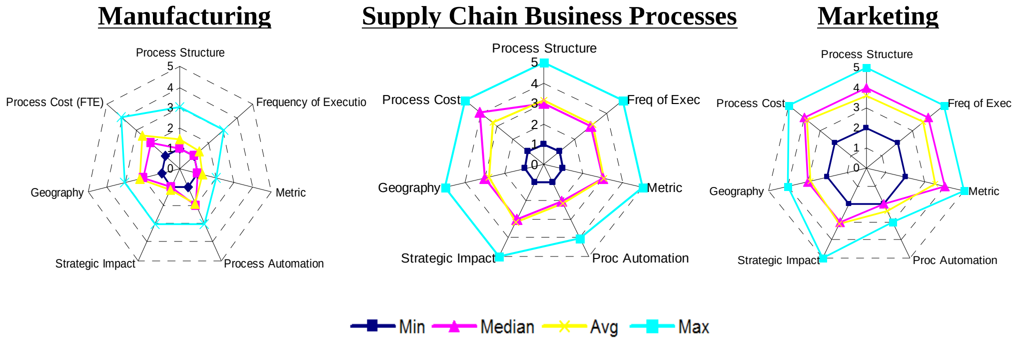
Lean Six Sigma was established to improve and streamline manufacturing processes. More recently the tools, approach and methodology of Lean Six Sigma have been applied to the transactional space, including healthcare and financial services (Atallah and Ramudhin, 2010). Applying Lean Six Sigma to non-manufacturing processes can present a unique set of challenges. Human intervention can be a significant source of variability (Bisgaard *et al*., 2002).

Table 5 illustrates a comparison with deploying Lean Six Sigma in the manufacturing space and the non-manufacturing space. The table highlights some of the challenges that a deployment champion might face in the transactional space. Typically, processes in the manufacturing space tend to be more structured with established process metrics and data that supports and facilitates process analysis. Additionally, manufacturing processes tend to be more conducive to Lean Six Sigma because the culture and mind-set of process owners in the manufacturing space tends to be more process driven. Also, it is easier to identify forms of waste in manufacturing processes since they tend to be more visible.

**Table 5.** Comparison of Manufacturing and Non-Manufacturing Challenges

| | Manufacturing | Non Manufacturing |
|---|---|---|
| Process Structure | ▪ More structured<br>▪ Can be physically viewed<br>▪ Better process documentation<br>▪ More repetitive<br>▪ Variability tends to be process, tool, operator or material based | ▪ Less Structured more contextual<br>▪ Lack of clearly defined rules with clear inputs, outputs controls and mechanism<br>▪ Significant amount of people to people interactions<br>▪ Human intervention can be a significant source of variability |
| Data & Metric | ▪ Well established metric that are measurement system<br>▪ Data tends to be more reliable<br>▪ Documented frequently and accurately | ▪ Very often there is a lack of data<br>▪ Data is less reliable |
| Culture & Mind-set | ▪ Culture is more process focused and data driven | ▪ The culture is less process focused, less scientific and data driven |
| Forms of Waste | ▪ Easier to detect forms of waste – tend to be physical<br>▪ Defects, Overproduction, Waiting, Transport, Inventory, Motion, Over processing | ▪ More difficult to detect forms of waste<br>▪ Approvals, hand-offs, unnecessary activities etc. |
| Tools | ▪ Tools were developed for application in Manufacturing | ▪ Most tools translate to the transactional space<br>▪ Some tools have found limited application (DOE) |

For the data set utilized in the cluster analysis, a comparison was conducted between the business processes that support supply chain execution and the manufacturing processes. Additionally, more data was collected on processes in the marketing space. The spider chart in Figure 18 depicts the differences between the manufacturing processes, supply chain supporting business/transactional processes and processes in the marketing space. The chart shows the minimum, median, average and the maximum scores for each business segment relative to the 7 process characteristics and the table has the average scores. Note the average scores for the manufacturing processes were rated higher in all categories (refer to Table 3). The factor related to process performance was left out of this analysis to essentially compare the characteristics of the processes and to maintain confidentiality of process performance.



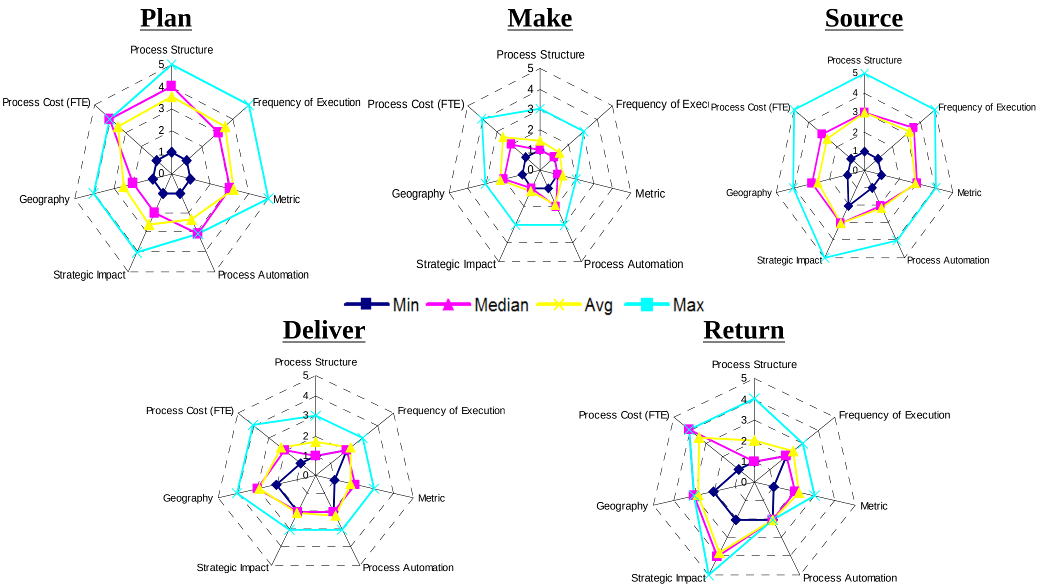
(a) (b) (c)

| Process | Process Structure | Frequency of Execution | Metric | Process Automation | Strategic Impact | Geographical Spread | Process Cost |
|---|---|---|---|---|---|---|---|
| Manufacturing | 1.45 | 1.36 | 1.27 | 1.91 | 1.18 | 2.18 | 2.55 |
| Business Processes | 3.11 | 3.07 | 3.02 | 2.11 | 3.18 | 2.77 | 3.26 |
| Marketing | 3.61 | 3.63 | 3.51 | 2.39 | 3.10 | 2.88 | 3.83 |

**Fig. 18.** Comparison of Manufacturing and Non-Manufacturing processes

In general manufacturing processes tend to be more structured, and have more data in place to baseline and quantify processes.

This isn’t surprising since the genesis of process improvement and Lean Six Sigma is in manufacturing. More recently, however, this has translated to the transactional space. Interestingly enough, about 30% of the processes reviewed had attributes that made them desirable candidates for Lean Six Sigma. Some interesting observations can be made from Figure 18. Marketing processes tend to be less structured and lack an adequate metric and measurement system. This isn’t surprising since Marketing has traditionally been an area dominated by “creative” processes that are contextual. Additionally, Figure 19 has a more granular view of the supply chain execution processes as it relates to the Plan, Make, Source, Deliver and Return segments of the SCOR model (http://supply-chain.org/)



| Process | Process Structure | Frequency of Execution | Metric | Process Automation | Strategic Impact | Geographical Spread | Process Cost |
|---|---|---|---|---|---|---|---|
| Plan | 3.54 | 3.46 | 3.23 | 2.31 | 2.54 | 2.46 | 3.46 |
| Make | 1.45 | 1.36 | 1.27 | 1.91 | 1.18 | 2.18 | 2.55 |
| Source | 3.00 | 3.18 | 2.88 | 2.16 | 3.04 | 2.61 | 2.61 |
| Deliver | 1.67 | 2.22 | 1.78 | 2.22 | 2.11 | 2.89 | 2.22 |
| Return | 2.00 | 2.40 | 2.20 | 2.00 | 3.80 | 2.80 | 3.40 |

**Fig. 19.** Comparisons of Business Functions

For the data set considered, the planning processes are centralized but less structured. The manufacturing processes are metric driven, structured, and executed frequently with a high operating cost. These processes are centralized with a high strategic impact and are manual in nature. The delivery and return processes are structured with available metric. Figure 19 has the averages scores for the functional areas and enables a Lean Six Sigma deployment champion to evaluate the compatibility of various business functions to Lean Six Sigma based on the process characteristics described in Table 3.

## 6. Conclusions and Future Work

The ever changing nature of the global economy has forced many organizations to re-examine their supply chains. Products and services traditionally executed in-house are now being delivered by contractors, vendors and suppliers half way across the globe. This continuous pressure to compete on price has led to increased process complexity, resulting in longer lead times and increased product and process defects. Many companies have embraced these challenges and have resorted to quality improvement programs like Lean Six Sigma to deliver on efficient and effective processes. Lean Six Sigma gained momentum in the early nineties, since then many companies have had success using the methodology. The literature is rich in describing the success criteria and speaks through the importance of aligning the program with the organizations strategic goals.

On the other hand many companies have struggled with adopting and sustaining their programs and much of this lack of success can be attributed to a week project identification and selection process (Kumar and Antony, 2009; Zimmerman and Weiss, 2005; Mader, 2008).

While most of the literature speaks through this consistently, there is a lack of quantifiable/scientific way to highlight focus areas in the supply chain that are Lean Six Sigma conducive. The research presented in this paper enables a deployment champion to use a systematic, holistic, data driven approach to indentify parts of the business that are conducive to the Lean Six Sigma methodology. An unsupervised learning approach using a clustering algorithm is used to group processes with similar characteristics. The agglomerative hierarchical clustering approach groups processes based on eight characteristics: strategic impact, process performance, process structure, process cost, level of automation, frequency of execution, existence of metric/process measurement, and the geographical dispersion of the process. This approach enables deployment champions to perform an assessment prior to deploying Lean Six Sigma. Additionally, the model acts as a deployment roadmap by establishing a priority for the deployment based on a desirability index. A case study is presented using data from a global company and the use of the methodology is demonstrated in the business process space. Approximately 33% of the processes that were characterized were Lean Six Sigma conducive. Additionally the model helps organization identify parts of the business that lack process metrics. The research also provides a comparison of manufacturing based processes with processes that are more services oriented. This will enable Six Sigma practitioners to understand the inherent differences in deploying Lean Six Sigma in various business sectors. The research presented in the paper highlights the subset of processes that are good candidates for a Lean Six Sigma project. This does not preclude an organization from using other transformational levers on the remaining processes. Other transformational initiatives may include changes in the business model, investing in IT and Infrastructure, improved communications and better visibility in the supply chain, improved market intelligence, mathematical modeling and other industrial engineering techniques. In addition, education programs and revisiting policy and procedures can aid as well. Processes in Figure 17 that do not have a high desirability score might be candidates for some of these approaches.

The model described in this paper uses a hierarchical clustering approach based on the squared Euclidean distances. Consequently, processes which are joined in a clustering step can never be separated. Future work could include non hierarchical clustering approaches like the K-means clustering. The project identification model described in the paper groups processes that are Lean Six Sigma conducive. Future work will be aimed at portfolio optimization and aiding the deployment champion in optimizing the Lean Six Sigma portfolio across the life cycle of the deployment. Considerations will be made to accommodate multiple objectives like: Return on investment, Lean Six Sigma penetration into the DNA of the organization, and improved customer satisfaction. Deployment champions are often faced with the question: How many projects can be executed given the limited resource? What is the ideal project mix? How do you maximize your return on investment? How quickly do you deploy the methodology for the program to be sustainable? For a portfolio of projects, the process of identifying a subset of priority projects to execute given a set of multiple objectives is a non-trivial decision. As the portfolio grows in size this decision becomes significantly more difficult. The portfolio optimization model will aid managers is making these decisions.

## Reference:

Atallah, B. and Ramudhin, A. (2010) Improving Healthcare Reliability by Integrating Six-Sigma in a Business Process Modeling and Analysis Strategy. *IEEE International Conference on Industrial Engineering and Engineering Management (IEandEM 2010)*, 2234-2238.

Banuelas, R., Tennant, C., Tuersley, I. and Tang, S. (2006) Selection Of Six Sigma Projects In UK. *The TQM Magazine*, 18(5), 514-527.

Bisgaard, S., Hoerl, R, Snee, R. (2002) Improving Business Processes with Six Sigma. *ASQ Annual Quality Congress Proceedings*, 701-704.

Bodek, N. (2004), *Kaikaku: The Power and Magic of Lean - A study in knowledge transfer*, PCS Press, Vancouver, WA.

Breyfogle, F.W. (2003*), Implementing Six Sigma*, Wiley and Sons Inc., Hoboken, New Jersey.

Cheng-Ru, Wua., Chin-Tsai, Lin., Pei-Hsuan, Tsai., (2010) Evaluating business performance of wealth management banks. *European Journal of Operational Research*, 207(2), 971-979.

Coronado, R.B. and Antony, J. (2002) Critical Success Factors for the Successful Implementation of Six Sigma Projects in Organizations. *TQM Magazine*, 14, 92–99.

De Mast, J. (2004) A Methodological Comparison of Three Strategies for Quality Improvement. *International Journal of Quality and Reliability Management*, 21(2), 198-213.

Derringer, G. and Suich, R. (1980) Simultaneous optimization of several response variables. *Journal of Quality Technology*, 12, 214–219.

Duarte, B.M., Montgomery, D.C., Fowler, J. W., Konopka, J. (2011) Deploying LSS in a Global Enterprise – Project Identification. *Arizona State University technical report.*

Gates, R. (2007) Deployment: Start Off on The Right Foot. *Quality Progress*, 40(8), 51.

Gonzalez-Padron, T. L., (2010) Knowledge Management and Balanced Scorecard Outcomes: Exploring the Importance of Interpretation, Learning and Internationalit. *British Journal of Management*, 21, 967–982.

Hahn, G.J., Doganaksoy, N. and Hoerl, R. (2000) The Evolution of Six Sigma. *Quality Engineering*, 12(2), 317-326.

Harry, M.J. (1998) Six Sigma: A Breakthrough Strategy for Profitability. *Quality Progress*, 31(5), 60–64.

Hu, G., Wang, L., Fetch, S., and Bidanda, B. (2008) A Multi-Objective Model for Project Portfolio Selection to Implement Lean and Six Sigma Concepts. *International Journal of Production Research*, 46(23), 6611–6625.

In-Jun Jeong, Kwang-Jae Kim. (2009) An Interactive Desirability Function Method to Multiresponse Optimization. *European Journal of Operational Research*, 195, 412–426.

J.R. Evans, and W.M. Lindsay, (2008) *Managing For Quality and Performance Excellence*, Thomson South-Western, Ohio, USA.

Kraus, K., and Lind, J. (2010) The impact of the corporate balanced scorecard on corporate control—A research note. *Management Accounting Research*, 21, 265–277.

Kumar, D., Nowickib, D., Ramirez, J., and Verma, D. (2008) On the Optimal Selection of Process Alternatives in a Six Sigma Implementation. *International Journal of Production Economics*, 111, 456–467.

Kumar, M. and Antony, J. (2009) Project Selection and Its Impact on the Successful Deployment of Six Sigma. *Business Process Management Journal*, 15(5), 669-686.

Kumar, U.D., Saranga, H., Ramirez-Marquez, J. and Nowicki, D. (2007) Six Sigma Project Selection Using Data Envelopment Analysis. *The TQM Magazine*, 19(5), 419-441

Linderman, K., Schroeder, R., Zaheer, S., and Choo, A. (2003) Six Sigma: A Goal-Theoretic Perspective. *Journal of Operations Management*, 21, 193–203.

Mader, D.P. (2007) How to identify and Select Lean Six Sigma Projects. *Quality Progress*, 40(7), 58.

Mader, D.P. (2008) What comes after the low-hanging fruit. *Quality Progress*, 41(8), 58-60.

Montgomery, D.C, (2010) A Modern Framework For Achieving Enterprise Excellence. *International Journal of Lean Six Sigma*, 1(1), 56-65.

Montgomery, D.C. (2009), *Introduction to Statistical Quality Control,* 6th edition, Wiley, New York, NY.

Montgomery, D.C. and Woodall, W.H. (2008) An Overview of Six Sigma. *International Statistical Review*, 76(3), 329-46.

Myers, R.H., Montgomery, D.C. and Anderson-Cook, C.M. (2009), *Response Surface Methodology,*3rd edition, Wiley, New York, NY.

Ren, X. and Zhang, G, (2008) Research on Decision Support for Six Sigma Project Selection Based On Fuzzy Evaluation. *4th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM),* 11, 1-11.

Saaty, T. L., (2008) Decision Making With the Analytic Hierarchy Process. *International. Journal of Services Sciences*, 1(1), 83

Schroeder, R.G., Linderman, K., Liedtke, C., and Choo, A. (2008) Six Sigma: Definition and Underlying. *Journal of Operations Management, 536-554*.

Snee, R. and Hoerl, R. (2003), *Leading Six Sigma*, Prentice Hall, Upper Saddle River, NJ.

Snee, R.D and Rodebaugh (2002) Project Selection Process. *Quality Progress*, 78-90.

Spear, S. and Brown, K. (1999) Decoding the DNA of the Toyota Production System. *Harvard Business Review,* 96-106.

Su, Chao-Ton. and Choua, Chia-Jen. (2008) A Systematic Methodology For The Creation Of Six Sigma Projects: A Case Study of Semiconductor Foundry. *Expert Systems with Applications,* 34(4), 2693-2703.

Szeto, A.Y.T. and Tsang, A.H.C. (2005) Antecedents to Successful Implementation of Six Sigma. *International Journal of Six Sigma and Competitive Advantage*, 1(3), 307-22.

Thomas, A.J., Rowlands, H., Byard, P., and Rowland-Jones, R. (2008) Lean Six Sigma: An Integrated Strategy for Manufacturing Sustainability. *International Journal of Six Sigma and Competitive Advantage*, 4(4), 333-354.

Xu Rui, and Wunsch, D.C. (2009), *Clustering*, Wiley and Sons, New York, NY.

Yang, T. and Hsieh, C., (2008) Six-Sigma Project Selection Using National Quality Award Criteria and Fuzzy Multiple Criteria Decision-Making Method. *Wireless Communications, Networking and Mobile Computing, WiCOM '08. 4th International Conference on 12-14,*1 – 4.

Zimmerman, J.P. and Weiss, J. (2005) Six Sigma's Seven Deadly Sins. *Quality*, 44(1), 62-66.

Zua Xingxing, Fredendallb, L. D., and Douglas, T. J., (2008) The Evolving Theory of Quality Management: The Role of Six Sigma. *Journal of Operations Management,* 26(5), 630-650.

Chapter 4

# MULTI-PERIOD, MULTI-OBJECTIVE LEAN SIX SIGMA PORTFOLIO OPTIMIZATION

## 1. Abstract

Lean Six Sigma has been around for over two decades. Many companies have adopted this Quality Improvement initiative with a great degree of success. Various deployment strategies have been presented in the literature and critical success factors have been discussed. A crucial element of any Lean Six Sigma deployment is project selection and prioritization. Very often the deployment champion is faced with the decision of selecting a portfolio of Lean Six Sigma projects that meet multiple objectives which could include: maximizing productivity, maximizing customer satisfaction or maximizing the return on investment, while meeting certain budgetary and strategic constraints. The model presented in this paper is a multi-period knapsack problem that maximizes the expected net savings of the Lean Six Sigma portfolio over the life cycle of the Lean Six Sigma deployment. In this paper, the lifecycle of the deployment includes a pilot phase, a focused deployment phase and a full-scale deployment phase. A case study is presented that demonstrates the application of the model in a large multinational company.

**Keywords:** Lean Six Sigma, Portfolio Optimization, Knapsack problem

## 2. Introduction

The globalization of the economy has forced many companies to re-examine the way they do business. Supply chain networks now span multiple geographies as companies continue to take advantage of lower cost regions. Competence and skill are not circumscribed by geography. Outsourcing and global resourcing are now becoming a way of life. The global nature of supply networks have resulted in increased process complexity and longer lead times. Many organizations have employed to Lean Six Sigma as a quality improvement initiative to circumvent process complexity, increase productivity and to remain competitive. Since its inception in the 80's, many companies have experienced tremendous success with Six Sigma. The General Electric (GE) story is one that is well documented and speaks through savings/benefits in the order of billions of dollars (Snee and Hoerl, 2003). The integration of Lean techniques (developed by Toyota) with Six Sigma principles has been a direction that many companies have taken. The focus on waste elimination and variability reduction has helped improve operational efficiency and process effectiveness. Since it gained popularity in Motorola and GE, the methodology has been adopted my many companies like Ford, DuPont, 3M, Dow Chemicals and Honeywell. At present, the methodology is being carried out in 35 percent of companies listed in Forbes top 500 (Ren and Zhang, 2008). The literature consistently speaks of the success that many companies have had with Lean Six Sigma. It also discusses some of the critical success factors, including project identification and selection (Mader, 2007). Selecting a Lean Six

Sigma projects is one of the most frequently discussed issues in the literature today (Kumar and Anthony, 2009c). Zimmerman and Weiss (2005) conducted a survey of companies that applied Lean Six Sigma and highlighted the importance of project selection and prioritization. In the article, the authors consider project selection and prioritization as one of the most important aspects of a successful Lean Six Sigma deployment. There are several approaches to identify Lean Six Sigma projects; Banuelas *et al.* (2006) conducted a survey of companies in the United Kingdom. The results of their work revealed that most companies' use brainstorming techniques, Critical-to-Quality (CTQ) trees, focus groups, interviews, customer visits, Quality Function Deployment (QFD), Kano analysis, and surveys to identify and prioritize Lean Six Sigma projects. A few companies use value stream mapping, and balanced scorecards as an aid in the identification of projects. The study also indicated that cost-benefit analysis, Pareto charts, un-weighted scoring models were the most popular prioritization approaches.

Lean Six Sigma portfolio optimization is a critical element in the overall deployment. Having identified a number of potential Lean Six Sigma projects, deployment champions are often faced with the following questions: How many projects can be executed given a limited number of resources? What is the ideal project mix? How do you maximize your return on investment? How quickly do you deploy the methodology for the program to be sustainable? For a portfolio of projects, the process of identifying a subset of priority projects to execute given a set of multiple objectives with multiple constraints is a non-trivial decision. As the portfolio grows in size this decision becomes significantly more difficult. The literature is rich in portfolio optimization. The problem of achieving the most desirable outcome by allocating limited resources to competing activities is perhaps the most common application of operations research. Traditionally, Six Sigma project selection uses impact versus effort to prioritize project. Kumar and Anthony, (2009c) proposed a hybrid methodology using an Analytic Hierarchy Process (AHP) and a Project Desirability Matrix (PDM) for project prioritization. Su and Choua, (2008) developed a very similar approach using Analytic Hierarchy Process (AHP) models in conjunction with Failure Mode Effects Analysis (FMEA) to evaluate the risk of each project in a semiconductor company. Ren and Zhang, (2008) proposed an evaluation method for project selection based on a multi-criteria decision-making method that uses fuzzy set theory and Kumar *et al.*, (2007a, 2008b) describe a method to prioritize Lean Six Sigma projects using data envelopment techniques. In their research a mathematical model is used to select one or more Six Sigma projects that will result in the maximum benefit to the organization. Yang and Hsieh, (2008) also use a hierarchical criteria evaluation process for project selection using a fuzzy multi-criteria decision-making method. The approach is demonstrated through a case study of a component manufacturer. Kahraman (2008) presented a combined fuzzy Analytic Hierarchy Process (AHP) and fuzzy goal programming approach to determine the preferred compromise solution for a six-sigma project selection problem with multiple objectives. In the paper, the author considers several factors including the maximization of financial benefits of the projects, maximization of process capability, maximization of customer satisfaction, minimization of cost, minimization of project completion time and the minimization of risk. A fuzzy Analytic Hierarchy Process (AHP) is then used to specify judgment about the relative importance of each goal in terms of its contribution to the achievement of the overall goal. Stewart (1991) discusses a multi-criteria decision support system for research and development (R&D) project selection carried out in a large electric utility corporation. He proposes a non-linear knapsack problem. Sowlati *et al.* (2005) presents a model using a data envelopment analysis framework for prioritizing information system based projects. A set of sample/artificial projects is created for which the criteria and priority scores are defined by decision makers. Each project is compared to the set of defined projects and receives a score. The model is tested on a real case of prioritizing information system based projects at a large financial institution. De Lima and De Sousa (2009) use a Multi-criteria Decision Aid (MDA) approach to support the decision-making process for research and development projects for the Brazilian aerospace sector. The proposed method makes use of existing methods and techniques found in the literature, such as cognitive mapping and Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) to prioritize projects. Manalo (2010) use an Analytic Hierarchy Process (AHP) to optimize capital investment decisions. The model developed used performance measurements including service cost, support cost and social cost in addition to more traditional methods like net present value to prioritize their project portfolio. Kendrick (2002) also suggests the use of an Analytic Hierarchy Process (AHP) method in Lean Six Sigma prioritization decisions. Dickinson *et al*., (2001) developed a dependency matrix approach for project prioritization at Boeing Corporation. The authors use a dependency matrix, which quantifies the interdependencies between projects. A nonlinear, integer program model was then developed to optimize project selection. The model also balances risk, overall objectives, and the cost and benefit of the entire portfolio. Abe (2007) propose a two-stage methodology based on (1) correlation analytics for identifying key drivers of business performance and (2) advanced portfolio optimization techniques for selecting optimal business-transformation portfolios given a set of budget constraints. Hu *et al.* (2008) presents a multi-objective formulation for project portfolio selection problem in manufacturing companies. The model presented is a multi-objective formulation where the benefit objective function is novel and the weights of the multiple objectives can be flexibly determined by the corporate management team. The output is a Pareto frontier chart that allows decision makers to have the flexibility of choosing the optimal decision based on the specific focus which may change over time. The two objectives considered in the research are to minimize the cost of implementing the portfolio while maximizing the return on investment. In their objective function, Hu *et.al* (2008) have gone beyond the simple summation of the benefit from each project chosen, they have also considered the interactions that may exist among projects during implementation. The model proposed considers three constraints. 1) The available number of Black Belt resources to execute projects. 2) A diversity constraint is included to diversify the portfolio and 3) A constraint on the number of projects that can be executed is also imposed. Kumar *et al.*, (2008b) present two optimization models that can assist management in choosing process improvement opportunities. The first model maximizes the quality level of a process under cost constraint, while the second model maximizes returns. Typically the literature shows that companies tend to achieve a better result when applying a portfolio based approach to project selection.

A significant amount of work has been done in the area of Lean Six Sigma project selection, prioritization and portfolio optimization. Duarte *et al.* (2011) describe an analytical approach to identify Lean Six Sigma projects using hierarchical clustering. Figure 20 is an illustration of the model proposed by Duarte *et al.* (2011). This paper serves as an extension of that work by describing a Lean Six Sigma portfolio optimization model. This corresponds to “#3” in Figure 20. The model assumes that the first 8 steps of project identification have been completed and that the deployment champion is presented with a list of potential Lean Six Sigma projects. The task is to optimize the Lean Six Sigma portfolio across the lifecycle of a Lean Six Sigma deployment.

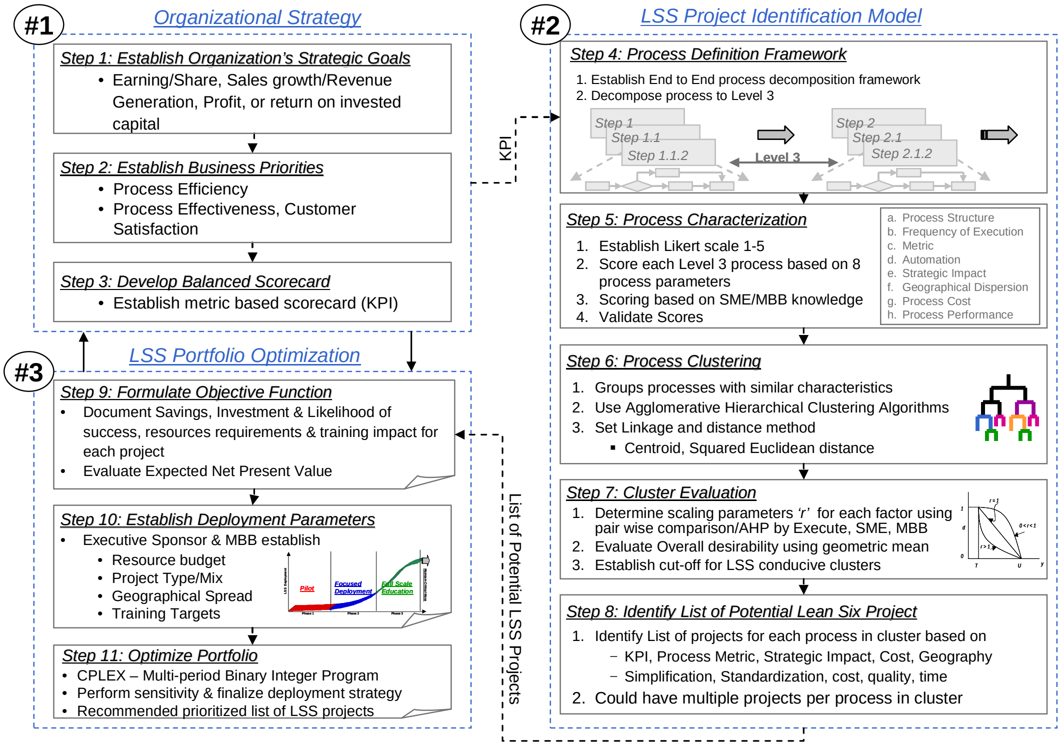


**Fig. 20.** Lean Six Sigma Project Identification and Prioritization Model

Most companies will go through an evolutionary Lean Six Sigma deployment, which consists of multiple phases including; 1) A Pilot or Proof of Concept phase, 2) A Focused Deployment phase within a specific area of the business 3) A Full-Scale Deployment phase resulting in mass education across the organization. In each of these phases, the deployment champion could have multiple objectives which vary from maximizing the likelihood of success and cost reduction to minimizing the investment required to sustain the program. Section 3 describes a multi-period, 0-1 knapsack problem, where the value of each potential project considered in the portfolio is phase dependent.  A case study is then presented in section 4 to demonstrate the application of the model in a large multi-national organization.

Finally, a sensitivity analysis is presented in section 5, followed by conclusions and future research in section 6.

## 3. The Lean Six Sigma Portfolio Optimization Model

In most companies Lean Six Sigma is deployed in a phased approach. The deployment typically includes a pilot or proof of concept phase, where very specific business problems are addressed. This is the most important phase as success in resolving an age old problem can demonstrate the usefulness of the methodology and help gain buy-in. Most companies focus on efficiency and cost reduction, with the intention of sparking an interest through pilot projects that demonstrate the power of Lean Six Sigma. Investments are made on education to train Business Leaders, Champions, Black Belts, and Master Black Belts and on executing projects. The second phase tends to be a Focused deployment. It is in this phase that most companies invest in more black belt resources to expand their program and thus achieve an accelerated Return on Investment (ROI). Green belt and Yellow belt training is typically carried out in this phase in an attempt to drive Lean Six Sigma into the DNA of the organization. Most successful companies have used this approach to accelerate Lean Six Sigma awareness. A Full Scale Deployment is accompanied by company wide education programs and an increased investment in black belt/master black belt resources, tools, and infrastructure to support the portfolio.

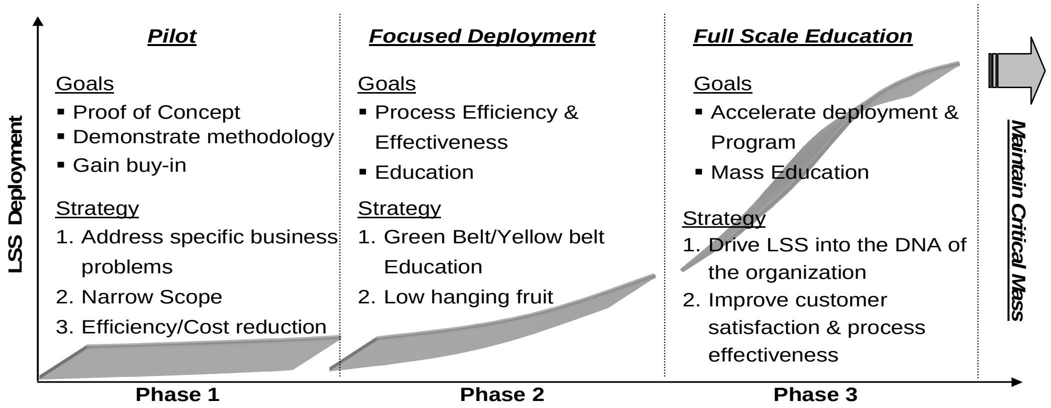


**Fig. 21.** Lean Six Sigma Deployment Strategy/Life Cycle

Figure 21 illustrates the goals, objectives and strategy in each phase of the deployment. For a detailed discussion of Lean Six Sigma deployment strategies refer to (Breyfogle, 2003) and (De Mast, 2004).

### List of Symbols

| | |
|---|---|
| $x_{ijk}$ | Binary decision variable that represents the $i^{th}$ project of type *j* in phase *k* |
| $e_{ijk}$ | Expected Net Savings of the $i^{th}$ project of type *j* in phase *k* |
| $b_{ijk}$ | Percentage of the utilization of Black Belt needed to execute the $i^{th}$ project of type *j* in phase *k* |
| $R_k$ | Total number of available Black Belt resources in phase *k*. |
| $d_{ijk}$ | Binary variable that determines if the $i^{th}$ project of type *j* in phase *k* is an effectiveness |
| $D_k$ | $D_k$ is a threshold value for effectiveness based projects in phase *k* |
| $gb_{ijk}$ | Binary variable that determines if $i^{th}$ project of type *j* in phase *k* is a green belt project. |
| $yb_{ijk}$ | Binary variable that determines if $i^{th}$ project of type *j* in phase *k* is a yellow belt project. |
| $GB_k$ | Minimum number of Green Belt projects that need to be executed in phase *k* |
| $YB_k$ | Minimum number of Yellow Belt projects that need to be executed in phase *k* |

| | |
|---|---|
| $g_{ijk}$ | Binary variable that determines if the $i^{th}$ project of type *j* in phase *k* is being executed in a growth market |
| $GM_k$ | Threshold number of projects that must be executed in the growth markets in phase k. |
| $a_{ijk}$ | Percentage of workforce trained by executing the $i^{th}$ project of type *j* in phase *k* |
| $DNA_k$ | Threshold percentage of workforce that must be trained in phase *k* of the deployment |
| $s_{ijk}$ | binary variable that determines if the $i^{th}$ project of type *j* in phase *k* is in the services space |
| $SVC_k$ | Minimum percentage of the portfolio that has to be services based |
| $r$ | Discount rate |

### 3.1. *Model Objective Function*

The model presented in this research is a multi-period, 0-1 knapsack problem where the objective is to ascertain the mix of Lean Six Sigma projects to include in each phase of the portfolio so as to maximize the expected net savings across the lifecycle of the deployment.

$$Max\ Expected\ Net\ Savings = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t} e_{ijk}\, x_{ijk} \qquad (1)$$

Equation (1) is a representation of the objective, where $e_{ijk}$ is the expected net savings associated with executing the $i^{th}$ project of type *j* in phase *k* and $x_{ijk}$ is a binary decision variable that indicates whether or not the $i^{th}$ project of type *j* is selected in phase $k \;\; \forall i = 1,2,3...n,\ \forall j = 1,2,3...m,\ \forall k = 1,2,3...t$

Therefore,

$$x_{ijk} = \begin{cases} 1 & \textit{If the decision is to select the } i^{th} \textit{ project of type j in phase k} \\ 0 & \textit{If the decision is not to select the } i^{th} \textit{ project of type j in phase k} \end{cases}$$

The expected net savings for each project is the product of the net present value of savings for the project, and the likelihood of success of the project. Equation (2) has the formula for the expected net savings.

$$\begin{aligned} Expected\ Net\ Savings\ e_{ijk} &= (Net\ Present Value\ of\ \ Savings) * \\ &\quad (Likelihood\ of\ \ Success) \end{aligned} \tag{2}$$

The likelihood of success of the project in this research is defined as the probability of successful completion of the project. For each project the likelihood of success is independent of other projects in the portfolio and depends on several factors including the complexity of the project, the availability of data and baseline metric, the structure of the process and its conduciveness to Lean Six Sigma, executive support and sponsorship within the area and prior knowledge of successful transformational activity in the space. The Net Present Value of Savings for a project in a particular phase is given in equation (3), where *r* is the discount rate per period, and *t* is the number of periods.

$$Net\ \ Present\ Value\ of\ \ Savings = \frac{(Savings - Investment)}{(1+r)^t} \tag{3}$$

The investment required to execute each project includes the education and training costs associated with training business leaders, process owners, yellow belts and green belts. Additionally, there are costs associated with infrastructure, tools, and IT as a consequence of process transformation, and finally costs associated with reporting, communication and governance. The savings associated with the project could be hard, soft or strategic.

## 3.2. *Model Constraints*

There are several constraints that have been considered while formulating the model. These constraints have been developed bearing in mind that the project portfolio is for a company that's about to deploy Lean Six Sigma world wide. Additionally it is the strategy of the organization to deploy Lean Six Sigma in the manufacturing and business process space, simultaneously. The model implicitly assumes that executing projects in a particular business space, results in the training and education of subject matter experts engaged in the project. Subsequently, the model assumes that deploying and implementing Lean Six Sigma go hand in glove.

### *3.2.1. Resource/Budget Constraints*

While deploying Lean Six Sigma, the executive sponsor often has a fixed budget which can be utilized to hire or train Master Black Belts, Black Belts, Green belts and Yellow Belts. The budget dictates the number of black belt resources that can be utilized in each phase, which in turn dictates the number of projects executed.

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t} b_{ijk} x_{ijk} \leq R_k \tag{4}$$

Equation (4) is the resource constraint, where, $b_{ijk}$ is the percentage of the utilization/time of Black Belt needed to execute the $i^{th}$ project of type $j$ in phase $k$, and $R_k$ is the total number of available Black Belt resources in phase $k$.

### *3.2.2. Project Mix Constraints*

In this model Lean Six Sigma projects are classified as 1) Efficiency based projects, which help drive productivity, cost reduction and bottom line savings. 2) Effectiveness based projects, which are focused on driving value for the end customer. Effectiveness based projects may not necessarily translate into hard or soft savings for the organization but they do impact customer satisfaction, thus helping maintain a strong customer base and potential revenue generation down the road. These constraints are shown in equation (5) and ensure that there is a healthy mix of efficiency and effectiveness based projects in each phase.

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t} d_{ijk}\, x_{ijk} \geq D_k \tag{5}$$

$d_{ijk}$ is a binary parameter that determines if the $i^{th}$ project of type $j$ in phase $k$ is an effectiveness based project. $D_k$ is a threshold value that ensures a certain percentage of the portfolio in phase $k$ is effectiveness based.

### *3.2.3 Project Heterogeneity Constraints*

Projects are classified as Yellow Belt projects, Green Belt projects or Black Belt projects based on their complexity and ease of execution. The constraints shown in equation (6) and (7) ensure that the portfolio has a mix of yellow belt and green belt projects in each phase. Incidentally, the assumption made is that Yellow Belt and Green Belt projects require subject matter experts in the area to be trained and certified in the methodology and thus help with disseminating process transformation skills and with driving Lean Six Sigma into the DNA of the organization.

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t} gb_{ijk}\, x_{ijk} \ge GB_k \tag{6}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t} yb_{ijk}\, x_{ijk} \ge YB_k \tag{7}$$

In equation (6) and (7), $gb_{ijk}$ is a binary parameter that determines if $i^{th}$ project of type $j$ in phase $k$ is a green belt project. Similarly, $yb_{ijk}$ is a binary parameter that determines if $i^{th}$ project of type $j$ in phase $k$ is a yellow belt project. $GB_k$ and $YB_k$ are the minimum number of Green Belt and Yellow Belt projects that need to be executed in phase $k$. There is no restriction on the number of Black Belt projects that can be executed.

### *3.2.4 Geographical Constraints*

The Lean Six Sigma portfolio described in this paper is for a multinational organization. Projects can be executed in North America, South America, Europe and the Middle East, Asia, and Australia and New Zealand. This constraint will force the portfolio to include projects from lower cost jurisdiction and growth markets (e.g. Asia). Often the savings associated with these projects can be a fraction of the savings of projects in higher cost jurisdictions. These constraints will ensure that a certain number of projects will be executed in growth markets.

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t} g_{ijk} x_{ijk} \geq GM_k \tag{8}$$

In equation (8) $g_{ijk}$ is a binary parameter that determines if the $i^{th}$ project of type $j$ in phase $k$ is being executed in a growth market (Asia) and $GM_k$ is the minimum total number of projects that must be executed in the growth markets in phase k.

### *3.2.5 Lean Six Sigma Training/DNA Constraints*

As mentioned before, the model implicitly assumes that executing projects in a particular business space, results in the training and education of subject matter experts engaged in the projects. Therefore, deploying Lean Six Sigma is a combination of implementation and training. Green Belt and Yellow Belt projects are normally led and executed by subject matter experts under the mentorship of a Black Belt or a Master Black Belt. Black Belt projects on the other hand are project managed and led by the Black Belts themselves. The assumption made in this paper is that Green Belt and Yellow Belt projects do more in driving Lean Six Sigma into the DNA of the organization since more people are trained to execute small projects.

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t} a_{ijk} x_{ijk} \geq DNA_k \tag{9}$$

For each potential project, a percentage of the workforce is trained in Lean Six Sigma as a consequence of executing the project. This percentage of trained workforce is a function of the number of people engaged in the supporting processes and the type of project being executed (yellow belt, green belt or black belt). In equation (9) $a_{ijk}$ is the percentage of workforce trained by executing the $i^{th}$ project of type $j$ in phase $k$ and $DNA_k$ is the minimum percentage of workforce that must be trained in phase $k$ of the deployment

### *3.2.6 Manufacturing and Services Constraints*

Lean Six Sigma found its roots in the manufacturing space and more recently has been applied to business processes and the transactional space, where it has also found success. This constraint ensures that a certain percentage of the Lean Six Sigma portfolio in each phase is due to projects from the business process space in addition to manufacturing based projects.

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t} s_{ijk}\,x_{ijk} \geq SVC_k \tag{10}$$

In equation (10) $s_{ijk}$ is a binary parameter that determines if the $i^{th}$ project of type $j$ in phase $k$ is in the services space (addressing a business process). $SVC_k$ is the minimum percentage of the portfolio that has to be services based.

## 4. Data Set

A set of sample/artificial projects was created. The data set contains 200 potential Lean Six Sigma projects. 20% of the projects are Yellow Belt projects, 30% are Green Belt projects and 50% are Black Belt projects. The data set contains projects from across the globe including 15% from Australia and New Zealand, 25% from North America, 10% from South America, 25% from Europe and the Middle East, and 25% from Asia (Growth Markets). The attributes of each project were generated to represent a real world scenario and Figure 22 has the distribution of project types and geographies. The scatter plot shows the savings/benefits, the investment and the likelihood of success for each project. Once again, the goal is to pick a portfolio of Lean Six Sigma projects across the life cycle of the deployment so as to maximize the expected net savings of the portfolio. The lifecycle consists of three phases of the deployment – The Pilot Phase, The Focused deployment phase and the Full-Scale deployment phase.

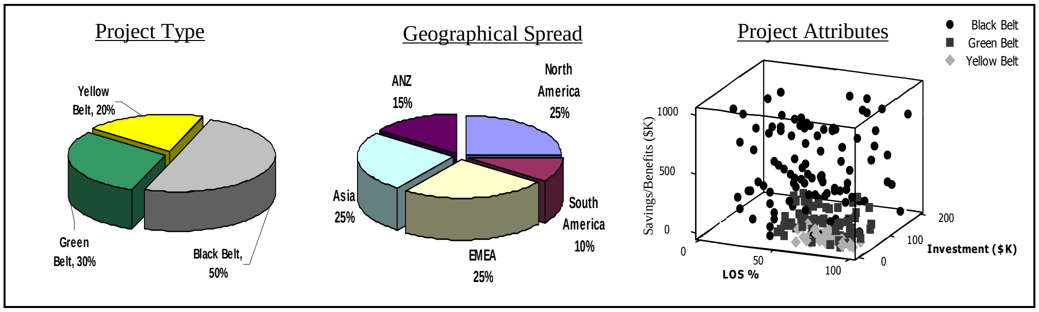


**Fig. 22.** Characteristics of Data Set

Additionally, 25% of the data set has effectiveness based projects and 40% of the data set contains projects from the Business Process/Services space, consequently

60% of the projects are manufacturing based projects. Table 6 contains the formulas used to generate the attributes of the projects. The attributes of a project are based on a random variable between a pre-defined range as shown in Table 6. A point to note is that Black belt projects in general bring in larger savings (hard/soft or strategic) and in general require a large investment. Additionally, the more complex nature of a Black Belt project requires a large percentage of the resource's available capacity. Green Belt or Yellow belt projects project tend to be smaller in scope and less complex in nature, thus the likelihood of success of these projects are generally higher than a Black Belt project. Also, Green Belt and Yellow Belt projects require the subject matter experts to be trained in the methodology, consequently these projects in general they have a higher impact in driving lean Six Sigma into the DNA of the organization

**Table 6.** Characteristics of Data Set

| Project Type | Savings/Benefits ($K) | Investment ($K) | Resource required (FTE) | LOS (%) | DNA- Training (%) |
|---|---|---|---|---|---|
| BB | Rand($100–$1,000) | Rand($0-$200) | Rand (0.4 –.85) | Rand (10%-100%) | Rand (.005%-.15%) |
| GB | Rand($20-$250) | Rand($0-$100) | Rand(0.1-.2) | Rand (40%-100%) | Rand (.015%-.35%) |
| YB | Rand($10-$100) | Rand($0-$50) | Rand(.05-.1) | Rand (60%-100%) | Rand (.01%-.25%) |

Table 7 has the model parameters for each of the constraints. The number of black belt resources available in the pilot phase is 5. Phase #2 and Phase #3 have 10 and 15 resources respectively, representing a ramp up in the number of black belts that support the deployment. This ramp up could represent additional employees being trained as black belts or new hires being brought into the program. The project mix constraints represent the percentage of the portfolio that must address effectiveness based projects. Phase 1 has a 20% constraint on the portfolio, ensuring that the deployment is not solely focused on cost reduction and return on investment. As the deployment progresses, this constraint is increased in increments of 5%. The heterogeneity constraints ensure that a certain number of yellow belt and green belt projects are selected in each phase. This constraint will help with driving Lean Six Sigma into the DNA of the organization, perhaps at the expense of the return on investment, since Black Belt projects in general will bring in a larger annualized saving. The geographical constraints indicate that at least 10 projects must be selected in a growth market (Asia in this scenario) in phase #1, 15 projects in phase #2 and 20 projects in phase #3. This will ensure that the deployment has a world wide presence.

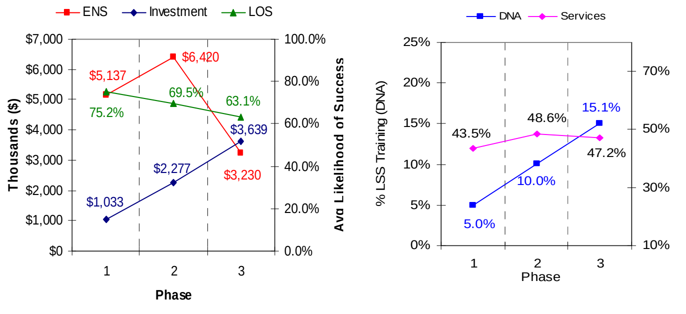
**Table 7.** Model Parameters

| Model Parameters | Phase 1 Pilot | Phase 2 Focused Deployment | Phase 3 Full Scale Deployment |
|---|---|---|---|
| Resources Constraint ($R_k$) | 5 | 10 | 15 |
| Project Mix Constraint($D_k$) | 20% | 25% | 30% |
| Heterogeneity Constraint ($YB_k$) | 5 | 10 | 15 |
| Heterogeneity Constraint ($GB_k$) | 10 | 15 | 20 |
| Geographical Constraint ($GM_k$) | 10 | 15 | 20 |
| Training Constraint ($DNA_k$) | 5% | 10% | 15% |
| Services Constraint ($SVC_k$) | 40% | 40% | 40% |

There is a requirement that at least 5% of the workforce is trained in Lean Six Sigma at the end of each phase. Cumulatively, this amounts to 10% in phase #2 and 15% in phase #3.

As discussed in the previous section, executing yellow belt and green belt projects results in a higher number of trained Lean Six Sigma employees since these projects are led and managed by subject matter experts under the mentorship of a black belt. Finally, the Manufacturing and Services constraint will ensure that at least 40% of the portfolio addresses business processes. This will help prevent a purely manufacturing focus with the Lean Six Sigma deployment. The model parameters and constraints described above are set based on the executive sponsor’s budget and the deployment strategy. Clearly, these parameters might change based on type of organization, its geographical spread and the strategy of the deploying executive.

IBM’s ILOG CPLEX Optimization Studio v 12.2 was used to build the multi-period, 0-1 knapsack problem. The run time for the model was fifteen minutes, and was fairly quick for a data set of two hundred projects. Figure 23(a) shows the expected net savings, the investment and the likelihood of success of the portfolio in each of the three phases.



|  | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| YB | 7 | 10 | 15 |
| GB | 10 | 15 | 20 |
| BB | 6 | 12 | 18 |
| **Total # Projects** | **23** | **37** | **53** |
| Projects in GMU | 10 | 15 | 20 |
| # of Effectiveness | 5 | 10 | 16 |
| DNA | 5.0% | 10.0% | 15.1% |
| Expected Net PV |  |  | $14,787 |
| Total Invest |  |  | $6,949 |
| Average LOS |  |  | 69.3% |

(a) (b) (c)

**Fig. 23.** Model Results

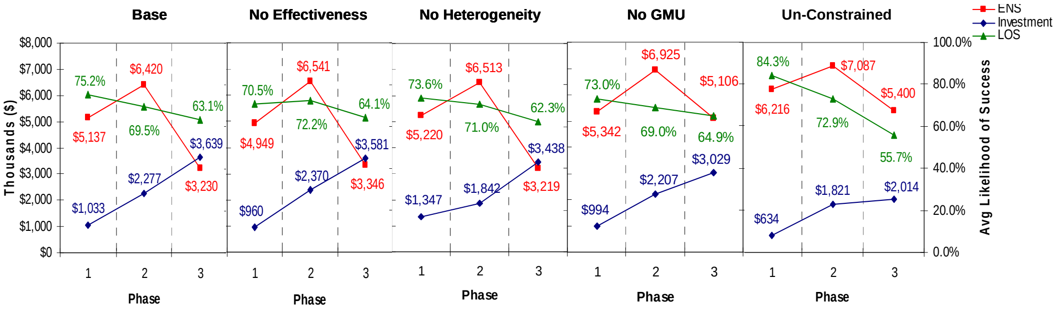
A total of 23 projects were selected in phase #1 with a likelihood of success of 75.2%. The expected net savings associated with these projects is a little over $5.1 million with an investment of $1.03 million. 10 projects were selected from Asia and a total of 5 projects were effectiveness based. A majority of the projects selected are green belt projects and yellow belt projects to meet the project heterogeneity constraints. As the number of resources in phase #2 is increased to 10, the expected net savings for the portfolio increases to $6.4 million with an investment of $2.27 million. The likelihood of success for phase #2 is 69.5%. The total number of projects selected in phase #2 is 37. Phase #3 has 15 black belt resources, 5 more than phase #2. A total of 53 projects are selected in phase #3 with an expected net savings of $3.2 million with an investment of $3.6 million. The reduced ratio of net savings to investment can be attributed to the fact that most of the high value projects have been selected in phase #1 and #2. Additionally, the model constraints, especially the geographical constraints, force the portfolio to include projects with a lower return on investment. Phase #3 has a total of 18 black belt projects and the portfolio has 61.7% likelihood of success. Incidentally, 20 projects are from Asia, and 16 effectiveness based projects were selected in phase #3. Figure 23(c) has a summary of the portfolio by phase.

Figure 23(b) shows the percentage of the workforce trained as result of executing the portfolio. By the end of phase 3 a total of 15.1% of the population was trained in some form of Lean Six Sigma education. This could include business leader education and general Lean Six Sigma awareness. Figure 23(b) also shows the percentage of the portfolio that has services based projects in each phase. At the end of phase #3 the total expected net savings is $14.7million with an investment of $6.9 million. A total of 113 projects were selected across the three phases.

## 5. Sensitivity Analysis

The model presented in the previous section has certain restrictions on the composition of the portfolio. There is a stipulation that the portfolio contains a certain percentage of effectiveness based projects, which may reduce the total expected net savings but improves customer satisfaction. Additionally, the portfolio has a heterogeneity constraint which forces the inclusion of a certain number of green belt and yellow belt projects, which may bring in a relatively small return on investment, but in turn help with driving Lean Six Sigma into the DNA of the organization. Projects executed in lower cost jurisdiction may also have a smaller expected net savings potential. A sensitivity analysis was conducted to evaluate the impact of each of these constraints on the portfolio. Figure 23 enables the deployment champion and executive sponsor to ascertain the impact of each constraint on the portfolio

The first graph in Figure 24 is the base case model with all the constraints included. The results are the same as those presented in Figure 23. The second graph represents the results of the model with a relaxation on the effectiveness constraint.



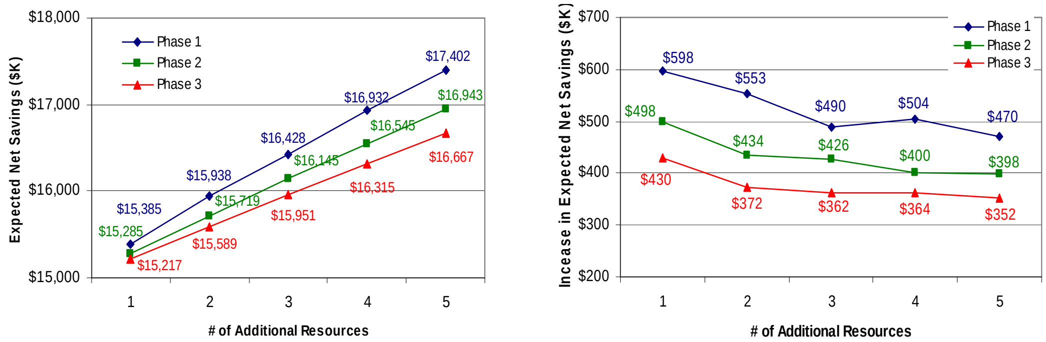
| | Base Model | | | No Effectiveness | | | No Heterogeneity | | | No GMU | | | Un-Constrained | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ph 1 | Ph 2 | Ph 3 | Ph 1 | Ph 2 | Ph 3 | Ph 1 | Ph 2 | Ph 3 | Ph 1 | Ph 2 | Ph 3 | Ph 1 | Ph 2 | Ph 3 |
| YB | 7 | 10 | 15 | 6 | 10 | 15 | 14 | 7 | 9 | 6 | 10 | 15 | 0 | 4 | 0 |
| GB | 10 | 15 | 20 | 10 | 15 | 20 | 11 | 18 | 14 | 10 | 15 | 20 | 3 | 12 | 8 |
| BB | 6 | 12 | 18 | 6 | 12 | 18 | 5 | 11 | 20 | 7 | 11 | 17 | 8 | 13 | 23 |
| Total # Projects | 23 | 37 | 53 | 22 | 37 | 53 | 30 | 36 | 43 | 23 | 36 | 52 | 11 | 29 | 31 |
| Projects in GMU | 10 | 15 | 20 | 10 | 15 | 20 | 10 | 15 | 20 | 3 | 6 | 15 | 0 | 0 | 0 |
| # of Effectiveness | 5 | 10 | 16 | 6 | 10 | 12 | 6 | 9 | 13 | 5 | 9 | 16 | 0 | 0 | 0 |
| **Expected Net Savings ($K)** | **$14,787** | | | **$14,837** | | | **$14,952** | | | **$17,372** | | | **$18,703** | | |
| **Total Investment ($K)** | **$6,949** | | | **$6,911** | | | **$6,627** | | | **$6,230** | | | **$4,469** | | |
| **Avg Likelihood of Success** | **69.30%** | | | **68.95%** | | | **68.96%** | | | **68.99%** | | | **70.90%** | | |

**Fig. 24.** Sensitivity Analysis on Constraints

The portfolio isn't forced to include a certain percentage of effectiveness based projects; as a result the total savings at the end of the three phases is $50K higher than the base case. This is not a significantly higher that the base model given the total investment and the total net savings. The third and forth graphs represent the relaxation on the project heterogeneity and geographical constraints respectively. Relaxing the project heterogeneity constraint allows the portfolio to include considerably more black belt projects that have a higher net savings. The resulting portfolio has a total expected net savings of $14.9 million with an investment of $6.6 million. In the next graph, one can see that a total expected net savings of $17.3 million can be achieved with an investment of $6.2million when the geographical constraint is relaxed. This allows the portfolio to include projects from higher cost jurisdiction which have a higher net present savings opportunity.

From Figure 24, the geographical constraints have the highest impact on the expected net present value and would thus be the first factor that the deployment champion might consider relaxing. Finally, an unconstrained model has an expected net savings of $ 18.7 million with an investment of $4.4 million by executing a total of 71 projects in the three phases. While the total count of projects seems smaller, most of the projects are black belt projects that require more resources.

Clearly, the number of available resources dictates the number of projects that can be selected in each phase. Figure 25 is a sensitivity analysis on the number of resources at each phase. Figure 25(a) depicts the total expected net savings at the end of phase 3 by increasing the number of resources in each phase by increments of 1. Figure 25(b) depicts the increase in savings for each additional resource. Intuitively, phase #1 has the highest increase in expected net savings for each additional resource and each phase has an increase in total expected net savings at a decreasing rate.



(a) (b)

**Fig. 25.** Sensitivity Analysis on Resources

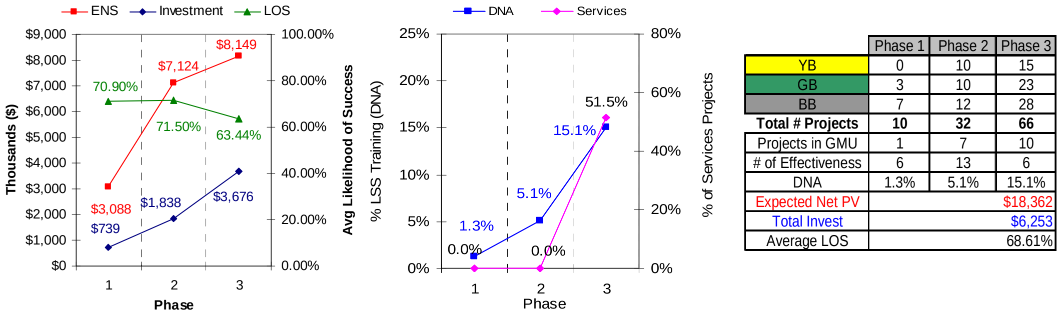
The model presented above can be used as a decision support tool by the deployment champions to test "what-if" scenarios. Consider the following scenario: The organization is currently facing quality issues with its product line. As a result the company has unsatisfied customers and this could potentially impact revenue in the future. Based on the strategic direction of the organization, the deployment champion has decided to focus the initial phases of the Lean Six Sigma deployment on improving the effectiveness of its manufacturing processes. Additionally, the direction is to not focus on green belt/yellow belt projects or on training in the initial phase. The organization is willing to invest in more black belts and is willing to expand the deployment to growth markets (Asia) once its initial manufacturing issues have been resolved. The new parameters for the model are presented in Table 8. These parameters are typically chosen based on input from the executive sponsor in conjunction with the organization's strategy. Typically, the budget dictates the number of black belt resources that can be hired/trained in each phase of the deployment to support the portfolio.

**Table 8.** Revised Model Parameters

| Model Parameters | Phase 1 Pilot | Phase 2 Focused Deployment | Phase 3 Full Scale Deployment |
|---|---|---|---|
| Resources Constraint ($R_k$) | 5 | 10 | 20 |
| Project Mix Constraint($D_k$) | 60% | 40% | 0% |
| Heterogeneity Constraint ($YB_k$) | 0 | 10 | 15 |
| Heterogeneity Constraint ($GB_k$) | 0 | 10 | 15 |
| Geographical Constraint ($GM_k$) | 0 | 0 | 10 |
| Training Constraint ($DNA_k$) | 0% | 0% | 10% |
| Services Constraint ($SVC_k$) | 0% | 0% | 10% |

The composition of the portfolio, including the project mix, the number of green belt and yellow belt projects, the training constraints and geographical spread are established based on a collaborative decision between the executive sponsors and the deployment champion and is influence by the desired rate and pace of the deployment strategy.

Figure 26 shows the results of running the model with the revised parameters. Since the initial phases of the deployment are primarily focused on improving the quality of the manufacturing processes, the portfolio comprises of projects that are more effectiveness based and may not have as high an expected net savings as the previous scenario. Figure 26(a) shows that the expected net savings for the first two phases is approximately $10.2million with an average likelihood of success of 71.2%, compared to the original scenario which has an expected net savings of $11.5million with an average likelihood of success of 72.4%. In phase #3 there isn't a restriction on the project mix or a mandate to run manufacturing based projects and with the additional resources (20 black belts), the expected net savings increases to $8.1million.



| | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| YB | 0 | 10 | 15 |
| GB | 3 | 10 | 23 |
| BB | 7 | 12 | 28 |
| **Total # Projects** | **10** | **32** | **66** |
| Projects in GMU | 1 | 7 | 10 |
| # of Effectiveness | 6 | 13 | 6 |
| DNA | 1.3% | 5.1% | 15.1% |
| Expected Net PV | | | $18,362 |
| Total Invest | | | $6,253 |
| Average LOS | | | 68.61% |

(a) (b) (c)

**Fig. 26.** Revised Model Results

Figure 26(b) shows the percentage of the workforce trained as a result of executing the portfolio and Figure 26(c) summarizes the number and type of projects that can be executed based on the selected model parameters.

## 6. Conclusion and Future Work

The ever changing nature of the global economy has forced many organizations to relook at their supply chains. Products and services are being delivered through processes executed in multiple geographies and the pressure to compete on price and quality is becoming critical. Many companies have embraced these challenges and have turned to Lean Six Sigma as a means to drive process efficiency and effectiveness. The literature describes the critical success factors and consistently speaks of the importance of project identification, selection and prioritization (Mader, 2007).

A significant amount of work has been done in the area of portfolio optimization. The research presented in this paper, however, is aimed at optimizing a portfolio for a company that is about to deploy Lean Six Sigma. The model presented in this paper is a multi-period 0-1 knapsack problem that maximizes the expected net savings of the Lean Six Sigma portfolio over the life cycle of the Lean Six Sigma deployment. Three phases are considered in the life-cycle; A Pilot phase, A Focused Deployment phase, and a Full-Scale Deployment phase. Additionally, the objective of the model is to maximize the expected net savings of the portfolio.

Provision is made to include projects from both the transactional space as well as from the manufacturing space, and constraints force the model to maintain a minimum level of project heterogeneity while ensuring that the portfolio is global.

This research demonstrates the usefulness of mathematical programming as applied to Lean Six Sigma portfolio selection. Currently the model assumes that all black belt resources are homogeneous. Future research will include the assignment of projects to black belts based on their geographical location and level of experience and expertise. Provision can be made to consider the interdependencies of projects, and priority can be placed on projects that collectively impact a product line, ensuring that process transformation is more end to end in nature. The model described in this paper generates an optimized Lean Six Sigma portfolio that can be executed over the course of three phases. However, at the end of phase 1 the model can be re-run with the inclusion of new projects, since things likely change over time. Future research will consider a rolling horizon.

Finally, the model presented in this paper can be used as a decision support tool by deployment champions looking to deploy Lean Six Sigma in a global enterprise. It enables the decision maker to test various scenarios by playing “what- if” games. Decisions on the number of black belt resources to hire in each phase, the project mix, and the deployment strategy can be tested. In summary, the model can be used as a useful tool in developing the overall strategy of Lean Six Sigma implementation and deployment in a global enterprise.

## References

Abe, N., Akkiraju, R., Buckley, S., Ettl, M., Huang, P., Subramanian, D., Tipu, F., (2007) On optimizing the selection of business transformation projects, *IBM Systems Journal*, 46, 4.

Banuelas, R., Tennant, C., Tuersley, I. and Tang, S. (2006) Selection of Six Sigma Projects in UK. *The TQM Magazine*, 18(5), 514-527

Breyfogle, F. W., (2003) *Implementing Six Sigma,* John Wiley and Sons Inc., Hoboken, New Jersey.

De Lima, A. S., De Sousa, J. H. D., (2009). A Proposed Method for Modeling Research and Development Project Prioritization Criteria, *PICMET '09 - 2009 Portland International Conference on Management of Engineering and Technology*, 599-608.

De Mast, J., (2004) A Methodological Comparison of Three Strategies for Quality Improvement. *International Journal of Quality and Reliability Management*, 21(2), 198-213.

Dickinson, M. W., Thornton, A. C., and Graves, S. (2001) Technology Portfolio Management: Optimizing Interdependent Projects over Multiple Time Periods. *IEEE Transactions on Engineering Management,* 48(4), 518–527.

Hu, G., Wang, Fetch, S., Bidanda, B., (2008) A Multi-Objective Model for Project Portfolio Selection to Implement Lean and Six Sigma Concepts, *International Journal of Production Research,* 46(23), 6611–6625.

Kahraman, C. Büyüközkan, G. (2008) A Combined Fuzzy AHP and Fuzzy Goal Programming Approach for Effective Six-Sigma Project Selection*. Journal of Multiple-Valued Logic and Soft Computing*, 14(6), 599-615

Kendrick, J.D., Saaty, D. (2007) Use Analytic Hierarchy Process For Project Selection*. ASQ Six Sigma Forum Magazine. Milwaukee*: 6(4); 22

Kumar, U.D., Saranga, H., Ramirez-Marquez, J. and Nowicki, D. (2007a) Six Sigma Project Selection Using Data Envelopment Analysis. *The TQM Magazine,* 19(5), 419-441.

Kumar, D., Nowickib, D., Ramirez, J., and Verma, D. (2008b) On the Optimal Selection of Process Alternatives in a Six Sigma Implementation. *International Journal of. Production Economics,* 111, 456–467.

Kumar, M. and Antony, J. (2009c) Project Selection and Its Impact on the Successful Deployment of Six Sigma. *Business Process Management Journal*, 15(5), 669-686.

Mader, D. P. (2007) How to identify and Select Lean Six Sigma Projects. *Quality Progress*; 40(7), 58.

Manalo, R.G., (2010) Comparing Project Prioritization Method and Net Present Value Method of Capital Rationing Using Kendall's Tau Distance. *2010 IEEE International Conference on Management of Innovation and Technology (ICMIT 2010),* 95-100.

Ren, X. and Zhang, G., (2008) Research on Decision Support for Six Sigma Project Selection Based On Fuzzy Evaluation. *4th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM),* 11, 1-11.

Snee, R., Hoerl, R., 2003. *Leading Six Sigma*, Pearson Education Inc.

Sowlati, T., Paradi, J.C., Suld, C., (2005) Information systems project prioritization using data envelopment analysis. *Mathematical and Computer Modeling*, 41(11), 1279-1298.

Stewart, T.J. (1991) A Multi-Criteria Decision Support System for RandD Project Selection. *The Journal of the Operational Research Society*, 42, 17–26.

Su, Chao-Ton. and Choua, Chia-Jen., (2008) A Systematic Methodology for the Creation of Six Sigma Projects: A Case Study of Semiconductor Foundry, *Expert Systems with Applications,* 34(4), 2693-2703.

Yang, Taho and Hsieh, Chiung-His, (2008) Six-Sigma Project Selection Using National Quality Award Criteria and Fuzzy Multiple Criteria Decision-Making Method. *Wireless Communications, Networking and Mobile Computing, WiCOM '08. 4th International Conference on 12-14 Oct. 2008,* 1 – 4.

Zimmerman, J.P. and Weiss, J., (2005) Six Sigma’s Seven Deadly Sins. *Quality*, 44(1), 62-66.

# Chapter 5

# CONCLUSIONS AND FUTURE WORK

The ever changing nature of the global economy has forced many organizations to outsource parts of their business that are either not their core competence or that can be executed in a lower cost jurisdiction. Products and services traditionally executed in-house are now being delivered by contractors, vendors and suppliers half way across the globe. This continuous pressure to compete on price has led to increased process complexity, resulting in longer lead times and increased product and process defects. Many companies have embraced these challenges to compete in this complex environment, and have resorted to quality improvement programs to deliver efficient and effective processes. The most popular of these quality initiatives, Six Sigma, dates back to the 80's.

The success that companies have had with Six Sigma is well documented. The literature is rich in describing deployment strategies and speaks of the importance of aligning the program with the organizations strategic goals (Coronado and Anthony, 2002). Many companies, however, have struggled with adopting and sustaining their programs and much of this lack of success can be attributed to weak project identification and selection processes (Mader, 2007). While most of the literature highlights this consistently, there is a lack of quantifiable/scientific way to identify focus areas in the supply chain that are Lean Six Sigma conducive. The research presented in this paper enables an organization to use a systematic, holistic, data driven approach to deploy Lean Six Sigma. Figure 27 is a representation of the project identification and prioritization framework.

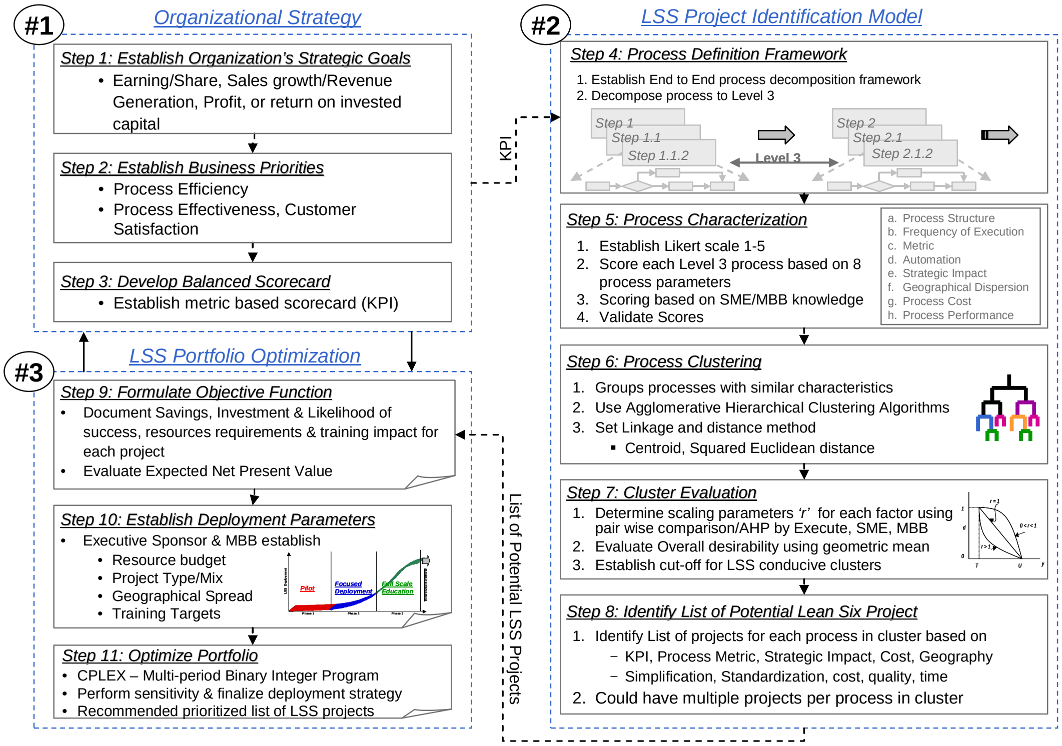


**Fig. 27.** Lean Six Sigma Project Identification and Prioritization Model

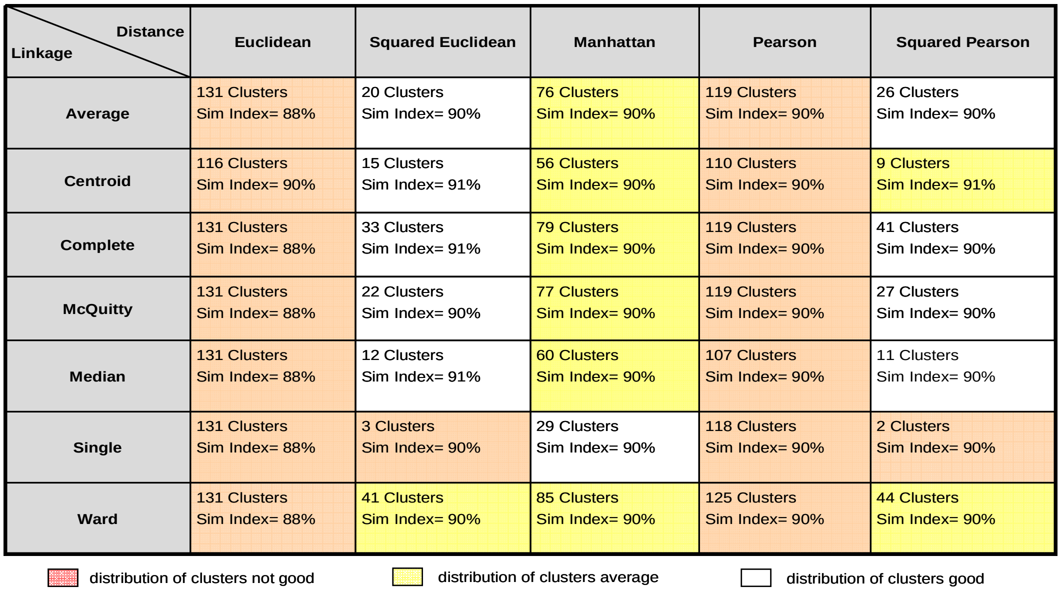
An unsupervised learning approach using a clustering algorithm is employed to group processes with similar characteristics. The agglomerative hierarchical clustering approach groups processes based on eight characteristics: strategic impact, process performance, process structure, process cost, level of automation, frequency of execution, existence of metric/process measurement, and the geographical dispersion of the process. This approach enables deployment champions to perform an assessment prior to deploying Lean Six Sigma.

Additionally, the model acts as a deployment roadmap by establishing a priority for the deployment based on a desirability index. A case study is presented using data from a global company and the use of the methodology is demonstrated in the business process space. Approximately 33% of the processes that were characterized were Lean Six Sigma conducive. While the research presented in the paper highlights the subset of processes that are good candidates for a Lean Six Sigma project, this does not preclude an organization from using other transformational levers on the remaining processes. Other transformational initiatives may include changes in the business model, investing in IT and Infrastructure, improved communications and better visibility in the supply chain, improved market intelligence, mathematical modeling and other industrial engineering techniques. In addition, education programs and revamping policy and procedures can aid as well.

A point to note is that the model described in this paper is a decision support tool, and cannot be used in a vacuum. With Lean Six Sigma’s strong focus on Voice of the Customer (VOC), it isn’t uncommon that a burning platform or a specific business problem highlighted by management may be a priority. Hence, while deploying Lean Six Sigma provision must be made to incorporate management input. The process characterization process also provides executives with an assessment of the maturity of their processes. The evaluation criterion highlights parts of the business that are manual, unstructured and lack process metric.

Additionally, a comparison between manufacturing and non manufacturing processes is conducted. This will provide insight into the inherent differences in deploying Lean Six Sigma in various business sectors. The process characterization is also extend to the Sales and Marketing space, and area typically not associated with Lean Six Sigma.

As described in the preceding paragraphs, the first half of this research is focused on Lean Six Sigma project identification. A hierarchical clustering approach based on the squared Euclidean distances is utilized to group processes that have similar characteristics. Consequently, processes which are joined in a clustering step can never be separated. Future work could include non hierarchical clustering approaches like the K-means clustering.

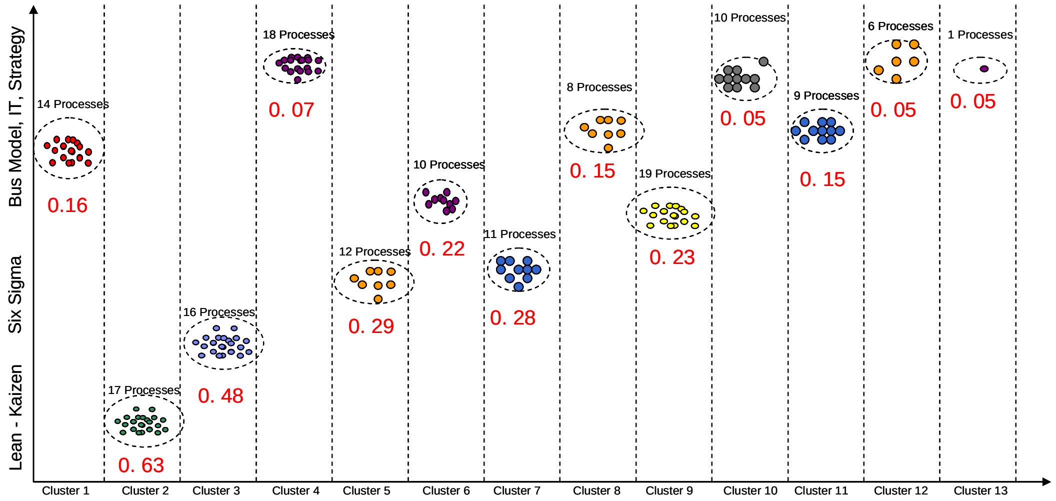


| Distance / Linkage | Euclidean | Squared Euclidean | Manhattan | Pearson | Squared Pearson |
|---|---|---|---|---|---|
| **Average** | 🟥 131 Clusters<br>Sim Index= 88% | ⬜ 20 Clusters<br>Sim Index= 90% | 🟨 76 Clusters<br>Sim Index= 90% | 🟥 119 Clusters<br>Sim Index= 90% | ⬜ 26 Clusters<br>Sim Index= 90% |
| **Centroid** | 🟥 116 Clusters<br>Sim Index= 90% | ⬜ 15 Clusters<br>Sim Index= 91% | 🟨 56 Clusters<br>Sim Index= 90% | 🟥 110 Clusters<br>Sim Index= 90% | 🟨 9 Clusters<br>Sim Index= 91% |
| **Complete** | 🟥 131 Clusters<br>Sim Index= 88% | ⬜ 33 Clusters<br>Sim Index= 91% | 🟨 79 Clusters<br>Sim Index= 90% | 🟥 119 Clusters<br>Sim Index= 90% | ⬜ 41 Clusters<br>Sim Index= 90% |
| **McQuitty** | 🟥 131 Clusters<br>Sim Index= 88% | ⬜ 22 Clusters<br>Sim Index= 90% | 🟨 77 Clusters<br>Sim Index= 90% | 🟥 119 Clusters<br>Sim Index= 90% | ⬜ 27 Clusters<br>Sim Index= 90% |
| **Median** | 🟥 131 Clusters<br>Sim Index= 88% | ⬜ 12 Clusters<br>Sim Index= 91% | 🟨 60 Clusters<br>Sim Index= 90% | 🟥 107 Clusters<br>Sim Index= 90% | ⬜ 11 Clusters<br>Sim Index= 90% |
| **Single** | 🟥 131 Clusters<br>Sim Index= 88% | 🟥 3 Clusters<br>Sim Index= 90% | ⬜ 29 Clusters<br>Sim Index= 90% | 🟥 118 Clusters<br>Sim Index= 90% | 🟥 2 Clusters<br>Sim Index= 90% |
| **Ward** | 🟥 131 Clusters<br>Sim Index= 88% | 🟨 41 Clusters<br>Sim Index= 90% | 🟨 85 Clusters<br>Sim Index= 90% | 🟥 125 Clusters<br>Sim Index= 90% | 🟨 44 Clusters<br>Sim Index= 90% |

🟥 distribution of clusters not good 🟨 distribution of clusters average ⬜ distribution of clusters good

**Fig. 28.** Comparison of Various Distance and Linkage Methods on Data Set

In addition to the squared Euclidean distance from the centroid, a sensitivity analysis could be performed based on other linkage and distance base alternatives to evaluate the impact on process clustering. Figure 28 shows some preliminary results based on various distance and linkage methods using hierarchical clustering. In Figure 28 the distance and linkage methods are broken up into three categories based on the performance of the clustering algorithm. Ideally, the processes should be grouped in a few clusters where the similarity of processes within the same cluster is high. The clustering algorithm was terminated when the similarity index in the cluster was close to 90%. Figure 29 shows the results on the data set using K-means clustering. Clusters 2, and 3 are the most desirable from a Lean Six Sigma standpoint are contain the same processes that were identified using the hierarchical clustering algorithm described in chapter 3.



**K-Means**

| | Clusters | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** |
| **Process Structure** | 2.6 | 1.5 | 2.1 | 4.0 | 3.6 | 3.6 | 4.3 | 2.5 | 2.2 | 4.2 | 4.6 | 3.5 | 5.0 |
| **Frequency of execution** | 3.2 | 1.8 | 1.8 | 3.9 | 4.0 | 4.2 | 2.0 | 3.1 | 2.9 | 4.3 | 2.8 | 3.3 | 4.0 |
| **Process Metric/Measurement** | 3.2 | 1.6 | 1.9 | 3.9 | 3.4 | 2.8 | 3.5 | 3.3 | 2.2 | 3.8 | 4.2 | 3.8 | 5.0 |
| **Process Automation** | 2.0 | 1.9 | 2.0 | 2.2 | 2.2 | 2.7 | 1.3 | 3.0 | 3.0 | 1.0 | 1.1 | 2.5 | 1.0 |
| **Strategic Impact** | 4.0 | 2.2 | 1.9 | 4.3 | 2.8 | 2.6 | 2.4 | 4.3 | 3.3 | 4.2 | 2.3 | 4.7 | 2.0 |
| **Geographical Spread** | 2.4 | 2.4 | 2.8 | 2.1 | 2.1 | 1.6 | 3.5 | 3.8 | 3.2 | 2.9 | 3.4 | 4.5 | 2.0 |
| **Process Cost** | 3.9 | 1.1 | 3.4 | 4.3 | 1.6 | 3.7 | 1.5 | 2.6 | 4.2 | 4.7 | 3.9 | 4.3 | 3.0 |

**Fig. 29.** ***K-Means Clustering***

Currently, the model does not have the capability to link processes/clusters that are a part of a specific product line or market segment. Future research will need to address this gap by ensuring that processes within a cluster are more horizontally integrated across the supply chain

The second half of this dissertation is focused on Lean Six sigma portfolio optimization. Having identified parts of the business that are Lean Six Sigma conducive, the next challenge is to select a portfolio of projects that meets the goals of the organization. Deployment champions are often faced with the following questions: How many projects can be executed given the limited resource? What is the ideal project mix? How do you maximize your return on investment? How quickly do you deploy the methodology for the program to be sustainable? For a portfolio of projects, the process of identifying a subset of priority projects to execute given a set of multiple objectives is a non-trivial decision. As the portfolio grows in size this decision becomes significantly more difficult. The portfolio optimization model will aid managers is making these decisions.

A significant amount of work has been done in the area of Lean Six Sigma portfolio optimization. The research presented in this dissertation, however, is aimed at optimizing a portfolio for a company that is about to deploy Lean Six Sigma. The model presented in this paper is a multi-period 0-1 knapsack problem that maximizes the expected net savings of the Lean Six Sigma portfolio over the life cycle of the Lean Six Sigma deployment. Three phases are considered in the life-cycle; A Pilot phase, A Focused Deployment phase, and a Full-Scale Deployment phase. Additionally, the objective of the model is to maximize the expected net savings of the portfolio. Provision is made to include projects from both the transactional space as well as from the manufacturing space, and constraints force the model to maintain a level of project heterogeneity while ensuring that the portfolio is global.

This research demonstrates the usefulness of mathematical programming as applied to Lean Six Sigma portfolio selection. Currently the model assumes that all black belt resources are homogeneous. Future research will include the assignment of projects to black belts based on their geographical location and level of experience and expertise. Provision can be made to consider the interdependencies of projects, and priority can be placed on projects that collectively impact a product line, ensuring that process transformation is more end to end in nature.

Finally, the model presented in this paper can be used as a decision support tool by deployment champions looking to deploy Lean Six Sigma in a global enterprise. It enables the decision maker to test various scenarios by playing “what- if” games. Decisions on the number of black belt resources to hire in each phase, the project mix, and the deployment strategy can be tested. In summary, the model can be used as a useful tool in developing the overall strategy for the deployment and implementation of Lean Six Sigma in a global enterprise.

# REFERENCES

Abe, N., Akkiraju, R., Buckley, S., Ettl, M., Huang, P., Subramanian, D., Tipu, F., (2007) On optimizing the selection of business transformation projects, *IBM Systems Journal*, 46, 4.

Abonyi, J. and Feil, B. (2007) *Cluster Analysis for Data Mining and System Identification*, Birkhauser Verlag, Germany.

Atallah, B. and Ramudhin, A. (2010) Improving Healthcare Reliability by Integrating Six-Sigma in a Business Process Modeling and Analysis Strategy. *IEEE International Conference on Industrial Engineering and Engineering Management (IEandEM 2010)*, 2234-2238.

Backer, E. and Jain, A. (1981) A Clustering Performance Measure Based on Fuzzy Set Decomposition. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *PAMI*, 3(1), 66-75.

Banks, D., House, L., McMorris, F., Arabie, P., Gaul, W. (2004) Classification, Clustering, and Data Mining Applications. *Proceedings of the meeting of International Federation of Classification Societies (IFCS)*, 25-32.

Banuelas, R., Tennant, C., Tuersley, I. and Tang, S. (2006) Selection of Six Sigma Projects in UK. *The TQM Magazine*, 18(5), 514-527

Bisgaard, S., Hoerl, R, Snee, R. (2002) Improving Business Processes with Six Sigma. *ASQ Annual Quality Congress Proceedings*, 701-704.

Bodek, N. (2004) *Kaikaku: The Power and Magic of Lean - A study in knowledge transfer*, PCS Press, Vancouver, WA.

Breyfogle, F. W., (2003) *Implementing Six Sigma*, John Wiley and Sons Inc., Hoboken, New Jersey.

Cheng-Ru, Wua., Chin-Tsai, Lin., Pei-Hsuan, Tsai., (2010) Evaluating business performance of wealth management banks. *European Journal of Operational Research*, 207(2), 971-979.

Coronado, R.B. and Antony, J. (2002) Critical Success Factors For the Successful Implementation of Six Sigma Projects in Organizations. *TQM Magazine*, 14, 92–99.

De Lima, A. S., De Sousa, J. H. D., (2009). A Proposed Method for Modeling Research and Development Project Prioritization Criteria, *PICMET '09 - 2009 Portland International Conference on Management of Engineering and Technology*, 599-608.

De Mast, J. (2004) A Methodological Comparison of Three Strategies for Quality Improvement. *International Journal of Quality and Reliability Management,* 21(2), 198-213.

Derringer, G. and Suich, R. (1980) Simultaneous optimization of several response variables. *Journal of Quality Technology,* 12, 214–219.

Dickinson, M. W., Thornton, A. C., and Graves, S. (2001) Technology Portfolio Management: Optimizing Interdependent Projects over Multiple Time Periods. *IEEE Transactions on Engineering Management,* 48(4), 518–527.

Duarte, B.M., Montgomery, D.C., Fowler, J. W., Konopka, J. (2011) Deploying LSS in a Global Enterprise – Project Identification. *Arizona State University technical report.*

Gates, R. (2007) Deployment: Start Off on The Right Foot. *Quality Progress*, 40(8), 51-58.

Gonzalez-Padron, T. L., (2010) Knowledge Management and Balanced Scorecard Outcomes: Exploring the Importance of Interpretation, Learning and Internationalit. *British Journal of Management*, 21, 967–982.

Hahn, G.J., Doganaksoy, N. and Hoerl, R. (2000) The Evolution of Six Sigma. *Quality Engineering*, 12(2), 317-326.

Harry, M.J. (1998) Six Sigma: A Breakthrough Strategy for Profitability. *Quality Progress,* 31(5), 60–64.

Harry, M.J. (1998) Six Sigma: A Breakthrough Strategy for Profitability. *Quality Progress,* 31(5), 60–64.

Hu, G., Wang, Fetch, S., Bidanda, B., (2008) A Multi-Objective Model for Project Portfolio Selection to Implement Lean and Six Sigma Concepts, *International Journal of Production Research*, 46(23), 6611–6625.

Hu, G., Wang, L., Fetch, S., and Bidanda, B. (2008) A Multi-Objective Model for Project Portfolio Selection to Implement Lean and Six Sigma Concepts. *International Journal of Production Research*, 46(23), 6611–6625.

In-Jun Jeong, Kwang-Jae Kim. (2009) An Interactive Desirability Function Method to Multiresponse Optimization. *European Journal of Operational Research*, 195, 412–426.

J.R. Evans, and W.M. Lindsay, (2008) *Managing For Quality and Performance Excellence*, Thomson South-Western, Ohio, USA.

Kahraman, C. Büyüközkan, G. (2008) A Combined Fuzzy AHP and Fuzzy Goal Programming Approach for Effective Six-Sigma Project Selection. *Journal of Multiple-Valued Logic and Soft Computing*, 14(6), 599-615

Kendrick, J.D., Saaty, D. (2007) Use Analytic Hierarchy Process For Project Selection. *ASQ Six Sigma Forum Magazine. Milwaukee*: 6(4); 22

Kraus, K., and Lind, J. (2010) The impact of the corporate balanced scorecard on corporate control—A research note. *Management Accounting Research*, 21, 265–277.

Kumar, D., Nowickib, D., Ramirez, J., and Verma, D. (2008) On the Optimal Selection of Process Alternatives in a Six Sigma Implementation. *International Journal of Production Economics*, 111, 456–467.

Kumar, M. and Antony, J. (2009) Project Selection and Its Impact on the Successful Deployment of Six Sigma. *Business Process Management Journal*, 15(5), 669-686.

Kumar, U.D., Saranga, H., Ramirez-Marquez, J. and Nowicki, D. (2007) Six Sigma Project Selection Using Data Envelopment Analysis. *The TQM Magazine*, 19(5), 419-441.

Linderman, K., Schroeder, R., Zaheer, S., and Choo, A. (2003) Six Sigma: A Goal-Theoretic Perspective. *Journal of Operations Management*, 21, 193–203.

Mader, D.P. (2007) How to Identify and Select Lean Six Sigma Projects. *Quality Progress*, 40(7), 58-62.

Mader, D.P. (2008) What comes after the low-hanging fruit?. *Quality Progress*, 41(8), 58-61.

Manalo, R.G., (2010) Comparing Project Prioritization Method and Net Present Value Method of Capital Rationing Using Kendall's Tau Distance. *2010 IEEE International Conference on Management of Innovation and Technology (ICMIT 2010)*, 95-100.

Montgomery, D.C, (2010) A Modern Framework For Achieving Enterprise Excellence. *International Journal of Lean Six Sigma*, 1(1), 56-65.

Montgomery, D.C. (2009), *Introduction to Statistical Quality Control*, 6th edition, Wiley, New York, NY.

Montgomery, D.C. and Woodall, W.H. (2008) An Overview of Six Sigma. *International Statistical Review*, 76(3), 329-46.

Myers, R.H., Montgomery, D.C. and Anderson-Cook, C.M. (2009), *Response Surface Methodology,*3rd edition, Wiley, New York, NY.

Ren, X. and Zhang, G, (2008) Research on Decision Support for Six Sigma Project Selection Based On Fuzzy Evaluation. *4th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM),* 11, 1-11.

Saaty, T. L., (2008) Decision Making With the Analytic Hierarchy Process. *International. Journal of Services Sciences*, 1(1), 83

Schroeder, R.G., Linderman, K., Liedtke, C., and Choo, A. (2008) Six Sigma: Definition and Underlying. *Journal of Operations Management, 536-554*.

Snee, R. and Hoerl, R. (2003) *Leading Six Sigma*, Prentice Hall, Upper Saddle River, NJ.

Snee, R., Hoerl, R., 2003. *Leading Six Sigma*, Pearson Education Inc.

Snee, R.D and Rodebaugh (2002) Project Selection Process. *Quality Progress*, 78-90.

Sowlati, T., Paradi, J.C., Suld, C., (2005) Information systems project prioritization using data envelopment analysis. *Mathematical and Computer Modeling*, 41(11), 1279-1298.

Spear, S. and Brown, K. (1999) Decoding the DNA of the Toyota Production System. *Harvard Business Review*, 96-106.

Stewart, T.J. (1991) A Multi-Criteria Decision Support System for RandD Project Selection. *The Journal of the Operational Research Society*, 42, 17–26.

Su, Chao-Ton. and Choua, Chia-Jen. (2008) A Systematic Methodology For The Creation Of Six Sigma Projects: A Case Study of Semiconductor Foundry. *Expert Systems with Applications*, 34(4), 2693-2703.

Szeto, A.Y.T. and Tsang, A.H.C. (2005) Antecedents to Successful Implementation of Six Sigma. *International Journal of Six Sigma and Competitive Advantage*, 1(3), 307-322.

Thomas, A.J., Rowlands, H., Byard, P., and Rowland-Jones, R. (2008) Lean Six Sigma: An Integrated Strategy for Manufacturing Sustainability. *International Journal of Six Sigma and Competitive Advantage*, 4(4), 333-354.

Xu Rui, and Wunsch, D.C. (2009), *Clustering*, Wiley and Sons, New York, NY.

Yang, Taho., and Hsieh, Chiung-His. (2008) Six-Sigma Project Selection Using National Quality Award Criteria and Fuzzy Multiple Criteria Decision-Making Method. *Wireless Communications, Networking and Mobile Computing, WiCOM '08. 4th International Conference on 12-14 Oct. 2008,* 1 – 4.

Zhang J., and Liu Wenchi. (2007) A study on implementing six-sigma in banking service. *3rd International Conference on Wireless Communications, Networking, and Mobile Computing - WiCOM '07*, 3246-3249.

Zimmerman, J.P. and Weiss, J. (2005) Six Sigma’s Seven Deadly Sins. *Quality*, 44(1), 62-66.

Zua Xingxing, Fredendallb, L. D., and Douglas, T. J. (2008) The Evolving Theory of Quality Management: The Role of Six Sigma. *Journal of Operations Management*, 26(5), 630-650.

# APPENDIX A

# CLUSTER ANALYSIS

# Agglomerative Hierarchical Clustering results using Squared Euclidean Distance and Centroid Linkage

```
Squared Euclidean Distance, Centroid Linkage
Amalgamation Steps
                                                         Number
        Number                                           of obs.
            of   Similarity  Distance  Clusters     New  in new
Step  clusters        level     level  joined   cluster  cluster
   1       150      100.000    0.0000   41  137       41        2
   2       149      100.000    0.0000   74  131       74        2
   3       148      100.000    0.0000  123  125      123        2
   4       147      100.000    0.0000  118  119      118        2
   5       146      100.000    0.0000  117  118      117        3
   6       145      100.000    0.0000  114  115      114        2
   7       144      100.000    0.0000  113  114      113        3
   8       143      100.000    0.0000  105  112      105        2
   9       142      100.000    0.0000  101  106      101        2
  10       141      100.000    0.0000   97  102       97        2
  11       140      100.000    0.0000   99  101       99        3
  12       139      100.000    0.0000    6   97        6        3
  13       138      100.000    0.0000   55   94       55        2
  14       137      100.000    0.0000   46   83       46        2
  15       136      100.000    0.0000    4   38        4        2
  16       135      100.000    0.0000   26   27       26        2
  17       134      100.000    0.0000   16   17       16        2
  18       133      100.000    0.0000    2    5        2        2
  19       132      100.000    0.0000    3    4        3        3
  20       131       98.592    1.0000  145  151      145        2
  21       130       98.592    1.0000   58  146       58        2
  22       129       98.592    1.0000   91  144       91        2
  23       128       98.592    1.0000  141  143      141        2
  24       127       98.592    1.0000   65  142       65        2
  25       126       98.592    1.0000   57  135       57        2
  26       125       98.592    1.0000   74  132       74        3
  27       124       98.592    1.0000   81  130       81        2
  28       123       98.592    1.0000  105  111      105        3
  29       122       98.592    1.0000  107  109      107        2
  30       121       98.592    1.0000   99  108       99        4
  31       120       98.592    1.0000    6  103        6        4
  32       119       98.592    1.0000   52   92       52        2
  33       118       98.592    1.0000   60   89       60        2
  34       117       98.592    1.0000   23   87       23        2
  35       116       98.592    1.0000   76   78       76        2
  36       115       98.592    1.0000   46   75       46        3
  37       114       98.592    1.0000   68   71       68        2
  38       113       98.592    1.0000   40   41       40        3
  39       112       98.592    1.0000   11   32       11        2
  40       111       98.592    1.0000   28   30       28        2
  41       110       98.592    1.0000    2    3        2        5
  42       109       98.552    1.0278   40   57       40        5
  43       108       98.435    1.1111   74   77       74        4
  44       107       98.239    1.2500  100  107      100        3
  45       106       98.239    1.2500   65   88       65        3
  46       105       98.239    1.2500   81   86       81        3
  47       104       98.279    1.2222   79   81       79        4
  48       103       98.239    1.2500   28   29       28        3
  49       102       97.975    1.4375   60   79       60        6
  50       101       97.966    1.4444   98  105       98        4
  51       100       98.239    1.2500   98   99       98        8
  52        99       97.966    1.4444    1   46        1        4
  53        98       97.809    1.5556   51   65       51        4
  54        97       97.809    1.5556   26   28       26        5
  55        96       98.085    1.3600   20   26       20        6
  56        95       97.732    1.6100    2  141        2        7
```

```
 57         94       97.447    1.8125    1   70        1        5
 58         93       97.183    2.0000  148  149      148        2
 59         92       97.887    1.5000  104  148      104        3
 60         91       97.183    2.0000   19  147       19        2
 61         90       97.183    2.0000   85  140       85        2
 62         89       97.183    2.0000  136  139      136        2
 63         88       97.183    2.0000   50  129       50        2
 64         87       97.183    2.0000  121  126      121        2
 65         86       97.887    1.5000   93  121       93        3
 66         85       97.183    2.0000  122  123      122        3
 67         84       97.183    2.0000   13  120       13        2
 68         83       97.183    2.0000   24  116       24        2
 69         82       97.183    2.0000   10  110       10        2
 70         81       97.183    2.0000   25   72       25        2
 71         80       97.183    2.0000   16   67       16        3
 72         79       97.183    2.0000   59   66       59        2
 73         78       97.183    2.0000   54   55       54        3
 74         77       97.457    1.8056   54  145       54        5
 75         76       97.183    2.0000    8   44        8        2
 76         75       97.183    2.0000   21   36       21        2
 77         74       97.261    1.9444   20   21       20        8
 78         73       96.987    2.1389   16   76       16        5
 79         72       96.982    2.1429    2   22        2        8
 80         71       97.161    2.0156    2   51        2       12
 81         70       96.901    2.2000   47   54       47        6
 82         69       96.909    2.1944   47   59       47        8
 83         68       97.029    2.1094   47   91       47       10
 84         67       96.831    2.2500   68   90       68        3
 85         66       97.183    2.0000   68   80       68        4
 86         65       96.923    2.1850    1   68        1        9
 87         64       96.831    2.2500   48   52       48        3
 88         63       96.831    2.2500   11   42       11        3
 89         62       96.655    2.3750   98  117       98       11
 90         61       96.644    2.3827    1   45        1       10
 91         60       96.523    2.4688   20   63       20        9
 92         59       96.479    2.5000   19  150       19        3
 93         58       96.479    2.5000   85  136       85        4
 94         57       96.401    2.5556   60  133       60        7
 95         56       96.391    2.5625    6   95        6        5
 96         55       96.282    2.6400    6   48        6        8
 97         54       96.235    2.6728   20   24       20       11
 98         53       96.264    2.6529   20  127       20       12
 99         52       96.148    2.7347   49   60       49        8
100         51       96.127    2.7500   25   58       25        4
101         50       96.056    2.8000   37   47       37       11
102         49       95.775    3.0000   53  134       53        2
103         48       96.127    2.7500   33   53       33        3
104         47       95.775    3.0000   34   96       34        2
105         46       96.127    2.7500   10   34       10        4
106         45       95.775    3.0000   14   73       14        2
107         44       95.775    3.0000   35   39       35        2
108         43       95.657    3.0833   14  104       14        5
109         42       95.576    3.1408    6   37        6       19
110         41       95.290    3.3438   49  138       49        9
111         40       95.271    3.3578    6   14        6       24
112         39       95.501    3.1944    6   93        6       27
113         38       95.158    3.4375   13   25       13        6
114         37       95.028    3.5300    1   61        1       11
115         36       94.748    3.7292   11   20       11       15
116         35       94.770    3.7131    2   11        2       27
117         34       94.747    3.7297    6   98        6       38
118         33       94.620    3.8200    8   16        8        7
119         32       94.611    3.8264    1   69        1       12
120         31       94.514    3.8950   40   85       40        9
121         30       94.053    4.2222   12  122       12        4
122         29       93.906    4.3264   10   33       10        7
123         28       93.734    4.4491    6   12        6       42
124         27       93.665    4.4976    1    8        1       19
```

```
 125        26      93.662    4.5000    7   50        7        3
 126        25      93.320    4.7425    2   23        2       29
 127        24      92.895    5.0448   49   74       49       13
 128        23      92.796    5.1145    1    7        1       22
 129        22      92.575    5.2716   40   43       40       10
 130        21      91.978    5.6956    6  113        6       45
 131        20      91.549    6.0000   64   82       64        2
 132        19      92.437    5.3698   49   64       49       15
 133        18      91.549    6.0000    9   15        9        2
 134        17      92.684    5.1944    9   13        9        8
 135        16      91.499    6.0357   10   35       10        9
 136        15      91.393    6.1111   18   19       18        4
 137        14      91.312    6.1682    2   10        2       38
 138        13      92.264    5.4924    2   31        2       39
 139        12      90.892    6.4667   49   84       49       16
 140        11      90.630    6.6530    1    6        1       67
 141        10      91.050    6.3542    1    2        1      106
 142         9      91.200    6.2479    1   56        1      107
 143         8      90.814    6.5221    1  100        1      110
 144         7      90.223    6.9419    9   40        9       18
 145         6      88.870    7.9023   18   49       18       20
 146         5      88.123    8.4330    1    9        1      128
 147         4      85.394   10.3700   18   62       18       21
 148         3      81.119   13.4056    1   18        1      149
 149         2      74.183   18.3300    1  128        1      150
 150         1      73.719   18.6598    1  124        1      151
```

```
Final Partition
Number of clusters: 15
                        Within   Average   Maximum
                       cluster  distance  distance
           Number of    sum of      from      from
        observations   squares  centroid  centroid
Cluster1          22    68.409   1.69835   2.45497
Cluster2          29    77.034   1.57376   2.51180
Cluster3          45   147.733   1.76118   2.33936
Cluster4           8    20.625   1.55328   2.13234
Cluster5           9    26.889   1.69485   2.23883
Cluster6           4     7.250   1.30505   1.85405
Cluster7           1     0.000   0.00000   0.00000
Cluster8          10    20.300   1.37938   2.06640
Cluster9          15    40.000   1.54606   2.38048
Cluster10          1     0.000   0.00000   0.00000
Cluster11          1     0.000   0.00000   0.00000
Cluster12          1     0.000   0.00000   0.00000
Cluster13          3     1.333   0.65404   0.74536
Cluster14          1     0.000   0.00000   0.00000
Cluster15          1     0.000   0.00000   0.00000
```

```
Cluster Centroids

Variable                    Cluster1  Cluster2  Cluster3  Cluster4  Cluster5
Process Structure            3.59091   2.24138   3.73333     4.750   2.66667
Frequency of Execution       4.00000   2.44828   3.86667     2.625   3.11111
Process Measurement/Metric   3.22727   2.10345   3.64444     4.375   3.33333
Process Automation           2.31818   2.65517   1.80000     1.125   3.00000
Strategic Impact             2.59091   2.75862   4.11111     2.250   4.22222
Geography                    1.90909   3.06897   2.66667     3.250   3.88889
Process Cost (FTE)           2.40909   3.82759   4.22222     3.750   2.77778
```

```
Variable                    Cluster6  Cluster7  Cluster8  Cluster9  Cluster10
Process Structure               1.50         2       4.3   1.40000          4
Frequency of Execution          1.25         4       1.9   1.73333          4
Process Measurement/Metric      1.75         2       3.6   1.66667          2
Process Automation              1.50         3       1.2   1.73333          4
Strategic Impact                1.50         3       2.4   2.13333          4
Geography                       2.00         5       3.5   2.46667          2
Process Cost (FTE)              3.75         4       1.4   1.13333          4

Variable                    Cluster11  Cluster12  Cluster13  Cluster14
Process Structure                   2          3    2.00000          2
Frequency of Execution              2          3    3.00000          5
Process Measurement/Metric          1          1    3.00000          4
Process Automation                  4          3    3.00000          3
Strategic Impact                    4          2    4.33333          5
Geography                           2          2    1.00000          5
Process Cost (FTE)                  1          1    4.33333          5

                                          Grand
Variable                    Cluster15  centroid
Process Structure                   3   3.08609
Frequency of Execution              1   3.04636
Process Measurement/Metric          4   2.99338
Process Automation                  1   2.09272
Strategic Impact                    5   3.15232
Geography                           5   2.75497
Process Cost (FTE)                  5   3.23179


Distances Between Cluster Centroids

           Cluster1  Cluster2  Cluster3  Cluster4  Cluster5  Cluster6  Cluster7
Cluster1    0.00000   2.99853   2.57934   3.11245   2.97274   4.21694   4.09318
Cluster2    2.99853   0.00000   3.08068   3.75809   2.48360   2.48550   2.53231
Cluster3    2.57934   3.08068   0.00000   2.75530   2.61496   4.79573   3.72757
Cluster4    3.11245   3.75809   2.75530   0.00000   3.79741   4.64859   4.72196
Cluster5    2.97274   2.48360   2.61496   3.79741   0.00000   4.63739   2.68972
Cluster6    4.21694   2.48550   4.79573   4.64859   4.63739   0.00000   4.63006
Cluster7    4.09318   2.53231   3.72757   4.72196   2.68972   4.63006   0.00000
Cluster8    3.14448   3.88630   4.01723   2.63474   3.57990   4.51193   4.98698
Cluster9    3.85529   3.20505   5.23493   5.21506   4.12011   2.78762   4.75395
Cluster10   3.00447   3.16754   2.85294   4.58769   3.23370   5.14174   3.87298
Cluster11   4.27780   3.73689   5.40014   6.30848   3.86021   4.63006   5.00000
Cluster12   3.01956   3.45396   5.00059   5.22464   4.15145   3.99218   4.69042
Cluster13   3.40774   2.88123   2.90695   4.78042   3.36833   4.06116   4.45970
Cluster14   5.16364   4.51803   3.56298   5.38952   3.35180   6.66615   3.16228
Cluster15   5.80983   4.37456   4.04493   4.24816   3.97368   5.51702   4.79583

           Cluster8  Cluster9  Cluster10  Cluster11  Cluster12  Cluster13
Cluster1    3.14448   3.85529    3.00447    4.27780    3.01956    3.40774
Cluster2    3.88630   3.20505    3.16754    3.73689    3.45396    2.88123
Cluster3    4.01723   5.23493    2.85294    5.40014    5.00059    2.90695
Cluster4    2.63474   5.21506    4.58769    6.30848    5.22464    4.78042
Cluster5    3.57990   4.12011    3.23370    3.86021    4.15145    3.36833
Cluster6    4.51193   2.78762    5.14174    4.63006    3.99218    4.06116
Cluster7    4.98698   4.75395    3.87298    5.00000    4.69042    4.45970
Cluster8    0.00000   3.69730    5.14490    4.98698    3.93319    5.35651
Cluster9    3.69730   0.00000    5.39135    3.11983    2.54296    4.75161
Cluster10   5.14490   5.39135    0.00000    4.24264    4.12311    2.86744
Cluster11   4.98698   3.11983    4.24264    0.00000    2.64575    4.26875
Cluster12   3.93319   2.54296    4.12311    2.64575    0.00000    4.74927
Cluster13   5.35651   4.75161    2.86744    4.26875    4.74927    0.00000
Cluster14   6.34586   6.90411    4.58258    6.70820    6.92820    4.67856
Cluster15   4.96689   6.21825    5.83095    6.78233    7.14143    5.18545
```

```
             Cluster14  Cluster15
Cluster1      5.16364    5.80983
Cluster2      4.51803    4.37456
Cluster3      3.56298    4.04493
Cluster4      5.38952    4.24816
Cluster5      3.35180    3.97368
Cluster6      6.66615    5.51702
Cluster7      3.16228    4.79583
Cluster8      6.34586    4.96689
Cluster9      6.90411    6.21825
Cluster10     4.58258    5.83095
Cluster11     6.70820    6.78233
Cluster12     6.92820    7.14143
Cluster13     4.67856    5.18545
Cluster14     0.00000    4.58258
Cluster15     4.58258    0.00000
```

# APPENDIX B

# CPLEX CODE FOR MULTI-PERIOD OPTIMIZATION MODEL

```
/*********************************************
 * OPL 12.2 Model
 * Author: Brett Duarte
 * Creation Date: Sep 16, 2011 at 10:51:43 AM
 *********************************************/
/*********************************************
 * OPL 12.2 Model - Multi-period Knapsack
 *********************************************/

/* 200 Projects were considered in the Data set
int   NbProjects = 200;
range Project1 = 1..NbProjects;
range Project2 = 1..NbProjects;
range Project3 = 1..NbProjects;

/* declaration of the decision variable*/
dvar boolean      x[Project1];
dvar boolean    y[Project2];
dvar boolean    z[Project3];

/* declaration of model parameters*/
float ExpNetSavings1[Project1] = ...;
float ExpNetSavings2[Project2] = ...;
float ExpNetSavings3[Project3] = ...;
float Training1[Project1] = ...;
float Training2[Project2] = ...;
float Training3[Project3] = ...;
float HdCount1[Project1] = ...;
float HdCount2[Project2] = ...;
float HdCount3[Project3] = ...;
float Effectiveness1[Project1] = ...;
float Effectiveness2[Project2] = ...;
float Effectiveness3[Project3] = ...;
float Geo1[Project1] = ...;
float Geo2[Project2] = ...;
float Geo3[Project3] = ...;
float GB1[Project1] = ...;
float GB2[Project2] = ...;
float GB3[Project3] = ...;
float YB1[Project1] = ...;
float YB2[Project2] = ...;
float YB3[Project3] = ...;
float servicesprojects1[Project1] = ...;
float servicesprojects2[Project2] = ...;
float servicesprojects3[Project3] = ...;

/* Objective function */
/* Objective is to maximize the Expected Net Savings over all 3 phases

maximize
      sum(j in Project1) ExpNetSavings1[j] * x[j]+ sum(j in Project2)
        ExpNetSavings2[j]*y[j]+ sum(j in Project3)
ExpNetSavings3[j]*z[j];
/* Model Constraints */
subject to {
```

```
/* Constraint #1 is on the Black Belt resources available in each phase

ctHdcount1: sum(j in Project1) HdCount1[j] * x[j]<=5;
  sum(j in Project2) HdCount2[j] * y[j]<=10;
  sum(j in Project3) HdCount3[j] * z[j]<=15;

/* Constraint #2 is on Training, at least 5% of workforce in each phase

ctTraining1: sum(j in Project1) Training1[j] * x[j] >= 5;
  sum(j in Project2) Training2[j] * y[j] >= 5;
  sum(j in Project3) Training3[j] * z[j] >= 5;

/* Constraint #3 is on Effectiveness projects. 20%, 25%, 30% of
portfolio must contain effectiveness projects in each phase.

sum(j in Project1) Effectiveness1[j] * x[j] >= 0.20* sum(j in
      Project1)x[j];
sum(j in Project2) Effectiveness2[j] * y[j] >= 0.25* sum(j in
      Project1)y[j];
sum(j in Project3) Effectiveness3[j] * z[j] >= 0.30* sum(j in
      Project1)z[j];
  //sum(j in Project1) Effectiveness1[j] * x[j] >= 0;
  //sum(j in Project2) Effectiveness2[j] * y[j] >= 0;
  //sum(j in Project3) Effectiveness3[j] * z[j] >= 0;


/* Constraint #4 is Geographical Constraint forcing atleast 10, 15,20,
projects to be executed in Asia
  ctGeo1: sum(j in Project1) Geo1[j] * x[j] >= 10;
  sum(j in Project2) Geo2[j] * y[j] >= 15;
  sum(j in Project3) Geo3[j] * z[j] >= 20;
  //sum(j in Project1) GB1[j] * x[j] >= 0.2* sum(j in Project1)x[j];
  //sum(j in Project2) GB2[j] * y[j] >= 0.3* sum(j in Project1)y[j];
  //sum(j in Project3) GB3[j] * z[j] >= 0.3* sum(j in Project1)z[j];
  //sum(j in Project1) YB1[j] * x[j] >= 0.2* sum(j in Project1)x[j];
  //sum(j in Project2) YB2[j] * y[j] >= 0.3* sum(j in Project1)y[j];
  //sum(j in Project3) YB3[j] * z[j] >= 0.3* sum(j in Project1)z[j];

/* Constraint #5 is constraint on heterogeneity of projects – Green
Belt Projects
  sum(j in Project1) GB1[j] * x[j] >= 10;
  sum(j in Project2) GB2[j] * y[j] >= 15;
  sum(j in Project3) GB3[j] * z[j] >= 20;

/* Constraint #6 is constraint on heterogeneity of projects – Yellow
Belt Projects

  sum(j in Project1) YB1[j] * x[j] >= 5;
  sum(j in Project2) YB2[j] * y[j] >= 10;
  sum(j in Project3) YB3[j] * z[j] >= 15;

/* Constraint #7 is constraint to ensure that the portfolio includes
a % of projects from the services space
```

```
  sum(j in Project1) servicesprojects1[j] * x[j] >=
      0.4* sum(j in Project1)x[j];
  sum(j in Project2) servicesprojects2[j] * y[j] >=
      0.4* sum(j in Project2)y[j];
  sum(j in Project3) servicesprojects3[j] * z[j] >=
      0.4* sum(j in Project3)z[j];
  //sum(j in Project1) servicesprojects1[j] * x[j] >=0;
  //sum(j in Project2) servicesprojects2[j] * y[j] >=0;
  //sum(j in Project3) servicesprojects3[j] * z[j] >=10;

   /*x[1]+y[1] <=1;
   x[2]+y[2] <=1;
   x[3]+y[3] <=1;*/

/* This constraint insures that if a project is selected in a
particular phase, then it cannot be selected again in another phase.

     forall(j in Project1)
      x[j]+ y[j]+ z[j]<=1;
}


/* Code to find Shadow prices
/*main{
  thisOplModel.generate();
  cplex.solve();
  writeln("dual for ctHdcount1="+thisOplModel.ctHdcount1.dual);
}*/
```