Analytical Quality Control in Shipping Operation Using Six Sigma Principles

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Zhuohua Qu

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Abstract

A large number of benefits achieved through the successful implementation of Six Sigma programmes in different industries have been documented. However, very little research has been conducted on their applications in the shipping sector, especially in the Onshore Service Functions (OSFs) of shipping companies. Literature shows that heavy human involvement in the service industries such as shipping leads to a high volume of uncertainties which are difficult to be correctly and effectively measured or managed by simply using the traditional data analysis and statistical methods in Six Sigma. The aim of this study is to develop new quantitative analytical methodologies to enable the application and implementation of Six Sigma to improve the service quality of OSFs in shipping companies. Intensive investigations on the feasibility and effectiveness of the developed new methods and models through case studies in world leading container ship lines and shipping management companies have been carried out to ensure the achievement of the aim.

This study firstly reviews the evolvement of quality control and some typical methods in the area, the development of Six Sigma, its tools and current applications, especially in the service industries. It is followed by a new framework of the Six Sigma implementation in the OSFs of shipping companies which is supported by a few real process excellence projects carried out in a world-leading ship line. In the process of the framework development, various issues and challenges appear largely due to the existence of uncertainties in data such as ambiguity and incompleteness caused by extensive subjective judgements. Advanced methods and models are developed to tackle the above challenges as well as complement the traditional Six Sigma tools so that the new Six Sigma methodologies can be confidently applied in situations where uncertainties in data exist at different levels.

A new fuzzy Technique for Order Preference by Similarity to an Ideal Solution

(TOPSIS) method is developed by combining the traditional TOPSIS, fuzzy numbers and interval approximation sets to facilitate the effective selection of Six Sigma projects and achieve the optimal use of resources towards the company objectives. A revised Failure Mode and Effects Analysis (FMEA) model is proposed in the "Analyse" step in Six Sigma to improve the capability of classical FMEA in failure identification in service industries. The new FMEA model uses the Analytical Hierarchy Process (AHP) and Fuzzy Bayesian Reasoning (FBR) approaches to increase the accuracy of failure identification while not compromising the easiness and visibility of the Risk Priority Number (RPN) method. Decision Making Trial and Evaluation Laboratory (DEMATEL) and Analytical Network Process (ANP) methods are incorporated with Fuzzy logic and Evidential Reasoning (ER), for the very first time to generate a Key Performance Indicators (KPIs) management method where the weights of indicators are rationally assigned by considering the interdependency among the indicators. Incomplete and fuzzy evaluations of the KPIs are synthesised in a rational way to achieve a compatible and comparable result.

It is concluded that the newly developed Six Sigma framework together with its supporting quantitative analytical models has made significant contribution to facilitate the quality control and process improvement in shipping companies. It has been strongly evidenced by the success of the applications of the new models in real cases. The financial gains and continuous benefits produced in the investigated shipping companies have attracted a wider range of interests from different service industries. It is therefore believed that this work will have a high potential to be tailored for a wide range of applications across sectors and industries when the uncertainties in data exceed the ability that the classical Six Sigma tools and methods possess.

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Abbreviations

AHP	Analytical Hierarchy Process
ANFIS	Adaptive Neural Fuzzy Inference Systems
ANP	Analytical Network Process
ANSI	American National Standards Institute
BB	Black Belt
BN	Bayesian Networks
BOA	Bank of America
BPR	Business process re-engineering
BSI	British Standards Institute
C&E Matrix	Cause and Effect Matrix
CEO	Chief Executive Officer
COPQ	Cost Of Poor Quality
CPT	Conditional Probability Table
CSFs	Critical Success Factors
CTQ	Critical To Quality
CWQT	CompanyWide Quality Control
DEA	Data Envelopment Analysis
DEMATEL	Decision Making Trial and Evaluation Laboratory
DFSS	Design for Six Sigma
DMAIC	Define, Measure, Analyse, Improve, and Control
DOE	Design Of Experiment
DPMO	Defects Per Million Opportunities
EFA	Exploratory Factor Analysis
ER	Evidential Reasoning
FAHP	Fuzzy Analytical Hierarchy Process
FBR	Fuzzy Bayesian Reasoning
FER	Fuzzy Evidential Reasoning
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FNIS	Fuzzy Negative Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
FuRBaR	Fuzzy Rule-Based Bayesian Reasoning
GB	Green Belt
GE	General Electric
GR&R	Gage Repeatability and Reproducibility
ID	Influence Diagram
ISM	International Safety Management
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
LCL	Lower Control Limit

LSL	Lower Specification Limit
MBB	Master Black Belt
MCDM	Multiple Criteria Decision Making
NIS	Negative Ideal Solution
OSFs	Onshore Service Functions
PBR	Possible Best Rating
PCA	Process Capability Analysis
PDCA	Plan-Do-Check-Act
PDM	Project Desirability Matrix
PIS	Positive Ideal Solution
PMBOK	Project Management Body of Knowledge
PWR	Possible Worst Rating
QMS	Quality Management System
RIMER	Rule based Inference Methodology using the Evidential Reasoning algorithm
RPN	Risk Priority Number
SPC	Statistical Process Control
SWOT	Strength, Weakness, Opportunities and Threats
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
TPFN	Trapezoidal Fuzzy Number
TQM	Total Quality Management
UCL	Upper Control Limit
USL	Upper Specification Limit
VOC	Voice Of Customer
FRB	Fuzzy Rule Base
IDS	Intelligent Decision System

Chapter 1. Introduction

1.1 Research Introduction

The past decades have witnessed increasing competition in the global market and companies are operating in an ever increasing competitive environment. In order to maintain their competitiveness, companies are paying increasing attention to enhance their performances in order to retain customers, especially under the current economic environment. Profitability alone is not sufficient to discriminate excellence. The shipping industry carries around 90% of world trade (I.C.S., 2013) and plays an important role in global economic development and world prosperity. Due to the fact that shipping is a capital intensive and highly dangerous industry, quality control in ship building, maintenance and operations has always attracted the attention of stakeholders. Thus many shipping companies have adopted quality management systems (QMS) to ensure and improve safety in ship operations, including: Total Quality Management (TQM), ISO quality management systems, and the International Safety Management (ISM) code. However, shipping includes not only the carriage of goods by sea, but also the associated services, such as customer support, finance and accounting. Globalisation has accelerated the exposure of companies to competition and shipping alone could hardly achieve sustainable competitive differentiation. As a result, companies are increasingly investigating the ways of improving the associated services provided by their onshore service functions (OSFs) to better meet customer requirements and reduce unnecessary costs.

Six Sigma is a business strategy that uses a well-structured methodology to improve process performance and eliminate defects in order to achieve continuous improvement within the business process. Having seen the remarkable improvements resulting from the Six Sigma implementation in General Electric (GE), businesses in many sectors are joining the Six Sigma brand wagon, including construction, healthcare, banking and many more. Six Sigma has been successfully implemented for over 20 years across different industries with significant improvements achieved. It has been used to continuously improve business processes, reduce costs and improve customer satisfaction while maintaining profitability. However, most of the studies of the implementation of Six Sigma in service industries have focused mainly on some particular sectors such as supply chain management, banking and health care. Limited studies of investigating the applications of Six Sigma in the shipping related industries have been found in port security studies (Ung *et al.*, 2007), maritime training and education (Er and Gurel, 2005) and container terminal operations (Nooramin *et al.*, 2011). No studies are found in the literature on the application of Six Sigma in OSFs of shipping companies. Research has also revealed several unique challenges in applying Six Sigma in OSFs of shipping companies. These include invisible work processes, lack of qualified information and vast differentiation among customer needs. As a result there is a significant research gap to be fulfilled.

This chapter gives a brief introduction and essentially "sets the scene" for the thesis by: explaining the research objectives, primary and subsidiary; presenting the proposed methodology and describing the layout and scope of the thesis.

1.2 Research Questions and Objective

Six Sigma works best when it uses hard data as the foundation for process improvement. It is the reason why one of the general interpretations of this programme is that it is heavy on statistics. However, Chakrabarty and Chuan (2009)'s study has revealed that over 72% of service companies that responded to the survey consider data collecting is a barrier in Six Sigma implementation. In OSFs, due to the fact of undefined processes, interviews and brainstorming are the tools frequently used which often result in a large number of uncertainties due to the presentation of qualitative and ambiguous data. It therefore becomes difficult to define quality and apply some of the existing statistical tools. Traditional use of quantitative data in analysis turns into a challenge during Six Sigma applications. Lack of qualified data can lead to difficulties in many phases of the implementation process which may lead to ineffective improvement actions.

The existing literature on Six Sigma is mainly focusing on its implementation processes, including application practices and frameworks in different industries and key success factors. Very few studies, if any, provide in-depth research on enhancing its toolsets in an environment where uncertainty and qualitative information exist at large. The main aim of this research is therefore to:

Enhance Six Sigma's application in OSFs by incorporating uncertainty analysis and multi-attribute decision making techniques into the methodology.

In order to achieve this aim, a number of subsidiary objectives need to be addressed. They are:

- To identify the applicability of Six Sigma in OSFs of shipping companies.
- To develop a method that can effectively select projects during Six Sigma applications.
- To revise Failure Mode and Effects Analysis (FMEA) to improve its accuracy and the ability to deal with uncertainties.
- To create a new approach to enable the management and synthesise of both quantitative and qualitative KPIs.

Given the lack of studies of Six Sigma in OSFs of shipping companies and of improving Six Sigma toolsets in treating uncertainties, research in this topic is necessary. How to improve the ability of Six Sigma in handling uncertainties in OSFs of shipping companies will be significant to both academics and practitioners.

1.3 Scope of Research

The research scope is set up to serve the core of this thesis which is to enhance the applicability of Six Sigma in an uncertain environment. It is desirable to improve some of Six Sigma tools by introducing techniques in uncertainty treatment, which is one of the main features of OSFs of shipping companies, to overcome the difficulties often encountered during process improvement practices. The document therefore only explains the relevant theories and methods up to the level at which they are used to suit the aims clarified above instead of providing an in-depth theoretical and mathematical treatise of the theories themselves. It is also the intention of this research to encourage further academic studies in Six Sigma and promote its applications in wider areas. Data in this research is mostly from industrial projects associated with the collaborators of this PhD work. However, in circumstances of lack of objective information, the data for the illustrated cases demonstrated in this study is from domain experts specialising in the shipping industry.

1.4 Structure of the Thesis

The thesis contains seven chapters. Following the description of the research scene in ***Chapter 1***, ***Chapter 2*** reviews the important literature relating to the current study. It includes the evolvement of quality control and most frequently used methods, the development of Six Sigma, its important tools, its applications in the service industries and the concepts of some popular uncertainty treatment methods. The emphasis and kernel of the thesis start with Chapter 3 and end with Chapter 7. They are presented as follows in a detailed and interrelated manner.

Although widely used in many industries Six Sigma's applications in the shipping sector, especially the OSFs are very few. In ***Chapter 3***, a framework is proposed for the application of Six Sigma in the OSFs of shipping companies after identifying the needs of quality improvement. Following a case study of the implementation of Six

Sigma in the OSFs of a shipping company, issues and barriers to the implementation are identified. The rest of the research is to address the identified issues particularly those caused by the existence of uncertainties.

The purpose of ***Chapter 4*** is to improve the Six Sigma project selection process. Previous studies in this subject are reviewed in detail. It is identified that none of those reviewed methods are sufficient and practical to handle the uncertainties present in Six Sigma project selection process in the OSFs of shipping companies. A new method is needed which can handle different types of data and allow the evaluations to be expressed with belief degrees. A new fuzzy Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method is therefore developed. The innovated application of trapezoidal numbers in fuzzy TOPSIS enables the merge of the data from multiple sources to facilitate Six Sigma project selections under uncertainty.

Chapter 5 presents a revised FMEA model. It addresses the concerns from literature and practices in the application of FMEA by using the Analytical Hierarchy Process (AHP) and Fuzzy Bayesian Reasoning. The revised model assigns different weights for the three criteria (Severity, Occurrence and Detection) and provides the option of evaluation in both linguistic terms and crisp numbers.

Performance measurement is critical in process improvement. After the implementation of improvement methods or upon the completion of a Six Sigma project, KPIs are designed and maintained to continuously monitor the process performance. They allow a company to have a clear view of its performance towards the company goal. An accurate and well managed KPIs system is a powerful tool to detect improvement opportunities, perform effective benchmarking and to provide solid foundations for decision making. However, KPIs are often deemed as quantitative measures and their different priorities to the business objective and interdependency are ignored. ***Chapter 6*** makes use of DEMATEL and ANP methods in determining the interdependency among KPIs and their weights in contributing to the primary objective. The integration of fuzzy logic and ER makes it possible to accommodate both qualitative and quantitative data which are synthesized to achieve comparable and compatible results.

The thesis concludes in ***Chapter 7***. It distils the key findings from this study. The outcomes of the study are emphasised by demonstrating their academic and practical contributions to enhancing Six Sigma with an ability of dealing with uncertainty. It also gives the recommendations for future research.

A graphical flowchart is presented in Figure 1.1 for clarifying the structure of this thesis.

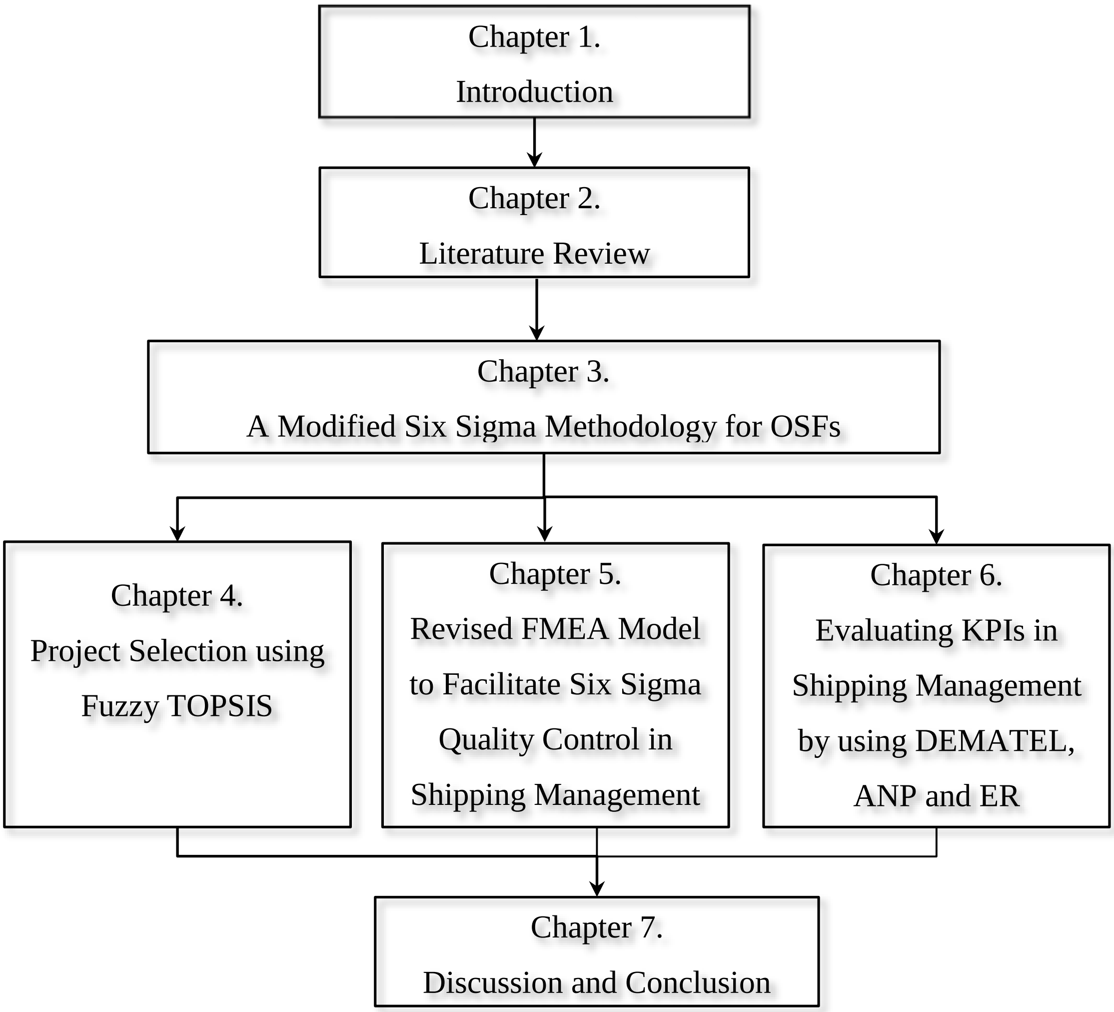


Figure 1.1 The structure of the thesis

1.5 Conclusion

The basic concepts and needs for deploying Six Sigma in OSFs of shipping companies have been put forward. The main problems are identified and the research objectives are targeted. The scope of the research is clearly described by taking into account the resources and timeframe for this study. The research structure is also presented with the explanations on the contents in each of the seven chapters.

Chapter 2. Literature Review

2.1 Introduction

Quality is a concept that is very difficult to define. The Oxford dictionary describes quality as "the standard of something as measured against other things of a similar kind; the degree of excellence of something". The ISO8402-1986 standard defines quality as "the totality of features and characteristics of a product or service that bears its ability to satisfy stated or implied needs". After reviewing many other authors' work, Oakland (2004) summarized that quality is simply meeting the customer requirements. "Good" and "bad" are the most frequently used words to describe quality in our daily life. No company wishes to be associated with bad quality. Despite the fact that "quality" has been deemed as an essential differentiator among organizations in today's market, it is difficult to gauge quality on an absolute scale. The development of statistical process control (SPC) has made it possible for companies to identify ways of improving the quality of products and services, and measure and monitor company performance. Many methods have emerged since the creation of SPC, such as TQM, ISO and Six Sigma.

Since its first application in Motorola, Six Sigma has been widely used by many world-class companies with significant quality improvement evidenced. Given its effectiveness and uniqueness in producing quantitative analysis results, Six Sigma has always been one of the most popular quality improvement methodologies in modern manufacturing and service industries. Although its popularity has led to an increasing level of interest from the academic community, Antony (2008) suggested that at the moment, Six Sigma is still not widely accepted by many academics in leading business and engineering schools across Europe.

This chapter produces an extensive review of the literature of quality control, some widely known methods and their comparisons to Six Sigma. It is also the aim of this chapter to conduct a thorough review of Six Sigma, containing its development and application, especially in the service industries. Issues that may affect its application in OSFs will be addressed at the end to highlight the research needs.

2.2 Review of Quality Control

2.2.1 History of Quality Control

During the early days, quality control was entirely based on personal preference or judgement. In the beginning of the twentieth century, a couple of individuals conducted statistical research in the UK into improved methods of agriculture (Tennant, 2001). Walter Shewhart was inspired and developed statistical methods in process control during the 1930s. His pioneering work, which is widely known today as "control chart", attempted to monitor and control processes to ensure a continued acceptable quality. He successfully brought together the disciplines of statistics, engineering, and economics and became known as the father of modern quality control. Since then, quality has been better understood through the work of W. Edwards Deming and Joseph Juran in the 1950s. They applied quality principles and techniques to processes and management of organizations. Their work has been highly appreciated in Japan where industrial systems had a reputation for cheap imitation products and an illiterate workforce at the time. Quality management practice developed and spread rapidly in Japanese plants and became a major theme in Japanese management philosophy. By the 1970s, the manufacturing industry in Japan was producing products more cheaply but with a better quality.

Quality management attracted serious interests from organizations in North America and Western Europe in the 1980s due to the tremendous competitive performance of Japan's manufacturing industry. US companies started introducing quality programmes and initiatives. TQM became the centre of these drives in most cases. By the last decade of the 20th century, although it was still being used in practice, TQM was considered a fad by many business leaders. New quality systems have evolved from the foundations of Deming, Juran and the early Japanese practitioners of quality, and quality has moved beyond manufacturing into service, healthcare, education and government sectors. Six Sigma quality management method was developed by Motorola in 1980s to improve its business process by minimizing defects which was then evolved into an organizational approach. The ISO 9000 (International Organization for Standardization) series of quality-management standards were published in 1987 which aimed at improving company performance through implementing and following a QMS. Table 2.1 lists the development of SPC in a time order.

Table 2.1 History of statistical process control

1930s	• Walter Shewhart developed statistical methods in process control
1950s	• Edwards Deming & Joseph Juran applied quality principles and techniques to process and management of organizations • Edwards Deming developed 14 points for management and encouraged the use of PDCA (Plan-Do-Check-Act) cycle (Deming cycle or Shewhart cycle) • Joseph Juran developed the quality trilogy
1960s	• Philip B. Crosby promoted the concept of "zero defects" • Quality control was introduced and developed quickly in Japan • "Total quality control" was first popularized by Dr. Armand V. Feigenbaum
1970s	• Japan developed and widely used quality control
1980s	• Quality control came back to the US • Six Sigma was developed by Motorola • The ISO 9000 series of quality-management standards were published • The Baldrige National Quality Program and Malcolm Baldrige National Quality Award were established by the U.S. Congress
Today	• Companies around world are continuously seeking ways to improve quality • Six Sigma becomes a way of business management

Apart from TQM, ISO 9000 and Six Sigma, Business Process Re-engineering (BPR) and Lean are also often used in business process improvement.

2.2.2 Total Quality Management (TQM)

TQM, an umbrella term for company-wide quality improvement efforts, came from the work of Deming and his direction in the rebuilding of Japanese production beginning in 1950 (Black and Revere, 2006). In 1969, the first international conference on quality control was held in Tokyo where the term "total quality" was used by Dr. Armand Vallin Feigenbaum in his paper for the first time, and referred to wider issues compared with the traditional understanding of quality, such as planning, organisation and management responsibility. Ishikawa presented a paper explaining how "total quality control" in Japan was different, its meaning "companywide quality control (CWQC)", and describing how all employees, from top management to the workers, must study and participate in quality control (Charantimath, 2011). Towards the end of the 1970s, America was facing a major quality crisis from the competition of Japan which started attracting attention from national legislators, administrators and the media. A 1980 NBC-TV News special report, "If Japan Can… Why Can't We?" highlighted how Japan had captured the world auto and electronics markets. Finally, U.S. organizations started their quality improvement by replicating CWQC which was later known as TQM. It is grounded in the original Deming cycle PDCA. Tobin (1990) defined TQM as a totally integrated programme for gaining competitive advantages by continuously improving every facet of organizational culture. TQM has soon become the prevailing business strategy adopted by industries around the world. The TQM approach advocates that (Kelada, 1996):

- The concept of quality extends well beyond the quality of the product.
- Everyone in an organization participates in the quality improvement process.
- Top management, starting with the Chief Executive Officer (CEO) and chief operations officer, demonstrates strong involvement and leadership.
- The emphasis is laid on attaining and surpassing customer satisfaction.
- External partners also participate in the total quality effort.

Many studies compare TQM with Six Sigma (Andersson *et al.*, 2006; Klefsjö *et al.*, 2001; Cheng, 2009; Black and Revere, 2006). Brun (2011) described TQM as the father of Six Sigma as many of the principles constituting the basis of TQM are also paramount in Six Sigma. It employs some of the same tools and techniques of TQM. They both share similar philosophy - continuous quality improvement is essential to long term business success and they both are top-down methods believing the importance of top management support in successful quality management. Klefsjö *et al*. (2001) stated that Six Sigma should be regarded as a methodology within the larger framework of TQM in that Six Sigma supports all the six values in TQM.

Although it has been popular for many years, the passion for TQM has faded whereas Six Sigma has been receiving increasing attention. According to Harari (1993) study, only about one-fifth, or at best one-third, of the TQM programmes in the US and Europe have achieved significant or even tangible improvements in quality, productivity, competitiveness or financial results. Among the reasons cited for TQM failure are excessive bureaucracy, focus on internal processes, avoidance of genuine organizational reform, faddism, and lack of innovation within the corporate culture (Green, 2007). Pande *et al.* (2000) outlined some reasons for the superiority of Six Sigma compared to TQM (Table 2.2).

2.2.3 ISO 9001

The low probability of success has driven companies away from TQM. They opted for ISO 9001 which is a management system standard. ISO 9001 is a set of standards for process management by following which a company can be certified through external auditing. ISO defines a standard as “a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose” (ISO, 2014). It aims at improving company performance through implementing and following a QMS. It is claimed by the ISO that their international standards can help businesses achieve cost saving, enhance customer satisfaction, access new markets and increase market share, *etc*. (ISO, 2014).

Table 2.2 Six Sigma vs. TQM

TQM	**Six Sigma**
Lack of integration, not connected with strategy and performance	High level of integration
Leadership apathy	Leadership at the vanguard
A fuzzy concept	A consistently repeated, simple message
An unclear goal	Ambitious goal
Strong attitudes or technical fanaticism	Adapting tools and degree of rigor to the circumstances
Failure to break down internal barriers	Priority on cross functional process management
Incremental vs exponential change	Incremental exponential change
Ineffective training	Effective belt system
Focus on product quality	Attention to all business processes

The ISO is a voluntary worldwide federation of national standards bodies from 165 countries (as of 2014) with each one representing one country, including the American National Standards Institute (ANSI), and the British Standards Institute (BSI). It was established in 1947 with the mission of promoting the development of standardization and related activities in the world with a view to facilitating the international exchange of goods and services, and to developing cooperation in the spheres of intellectual, scientific, technological and economic activity (ANSI, 2014). Its best-selling and most widely known document - ISO 9001, was published in 1987 together with ISO 9002 and ISO 9003. They have been revised several times by the standing technical committees and advisory groups with the last time in 2008. Among all the ISO 9000 family standards, ISO 9001:2008 is the only one that can be certified to. The ISO 9000 family addresses various aspects of quality management. Its standards provide guidance and tools for companies and organizations who want to ensure that their products and services consistently meet customers' requirements, and the quality is consistently improved (ISO, 2014). ISO 9001 series were developed and revised based on eight quality management principles (ISO, 2012) that can be used by management to help their organization towards improved performance and higher quality output:

- Customer focus.
- Leadership.
- Involvement of people.
- Process approach.
- System approach to management.
- Continual improvement.
- Factual approach to decision making.
- Mutually beneficial supplier relationships.

Right from the days of the release of the ISO 9000 series standards, ISO 9001 certifications have been occurring with high momentum in the majority parts of the world (Karthi *et al.*, 2012). Since its first release in 1987, the total number of organizations certified to ISO 9001 has exceeded one million and covers a wide range of industries. Seddon (1997) stated that the main practical advantage of ISO 9000 is that it enables organisations to tender for business they might otherwise not get. Douglas *et al.* (2003) study revealed that the top ranking benefits of ISO 9000 include organisational consistency, improved efficiency/performance, improved customer service and management control. Corbett *et al.* (2005) found that ISO 9000 indeed increases productivity. Poksinska *et al.* (2002) believed that ISO 9000 standards can be applied uniformly to organisations of any size or description, which is another important reason for its popularity.

However, ISO 9000 has received many criticisms. In Douglas *et al*. (2003) research, 49 percent of the survey respondents considered their organisations did not achieve any benefit with regard to reduced costs or waste and 53 percent perceived no benefits with respect to staff motivation/retention. Furthermore, Tennant (2001) pointed out that once a certificate has been achieved, quality standardization perhaps has little to motivate further improvement.

ISO9001 and Six Sigma are complementary to each other. There are studies suggesting the integration of Six Sigma and ISO9001 certification where ISO 9001 can be used to identify existing problems and Six Sigma can be used to resolve them (Pfeifer *et al.*, 2004; Karthi *et al.*, 2012; Lupan *et al.*, 2005).

2.2.4 Business Process Reengineering (BPR)

BPR was first bought to the attention of the business world by Hammer and Champy (1993), who defined BPR as "The fundamental rethinking and radical design of business processes to achieve dramatic improvement in critical, contemporary measures of performance such as cost, quality, service and speed". It aims at improving business performance by identifying opportunities for new business, for outsourcing, for improving business efficiency and for areas within the business where technology can be used to support business processes (Lindsay *et al.*, 2003). It restructures the operation by challenging each step involved and redesigns the whole working process. BPR assumes that the current processes in a business are inapplicable and suggests completely new processes to be implemented. Although it was not the intention, BPR becomes associated with company downsizing and redundancy. Goel and Chen (2008) suggested that re-engineering often results in huge short-term costs that need to be amortized over several years through increased future revenues resulting from the reengineering. Six Sigma, however, is a quality improvement programme with a clear methodology to improve current processes by reducing variation. Some differences between BPR and Six Sigma are listed in Table 2.3.

With the implementation of Six Sigma, some companies, such as Motorola and GE, realized that merely removing variation from processes and products could not meet the customer's requirement who demanded improved products. Design for Six Sigma

(DFSS) was therefore developed. It is not as mature as DMAIC and there is no standard defined methodology for DFSS. BPR and DFSS are all for process redesign but different in some ways given the fact that DFSS is based on Six Sigma's statistical thinking and customer focus. In Six Sigma, redesign is only a step to take if improvements are at their peak but there is still a large gap between customer requirements and process performance. Six sigma is often adopted as a management methodology that utilizes measures as a foundational tool for BPR. Pande *et al.* (2000) stated that two conditions must be met in order for the process redesign to work. They are "a major need, threat or opportunity exists" and "ready and willing to take on the risk". The main revolutions affecting business are "new technologies", "new regulations", "new competitors" and "new customer requirements" (Figure 2.1). When these emerge, a redesign of the process may need to be considered.

Table 2.3 BPR vs. Six Sigma

BPR	Six Sigma
Focus on cost, time, efficiency and productivity but not customers	Emphasis on customer requirements
Large scale, long execution times	Project can be small scale and completed in short time
Normally the execution needs the involvement of consulting firms	Can be executed by internal resources through effective training
Fundamental change of process, radical change	Incremental and continuous improvement on the current process
Often lead to redundancy	Lead to improved performance
May need long time to see the benefit achieved	Improvement can be visible at projects completion
IT is an enabler	Using statistical tools and controls
Lead to structure change	Lead to culture change
Does not have a standard methodology	Use DMAIC (Define-Measure-Analyse-Improve-Control) as the methodology

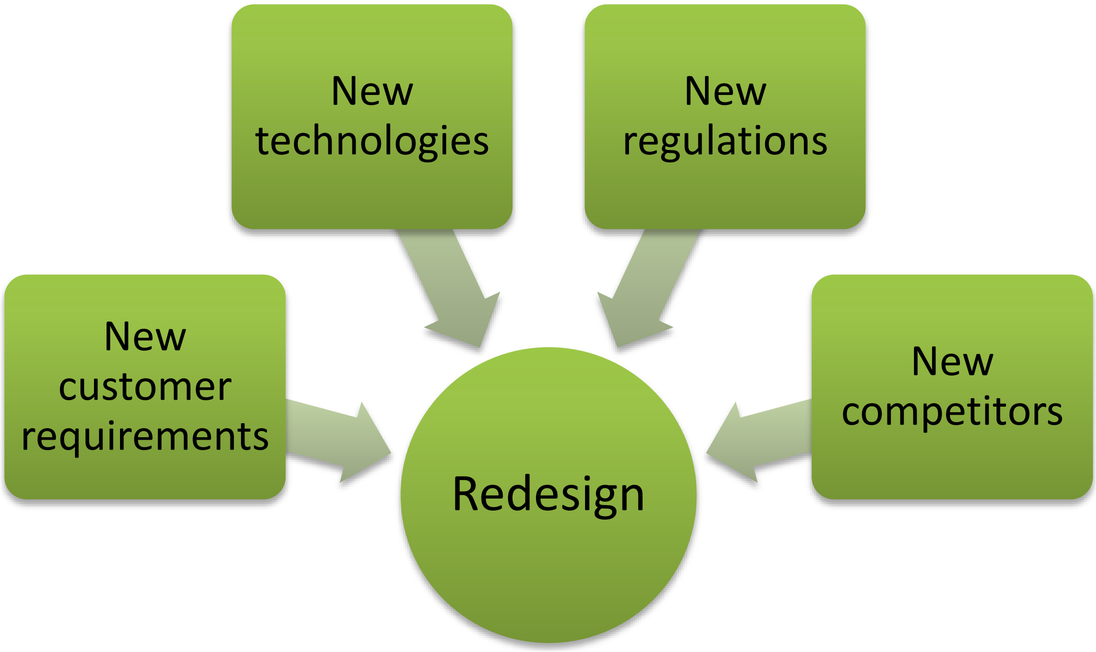


Figure 2.1 Main revolutions affecting business

2.2.5 Lean

Lean management originated from the Toyota production system and increased in popularity after the 1973 energy crisis. Womack *et al*. (1990) defined Lean production as a business and production philosophy that shortens the time between order placement and product delivery by eliminating waste from a product's value-stream. The Lean concept classified activities that bring a product or service to reality into different categories: value adding, non-value adding and non-value adding but necessary. The focus of Lean is to improve process flow by eliminating waste through cutting out activities that do not add value. Lean is based on the assumption that business performance can be improved by removing waste. Although Lean was developed in the manufacturing environment and seen as manufacturing oriented, other non-manufacturing industries have recognized that its techniques are also applicable in their areas. Bowen and Youngdahl (1998) listed several applications of the Lean concept in the service industries including retail, airline and hospital management; Swank (2003) explained in detail the utilization of Lean concept in Jefferson Pilot Financial to increase the productivity; Piercy and

Rich (2009) examined the applicability of Lean concept in a call centre to meet customers' requirement for "one-stop" call handling by redesigning the call handling process. Most researchers agreed that there is more commonality between Lean and Six Sigma tools and practices than differences (Shah *et al*., 2008). Lean and Six Sigma are often considered to offer features which complement each other and are increasingly being integrated in practice, but there is no consensus method (Proudlove *et al*., 2008). However, the DMAIC, as a logical, proven and solid approach, is applicable even in Lean-Six Sigma.

There are still many fundamental differences between the two methods. The relevant literature suggested that the Lean concept is best used for reducing wastes, improving efficiency of a process, reducing process time and improving space utilization, etc., while, Six Sigma is best used to reduce variation and identify root causes so as to improve performance. The differences between the two methods mainly lay in their objectives. Table 2.4 provides a comparison between the two methods.

Throughout the history of quality control, many approaches have set standards in quality. Apart from the ones reviewed above, some other well recognized quality control methods are listed in Table 2.5. However, due to their less relationship with Six Sigma, they have only been briefly introduced in this work.

2.3 Review of Six Sigma

2.3.1 History of Six Sigma

Six Sigma can be rooted back to the efforts of Joseph Juran and W. Edwards Deming. Their programmes for TQM in Japan, led to the adoption of the Six Sigma philosophy by Motorola in the 1980s, when Motorola found itself unable to compete in the consumer products market with Japanese companies. Its senior executive Art Sundry's famous critique, "Our quality stinks" accelerated the change process in Motorola.

Table 2.4 Lean vs. Six Sigma

	Lean	**Six Sigma**
Theory / objective	Improve business performance / flow time by removing waste and streamlining process flow	Improve process performance by reducing variation
Application methodology	Identify value desired by customers Identify value stream Make flow continuously Introduce Pull Manage towards perfection (less strong than DMAIC)	DMAIC
Use of Data	Less common	Data intensive
Focus	Process flow	Variation, process defects
Assumption	Business performance can be improved by removing waste	Problem exists but the causes are unknown.
Targeting problem	Flow problem, more visible problems	Good for root-cause, solution unknown problems
Approach	Operational, bottom-up approach	Top down approach
Training	Training while working along	Designed structural training

Table 2.5 Some quality control methods with a brief description

Taguchi Method	A statistical method developed by Genichi Taguchi to improve quality. The main objective in the Taguchi method is to design robust systems that are reliable under uncontrollable conditions.
Kaizen	A Japanese word for improvement, carrying the connotation in industry of all the non-contracted and partially contracted activities. Kaizen is defined by Brunet and New (2003) as a method consisting of pervasive and continual activities, outside the contributor's explicit contractual roles, to identify and achieve outcomes that he believes contribute to the organisational goals.
Quality Function Deployment (QFD)	An overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales) (Sullivan, 1986).
Zero Defect Programme	Developed by Mr. Philip Crosby and has emerged as a trending concept in quality management to eliminate defects. Zero defects defines a way of thinking and doing. It emphasises that defects are not acceptable and everyone should do things right the first time.

Like the American business style in the early 80s, Motorola was keeping its customer happy by reacting to (correcting) problems in the field, such as, large in-house repair facilities to fix anything it could find before it got into the field and many repair shops in the field to ensure that the customer receives quick service. As a result, the prevailing view was that quality costs extra money. But Sundry saw that quality through reaction is expensive. It takes a lot to support a reaction strategy: more people, more material, more steps, more time and especially more money (Persse, 2006). Bill Smith subsequently formulated the particulars of the Six Sigma methodology at Motorola in 1986. At the time, Six Sigma offered Motorola a simple and consistent way to track and compare performance to customer requirements and an ambitious target of practically-perfect quality (Pande *et al*., 2000) . In 1988 Motorola became the first company to capture the prestigious Malcolm Baldrige award. The following year, Motorola was awarded the Nikkei Award for manufacturing from Japan for creative excellence in products and service. Motorola had spent USD170 million on workers' education and training from 1983 to 1987, among which 40 percent in 1987 was devoted to quality matters. Until 1997, a decade from the beginning of the Six Sigma programme, Motorola had gone from a company in jeopardy to a market leader with its sales increasing by 20% each year and cumulative savings of USD14 billion (Pande *et al*., 2000).

Since the success of Six Sigma in Motorola, and particularly from 1995, an exponentially growing number of global firms have launched Six Sigma. Six Sigma became well known after Jack Welch made it a central focus of his business strategy in GE in 1995. He set the goal of becoming a Six Sigma quality company by 2000, 5 years less than Motorola. While Motorola has used Six Sigma to stay in business, for GE it was used to strengthen an already thriving company. Six Sigma was the most ambitious undertaking GE had ever taken. They believed that Six Sigma can change GE from one of the great companies to the greatest company in the world business. GE's focus on quality started in the late 1980s with the launch of the "Work-Out" programme that opened GE culture to ideas from everyone and everywhere. The resultant learning environment prepared the ground for Six Sigma.

GE has made Six Sigma a far broader concept than improving quality by reducing defects; it became a leadership development programme that can make a transformation of a company.

Six Sigma has been widely reckoned as one of the most useful process improvement and quality management programmes available. Other early adopters of Six Sigma who achieved well-publicized success include Honeywell (previously known as AlliedSignal), Citibank, Sony and GE (Antony and Banuelas, 2001).

The beauty of Six Sigma is that it can be used not only as an operational strategy to reduce the number of defects but also as a business strategy to improve business processes and evolve new business models (Kumar *et al.*, 2008). Therefore, although initially applied in manufacturing industries, Six Sigma has now been widely appreciated across other sectors.

2.3.2 Definition of Six Sigma

There are different perspectives on what "Six Sigma" is. Business media often describes Six Sigma as a "highly technical method used by engineers and statisticians to fine-tune products and processes" (Pande *et al.*, 2000). For many business organisations, it simply means "a measure of quality that strives for near perfection". They are all true, in part. Taking references from Motorola, Six Sigma can be defined and understood at three distinct levels: metric, methodology and management system.

As a metric: The foundation of Six Sigma lies in statistical thinking. Sigma, transliteration of Greek letter σ, means standard deviation in statistics and reflects the degree of deviation. Six-Sigma means six-time standard deviation between the average and the lower or upper limit. A sigma quality level indicates the frequency that defects are likely to occur. Higher sigma quality level is a sign that processes would produce fewer defects. One sigma level represents 691462.5 defects per million opportunities (DPMO), which translates to a percentage of non-defective outputs of 30.854%. The “Six Sigma” quality level is equal to 3.4 DPMO which translates to 99.99966% non-defective outputs. Table 2.6 provides a simple list of the Sigma levels with their associated DPMO values.

Table 2.6 Simplified sigma levels

Sigma level	Non-defective output (%)	DPMO
1	30.9	690,000
2	69.2	308,000
3	93.3	66,800
4	99.4	6,210
5	99.98	320
6	99.9997	3.4

As a methodology: Six Sigma is a systematic, highly disciplined, customer–centric and profit–driven business improvement initiative that is based on rigorous process-focused and project-driven methodology. Six Sigma uses data and statistical analysis to measure and improve company’s operational performance via the DMAIC framework (Tang *et al.*, 2007).

As a management system: It is often discovered that one of the difficulties facing Six Sigma projects is sustainability. Simply applying the methodology is not sufficient to drive the desired breakthrough improvements and results that are sustainable over time. It is found that sustainable and breakthrough improvements are realized by those organizations whose leadership has embraced Six Sigma and incorporated it into their vision, strategies and business objectives. When practiced as a management system, Six Sigma is a high performance system for executing business strategy.

Six Sigma has evolved over the last two decades and so has its definition. There exists no unique definition of Six Sigma. However, in business terms, Six Sigma can be defined as: A business improvement strategy of applying a statistical methodology, to identify and eliminate causes of defects & variations, and to achieve improvement of business profitability, reduction of cost of poor quality (COPQ) and improvement of the effectiveness and efficiency of all operations so as to meet or even exceed customers' needs and expectations.

The tools used in Six Sigma are by no means new, but it is not merely repackaging the old concepts to create a new term for project management. It integrates many existing techniques which are appropriate in its implementation and organizes them into a programme that can be built into business strategy and culture in order to achieve breakthrough and sustainable process improvement. Six Sigma includes as much effort on people excellence as technical excellence.

2.3.3 Benefits of Six Sigma

Six Sigma has enjoyed an unprecedented long period of popularity. It attracts organizations by achieving great benefits including tangible results, such as cost saving and waste reduction. Table 2.7 shows the benefits obtained from Six-Sigma applications in some large manufacturing companies (Mehrjerdi, 2011; Kwak and Anbari, 2006).

One of Six Sigma's most important elements is customer focus. It is suggested in Aboelmaged (2010)'s research that the most cited benefit of Six Sigma in the literature is "customer satisfaction". The study also summarized the benefits that Six Sigma can achieve for both manufacturing and service organisations through the literature review of previous relevant research. Antony (2004a) has also revealed some of the benefits of applying Six Sigma in the service industries (Table 2.8).

Table 2.7 Reported benefits and savings through Six Sigma in the manufacturing sector

Company name	Metric/Measures	Benefits/savings
Motorola (1992)	In-process defect levels	150 times reduction
Allied Signal / Honeywell (1999)	Financial	$600 million annual savings since 1994
Raytheon/aircraft integration systems	Depot maintenance inspection time	Reduced 88% as measured in days
Hughes aircraft's missiles systems group / wave soldering	Quality/productivity	Improved 1,000%/ improved 500%
GE (1999)	Financial	$2 billion
Motorola (1999) (www.motorala.com)	Financial	$15 billion in 11 years
Dow Chemical/Rail Delivery Project (The Dow Chemical Company)	Financial	$2.45 million in capital expenditures
Du Pont/Yerkes Plant in New York (2000)	Financial	More than $25 million savings
Telefonica de espana (2001)	Financial	€30 millions in the first ten months
Texas Instruments	Financial	$600 millions
Johnson and Johnson	Financial	$500 millions
Honeywell	Financial	$1.2 billions

Table 2.8 Benefits of Six Sigma in both manufacturing and service organisations

Manufacturing	• reduction in process variability • reduction in in-process defect levels • reduction in maintenance inspection time • improving capacity cycle time • improving inventory on-time delivery • increasing savings in capital expenditures • increase in profitability • reduction of operational costs • reduction in the COPQ • increase in productivity • reduction of cycle time

	• reduction of customer complaints • improved sales and reduced inspection
Service organizations	• improved accuracy of resources allocation • improving accuracy of reporting • reduced documentary defects • improving timely and accurate claims reimbursement • streamlining the process of service delivery • reduced inventory of equipment • reduced service preparation times • improved customer satisfaction • reduced defect rate in service processes • reduced variability of key service processes • transformation of organizational culture from fire-fighting mode to fire-prevention mode with the attitude of continuous improvement of service process performance • reduced process cycle time and hence achieve faster service delivery • reduced service operational costs • increased market share • improved cross-functional teamwork across the entire organization • increased employee morale • reduced number of non-value added steps in critical business processes through systematic elimination • leading to faster delivery of service, reduced COPQ (costs associated with late delivery, customer complaints, costs associated with misdirected problem solving, etc.) • increased awareness of various problem solving tools and techniques • leading to greater job satisfaction for employees • improved consistency level of service through systematic reduction of process variability and effective management decisions due to reliance on data and facts rather than assumptions and gut-feelings • improved effective management decisions due to reliance on data and facts rather than assumptions and gut-feelings.

Apart from those listed in Table 2.8, what also makes Six Sigma so attractive is the fact that the improvements are continuous and sustainable by changing the company culture and creating a learning organization. Pande *et al*. (2000) stated that Six Sigma can generate sustained success, set a performance goal for everyone, enhance value to customers, accelerate the rate of improvement, promote learning and "cross-pollination" and execute strategic change.

2.3.4 Methodology

Six Sigma is a project-based structured methodology aiming at reducing process defects and variability by taking account of customer requirements. Its implementation uses a five-step DMAIC methodology (Figure 2.2). DMAIC provides a roadmap with tools for conducting projects. Although similar to the PDCA cycle, the DMAIC emphasises results measurement and control, and has extensive use of statistics. DMAIC model has been adopted by many companies in Six Sigma implementation, such as ABB, Caterpillar and Intersil. It provides a consistent approach for organizations in adopting Six Sigma. DMAIC focuses on "customer needs" and "continuous measurement" to achieve improvement on current processes which are essential aspects in shipping company quality improvement. In the meantime, it also offers the opportunity to redesign the processes if it becomes necessary. Six Sigma did not introduce new tools, instead, it provides a different methodology for implementation which focuses on business infrastructure and bottom-line results.

2.3.5 Critical Success Factors (CSFs)

The successful implementation of Six Sigma projects is much more than just understanding the DMAIC tool set. Zimmerman and Weiss (2005) quoted a survey conducted by Aviation Week magazine in which among major aerospace companies, less than 50% expressed satisfaction on the results from Six Sigma projects, around 20% were somewhat satisfied and nearly 30% were dissatisfied. CSFs are those factors without which, it is difficult for a project to be successful. Many studies have suggested that the CSFs are necessary in order to make Six Sigma implementation successful. Table 2.9 lists some most frequently mentioned CSFs in the literature.

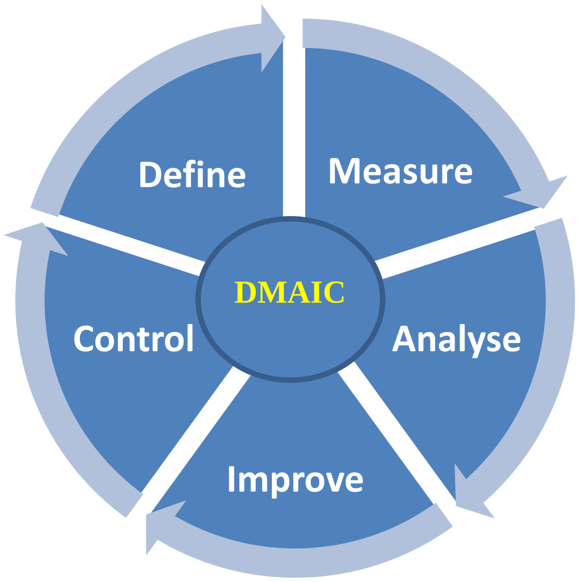


Figure 2.2 Six Sigma DMAIC model

Top management support / involvement

Top management support / involvement has been identified as the top CSF for successful Six Sigma implementation in most studies reviewed. Launching Six Sigma is a strategic decision that must be taken by senior management (Magnusson *et al.*, 2003). Different management support for a project will lead to significant variations in terms of the degree of acceptance or resistance to that project. The managers' commitments are not limited to communicating with the organization in all ways regarding the benefits of Six Sigma, demanding solid results, mandating compliance with Six Sigma work standards, removing obstacles during applications and building strong organization wide commitments, but very importantly, planning and actively participating in the whole implementation. Ken Lewis, CEO of Bank of America (BOA), led the first Green Belt (GB) project in the company and required each executive in the leadership team to complete GB training which sent a clear message of the support from the most senior leadership. Robert W. Galvin, the former CEO and chairman of Motorola, always asked for the Six Sigma reports from different divisions first in operation meetings; Dan Burnham, CEO of Raytheon personally teaches Six Sigma principles to other leaders in his company; Mike Parker, CEO of Dow Chemical participates actively and visibly in all the "waves" of the company's Black Belt (BB) training at its Six Sigma training centre in Atlanta, Georgia (Byrne, 2003). The success of Six Sigma lies in the commitment of top management and can only be initialized once the top manager's commitments are established.

Table 2.9 CSFs for successful implementation of Six Sigma

	Henderson and Evans (2000)	Pande *et al*. (2000)	Coronado and Antony (2002)	Byrne (2003)	Antony (2004a)	Brewer and Bagranoff (2004)	Nonthaleerak and Hendry (2008)	Firka (2010)
Top management support/ involvement	√	√	√	√	√	√	√	√
Training	√	√	√	√	√	√	√	
Statistical tools	√	√	√		√	√		√
Project selection			√		√	√		√
Organisation infrastructure	√		√		√			√
Connect to business strategy		√	√		√			√
Culture change			√		√	√		√
Customer focus		√	√		√			√
Rewards and recognition		√	√		√	√		

Training

One of the unique characteristics of Six Sigma compared with other quality methodologies is to have trained personnel leading and participating in projects. Training is a key ingredient to achieve success by following the Six Sigma way (Pande *et al*., 2000). Continuous learning contributes to sustaining the results achieved from Six Sigma and continuously renewing and improving them. Six Sigma training should not be limited to belts (Table 3.1 provides a detailed explanation of the belt system in Six Sigma), although their training is more in-depth and comprehensive, it should be cascaded throughout the organisation. Operators are the people who carry out the daily tasks and the main contributors to the quality of products and services. GE's Six Sigma implementation started with a heavy emphasis on training, 4% - 5% people were taken out of their daily task and trained full time to the most advanced level; another 50% were trained to intermediate level and "green belt training" was delivered to all its employees. It is worth mentioning that GE's experience in implementation of Six Sigma shows that the best of training and mentoring efforts would crumble without effective leadership (Nayab, 2011).

Effective training of BBs and any other Six Sigma project leaders is not limited to the knowledge and tools in Six Sigma, such as statistical methods, analytical techniques and measurement tools, but also project management and people skills, such as leading change and team collaboration. The contents of Six Sigma training could vary from different needs and providers (external and internal). Generally, the course for BBs is comprehensive and aiming at those who will become full-time Six Sigma project leaders/experts; the course for GBs covers a range of broad enough contents to prepare them for contributing to or managing projects, the course for operators needs to include basic concepts and knowledge of Six Sigma and some statistical tools that can be useful in their daily tasks.

Training indeed costs. Is it worth it? Most successful companies believe that training is worth the investment. Motorola invested USD50 million annually in Six Sigma training from 1987 to 1992 which represents 40 percent of their total training budget.

The reported return on investment ratio was 29:1, as Motorola estimated savings of USD2.4 billion from Six Sigma improvement projects during the same period (Magnusson *et al*., 2003).

Statistical tools

Six Sigma does not create any new statistical method, but adopts existing tools to improve processes and products through the DMAIC framework. Therefore, the ability of selecting and using the right tools according to different projects and issues is essential to the success of a project. Some frequently used tools are discussed in the next section.

Project selection

Six Sigma is a project-driven methodology. Selecting appropriate projects is essential to ensure the success of Six Sigma application. Breyfogle (2001) suggested that project selection is one of the most important factors for achieving success in Six Sigma applications. Zimmerman and Weiss (2005) believed that failure of correctly identifying and prioritizing improvement projects is one of the reasons many Six Sigma programmes fail. Pande *et al*. (2000) stated that good project selection is itself a process and if properly carried out, the potential benefits of Six Sigma can be substantially improved. Identification of high-impact projects at the initial stage of a programme will result in significant breakthroughs in a rapid timeframe. A project that is too large will cost valuable time as belts will struggle to cope. Selecting a Six Sigma project has therefore been one of the most often discussed issues in today's Six Sigma research. It will be further discussed in Chapter 4 of this thesis.

Organisation infrastructure

Six Sigma represents a new way of working and it relies on the collection and analysis of data and the use of numerous statistical tools for correcting defects (Byrne, 2003). The implementation of Six Sigma is to be supported by a robust infrastructure. Organisation infrastructure includes both human resources and IT. A company needs to have and be willing to provide adequate resources and investments for the implementation as Six Sigma implementation will change the job of a small but critical group of personnel who will become the catalyst of changes. It is essential to ensure that the resources are available when needed and that clear responsibilities are assigned according to the Six Sigma belt system. On the other hand, measurement and analysis are key elements in Six Sigma which all require extensive data from reliable systems. James Stanley, senior vice president of US operations for Howmet International Corp., a GE Aircraft Engines supplier, suggests "systems are vitally important. The systems have to give you data instantaneously . . . the IT infrastructure could make or break the Six Sigma effort. Data gathering is key" (Henderson and Evans, 2000). During the implementation, a company often identifies the need for a modified or completely new measurement system. A well-developed system can be used for not only collecting reliable and sufficient data but also monitoring performance towards achieving sustainable results.

Connect to business strategy

Berger *et al*. (2007) suggested that deploying Six Sigma as a business strategy through projects instead of tools is a more effective way to benefit from the time and money invested in Six Sigma training. A good business strategy is one that can be translated into quantifiable objectives. Six Sigma projects should be generated based on the needs of achieving those objectives, and target on process and performance bearing direct impacts on finance or operations linking to the strategy. The contribution of a project should be clearly stated in terms of finance. The application of Six Sigma requires a top-down management approach. Financial savings and aligning with business strategy help to motivate the top management team so as to achieve continuous improvement. Often the establishment of the connection between Six Sigma and business strategy can become a breakthrough point for some executives who might have resisted Six Sigma.

Culture change

Six Sigma is "change", changing the way of working, thinking, measuring, monitoring and managing. It is about creating a culture of continuous improvement and statistical thinking. Culture change is a prime factor to a lasting Six Sigma programme. When change happens, people affected are often unsure and sometimes afraid. "What have we done wrong?", "what is going to happen to me" and "it has always been the way of doing it" are some typical phrases mentioned. Companies which succeeded in managing change have identified that the best way to tackle resistance to change is through increased and sustained communication, motivation and education (Coronado and Antony, 2002). It is important that all employees understand the reason for the application of Six Sigma – identifying defects and making improvement, instead of being penalized. It will also make a great difference if employees are feeling responsible for the success of the Six Sigma programme and seeing the benefits resulting from their efforts. Culture change is a gradual process which once achieved, can make continuous improvement a gene of the business.

Customer focus

The philosophy of Six Sigma is to meet or exceed customers' expectation. Meeting customer requirements is the ultimate goal of Six Sigma. Correctly identified customer needs and gaps for improvement set the target for a Six Sigma project. In the meantime, considering and involving customers in Six Sigma implementation can develop a trust relationship, create knowledge transfer and increase customer loyalty.

Rewards and recognition

Recognition and rewards play a valuable role in motivating team members and sustaining the momentum of Six Sigma so as to establish a long term continuous improvement culture in an organization. Samsung believes that meaningful recognition and rewards for employees is one of the four factors that made Six Sigma successful throughout their international operations and culture (Yun and Chua, 2002). Shani and Docherty (2003) suggested that an effective reward system is essential to the sustainable results of a change programme. On successful completion of a project, leadership needs to identify ways to reward extraordinary participation by employees which will also send positive messages to the organisation of Six Sigma implementation. It helps to drive the enthusiasm throughout the organisation from a top-down level and therefore better promotes a companywide implementation.

2.4 Tools in Six Sigma

The systematic and rigorous tools associated with the Six Sigma of today were mostly included when the method was first developed by Motorola. Although most of the tools are not unique, they have been brought together to provide a well-stocked toolbox. Goh (2011) states that the statistical tools used in Six Sigma are logically aligned and integrated which is in response to the perception of "there is nothing new in Six Sigma but a repackaging of old concepts". Not all the tools are required to be used in every project. Different tools are adopted in the individual phases of a DMAIC cycle depending on the objectives. A brief review is given in this section of some of frequently mentioned and applied tools in Six Sigma projects in the service industries.

2.4.1 Project Charter

The Project Management Body of Knowledge (PMBOK) defines a project charter as a document that formally authorizes a project (Gilchrist, 2012). A project charter includes the information of business needs for the project, its scope, objectives and participants. It is normally issued and/or approved by a project sponsor. A signed off project charter is an agreement between the management and Six Sigma teams regarding the expected project outcomes. It is the first step in the DMAIC cycle and takes place in the Define phase of a Six Sigma project. The purpose of a project charter is to document the reasons for undertaking the project, its objectives and constraints, scope and anticipated benefits, set the project direction and define the measures of success, identify the main stakeholders and empower the project manager with the authority to carry out the project. Project charter works as an essential document which helps the project manager to effectively communicate with project participants and stakeholders regarding the project information, sets clear understanding of the responsibilities and accountabilities and provides motivation for the project team.

A Six Sigma project charter contains several parts:

- General information
    - ❖ Project title.
    - ❖ Project manager (BB or GB), sponsor, and mentor (Master Black Belt (MBB).
    - ❖ Project start date.
    - ❖ Anticipated project end date.

- Project overview
    - ❖ Business case / problem statement – outlines the business problems that need to be addressed.
    - ❖ Project goals / objectives – describes the expected outcomes of the project.
    - ❖ Expected financial benefits – provides all financial benefits.
    - ❖ Project scope – defines the boundaries of the project.
    - ❖ Major milestones – gives a breakdown of the anticipated project progress.
    - ❖ Project teams – summarises the selected team members, their roles and responsibilities.

- Signatures

- ❖ Project charter signatures – obtain signature from project sponsor / champion as an approval of the project.
- ❖ Project closure signatures – Signed by project sponsor / champion after the control phase as an agreement to accept the new process and the official closure of the project.

A Project Charter is the major deliverable of the project initiation. The length of the project charter is proportional to the size and complexity of the project.

2.4.2 Critical to Quality (CTQ) Tree

CTQ factors derive from voice of customer (VOC) and is a selection of the characteristics that are critical to customers (mainly external customers), processes (mainly internal customers and processes) and compliances (e.g. government and industry regulator) (Magnusson *et al*., 2003). They may include the upper and lower specification limits or any other factors related to the product or service (Yun and Chun, 2008). CTQs usually must be interpreted from the qualitative statements of the customers to a manageable quantitative business specification (He *et al.*, 2010). CTQ tree is a diagram to decompose broad customer requirements into specific, actionable business statements or measures that can be measured for meeting customer expectations. It is often seen in the define phase of a Six Sigma Project.

Identifying customer needs and creating a CTQ tree are time consuming processes and can involve several steps:

- Identify customers for the process to be improved.
- Collect customer requirements (VOC) – VOC can be obtained through customer surveys, interviews or expert judgements (brainstorming).
- Identify quality drivers for the requirements – These are also collected from customers or experts.
- Identify measurable performance requirements for each quality driver – Validation from customers is desirable regarding the identified requirements.

An example CTQ tree is presented in Figure 2.3 , where "I want good customer service" is a broad statement from customers and the quality drivers to the good customer service are "minimum mistakes" and "speedy response" which are finally presented by the measureable requirements "accuracy rate of invoices", "percentage of queries due to internal error", "time taken to return phone calls" and "time taken to resolve queries".

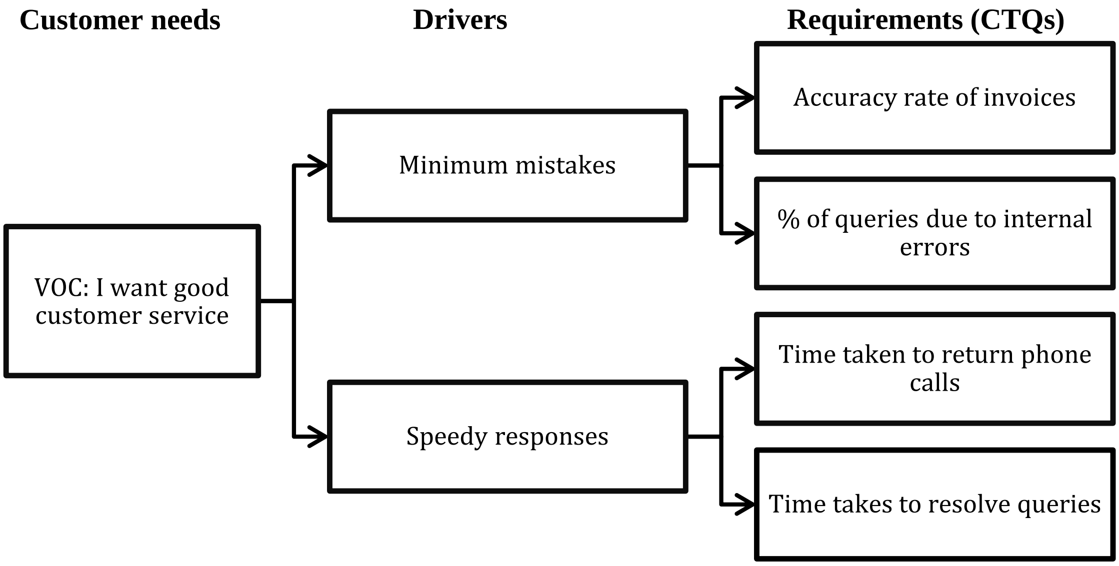


Figure 2.3 Example of a CTQ tree

During a project, several CTQ trees may be needed depending on the requirements of customers. Although most often used as a part of Six Sigma, CTQ tree can make an effective tool in various situations where quantifiable measures need to be identified from general and qualitative requirements.

2.4.3 Process Mapping

A process is a series of activities which takes inputs, transforms them by adding value, and produces outputs for customers (Figure 2.4). It is extremely difficult to improve a process without a thorough understanding of its steps and this may lead to costly mistakes. Process mapping is a tool to create process maps by gathering, organizing and presenting details of a process. A process map is a workflow diagram presenting the sequences of actions that comprise a process. It visualizes activities and interacts in a process to enable an organization to have an clear understanding of their current performance and provides opportunities to quickly identify bottlenecks, process imbalances and many other issues, by resolving which, the process can be improved. Many quality improvements in the service industries rely on a complete and accurate process map. The objective of the process mapping is to document and understand a process and improve it. Process mapping can be used in the define, measure and analyse phases in a Six Sigma project.

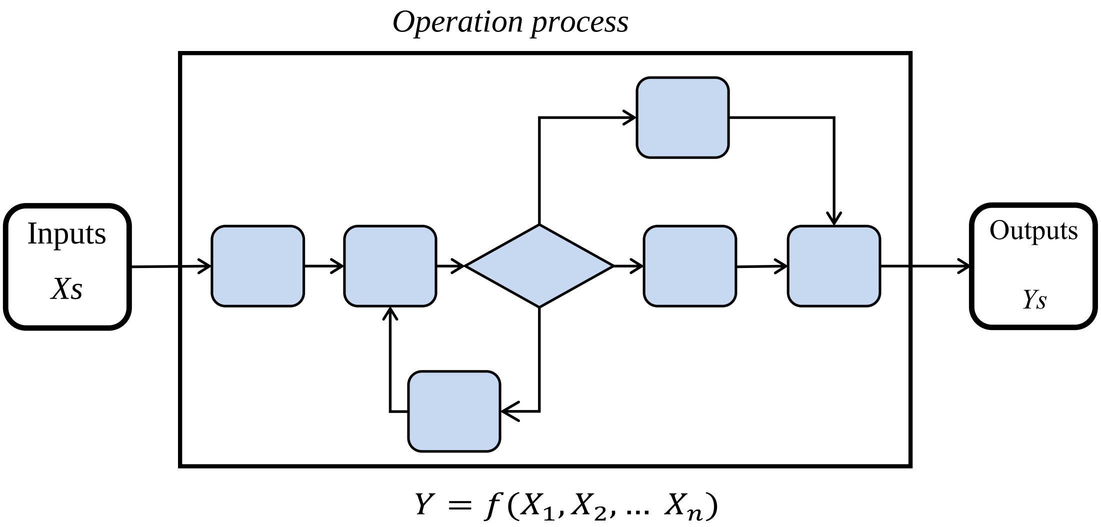


Figure 2.4 A process model

Process mapping is one of the easiest to grasp tools yet extremely effective. It can be carried out with certain guidance.

- Define the process to be measured and boundaries (start and end points).
- List first step and outline the major steps on the process.
- Identify detailed steps and their sequences.
- Draw symbols for each step.
- Add supplementary information.

- Verify the map until consensus is reached between all parties.
- Analyse process map and identify project opportunities.

A process can be mapped through conducting interviews or group discussions in workshops with company managers, staff and clients that are involved in the process.

2.4.4 Measurement System Analysis (MSA)

To measure a process with confidence, the measurement system for data collecting needs to be accurate and precise to avoid any variation generated by the system which will affect the identification of the true variation produced by processes. Figure 2.5 includes the possible variations that can result from a measurement system. Accuracy refers to the closeness to a defined target and is different from precision which represents the spread of measurement values. A MSA is a suite of tools to understand if the variation or part of the variation among the data collected from a process is contributed by the measurement system itself or the actual process being assessed. Measurement system variation can be caused by part variation, appraiser variation and equipment variation. The purpose of MSA is to (1) determine the extent of the total observed variability caused by a measurement system; (2) isolate the sources of variability in the system; and (3) assess the capability of the measurement system (Burdick *et al.*, 2003). In other words, it is to identify if a measurement system can generate precise and accurate data for the intended analysis. To ensure that measurement system variability is not detrimentally large, it is necessary to conduct a MSA (Peruchi *et al.*, 2014). MSA is an important part of a Six Sigma project to ensure that the data collected can reflect the actual variation of a process. It includes Gage Repeatability and Reproducibility (GR&R), bias analysis, stability analysis, discrimination analysis and kappa analysis.

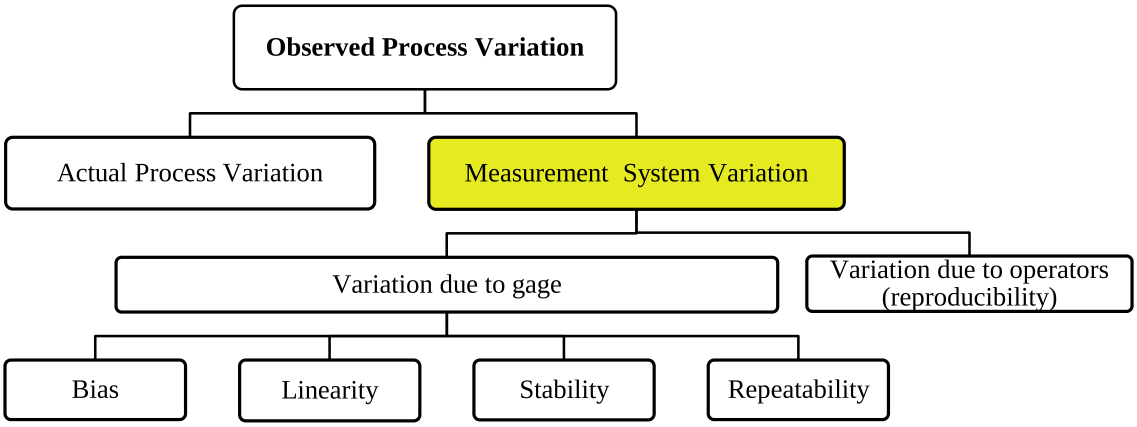


Figure 2.5 Possible variations from a measurement system

The most common study in MSA to evaluate statistical variations is GR&R. Repeatability and reproducibility refer to the extent to which similar results are obtained when the same object is measured multiple times. The degree of similarity of measurements done by the same operator and under identical circumstances is the repeatability, whereas reproducibility is the degree of similarity when multiple operators perform the measurements, possibly under varying conditions (Wieringen and Mast, 2008). GR&R is used to measure the precision of a measurement system. Two methods commonly used in a GR&R analysis are: (1) an analysis of variance (ANOVA) approach followed by estimation of the appropriate variance components; and (2) an X-bar and Range chart that estimates the standard deviations of the components of gage variability (Wang and Chien, 2010).

GR&R can be conducted by the following steps (George *et al.*, 2005):

- Identify elements of the measurement system (e.g. operators, equipment and parts/process, etc.).
- Select items to be included in the GR&R study. The items selected need to cover the entire range of process variation.
- Select 2-3 operators to participate in the study.
- Identify 5 to 10 times to be measured. Have each operator measure each item 2 to 3 times in random sequence.
- Gather data and analyse.

Statistical software, such as Minitab can effectively assist with the analysis of GR&R. Figure 2.6 is a graph example of GR&R study produced by Minitab. On the "Components of Variation" chart, the "Part-to-Part" bars are much higher than the other bars, which indicates that the most of the variation is from the true differences in the items being measured. The "R Chart by Operator" is a GR&R control chart and shows the variation in the measurements made by each operator on each part (Repeatability). If there are no points falling out the upper control limits (UCL), then that gage and operator can be considered repeatable. The measurement system reproducibility is represented by the "Xbar Chart by Operator". An out of control "Xbar Chart" in this test means the gage variance is much smaller than the differences in the items being measured. The "Response by Part" is to test if the items selected are suitable for the analysis. It displays the measurements for the parts from all operators. The spread between the highest and lowest values indicates the fitness of a part for the analysis and the decision is made according to the allowable amount of variation. For instance, item 10 has a much bigger spread compared with other items in Figure 2.6. Potential operators' issues are analysed through the "Response by Operator" chart. It plots the measurements for all items by each operator. The line connecting the averages should be nearly flat, otherwise, bias exists among operators. In the example, operator 2 tends to measure smaller than the other operators. The "Operator*Part Interaction" chart exposes the interaction between operators and the items. It presents measurements from operators for each item. The lines connecting the averages show the consistency among operators and a significantly diverged line indicates that there are operators consistently measuring some parts differently which needs to be investigated.

Bias, linearity and stability are used to measure the accuracy of a measurement system. Bias is a term to describe the difference between the average of measurements made on the same object and its true value. It includes operator bias, instrument bias and other forms of bias. The existence of biases affects the accuracy of a measurement system. The measurement system bias can be tested by using the "by operator", "by part" or "by instrument" graphs which can be generated by statistical software, such as Minitab.

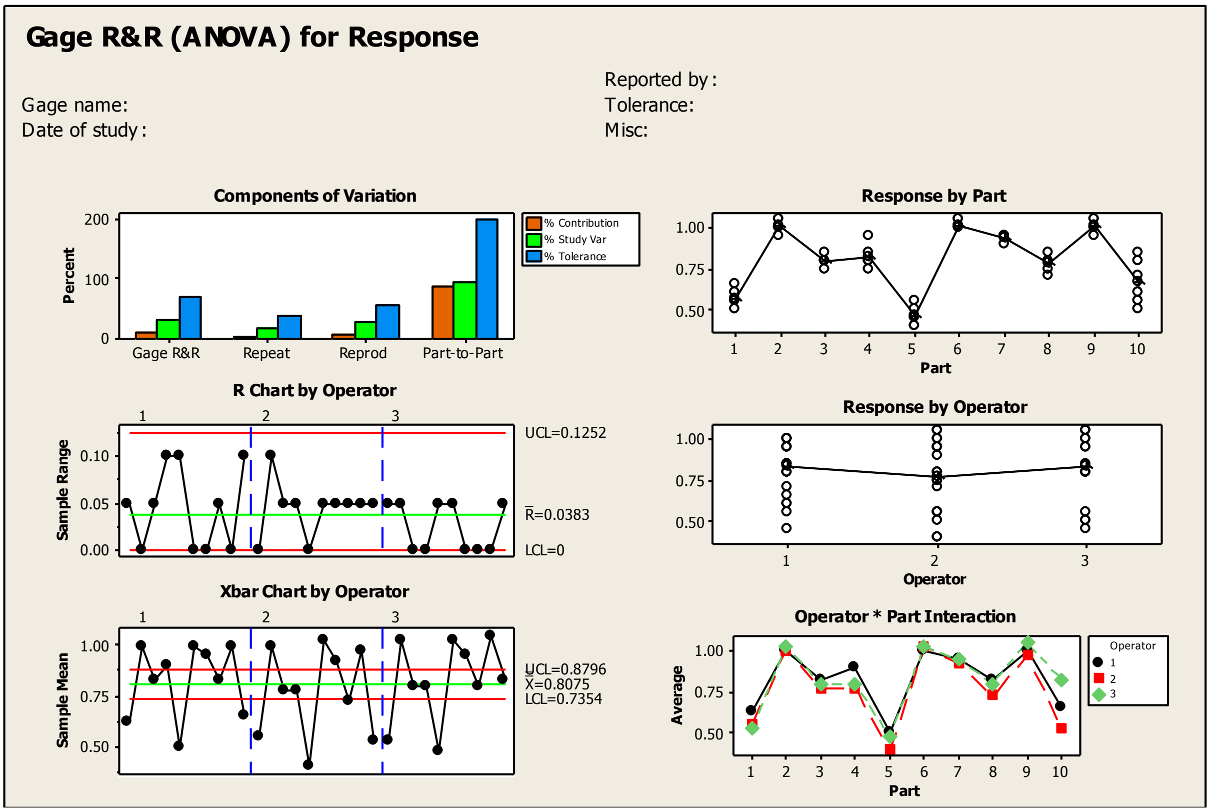


Figure 2.6 An example GR&R study through Minitab

Linearity is a measure of the consistency of bias over the range of the measurement system. Checking linearity requires at least 5 samples that cover the entire range of the measurement system to be repeatedly measured by the same operator. The linearity of a measurement system can be analysed by comparing the results from the test to the reference values. It can also be analysed through linearity plot.

Stability refers to the capability of a measurement system to produce the same values over time when measuring the same sample. It can be tested through repetitively measuring a master piece of sample over time and plotting the data on an Xbar chart.

Kappa analysis is a method to perform the MSA for attribute data. It compares the degree of consensus between appraisers. It is conducted through different appraisers making judgements over the same group of parts and the results that are compared with the expected value from the parts to obtain the Kappa statistic. Kappa statistic is a coefficient indicating the agreement percentage above the expected agreement by chance and its value is between 0 and 1.

All the studies in MSA can be performed through statistical software producing both graphical and statistical analyses.

2.4.5 Control Chart

Control chart which is also known as Shewhart chart, is a statistical-based tool for monitoring process, a graphical display of changes of a process over time with a set of rules for determining if a process is in statistical control. It is an important and one of the most often discussed tools in SPC. In a Six Sigma project, control charts are often used in the measure and control phases, where in the measure phase, it is used to distinguish between variations in a process resulting from common causes and special causes, while in the control phase, to confirm the impact of and test if the process remains in control after the implementation of solutions. It also helps an organization and the project teams to monitor the process performance over time to ensure its stability and enabling predictability. Table 2.10 lists the differences between common and special causes. There are different types of control charts that can be used at various situations depending on the data types and sample sizes. Figure 2.7 summarizes the applications of most commonly used control charts (George et al., 2005).

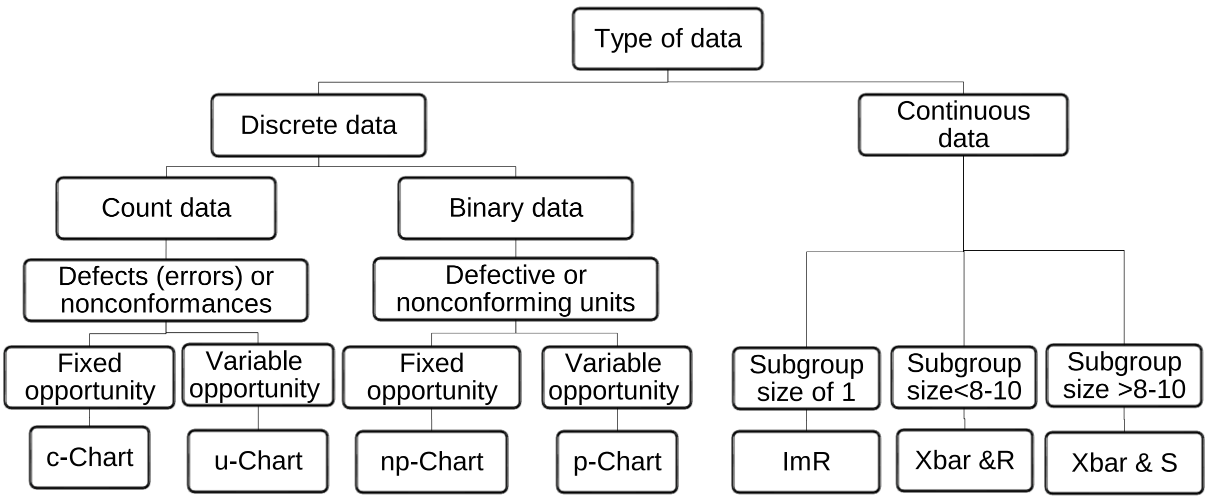
In order to create a control chart, the processes need to be closely studied so that sufficient and representative data can be collected. The steps of constructing a control chart for a process are as follows:

- Determine the data type.
- Define the rational subgroups.

- Determine sample size, time period and frequency for data collection.
- Select the appropriate control chart to be used.
- Collect data, construct and analyse the control chart.

Table 2.10 Common causes and special causes

Type of causes	Definition	Typical characteristics
Common causes	The usual, historical, quantifiable variation in a system. Process with only common causes presenting will run within its normal range	• Expected • Predictable range of values • Purely random
Special causes	Unusual, not previously observed, non-quantifiable variation. Process with presenting of special causes with display variation outside what is expected	• Unexpected • Unpredictable range of values • Not purely random



Fixed opportunity: the sample size or "unit" being sampled is constant
Variable opportunity: The sample size or "unite" being sampled changes

Figure 2.7 Control charts selection

Data plotted on a control chart is in the time sequence that they occurred. Control charts contain a central line which represents the average of the data and upper and lower lines stand for the UCL and lower control limits (LCL), respectively. These lines are determined from the data inputted. The control limits are based upon three times the standard deviation of the data inputted and therefore are also called 3-Sigma limits. Because the control limits are calculated from the process data, they are independent from customer expectations. Figure 2.8 is an example of a control chart which is statistically in control (within the UCL and LCL). The "measurement" (vertical axis) on the chart can represent any input or output that needs to be analysed.

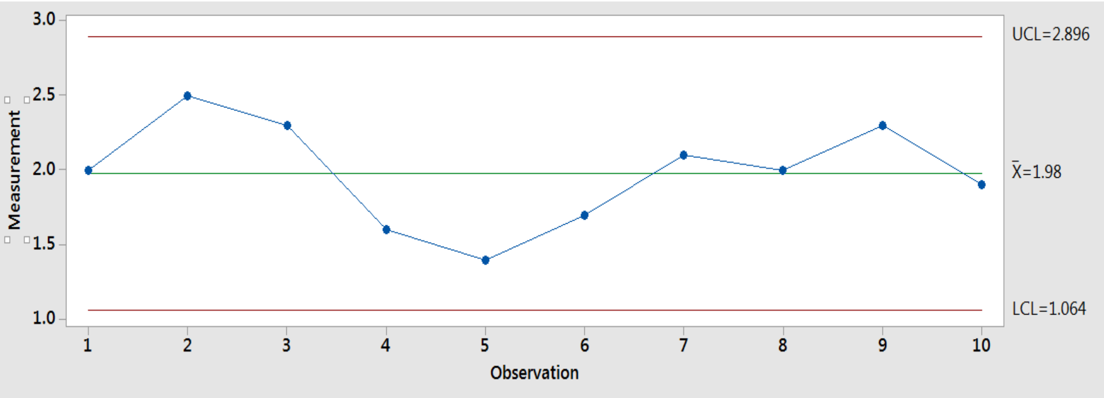


Figure 2.8 A sample control chart

There are eight rules to help the interpretation of control charts for identifying special causes. These rules assist to locate non-random patterns which indicate that the process is out of control. The eight standard rules are referred to as Western Electric Rules (WECO rules), Nelson Rules, AIAG (Automotive Industry Action Group) Rules, Juran Rules, Hughes Rules, Duncan Rules, Gitlow Rules and Westgard Rules. These rules supplement the basic rule – one point exceeds the control limits. The most popular rule is WECO rules and its supplemental rules which are listed below.

1) Points outside one of the 3-sigma control limits (Basic rule).
2) Two of the three consecutive points fall outside and on the same side of the 2-sigma control limits, but within 3-sigma control limits.

3) Four of the five consecutive points fall outside and on the same side of the 1-sigma control limits, but within 3-sigma control limits.
4) Eight consecutive points fall on the same side of the centreline.

Supplemental rules:

5) Six points in a row increasing or decreasing.
6) Fifteen points in a row within one sigma.
7) Fourteen points in a row alternating direction.
8) Eight points in a row outside one sigma.

When a special cause exists in a process, corrective actions need to be taken to address it. Control charts ensure that efforts are made towards the right areas. Morden data analysis software, such as, Minitab, can help with the creation of control charts. A process needs to be stable and in control (free from special causes) before the process capability can be assessed.

2.4.6 Process Capability Analysis (PCA)

The capability of processes can be characterized as the ability of the processes to provide products or services meeting the required quality criteria in the long term (Plura *et al.*, 2013). PCA is a measure of performance to evaluate the ability of a process to satisfy customers (in the form of specifications) (English and Taylor, 1993). PCA is based on the data collected from a process. It compares the inherent variability of an in-control process to the specification limits (customer requirements) by using Process Capability Indices (PCIs) which are statistical indicators of a process capability. The most widely used PCIs are C_p and C_{pk} (Table 2.11). Due to the fact the PICs are not associated with any unit, they can be used to compare capabilities between different processes. PCA is normally conducted in the measure phase of a Six Sigma project to present the current performance of a process, and in control phase as a final capability study to verify the improvement achieved.

Table 2.11 PCIs – C_p and C_{pk}

PCIs	Definition	Calculation
C_p	Process capability ratio - Overall comparison of process outputs vs. specification limits	$C_p = \frac{USL - LSL}{6\sigma}$
C_{pk}	Process index - Comparison of variation against USL and LSL, individually	$C_{pk} = Min\left[\frac{USL - \bar{X}}{3\sigma}, \frac{\bar{X} - LSL}{3\sigma}\right]$
		$\bar{X}$ stands for the mean of the data

As a key measure of the process performance, PCA provides a visual representation through the use of graphs, such as the histogram which also helps to assess and verify the process capability. Figure 2.9 is a sample PCA through histogram by using Minitab. The Upper Specification Limit (USL) and Lower Specification limit (LSL) are determined by customer requirements. Where LSL is preferred to be as minimal as possible, no LSL figure but a Lower Boundary (LB) is used in constructing the histogram. The “Within” (solid red line) represents the variation within subgroups, whereas the “Overall” (dotted line) shows overall standard deviation taking into account variation from the entire data set and looks at the total process variation.

A PCA normally involves the activities below:

- Determine customer requirements (USL and LSL).
- Collect process performance data.
- Check data normality – If data is normal, standard capability analysis can be carried out. However, if data is abnormal, it either needs to be normalized or another special type of capability analysis needs to be utilized.
- Generate PCIs and review results.

Computer software, such as Minitab, can assist with the PCA once the data is ready.

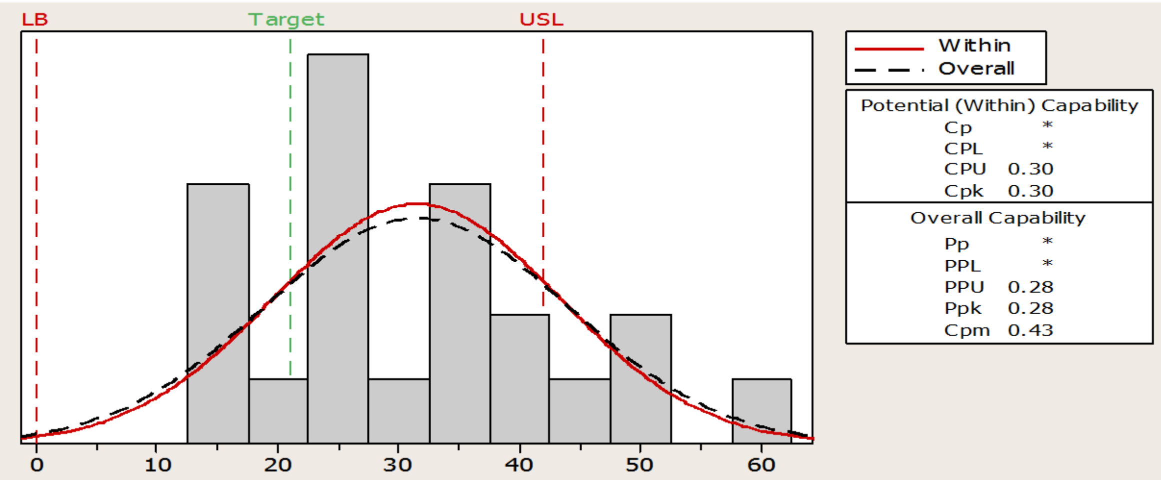


Figure 2.9 A sample PCA in histogram generated by using Minitab

2.4.7 Cause and Effect (C&E) Matrix

A C&E matrix is most often used to narrow the number of inputs generated from a process mapping down to a manageable amount according to their importance to customers' priorities. It is a useful tool in the measure phase of a Six Sigma project to filter the process inputs obtained from process mapping in order to identify the potential key process inputs that need to be further investigated for improving the key process outputs (CTQs). The elements of C&E matrix include process inputs and outputs where the latter are scored by their importance to customers and the former are scored against the latter.

A C&E matrix can be constructed by:

- Identifying key customer requirements (CTQs) which will be the outputs in the matrix.
- Assigning a priority score (1 to 10) to each output according to its importance to customers.
- Identifying process inputs through process mapping and transferring them onto the matrix.

- Rating each input against each output based on the strength of their relationship using relation scores. Table 2.12 provides a list of relation scores that are often used in practice.
- Obtaining final scores.
- Making a decision of the cut-off point in order to select the inputs that need to be further analysed.

Figure 2.10 provides an example of a C&E matrix.

Table 2.12 Relation scores for C&E matrix

Scores	**Judgment**
0	No relationship
1	Weak relationship
3	Medium relationship
9	Strong relationship

The calculation of the final scores for inputs is as follows:

Suppose there are n outputs and m inputs on a C&E matrix, let p_j ($j = 1,2,\ldots,n$) denote the priority score for the jth output, and r_{ij} ($i = 1,2,\ldots,m$) stand for the relation score for the ith input in relation to the jth output. Then the final score for the ith input, F_i can be obtained by using Equation (2.1).

$$F_i = \sum_{j=1}^{n} r_{ij} \times p_j \qquad (2.1)$$

The C&E matrix produces a reduced list of key process inputs to be further analysed by other relevant tools. It is worth mentioning that the results produced by a C&E matrix do not prioritize the inputs but only eliminate unimportant ones.

Rating of Importance to Customer	7	9	4	10	8	10	
	Paint thickness	Paint hardness	Rate	Coverage	Surface quality	Proper scheme	Total
Process Input							
Surface contamination	1	3	3	9	9	0	208
Surface roughness	0	1	3	3	9	0	123
Air pressure	9	1	9	9	9	0	270
Lot number	1	3	0	3	1	3	102
Nozzle type	9	0	3	9	9	0	237
Primer age	9	9	9	3	9	0	282
Ambient temp	1	3	9	0	3	0	94
Relative humidity	1	9	9	1	9	0	206
Surface contamination	1	9	3	9	9	1	272

Priority scores

CTQs

Final scores

Relation scores

Figure 2.10 An example of C&E matrix

2.4.8 Failure Mode and Effects Analysis (FMEA)

FMEA is a powerful tool for identifying and assessing potential failures and has been extensively used in a wide range of contexts. FMEA ranks possible failure modes based on three criteria: Severity (*S*), Occurrence (*O*) and Detection (*D*) (Table 2.13). A failure mode is assigned a score against each of these three criteria on an ordinal scale and a risk priority number (RPN) is then computed for the failure mode by multiplying the three ordinal scores. FMEA is one of the important methods used in Six Sigma applications. It can be used in many phases in Six Sigma projects. Table 2.14 provides a list of phases that FMEA can be used in, and its purposes.

FMEA can be conducted through brainstorming by the following steps.

- List all process steps/inputs on the FMEA table
- Identify all potential failure modes for each step/input
- Identify the possible effects for the failure modes and score their severity

- Identify the causes of those failure modes and rate their occurrence
- Identify any control in place to detect the issue and score the likelihood of detection
- Obtain RPN, rank all inputs and identify critical inputs that need to be addressed

Table 2.13 Explanation of Severity, Occurrence and Detection in FMEA

	Description	**The lowest score (1)**	**The highest score (10)**
Severity	severity of the potential effects of the failure on customers (both internal and external)	Low impact	High impact
Occurrence	Probability that a failure can occur during the expected lifetime of the product or service	Not likely to occur	Very likely to occur
Detection	Probability that the problem will be undetected before it reaches the end-user/customer	Very likely to be detected	Not likely to be detected

Table 2.14 FMEA applications in Six Sigma phases

Phase	**Purpose**
Measure	Failure prioritization – Identify and prioritize critical inputs associated causes of failures that need to addressed and
Analysis	Help to address where to look for root causes
Improve	Test solution and identify potential risks
Control	Monitor performance and enhance process

Table 2.15 is a sample FMEA form with explanation of its contents. Involving the right people has proven to be a key element in the successful application of FMEA. The team should include those that have good understanding of the process and can contribute to the identification of failures, such as process owners.

Table 2.15 FMEA form

Process Step/Input	**Potential Failure Mode**	**Potential Failure Effects**	**SEV**	**Potential Causes**	**OCC**	**Current Controls**	**DET**	**RPN**
What is the process step/ input under investigation?	In what ways can the input go wrong?	What is the impact on the key output variables once it goes wrong?	How Severe is the effect to the customer?	What causes the key input to go wrong?	How often does cause or failure mode occur?	What are the existing controls and procedures (inspection and test) that prevent either the cause or the failure mode?	How likely can the cause or failure mode be detected?	*S x O x D*

2.4.9 Pareto Charts

A Pareto chart is also called a Pareto diagram or Pareto analysis. It is a type of bar chart in which the vertical axis normally indicates frequency or cost, while the horizontal axis represents categories. It is used to graphically summarize and display the differences between groups of data. The bars on Pareto charts are arranged from left to right by the longest to shortest which enable the visualization of the category that has the most impact based on the criterion on the vertical axis. Figure 2.11 is an example of a typical Pareto chart. The Pareto chart is a useful tool in a Six Sigma project in identifying the most significant issues and is normally used in the analyse phase.

It is relatively simple to create a Pareto chart:

- Collect data for different categories
- Sort the data by frequency or total amount
- Draw bars for each category on the axis (this can be performed using statistical software)

There are many other tools in Six Sigma. Table 2.16 lists some typical ones with a brief description apart from those discussed above.

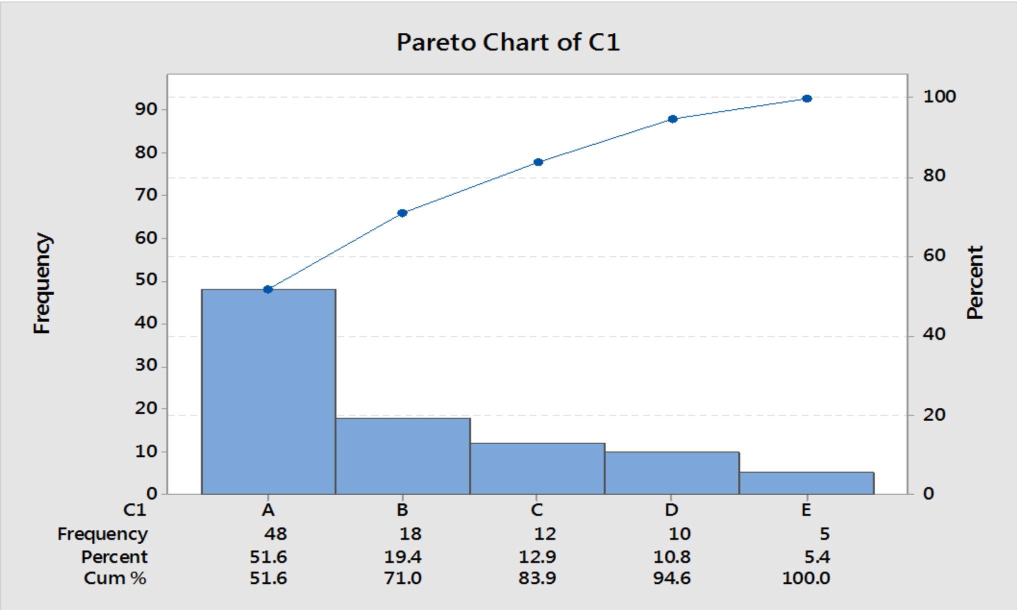


Figure 2.11 An example of typical Pareto chart

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Table 2.16 Useful tools in Six Sigma projects

Tools	Phase	Description
Affinity diagrams	Any phase	An effective tool to organise ideas, opinions and issues into natural groups or themes.
Cause and effect diagrams (fishbone or Ishikawa diagrams)	Analyse	A tool to display all potential causes of a problem and help to uncover the root causes.
Hypothesis Testing	Analyse	It uses a variety of statistical analyses to determine if any statistically significant difference among the observed relationship between two or more samples can be explained by random chance alone. Figure 2.12 lists the tests to choose in accordance with the data types.
Design of Experiments (DOE)	Improve	A powerful tool to analyse and identify the factors that have key influence on a process and optimise them through a variety of experimental situations.
Poka Yoke (Mistake proofing)	Improve	A method to ensure that human error is avoided in the future, or to make it impossible to make an error.
Pugh Matrix	Improve	A tool to compare and rank different concepts and help to arrive at an optimum that may be a hybrid or variant of others.
Control plan	Control	A document containing details of inspection points in a process and responsibility for each activity to ensure the sustainability of a process improvement in the long run.

Output Y (single)	Input Xs: Single X – Discrete	Input Xs: Single X – Continuous	Input Xs: Multiple X – Discrete	Input Xs: Multiple X – Continuous
Discrete	Chi-Square	Logistic Regression	Multiple Logistic Regression	Multiple Logistic Regression
Continuous	ANOVA Means/ Medians Tests	Correlation & Regression	ANOVA Medians Tests	Multiple Regression

Figure 2.12 Hypothesis testing road map

The application of tools is only one part of the Six Sigma process which alone will not secure the success of Six Sigma implementation. It works best in an environment with the top management support, effective training and the fulfilment of other CSFs during the Six Sigma implementation

2.5 Six Sigma in the Service Industries

Service industries have raised their awareness of meeting customer needs while remaining economically competitive with increasing market competition and customer expectation. However, research shows that the COPQ (rework, mistakes, and abandoned projects, etc.) in service-based businesses and processes typically run as high as 50 percent of the total budget (Pande *et al*., 2000). Thus, how to improve service quality has become a crucial issue in today's service industries.

Although Six Sigma was originally developed for manufacturing processes, traditional manufacturing companies are taking their Six Sigma experiences and moving them to their service operations. For example, the Ford Motor Company has achieved cost savings from successfully applying Six Sigma in its corporate real estate group, facility management and maintenance functions (Holtz and Campbell, 2004). Today service firms and service functions within many sectors are using Six

Sigma to improve their profits and performance. Six-Sigma is particularly attractive to the service sector due to its customer-driven methodology (Tagahaboni-Dutta and Moreland, 2004). It offers a disciplined approach to improve service effectiveness (i.e. meeting the desirable attributes of a service) and service efficiency (i.e. time and costs) (Antony, 2004a) leading to improved customer satisfaction. According to the survey conducted by DynCorp, 38.2% of the companies in the US with a Six-Sigma programme in place were service companies (Mekong Capital Ltd., 2004). A large number of examples of successful applications of Six Sigma in the service industries have been documented. For example, in the financial service sector, BOA applied Six Sigma to reduce defects in operations, cut unnecessary costs, improve efficiency and achieve a higher customer satisfaction level. Four years from its application in 2001, Six Sigma helped BOA to achieve two billion dollars in revenue gains and cost savings. Apart from BOA, American Express, GE Capital Corp., JP Morgan Chase, SunTrust Banks, HSBC and Citibank have all seen significant improvements in various sections through the implementation of Six Sigma projects. In the healthcare sector, Six sigma helped Commonwealth Health Corp., Thibodaux Regional Medical Centre, Good Samaritan Hospital and many more to achieve cost savings and improve quality of service.

Service industries are even more in need of Six Sigma than manufacturing due to the fact that the outputs tend to go directly to customers whereas in manufacturing most defects are either scrapped or fixed before shipping (Tennant, 2001). However, the implementation of Six Sigma in service industries has its difficulties. Six Sigma is known as a fact-based method, in other words, statistically-based. The products of service industries are normally intangible and involve direct customer communication and participation. They tend to have less measurable process with non-standard outputs and are not quantitatively oriented as manufactured products. The products of service industries are often consumed at the same time as they are produced and are highly variable depending on the service providers, which leads to more errors and higher variation. Therefore, lack of qualified data for decision making is a common issue which leads to difficulties in Six Sigma applications in the service industries. Antony (2004a) summarized some differences between service and manufacturing industries which affect the quality management (Table 2.17).

Table 2.17 Differences between service and manufacturing industries

	Service	**Manufacturing**
Measurement	Often an overlooked area	Normally have some in place
Use of process map	Uncommon	Very common
Qualified data	Not generally available	Can be obtained from measurement system
Uncontrollable factors	Large amount	Little
Human characteristics	Major influence	Less impact

Due to these characteristics of the service industries, it is very challenging to define and manage their quality. Many studies have been carried out to investigate the implementation of Six Sigma in service industries. Frings and Grant (2005) suggested the implementation of Six Sigma in healthcare by following a detailed step by step implementation structure. Jiantong and Wenchi (2007) demonstrated the application of the Six Sigma DMAIC methodology in banking services by using a case of reducing serving time of opening a bank account. Yuan *et al.* (2008) embedded DMAIC into four phases (confirming, preparing, starting up and implementation, and developing) for the implementation of Six Sigma in logistics cooperation. Yang *et al.* (2007) recorded the application of Six Sigma in supply chain management of Samsung by following a unique model DMAEV (define, measure, analyse, enable, and verify) according to the company needs. Benedetto (2003) discussed the methods used to resolve issues encountered during the implementation of a Six Sigma project in a radiology film library including difficulties in data collection, error tracking and training.

2.6 Decision Making under Uncertainty

Uncertainty is defined as a situation in which a person does not have appropriate quantitative and qualitative information to describe, prescribe or predict deterministically and numerically a system, its behaviour or other characteristics (Zimmermann, 2000). Uncertainty in principle is originated from failures, assumptions, consequence methodologies, unavailability or incompleteness of data.

Characteristics of OSFs of shipping companies render themselves a high level of uncertainty which affects the implementation of Six Sigma. Due to the large involvement of human activities in the operations, experts' subjective judgements are often used in order to obtain valid data. Numbers offer precision in scientific communication and efficiency of aggregation and manipulation, but their characterization of a person's experiences is usually far more impoverished than his or her words (Stiles, 1993). Effective handling of uncertainties and using of qualitative data can improve the applicability and accuracy of Six Sigma and increase its applicability in an environment where high uncertainties exist.

The implementation of Six Sigma in OSFs of shipping companies therefore needs to appropriately tackle the uncertainties inherently involved in the different steps of the DMAIC methodology. Many tasks such as project selection, fault measurement and failure analysis, KPI control and improvement, are essentially processes of multiple criterion decision making (MCDM) under uncertainty, requiring analysts to derive rational decisions from uncertain and incomplete data contained in different quantitative and qualitative forms. Typical MCDM problems are addressed through several crucial steps such as criteria selection, criteria importance analysis, alternative identification and evaluation. Well-established MCDM methodologies are therefore reviewed with respect to the steps in order to provide a holistic knowledge base on their applications in the context of shipping and maritime sectors. However, it is noteworthy that none of them is considered suitable under all MCDM environments and therefore hybrid approaches are often developed to deal with complex scenarios involving different types of uncertainties.

Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis has its mutual origins in the work of business policy academics at Harvard Business School and other American business schools from the 1960s onwards. The work of Andrews (1971) has been especially influential in popularizing the idea that a good strategy means ensuring a fit between the external situation a firm faces (threats and opportunities) and its own internal qualities or characteristics (strengths and weaknesses) (Hill and Westbrook, 1997). The applications of the SWOT analysis to select criteria in a multi-criteria situation have invariably been combined with AHP and/or TOPSIS (Arslan and Turan, 2009; Notteboom, 2011; Kandakoglu *et al.*, 2009; Celik and Kandakoglu, 2012), in which SWOT is often used to examine and determine the criteria while AHP is utilised to assign the priority of each criterion and to rank the alternatives. TOPSIS is sometimes used to replace AHP in the process of ranking the alternatives. For instance, the combination of SWOT analysis, AHP and TOPSIS has been used to aid ship owners to choose the suitable shipping registry (Kandakoglu *et al*., 2009). Furthermore, it has been seen that SERVQUAL (Kannan *et al.*, 2010) and Exploratory Factor Analysis (EFA) (Spearman, 1904; Fabrigar *et al.*, 1999) are used to select criteria in shipping. Kannan *et al*. (2010) proposed a framework based on AHP and SERVQUAL for benchmarking service quality of container shipping companies, while Chao and Lin (2011) combined EFA and fuzzy AHP for a two-phased method of evaluating advanced quay cranes in container terminals (Puttich, 2013).

AHP, as one of most widely used MDCM approaches, is capable of assisting criteria selection, criteria importance analysis and alternative evaluation. The best decision can be made when qualitative and quantitative aspects of a decision are included (Saaty, 1990). AHP uses the concept of pair-wise comparison to improve the efficiency of synthesising qualitative and quantitative evaluations in a decision process. It consists of four steps of establishing the hierarchy of criteria, making pair-wise comparison of the criteria and alternatives, estimating the weights of the criteria and the relative performance values of the alternatives with respect to each criterion, and aggregating the weights and performance values for alternative priority. The visibility and easiness characteristics of AHP contribute to its popularity in research projects across different industries. Vaidya and Kumar (2006) revealed that the AHP method is used in nearly 150 applications. Several examples are presented to demonstrate the AHP applications in the shipping and maritime sectors. AHP has been widely used in port choice and competitiveness evaluation (Lam and Dai, 2012; Yeo *et al.*, 2010; Yeo *et al.*, 2014) as well as in vessel selection (Yang *et al.*, 2009b; Xie *et al.*, 2008). Carlos Perez-Mesa *et al.* (2012) determined optimal allocation of ports between land and intermodal transport, taking into account environmental externalities. AHP has also been used to investigate the human reliability of ship operations (Ung *et al.*, 2006), design support evaluation for the offshore industry (Sii and Wang, 2003), selection of Nigerian ports regarding service quality (Ugboma *et al.*, 2004), and maritime regulation implementation by Karahalios *et al.* (2011).

The AHP has some advantages over other methods because of its simplicity and its ability to rank parts of a multi-criteria problem in a hierarchical structure (Chen and Lin, 2006). However it lacks the ability to model the interdependencies among the criteria, which constrains its applications in large engineering and management systems. Analytical Network Process (ANP) (Saaty, 1990) was developed to complement the AHP in a way that the criteria are presented in a network (instead of hierarchy) structure. Although showing some attractiveness in modelling interrelationship among the criteria, ANP still reveals some practical problems in its real applications. For instance, to construct the associated supermatrix ANP requires too much pair-wise comparison input information, which is often difficult to obtain using simple questionnaires. As a result, new methods are developed to seek for alternative solutions to weight distribution of the criteria in a network organisation. The hybrid of DEMATAL and ANP (D-ANP) (Chen, 2012; Vujanovic *et al.*, 2012; Tsai and Hsu, 2010; Lee *et al.*, 2011) or DEMATEL and AHP (D-AHP) (Dalalah *et al.*, 2011) is among the most popular in the relevant literature. The difference between D-ANP and D-AHP lies in that the former is to use the qualitative analysis of DEMATAL for identifying the criteria having interdependencies (and ignoring independent criteria), which can help simplify the requirements of input information in construction of supermatrix in ANP. The latter directly combines the result from the quantitative analysis of DEMATEL with the one from the AHP. By doing so, the weight of a criterion can be presented in terms of both its influence to the other criteria (through DEMATEL) and its relative importance in decision making (through AHP). Compared to the criteria weights assigned by subjective experts, another factor used to rationalise the weights is considered based on the objective information on performance evaluation of each alternative against the same criterion through entropy calculation. Entropy results are often combined with the ones from AHP in MCDM analysis (Yang *et al.*, 2009c; Chou and Liang, 2001).

Evaluating decision alternatives in a real-world scenario is a complex process as it frequently involves uncertainty in data. Complexity in MCDM is consequently caused by the rational handling of qualitative criteria and uncertain or missing information (Yang and Xu, 2002b). Such uncertainties are broadly categorized as fuzziness, incompleteness and randomness (Liu *et al.*, 2004). Fuzzy logic (Zadeh, 1965), ER (Yang and Xu, 2002b) based on Dempster-Shafer theory (Dempster, 1967; Shafer, 1976) and Bayesian network (BN) based on Bayesian probabilistic theory (Jensen, 2001) are used to tackle the three types of uncertainty respectively.

Fuzzy logic is a superset of conventional Boolean logic with extensions to account for imprecise information. Fuzzy logic permits vague information, knowledge and concepts to be used in an exact mathematical manner. Linguistic variables such as "definite", "likely", "average", "unlikely" and "impossible" are necessary media used to describe continuous and overlapping states. This enables qualitative and imprecise reasoning statements to be incorporated with fuzzy algorithms or fuzzy rule bases producing simpler, more intuitive and better-behaved models. Fuzzy logic is based on the principle that every crisp value belongs to all relevant fuzzy sets to various extents, called the degrees of membership. Pure fuzzy logic has extremely limited applications in business (the only popularised application is the Sony Palmtop) and the main use of fuzzy logic is as an underlying logic system for fuzzy expert decision making systems (Pai *et al.*, 2003). Fuzzy logic has been successfully applied for a wide range of single and MCDM problems. For instance, Chou (2010) proposes a fuzzy MCDM methodology for solving the container transhipment hub port selection dilemma under fuzzy environment. Wang and Lee (2010) utilise a fuzzy MCDM method for evaluating the financial performance of container shipping companies based on extended fuzzy preference relation and using linguistic weights. The application of fuzzy logic in MCDM becomes more compelling when being combined with AHP, (Bulut *et al.*, 2012; Hsu, 2012; Chao and Lin, 2011), TOPSIS (e.g. (Yeh and Chang, 2009; Durbach and Stewart, 2012; Yang and Wang, 2013; Kannan *et al.*, 2014), and PROMETHEE (e.g. (Shirinfar and Haleh, 2011; Gupta *et al.*, 2012; Tavakoli *et al.*, 2013)

The theory of evidence was first generated by Dempster (1967) and further developed by Shafer (1976). The Dempster-Shafer theory of evidence or D-S theory was originally used for information aggregation in expert systems as an approximate reasoning tool (Buchanan and Shortliffe, 1984; Mantaras, 1990) and then used in decision making under uncertainty and risk in contrast to Bayes decision theory (Yager, 1992; Yager, 1995). ER is developed on the basis of the D-S theory. The use of ER as a decision making tool has been widely reported in the literature. An important achievement of applying ER to decision analysis is to incorporate it into traditional MCDM methods for addressing the degree of belief associated with subjective judgements. The lack of data, the inability of assessors to provide precise judgements, or the failures of some assessors to provide judgements in group decision-making can result in an incomplete assessment (Yang and Xu, 2002b). An ER based decision making approach for MCDM problems with both qualitative and quantitative criteria under uncertainty was developed in the early 1990’s (Yang and Singh, 1994; Yang and Sen, 1994). The kernel of such an approach is an ER algorithm, which was generated by Yang and Singh (1994), later updated by Yang and Sen (1994) and further modified by Yang (2001) and Yang and Xu (2002b). ER is applied for ranking alternatives or selecting the best compromise alternative in a process, in which both quantitative and qualitative attributes are simultaneously satisfied as much as possible (Yang and Singh, 1994). Several applications of this approach are addressed in the maritime related literature (Yang, 2001; Sii *et al.*, 2001;

Yang *et al.*, 2005; Yang *et al.*, 2009c; Yang *et al.*, 2014).

A BN (also called belief network, or probabilistic network) is a graphical presentation of probability combined with a mathematical inference calculation. It can be used to represent dependencies between decision variables. Each variable represented as a node, is connected by directed links, represented as arrows or arcs, with conditional probability table (CPT) values assigned to the variables making up a BN (Jensen, 2001). The graphical representation makes BNs a flexible tool for constructing the models of causal impact between events, in particular when the causal impact has a random nature. A BN serves as a model for a part of the world and the relations in the model reflect causal impact between events. The reason for building these models is to use them when making decisions under a dynamic environment. In other words, the probabilities provided by the network are used to deal with the dynamic changes of variables and support some kind of decision making involving randomness.

It is possible to decompose multi-attribute/criteria utility functions in a similar way: a node is created to represent the attribute of interest, which has as its parents all the other attributes on which it depends. Furthermore, the utility node(s) will be created to have decision/deterministic and chance node(s) as parents, since the utility depends both on the state of the world and the actions performed by decision makers. The resulting graph is called an influence diagram (ID). The utility functions allow IDs to incorporate the notation of preference, which is necessary to wider decisions with multiple attributes. The precedence links attached in the diagrams make it possible to take decisions or perform actions in a sequential order. An ID was originally developed to substitute conventional decision trees in modelling and solving real world symmetric decision problems. An ID is solved by computing a strategy yielding the highest expected utility (Yang, 2006). In the framework of IDs, Gupta et al. (2012) provided a natural representation for capturing the semantics of decision making with a minimum of clutter and confusion for decision makers (Shachter and Peot, 1992) and offerd comparative advantages of easy numerical assessment and effective representation of independencies between variables over trees. These factors contributed to the widespread use of IDs as a tool for representing and analysing complex decision problems in recent years (Fenton and Neil, 2001; Willems *et al.*, 2005; Diehl and Haimes, 2004; Delcroix *et al.*, 2013; Yang *et al.*, 2009a).

In shipping quality control, linguistic terms exist together with numbers. Therefore, methods adopted for qualitative analysis in this study need the capability of handling both quantitative and qualitative data by investigating the aforementioned methods, models, theories and their combinations.

2.7 Discussion

Globalization exposed companies to an increasing market competition. Quality control has therefore become an increasingly attractive topic to both academics and practitioners. During the evolvement of SPC, different methods have been created, tested, discussed and criticized. Many of them have faded away for different reasons. Six Sigma, as an effective quality improvement methodology, is the most eye-catching method in today's quality control. It has been successfully implemented in many industries, including the service industry, to improve business performance and the benefits achieved have been well documented. The tools in Six Sigma are not newly created, but the principle of Six Sigma and the logical integration of those tools have made Six Sigma outperform the other quality control methods.

To enjoy the benefits that Six Sigma could bring to shipping, the existence of uncertainty needs to be carefully addressed by OSFs of shipping companies. The current methods in Six Sigma are inadequate in dealing with uncertainties. This chapter has reviewed some of the uncertainty treatment methods in detail which will be employed to improve the capability of Six Sigma tools so that they can be effectively and confidently used in OSFs.

Chapter 3. A Modified Six Sigma Methodology for OSFs of Shipping Companies

3.1 Introduction

Shipping is in its nature a service industry providing transportation. Quality, efficiency and safety are major factors in determining the success of a shipping company in an ever changing dynamic environment. Under today's global market competition, shipping, as a highly globalized industry, is constantly seeking ways to improve its competitiveness and maintain/increase its profitability. Owners are managing a large bundle of associated services for the clients to enable and support shipping operations. The quality of these services has been recognized as an essential part in meeting customers' satisfaction level. Six Sigma, as a statistically-based quality improvement methodology, has been successfully implemented in many industries to improve business performance, but not in shipping in general, or onshore service in particular, largely due to the unavailability and incompleteness of relevant data. This chapter aims at proposing a revised framework to implement Six Sigma in the OSFs of shipping companies to realize a more visible process that can be effectively measured, monitored and improved so as to better meet customer requirements. Through its implementation in a real test case in a world leading shipping line, the new framework demonstrates its feasibility in practice as well as its advance in facilitating quality improvement and cost saving in shipping operations particularly in the troughs of shipping cycles such as economic crisis.

3.2 The Needs of Six Sigma in the OSFs of Shipping Companies

Yilmaz and Chatterjee (2000) found that most service processes such as shipping, invoicing, billing, payroll, customer order entry, etc. are performing at a quality level of less than a 3.5 sigma, with a defect rate of over 23,000 ppm or 97.7 per cent yield. OSFs of shipping companies contain most of these functions mentioned and more. According to GE's 1996 annual report, it has been estimated that less than the Six Sigma quality, i.e., the three-to-four Sigma levels that are average for most U.S. companies, can cost a company as much as 10-15% of its revenues. A slight improvement on the Sigma level could dramatically reduce the number of defects and result in not only financial returns, but also higher customer satisfaction and loyalty. Research has suggested that it is more profitable to retain customers in the long term and that a 5% increase in customer loyalty can produce profit increases from 25% to 85% (Reichheld and Sasser, 1990). The top of the list of customer suggestions for improving shipping line performance includes "Advance notice of shipping delays", "Better trained / knowledgeable staff", "More cooperative", "Speedy document release", "Closer monitoring" and "Faster service/procedures" (Srinivas Durvasula *et al.*, 2002). It presents a need for improving service quality of OSFs in shipping companies. Antony (2004a) listed several benefits of applying Six Sigma in the service industries including fact based decision making, better understanding of customer needs, reliable and efficient operation, improved employee satisfaction, more stable performance, proactive company culture and improved cross-function teamwork. All of them will benefit the OSFs to improve their performance and better meet customer expectations.

In service industries, including the shipping sector, qualitative data is equally if not more important compared to quantitative data. Due to the lack of qualified quantitative data and the existence of uncertainties, subjective judgements are frequently needed to obtain information. There are no structured qualitative methods in the Six Sigma methodology to effectively deal with qualitative information. The current analytical tools in Six Sigma applications are mostly based on the use of quantitative data and require the transformation of qualitative data into quantitative data. This has limited the application of Six Sigma tools in an environment in which the uncertainty in data is high.

3.3 A Modified Six Sigma Methodology

OSFs of shipping companies have unique characteristics, which are human intensive, directly customer interactive, a large number of cross-department activities and evolving processes.

The traditional Six Sigma uses DMAIC as standard methodology (section 2.3.4). Although the importance of preparation and recognition have been recognized by many researchers and practitioners, in practice, they are often neglected or not well conducted by simply following the DMAIC methodology, which will compromise the project results. A newly modified framework of implementing Six Sigma, capable of modelling the quality control in OSFs of shipping companies, P-DMAIC-R, is proposed and presented in Figure 3.1 by taking into consideration the above issue and the features of shipping companies.

3.3.1 Top Management Support / Involvement

Suggested as the top CSF in the successful implementation of Six Sigma, top management support / involvement is a critical element in the success of Six Sigma. It is essential in ensuring the project is in line with the company strategy, securing sufficient resources, keeping motivation and removing barriers during the implementation process. Six Sigma's success demands the full support and personal involvement from the highest executive. According to an associate dean and professor of operations and manufacturing management at the John M. Olin School of Business, "The top executive must be part of Six Sigma (Andersen *et al.*), must change the agenda of upper management meetings so the quality initiative is right near the top" (Henderson and Evans, 2000). The success of Six Sigma lies in the commitment of top management and should only be initialized once the managers' commitments are fully established. This is especially important in OSFs of shipping companies where human activities are heavily involved in every part of the operation processes.

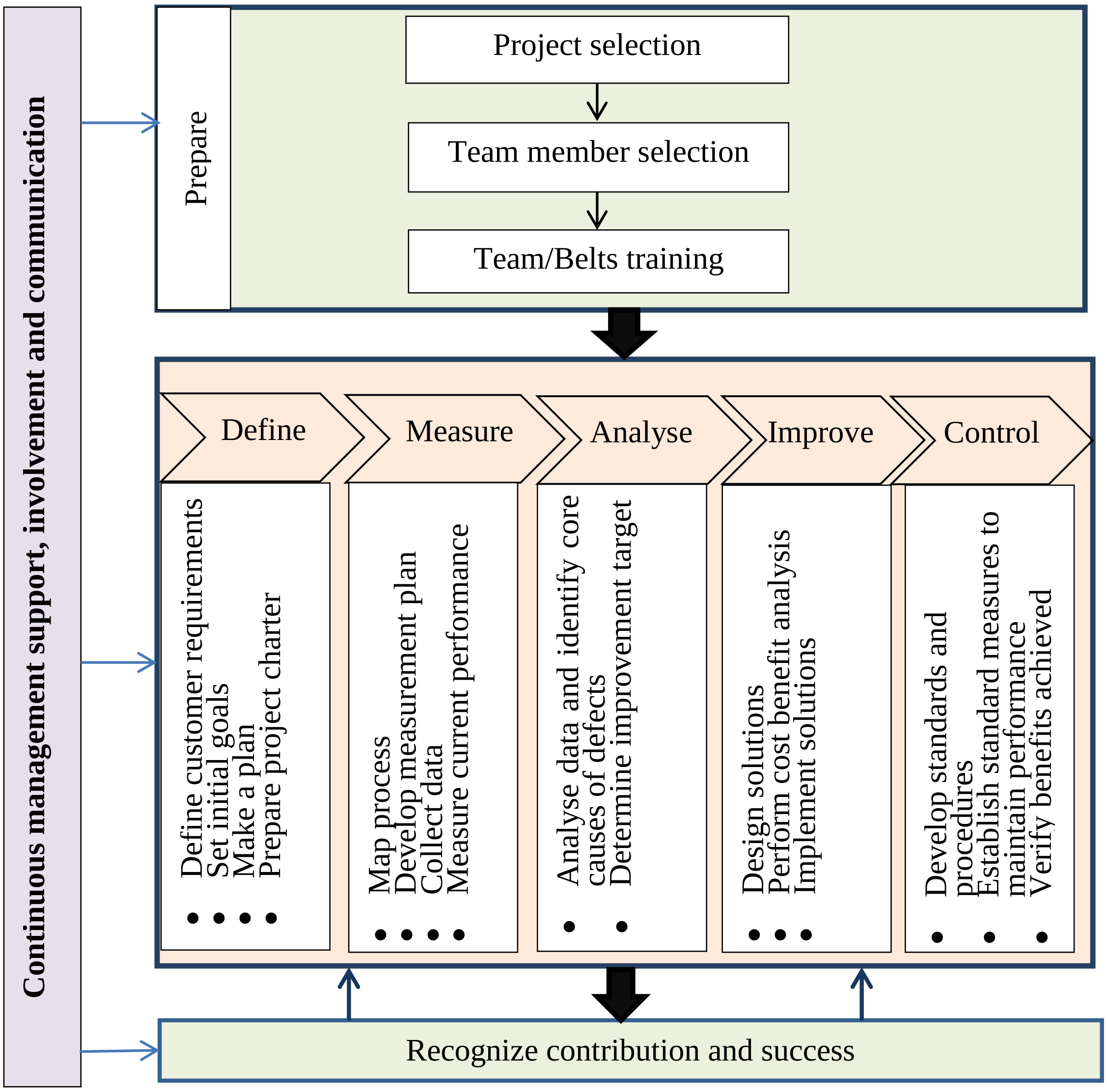

Figure 3.1 Framework of implementing Six Sigma in OSFs of shipping companies

3.3.2 Prepare

DMAIC has been widely accepted as the methodology for Six Sigma. Although project selection, team member selection and belt training have been recognized as important elements in Six Sigma applications, they are not being built into the standard methodology framework. They are indispensable for the successful implementation of Six Sigma in OSFs of shipping companies and therefore are structured into the framework as a new stage of the standard methodology, namely "prepare" (Figure 3.1).

Project selection

Six Sigma is a project-driven approach and an organisation can achieve the strategic goal through effectively accomplishing projects. Selecting the right project is one of the most critical CSFs for the effective deployment of a Six Sigma programme. Project selection is a process of evaluating individual projects to choose the one or ones that can meet organizations' current objectives. Literature has revealed that project selection is the most critical and mostly mishandled activity in the launching of Six Sigma (Pande *et al*., 2000). A right project is the one that can be completed within a reasonable time and delivers tangible benefits that the organization requires (such as, reducing cost or improving customer satisfaction). It is a multi-criteria decision making process which requires assessment of different criteria in a project selection process. Antony (2004b) pointed out that the prioritisation of projects in many organisations is still based on pure subjective judgement. Very few powerful tools are available for prioritising projects. Many studies have been conducted in project selection for Six Sigma projects (Kumar *et al.*, 2007; Su and Chou, 2008; Kumar *et al.*, 2009; Buyukozkan and Ozturkcan, 2010). However, the project selection process will be very challenging when the data used to describe the selection criteria is presented in various forms and effective data collection, transformation and aggregation become necessary. The selection process is normally conducted under the guidance of experienced Six Sigma practitioners, by personnel, normally senior managers, who have a good understanding and control over company objectives, finance requirements and resources allocation.

Team selection and training

Properly defined roles can facilitate a smooth Six Sigma implementation by providing a clear understanding of the responsibilities and accountabilities to the personnel involved. Six Sigma implementation involves a belt system which contains a dedicated Champion / Sponsor at the senior management level of the organisation, MBB for providing training courses, BBs as full time improvement experts, GBs among supervisors and other team members from operators and front-line staff (Magnusson *et al*., 2003). Table 3.1 provides an overview of the Six Sigma belt system.

A comprehensive training package needs to be provided to team leaders. There are different organizations in the market that can provide external training. A company can also hire qualified MBBs to provide training internally. The differences of internal and external trainings are listed in Table 3.2. Effective training of BBs and any other Six Sigma project leaders is not limited to the knowledge of Six Sigma tools, but also project management and people skills, such as team collaboration.

Table 3.1 Six Sigma belt system

Roles	**Position**	**Main Responsibilities**
Champion / Sponsor	Member of senior management team	*Driver of a project* • Set broad goals • Scope project • Secure resources, remove barriers, advocate progress and achievement
MBB	Full time experts	*Trainer and coach* • Provide Six Sigma trainings • Work as agent of change • Coach BB and GB
BB	Full time resource from the very best leaders	*Project Manager / Trainer* • Develop and maintain project charter and schedule • Select team members • Define and assist team members in using Six Sigma tools
GB	Middle management, supervisors	*Project Manager / team member* • Implement project by using tools and methodologies
Other team members	Operators	Provide information base on experience to support the measurement, analysis and improvement

3.3.3 DMAIC

DMAIC provides a consistent approach for organizations in implementing Six Sigma. It emphasises "customer needs" and "continuous measurement" to achieve improvement on current processes which are essential aspects in shipping company quality improvement. It also offers the opportunity to redesign the processes if it becomes necessary. Therefore, DMAIC can make an effective model in Six Sigma implementation used in OSFs of shipping companies.

Table 3.2 Key characteristics associated with internal versus external training (Kubiak, 2012)

Internal training	**External training**
Less expensive	Can be very expensive
Takes time to develop course material	A variety of courses can be delivered almost at a moment's notice
Requires that a certain number of high-level belts be on board to develop the material	Does not require high-level belts to be on board
Consistency of material content likely to degrade with large, decentralized organizations	Consistent material content
Future instructors can pair with current instructors for training	The development of internal instructors is unclear
Deployment paced by the rate instructors is developed	Instructors usually available almost at moment's notice

The "define" phase provides a top level project definition / charter with goals and plans. In this phase, "defect" in the process is defined and the COPQ is calculated to provide baseline data. The COPQ includes the costs of internal failures, external failures, appraisal (prediction, audit and detection) and prevention. They are the costs that would disappear if every task were continuously performed without deficiency every time and can be varied for different function areas or companies. Figure 3.2 presents an example of COPQ that may exist in a company. COPQ creates a burning platform as well as helps an organisation to identify areas that have direct bearing on profitability. Once the COPQ is identified, an aggressive but realistic goal needs to be set based on the CTQs. A realistic project plan/tracker with detailed breakdown of milestones is also developed in this phase. These are the major elements of a project charter which need to be reviewed and updated throughout the project implementation.

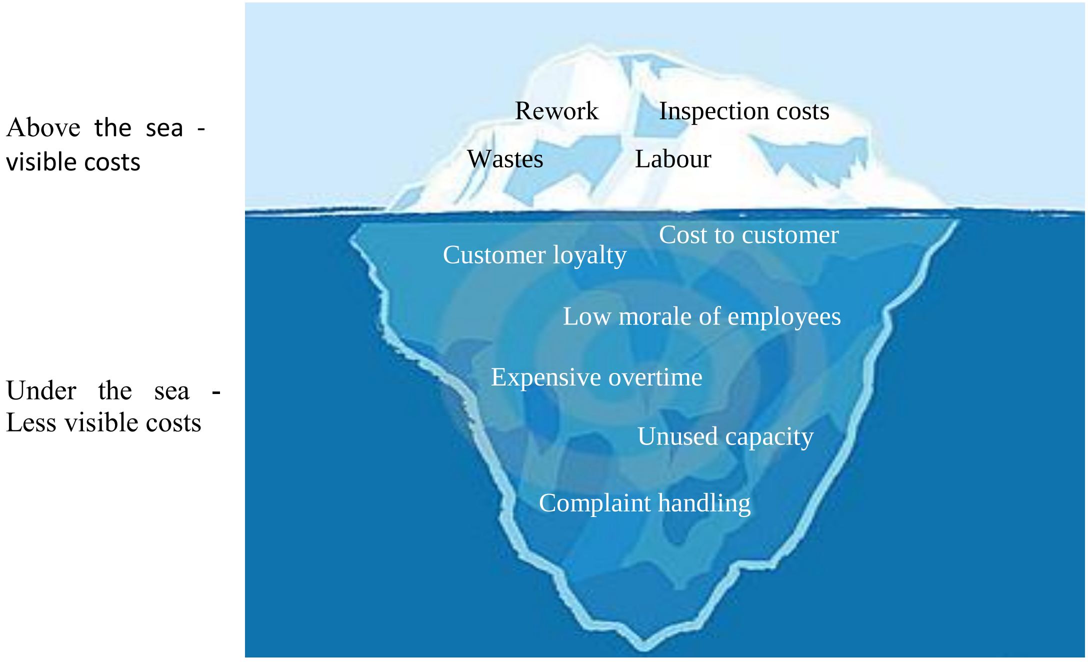

Figure 3.2 Example of Cost of Poor Quality

The objective of the "measure" phase is to collect data for measuring the current performance output (*Y*) according to the CTQs and obtain a clear view of the current processes. A well designed measurement plan includes specifications of information needed for data collection, such as, sample size, duration and data type. Table 3.3 shows an example of a measurement plan. Data is collected according to the measurement plan from a verified reliable source. Such data forms an accurate baseline which provides an understanding of the current performance, compared with the CTQs obtained from the define phase. A PCA is then performed to present the capability of the current process in meeting customer requirements. Obtaining qualified data (both historical and present) is proven to be difficult in service industries due to intangible products and less measurable quantitatively oriented processes. If there is no qualified data collection system available at the time of implementation or the available system cannot provide accurate information, a data collection plan needs to be specified in the measurement plan to collect useful data over a certain time period. Quantitative data based on experts' judgement may often be needed which can be analysed effectively in appropriate ways such as brainstorming. Also in the "measure" phase, the flows of a process are to be mapped out so that inputs and outputs of the process can be determined. Unlike manufactures, many of the OSFs of shipping companies do not have a standard process due to heavy human involvement. People can act differently in the same task. Therefore, it is valuable to map not only the "actual" process, but the "should-be" process and the "we-think it is" process. Comparing these process maps creates a structured and clear vision of the work flow and exposes hidden issues, such as unnecessary works, delays and bottlenecks of the process. This can provide opportunities for quick wins during a project implementation. A process can be mapped through conducting interviews and carrying out workshops with company managers, staff and clients involved in the process.

Table 3.3 Example of a measurement plan

Measure	**Factor**	**Type of data**	**Sample Size**	**Interval**	**Duration**	**Data source**
Time takes to resolve query	*Y*	Continuous	30	3 per day	10 random days in past 2 months	Query system

The "analyse" phase uses analytical tools to pinpoint and verify the vital factors (*Xs*) affecting output (*Y*) for the project team to focus the improvement efforts on. There are normally two paths in the analysis, the process path and the data path. The process path uses process tools to identify root causes of a problem. Those tools include but are not limited to: C&E matrix, FMEA and fault tree analysis. They are useful and effective in identifying root causes and relatively easy to be grasped by employees with little training. The data path includes data analysis tools that are required, such as, Pareto chart and hypothesis testing (e.g. T-test, ANOVA, Correlation and Regression, etc.). The use of statistics software, such as Minitab, can ease the process of data analysis. The two paths are complementary to each other. At this stage, the measurement plan can be updated to include a data collection plan for the *Xs* that need to be analysed in the data path.

The "improve" phase establishes and implements the best methods/solutions to improve performances based on the results obtained from the analysis phase. Methods for improvement are generated by studying the vital few "*Xs*". If the solution identification is not straightforward, DOE has been proven to be an effective tool to assist the design of possible solutions. Under the circumstance of multiple solutions, the best one can be identified through cost and benefit analysis and decision making tools, such as trial experiment and Pugh matrix where trial experiment assesses solutions by analysing data collected from simulations, experiments and trials, and Pugh matrix compares alternative solutions to a set of criteria in a form of matrix.

The "control" phase verifies the planned improvements and develops a control plan to monitor the performance to ensure that the improvement target has been achieved and can be sustained. A control plan is a document providing critical elements that must be controlled for satisfactory quality. It is developed by the project team in conjunction with those who will be responsible for the day to day running of the processes. A well designed control plan contains process inspection point and methods, clear statement of responsibility of monitoring and actions to take for out-of-control situations. Table 3.4 is an example of a control plan template. A control plan is a document to be reviewed and updated regularly.

Table 3.4 An example template of control plan

<table>
<tr><td colspan="7">Process Name:
Process Owner:
Phone:</td><td colspan="8">Date (origin):
Date (revised):
Authorized by:
Signature:</td></tr>
<tr><td colspan="15"></td></tr>
<tr><td></td><td>process</td><td colspan="2">Factors</td><td colspan="3">Specification</td><td colspan="2">capability</td><td colspan="4">Measurement</td><td colspan="2">Response</td></tr>
<tr><td>Responsible</td><td>process step</td><td>Input (X)</td><td>Output (Y)</td><td>LSL</td><td>Target</td><td>USL</td><td>Cp/ Cpk/%</td><td>Date</td><td>method</td><td>Sample Size</td><td>Frequency</td><td>Recorded</td><td>Action</td><td>Owner</td></tr>
</table>

3.3.4 Recognize Contribution and Success

Recognition and rewards have been identified as one of the CSFs in the literature. It can be at any stage when there is an achievement worth celebrating. Recognition and rewards help to maintain the enthusiasm of the project team during Six Sigma implementation, attract more attention from other employees and are important factors in motivating teams and achieving sustainable results.

The rewards can be in many forms and different for different levels of employees. Jack Welch, CEO of GE linked promotion and bonus to Six Sigma where 40% of the bonus for top management depended on the successful implementation of Six Sigma and GB were the minimum requirement for the promotion of any employee.

3.4 Implementation of Six Sigma in OSFs of Shipping Companies – a Real Case Study of a World Leading Shipping Line

The management team of a UK based OSF of a world leading liner shipping company is seeking ways to improve both their profitability and quality of the services in response to the increasing market competition during the economic crisis in 2008. The CEO has a strong belief in Six Sigma which was supported by the leadership team. As Six Sigma was a new concept to everyone in the organization, a

MBB was recruited externally to initialize the implementation.

3.4.1 Prepare

Project selection

There were several areas that the management team intended to address at the time. The criteria for initial project selection considered factors including urgency, duration, resources, potential benefits and applicability. To initiate a positive start for Six Sigma implementation, it was expected that a pilot project should achieve quick but significant results to establish the confidence among the employees and thus promote smooth future continuity. All potential projects were discussed during a brainstorming session among the management team. It appeared that with very limited information available and knowledge on project selection, a decision could only be made by taking an educated guess. Eventually, "reduce the amount of non-recovered wasted journey[1]" was selected as the pilot project due to its potential cost saving and the supportiveness from transport managers. The company at the time had suffered a significant loss on the payment towards wasted journeys which were not invoiced. The estimated duration for this project was around 4 to 5 months and the benefits could be substantial.

Team selection and training

In this project, the company CEO was appointed as the "Sponsor" who oversaw the improvement project and provided his support throughout the project implementation. The MBB was assigned to be the project leader responsible for providing Six Sigma training, communicating with the project sponsor, controlling project progress and being involved in the improvement process. Team members included supervisors and employees from the customer service department,

[1] "Non-recovered wasted journey" refers to inland haulages that were rejected but not paid by customers.

transportation department and finance department which have been identified as function areas involved in the process of incurring and dealing with wasted journeys. They are the persons who can and are willing to make contributions to the project.

Upon confirming the team, 3 weeks systematic Six Sigma training was provided. The training included knowledge of Six Sigma, tools and applications. The selected human resources achieved the certification of GB and BB after the training and became leaders in the future projects. Other team members were given training on the concept of Six Sigma and basic skills that were needed during the project implementation.

3.4.2 DMAIC

In this project, “defect” was defined as a “non-recovered wasted journey”. Initial baseline data was collected to reveal the current performance and COPQ was calculated. The CTQ for “the number of non-recovered wasted journeys” was provided by the top management team who acted as internal customers in this project. The project charter was prepared based on the COPQ, CTQ and project plan and signed off by the project sponsor.

There were two different systems available at the time of collecting data for the output (*Y*) “number of non-recovered wasted journeys”. In order to identify the most reliable source for data collection, the MSA was introduced (Figure 3.3). On the “Components of Variation” chart, the “Part-to-Part” bars were lower than the other bars, which indicated that many variations were from measurement systems instead of the true differences in the items being measured. The “Xbar chart by system” showed that the system variance was much bigger than the differences in the items being measured. The “Response by system” chart displayed the existence of bias between the two systems and the “System*Week Interaction” chart clearly presented the inconsistency of the two systems in measuring some parts. The results reflected a great difference existing between the measurements obtained from two systems. By a detailed study of the result, it was discovered that only one system recorded manual invoices for wasted journeys. The base line data was then revised accordingly based on the updated data collected. As the data was continuous data with subgroup size equals to 1, the I-MR (Individual and Moving Range) chart (Figure 3.4) was produced as the control chart. All individual data and moving ranges were within the UCL and LCL, which showed that the current process was stable and in control. PCA for the percentage of non-recovered wasted journeys was conducted as shown in Figure 3.5. The target has been set as "50% of non-recovered wasted journeys" at that stage of the project with maximum level (UB) of 100% and minimum level (LB) of 0%. The PCA indicated that majority of data collected contained 60% non-recovered wasted journeys and therefore, the current performance was not meeting the target. To identify all the inputs and outputs, the process of "booking for deliveries" was mapped out through workshops including personnel involved in the process.

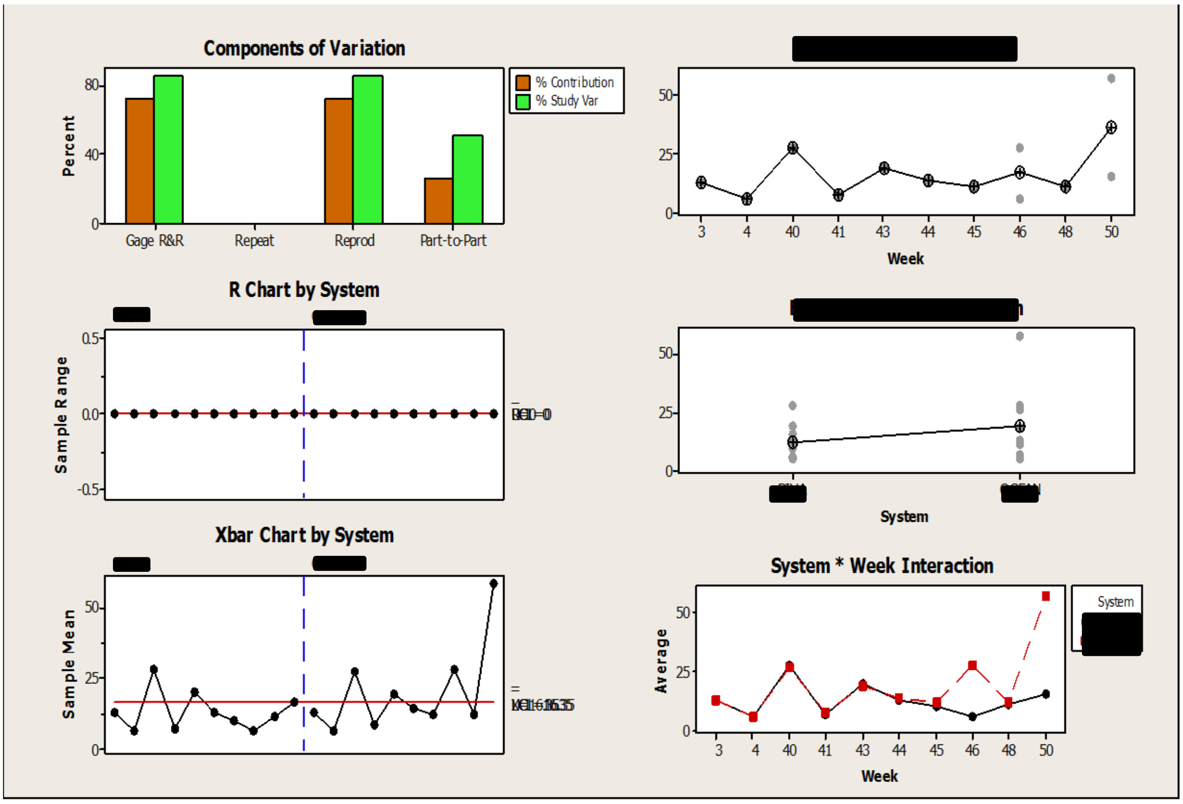

Figure 3.3 Measurement system assessment for two different systems

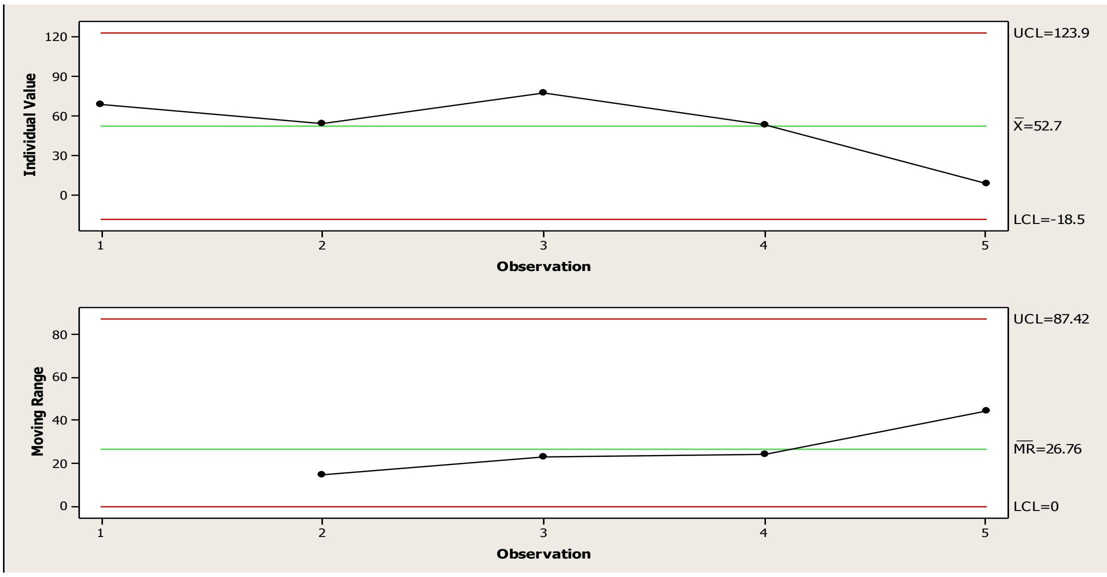

Figure 3.4 I-MR chart for percentage of non-recovered wasted journey

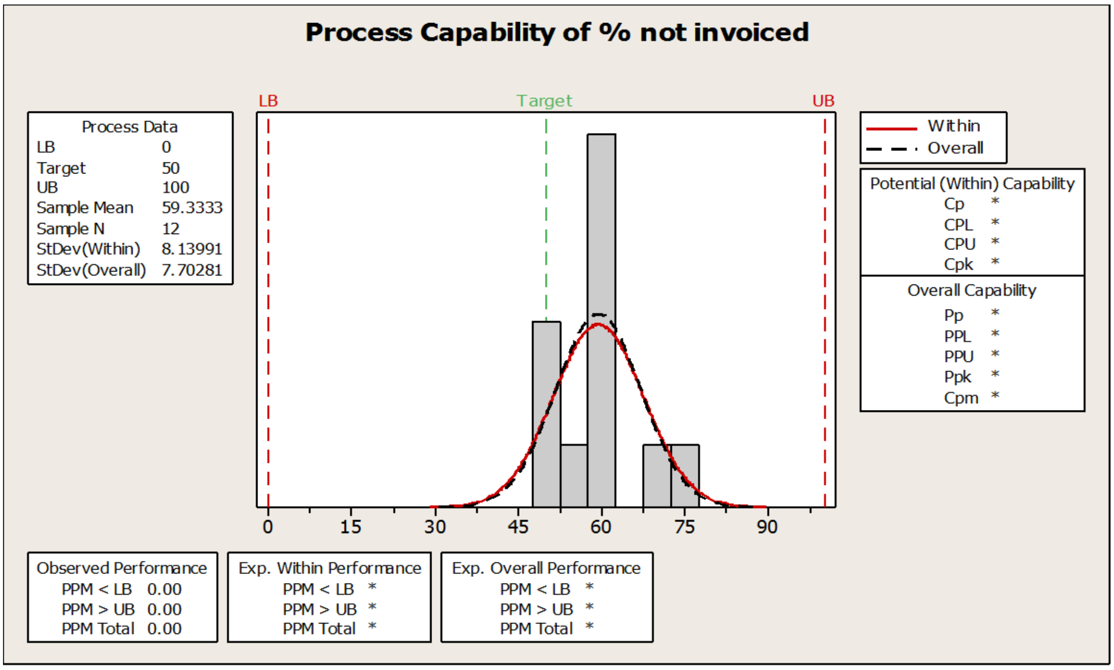

Figure 3.5 Process Capability Analysis of current process

In order to identify the vital few *Xs*, a C&E matrix was used to evaluate the correlation of inputs to outputs and therefore identify those inputs whose changes can greatly affect the outputs. It helps to narrow down the number of inputs that need to be further analysed by its importance to the outputs. Table 3.5 shows a few top ranked inputs from the C&E matrix in this project. The full matrix is presented in appendix 1. The priority scores for the "Rating of Importance to Customers" for process outputs were obtained through the subjective judgements of experts. The relation scores for process inputs were generated through workshops with people who were subject experts. Take the process step "Notification to transport team" and process input "Time of day" as an example. The team considered that it has strong relationships to all the key customer requirements (outputs). Therefore, 9 have been given against all outputs for this particular input. The total score was obtained through the use of Equation 2.1 as follows:

$$F_1 = \sum_{j=1}^{4} r_{ij} \times p_j = 9 \times 8 + 9 \times 10 + 9 \times 7 + 9 \times 7 = 288$$

In the same way, the total scores for all process inputs in the C&E matrix were calculated. Those inputs were then prioritized by using FMEA through analysing risks associated with failures. Appendix 2 contains the complete list of the FMEA analysis. The top rated five key process inputs are presented in Table 3.6, which were considered to be the possible key explanatory variables (Xs). The C&E matrix and FMEA were conducted through group discussions by involving resources from different sections of the process. It was found that using crisp scores was difficult as the team often could not provide an exact number for the evaluation with confidence.

Table 3.5 C&E matrix for non-recovered wasted journeys – top ranked inputs

Rating of Importance to Customer		8	10	7	7	
Process Step	**Process Inputs**	No. of Recoverable wasted Journeys (WJ)	No. of none recoverable WJ	Customer Satisfaction	Cost of WJ	Total
Notification to transport team	Time of day	9	9	9	9	288
Haulage collected/not collected	Container suitability	9	9	9	9	288
Haulage arranged	Accuracy of info	9	9	9	9	288
Receive instruction from customer	Type of instructions	9	9	9	9	288
Input data into system	Operator experience	9	9	9	3	246
Input data into system	Type of cargo	9	9	9	3	246

Table 3.6 FMEA for non-recovered wasted journey

Key Process Input	Failure Modes - What can go wrong?	Effects	SEV	Causes	OCC	Current Controls	DET	RPN
Container suitability	Customer did not request specific container details	Wasted journey (customer or company liability)	10	Customer makes assumptions that container will be suitable	8	No current control	9	720
Container suitability	Information not put on booking	Wasted Journey not recoverable	10	Human error	7	No current control	9	630
accuracy of info	Wrong date or time relayed	Wasted Journey company liable	10	Human error	7	No current control	9	630
accuracy of info	Wrong size container	Wasted journey company liable	10	Operator error, info not put on	6	No current control	9	540
accuracy of info	Load Reference not given	Wasted journey or detention	8	Customer does not give reference	7	No current control	9	504

In order to verify those *Xs*, a data collection plan (Table 3.7) was created. Statistical tools have been introduced for the data analysis, such as, Pareto chart (Figure 3.6). The analysis revealed that the main cause for "non-recovered wasted journey" was "company error" and "cancelled booking not invoiced due to not being logged into system".

Table 3.7 Data collection plan

Key Outputs	Variable	Method	Duration	Data source
Container Suitability	Customer Error Company Error	Count the number of wasted journeys due to incorrect containers (customer error vs. company error)	Oct - Feb	Invoice system and transport logging system
Accuracy of information	Customer Error Company Error	Count the number of wasted journeys that company is liable vs customer is liable and list detailed reasons	Nov - Feb	Invoice system and transport logging system

Through the analysis, it was discovered that there was no clear procedure for transportation booking cancellation at the time. Due to the existence of multiple systems which were in different formats, maintained by different departments and unable to be accessed by more than one user at a time, wasted journeys were often not logged into the centralized invoicing system which led to nearly undiscoverable non-invoiced wasted journeys. The need for an improved procedure and a better system for transportation cancellation became obvious. By collecting ideas and requirements from the departments involved in the process, a structured procedure and a new logging system were proposed which were promptly approved by the management team. The newly developed system and standard procedure were tested and verified by the selected personnel from all the departments involved before rolling out companywide.

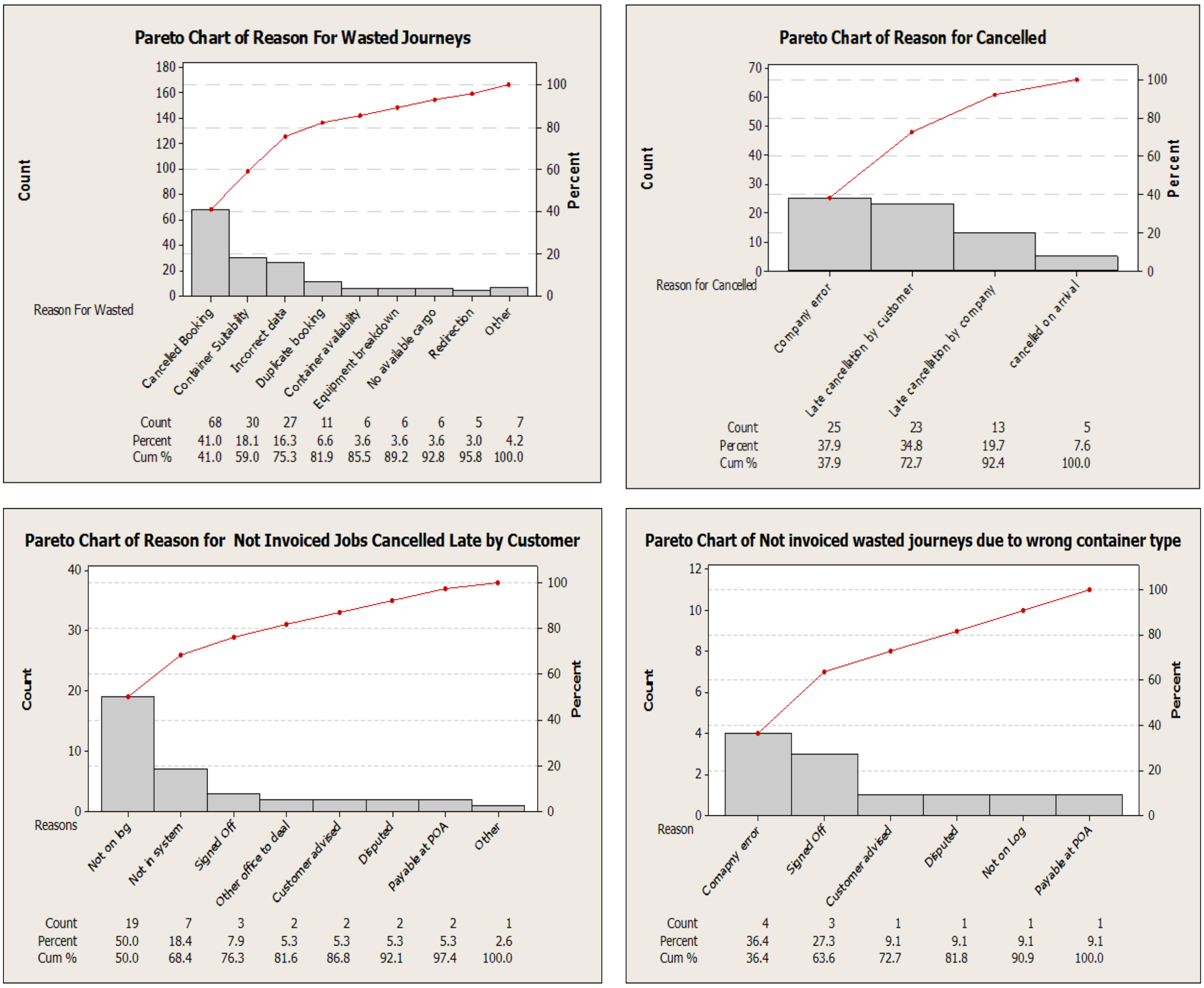

Figure 3.6 Pareto charts for reasons for non-invoiced wasted journeys

A detailed control plan (Table 3.8) was developed to provide a clear view of the objects, methods, responsibilities and reaction plan of monitoring. For example, the process step "Invoicing customer" with output "% wasted billed to customer exports" was required to have a process specification of over 50%. The measurement technique was to compare the number of billed wasted journeys vs. the number of total wasted journeys. The MSA needed to be 100% so that the measurement systems were consistent and can therefore be used with confidence. Monthly report was required for all wasted journeys. Control chart (I-MR chart) was to be produced to ensure that the process was in control. The manager was to be informed (Reaction plan) should there be any problem. Relevant Key Performance Indicators (KPIs) were also created to monitor the performances of different function areas.

Table 3.8 Control plan

Process:	Transport Recovery Costs	Core Team:	Date (Orig):			
Process Owner:						
Phone:			Date (Rev):			

Process Step	Output	Input	Process Specifications	Capability /Date	Measurement Technique	MSA Result	Sample Size	Sample Frequency	Control Method	Responsible Person	Reaction Plan
Invoicing Customer	% Wasted Billed to Customer Exports		> 50%		Total Wasted v % Billed	100% agreement	all	Monthly	I-MR Chart	[redacted]	Notify Manager of Area
Invoicing Customer	% Wasted Billed to Customer Imports		> 50%		Total Wasted v % Billed	100% agreement	all	Monthly	I-MR Chart	[redacted]	Notify Manager of Area
Database Update		Information Timeleness (Exports and Imports)	0 unactioned		Number of unactioned		all	Weekly	Excel report	[redacted]	Notify Manager of Area
Database Update		Amount Invoiced (Exports and Imports)	Break even		Haulier Costs v Costs Invoiced out		all(vehicle detentions, wasted Journeys, diversions)	Weekly	Excel report	[redacted]	Notify Manager of Area

The project was completed within the planned time frame and met its target. PCA (Figure 3.7) after ten months of the implementation of the improvement methods showed that a sustainable result has been achieved and the new process is capable of meeting the target.

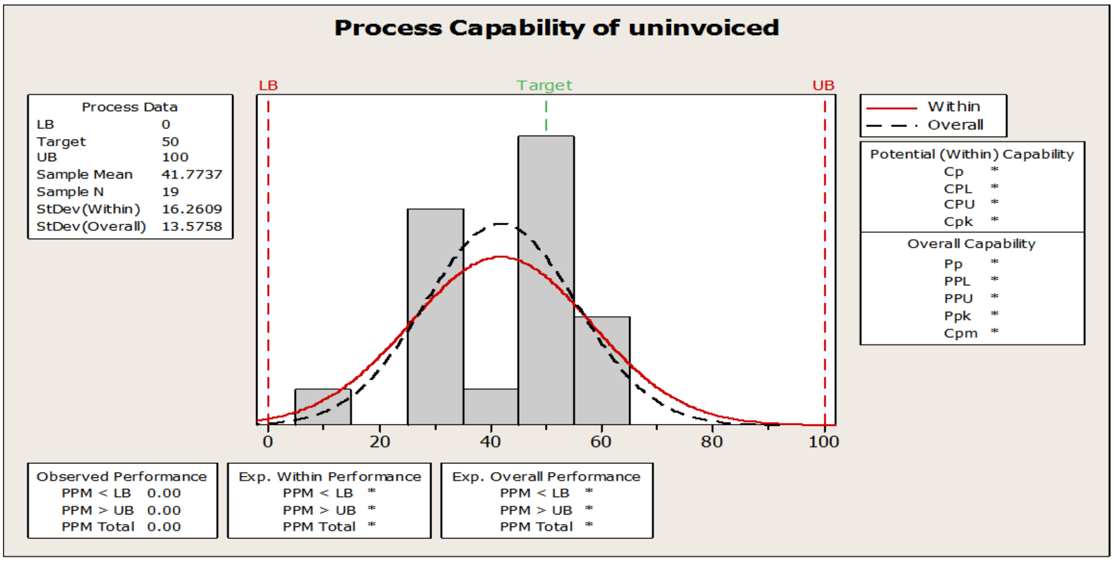

Figure 3.7 Process Capability Analysis for the new process

3.4.3 Recognize Contribution and Success

During the implementation of this Six Sigma project, progress and results were actively communicated within the organization by using company newsletters. On completion, its achievement was announced in companywide meetings. These have generated interests within the organization, created confidence within management team and have made a foundation for the implementation of Six Sigma throughout the organization.

3.5 Issues Encountered and Lessons Learned

3.5.1 Effective Tools in Project Selection

Selecting the right project is essential to the success of Six Sigma implementation. At the time of selecting a project, information required for making decisions is not always available and can only be gradually revealed with the progress of projects. For example, it is difficult to accurately predict the duration of a project or the exact costs at the planning stage of a project. It is therefore, strongly advised to utilize methods that can effectively handle the complexity and uncertainty in Six Sigma project selection.

3.5.2 Qualitative Data Analysis

Due to the fact that many process inputs in OSFs are heavily human involved, and are difficult to be defined or measured by using numerical values (e.g. operator experience), a large amount of data was collected based on experts' subjective judgements. The current most widely used methods (such as FMEA) only use crisp numbers which are sometimes difficult for experts to score confidently. This raised the need for a more reliable qualitative analysis method.

3.5.3 KPIs Management

In most organizations, KPIs are the main tools for assessing productivity and driving process improvement initiatives. Effectively using KPIs can also create the opportunities for identifying potential Six Sigma projects. The right KPIs can help measure what needs to be measured instead of what can be measured. However, in the traditional approaches, KPIs are often defined using quantitative data (Ahmad and Dhafr, 2002; Bose, 2006; Cheng *et al.*, 2011), which often force an organization to ignore the KPIs of a qualitative nature. This has constrained the applicability of KPIs in OSFs where the performance of many qualitative KPIs needs to be monitored and measured. Furthermore, KPIs are expected to be used for both assessing performance and benchmarking performance between different sectors in a company and/or among competitors. Due to the fact that KPIs for different inputs/outputs are mostly on different scales, it is very challenging to carry out a direct meaningful comparison without an effective methodology capable of transferring them into comparable units. An advanced KPIs management method that can handle both qualitative and quantitative data and effectively synthesise different KPIs is therefore desired.

3.5.4 Training

Six Sigma applications involve extensive and continuous training. The number of employees having higher education in the OSFs of the shipping company tends to be limited. It appears, very often, difficult for employees to understand the statistical tools of Six Sigma. This has led to the loss of resources during the implementation and the loss of interest in the programme within the organization. Therefore, selecting the right resource to participate in Six Sigma projects can be vital in OSFs. Hands-on learning provides the opportunity for people to put theory into practice and achieve better understanding of the concepts and tools. In practice, linking Six Sigma with assessment of performance can also help to increase the motivation within the workforce.

3.5.5 Resources Availability

The application of Six Sigma requires team members to be away from their normal daily work to attend team meetings and workshops, collect data and participate in other team works. Although agreement was obtained from managers for the allocation of resources, often employees are unavailable or behind planned schedule, due to heavy daily operational workloads. Six Sigma's application is a top-down method. Top management's involvement stands out to be substantial to avoid such situations. It could make a significant difference if Six Sigma is made to be a part of daily business and everybody, instead of the team members in the process, is responsible for its progress.

3.5.6 Effective Communication

Six Sigma involves changing existing ways of working and human behaviour. This has caused concerns across departments and across employees. "Have we done something wrong?" and "it has always been done in this way" are frequently mentioned. This led to less enthusiasm and sometimes resistance from employees and even managers during the implementation process. The issue can be lessened or eliminated by a more effective communication from top management throughout the project. A carefully structured and well executed communication plan that includes clearly conveying the vision, strategies and benefits for all the concerned at the beginning and throughout the implementation would provide better motivation and make the implementation smoother and increase the chances of success.

3.6 Conclusion

Six Sigma is a powerful methodology that links to business strategy to enable an effective and sustainable improvement in business processes. Its implementation is far more than using its tool sets. It becomes a part of business strategy and creates a new business culture, a culture of continuous leaning and improving and a culture of being responsible.

OSFs of a shipping company act an increasingly important role in the overall business service quality. The case study has proven that Six Sigma can be applied in the OSFs of a shipping company and the DMAIC method works well on their operational processes. However, some processes are difficult to be quantified, making data collection, monitoring and controlling tasks very challenging. Successful applications of Six Sigma can help OSFs of shipping companies to reduce process variation, cut unnecessary costs and increase profitability. It provides an opportunity to organizations to establish standard processes, increase the visibility of company operation and the ability of performance monitoring. Thus, organizations can better meet customer requirements and increase customer satisfaction. The implementation of Six Sigma requires abundant resources and time. It requires the participation of the best human resources in selected function areas which will lead them away from their regular daily tasks with the possibility of becoming a full time project leader in the future. It is important for an organization to fully understand the requirements for Six Sigma implementation, obtain commitments from the top management and become people-ready before introducing Six Sigma.

Chapter 4.   Project Selection Using Fuzzy TOPSIS

4.1   Introduction

The selection of correct projects is one of the most critical elements for successful applications of Six Sigma in any organization. The task is essentially a process of MCDM under uncertainty requiring analysts to derive rational decisions from ambiguous and incomplete data contained in different quantitative and qualitative forms.

When different Six Sigma projects are competing with each other for their implementation, management is interested in identifying those projects that can achieve the maximum benefit to the organization through either the increase of customer satisfaction or reduction of operational costs. In order to select the most beneficial project, an appropriate methodology needs to be developed and applied.

Six Sigma project selection is in nature a MCDM process. It features a large number of uncertainties, including unavailable and incomplete data and selection inference uncertainty. It has attracted much attention from the researchers on the development and application of appropriate project selection methodologies to tackle the uncertainties. The methods proposed include data envelopment analysis (DEA) (Kumar *et al*., 2007), real option (Tkac and Lyocsa, 2010), Delphil fuzzy multiple criteria decision-making (Yang and Hsieh, 2009), adaptive neural fuzzy inference systems (ANFIS) (Saghaei and Didehkhani, 2011), and fuzzy Analytical Hierarchy Process (FAHP) (Bilgen and Sen, 2012). A careful analysis of the merits and demerits of the techniques in the project selection literature indicates that they are lacking the capability of dealing with all the uncertainties identified in the Six Sigma project selection process.

TOPSIS is a useful method in the field of MCDM. The basic principle of the method is that the chosen alternative should have the shortest distance from a positive ideal solution (PIS) and farthest distance from a negative ideal solution (NIS). TOPSIS provides an easily understandable and programmable calculation procedure. It enables criteria and alternatives to be considered simultaneously. To handle uncertainties in real life MCDM, fuzzy theory has been introduced to TOPSIS. Its ability of handling fuzzy data and making selections has been widely recognized and used in many areas, such as plant location selection (Chu, 2002), energy network selection (Chamodrakas and Martakos, 2011), supplier selection (Zouggari and Benyoucef, 2012), transport system selection (Awasthi *et al*., 2011), energy technology selection (Kaya and Kahraman, 2011) and waste disposal method and site selection (Ekmekcioglu *et al*., 2010). However, the conventional fuzzy TOPSIS only uses single linguistic terms in the evaluation process which could lead to the loss of raw data and is not capable of handling any incompleteness and ignorance which occurred during the process.

This chapter aims at developing a novel conceptual fuzzy TOPSIS approach to help shipping companies identify the priority of Six Sigma projects and optimally use resources to improve their service quality. The new fuzzy TOPSIS method is capable of providing shipping companies with an accurate, effective and transparent decision tool for project selection under uncertainty. Compared with traditional fuzzy TOPSIS methods, it can effectively collect, transform and aggregate input data in various forms and tackle their fuzziness and incompleteness through a new fuzzification mechanism in a TOPSIS inference process. Consequently, the outcomes can be presented as crisp numbers and used to directly prioritize alternative projects. The new method is tested through a case study of Six Sigma project selection in a shipping quality control programme. It is believed that the proposed generic method can facilitate the application of TOPSIS in a wider MCDM context in which high uncertainty in data exists.

4.2 Literature on Six Sigma Project Selection Methodology

Projects are the core activity driving changes in Six Sigma organizations. Selecting the right project is one of the most important CSFs for the effective deployment of a Six Sigma programme. In a recent survey, 75% of the respondents admitted that they did not have a project section methodology that assured on-time completion of the project (Kumar *et al*., 2009). According to the study carried out by Banuelas *et al.* (2006), in the UK, among all the companies that responded, the most used project selection tools are cost-benefit analysis, Pareto chart and cause-effect matrix and only 8% used MCDM such as AHP. It is not difficult to see that the majority of companies are still not engaging with scientific methods to select projects and only a very few powerful decision tools are available in practice.

Six Sigma project selection is a MCDM process where lots of the information relating to the problem is complex, uncertain and interactive. Information required for making decisions or evaluations is not always available and can only be gradually revealed with the progress of projects (Choo, 2011). For example, it is difficult to accurately predict the duration of a project or the exact costs at the planning stage of projects. In order to handle the complexity and uncertainty in the Six Sigma project selection process, researchers have proposed different techniques recently.

Kumar *et al*. (2007) used DEA to evaluate important inputs and outputs of potential Six Sigma projects and therefore, identify projects that result in the maximum benefit to the organization. However, this method overlooked the uncertainties in decision making processes in the project selection process. Su and Chou (2008) adopted AHP and failure mode effects analysis (FMEA) as a combined method to make selections of Six Sigma projects where AHP was used to evaluate potential project benefits and then FMEA was used to assess risks for each project. The method was used in a semiconductor foundry as a case study. It was criticized that this approach isolates project benefit evaluation from project risk evaluation by separating them into two distinct steps and ignores the fact that an interaction may exist between them (Tkac and Lyocsa, 2010). Tkac and Lyocsa (2010) proposed a new model based on real option theory for evaluating Six Sigma projects which involves the stochastic nature of project outcomes, cost and uncertainty regarding future payoffs and managerial options. However, the usefulness of this model in practice may be perceived as limited due to its computational complexity and difficulty to use in real life situations (Padhy and Sahu, 2011). Kumar *et al*. (2009) used a hybrid approach of combining AHP with project desirability matrix (PDM) for Six Sigma project selection. It provided a relatively simple method to use in practice by rating potential projects against each criterion with a single linguistic term. However, in reality, it is often very difficult for decision makers to provide a confident evaluation based on a single linguistic description. Buyukozkan and Ozturkcan (2010) developed an integrated decision framework based on DEMATEL and AHP for selecting the most appropriate Six Sigma project alternative. DEMATEL is used to handle the interdependence in criteria and AHP is to calculate the weights of elements. Although showing some attractions, the above methods still reveal a problem in their practical implementation, which is to effectively evaluate alternatives against criteria without objective data.

Due to the lack of statistical data, project evaluation needs to be conducted using subjective judgements, which are often deemed to be imprecise. One realistic way to cope with imprecision is to use linguistic assessments. However, such linguistic descriptions define selection alternatives to a discrete extent so that they can at times be inadequate. Fuzzy set theory is well suited to modelling such subjective linguistic variables and dealing with discrete problems. Yang and Hsieh (2009) suggested using national quality award criteria as the Six Sigma project selection criteria. The weights of strategic criteria were determined by using a Delphi fuzzy MCDM method and the decision of project selection was analysed through defuzzification. Although the method considered the uncertainties in project selection, it only accepts linguistic terms as the inputs in the selection modelling thus arguably narrowing the range of raw data collection. Saghaei and Didehkhani (2011) used ANFIS to evaluate the utility of each project and fuzzy binary weighted additive goal programming model for selecting the optimal portfolio of projects to implement. Bilgen and Sen (2012) applied fuzzy AHP to handle the uncertainties in Six Sigma project selections. AHP is a powerful comparison decision making tool. However, it has its limitation when being used in project selection. It can only accommodate up to 9 criteria in any comparison matrix. It uses a hierarchy structure which means a matrix needs to be built for each sub-criterion and experts' opinions need to be gathered for every matrix. This involves a large amount of subjective data collection and is difficult to achieve a desirable consistency level.

To overcome the shortcomings in the existing methods, this study aims to develop a new fuzzy TOPSIS method that can be used to collect raw data, tackle uncertainties and deliver crisp results for easy ranking in a project selection process. The proposed method uses a new fuzzy transformation mechanism and a belief structure to deal with uncertainties and incompleteness occurring in an evaluation process. The selection process is presented in a flowchart framework and corresponding algorithms are computerised in an Excel file. It increases the accuracy and transparency of the project selection process while maintaining its easiness for use.

4.3 Fuzzy TOPSIS Methods

TOPSIS is one of the classical decision making methods for solving MCDM problems developed by Hwang and Yoon (1981). It is based on the principle that the chosen alternative should have the longest distance from the NIS, and the shortest distance from the PIS, i.e., the solution that maximizes the benefit criteria and minimizes the cost criteria (Zouggari and Benyoucef, 2012).

The traditional TOPSIS only evaluates alternatives and weights of criteria by crisp numbers which could be often difficult to reflect true subjective evaluations in practice. Fuzzy theory has therefore been introduced into TOPSIS to deal with the uncertainties in the real world. It has been well documented in the literature and commonly used in the process of group decision-making under a fuzzy environment. Triantaphyllou and Lin (1996) developed a fuzzy TOPSIS method in which each alternative was evaluated by using triangular fuzzy numbers. Chen (2000) extended the TOPSIS method to the fuzzy group decision making situation and defined the crisp Euclidean distance between two fuzzy numbers. Although enabling the use of TOPSIS in ambiguous estimations, Chen's method limits the type of data that can be accepted and therefore would lead to possible input information loss in the process. Chu (2002) proposed an interval arithmetic based fuzzy group TOPSIS model in which the membership function was aggregated by interval arithmetic and α-cuts of fuzzy numbers and alternatives were ranked by mean of the integral values. Byun and Lee (2005) proposed a modified fuzzy TOPSIS for the selection of a rapid prototyping process. However, it may lose the benefits of collecting fuzzy data due to the fact that the defuzzification is done at the early stage of the method. A similar issue exists in the study carried out by Tsaur *et al.* (2002) where defuzzification was done at the first stage and traditional TOPSIS steps were followed to evaluate the quality of airline service. Wang and Elhag (2006) introduced a fuzzy TOPSIS method on Alpha level sets and presented a nonlinear programming solution procedure.

The majority of fuzzy TOPSIS methods in the literature mainly consider situations where alternatives are valued by single linguistic variables against certain criteria. However, in a Six Sigma project selection process, it is found that very often decision makers could not accurately express their evaluation by a signal linguistic term. The evaluations described as a grade between two discrete linguistic variables indicate the ignorance and incompleteness in their judgment. Yang *et al.* (2011) developed an approximate TOPSIS method in order to accommodate interval input instead of only fuzzy numbers in decision matrices. This method provides users with options of using both quantitative and qualitative formats with belief degrees, and thus is capable of dealing with uncertainties and incompleteness by building belief degrees into the evaluation process. It also addresses the issue of interval values by splitting the single decision making matrix in the conventional fuzzy TOPSIS into the possible best rating (PBR) and possible worst rating (PWR) matrices. Although addressing the issue of incompleteness and interval data analysis, it increases the volume of calculation and weakens the visibility and easiness of the modelling. More importantly, the results obtained are presented in range values, making the final ranking debatable. The new fuzzy TOPSIS method proposed in this research uses a fuzzy transform mechanism to accommodate various forms of input data. It is capable of handling fuzziness, incompleteness and ignorance in data while delivering a crisp result for easy ranking and programming.

4.4 The New Approximate TOPSIS with Belief Structures

In practice, it is difficult for experts to give confident evaluations by only using single linguistic terms. They can be presented in various formats. Therefore, a belief structure is introduced to model the gaps between single linguistic terms (e.g. 50% Very good, 50% Good). Furthermore, there are situations where experts could not provide evaluations with 100% certainty (e.g. 90% Very good with 10% unknown). This kind of uncertainty is called “incompleteness” or “ignorance”. In order to facilitate the raw data collection as precisely as possible, the new fuzzy TOPSIS uses a new fuzzy transformation mechanism based on Trapezoidal Fuzzy Number (TPFN), although triangular fuzzy numbers are mostly used in the previous fuzzy TOPSIS studies. Introducing TPFN based transformation enables the fuzzy TOPSIS method to not only accommodate various types of input data, but also eliminate the unnecessary increased complexity in calculation in Yang *et al*. (2011)’s approximate TOPSIS as well as improve the accuracy of ranking results at the same time. The new method can accommodate more raw data under uncertainties while maintaining the easiness of TOPSIS with increased accuracy.

The framework of the new approximate TOPSIS method is outlined in Figure 4.1.

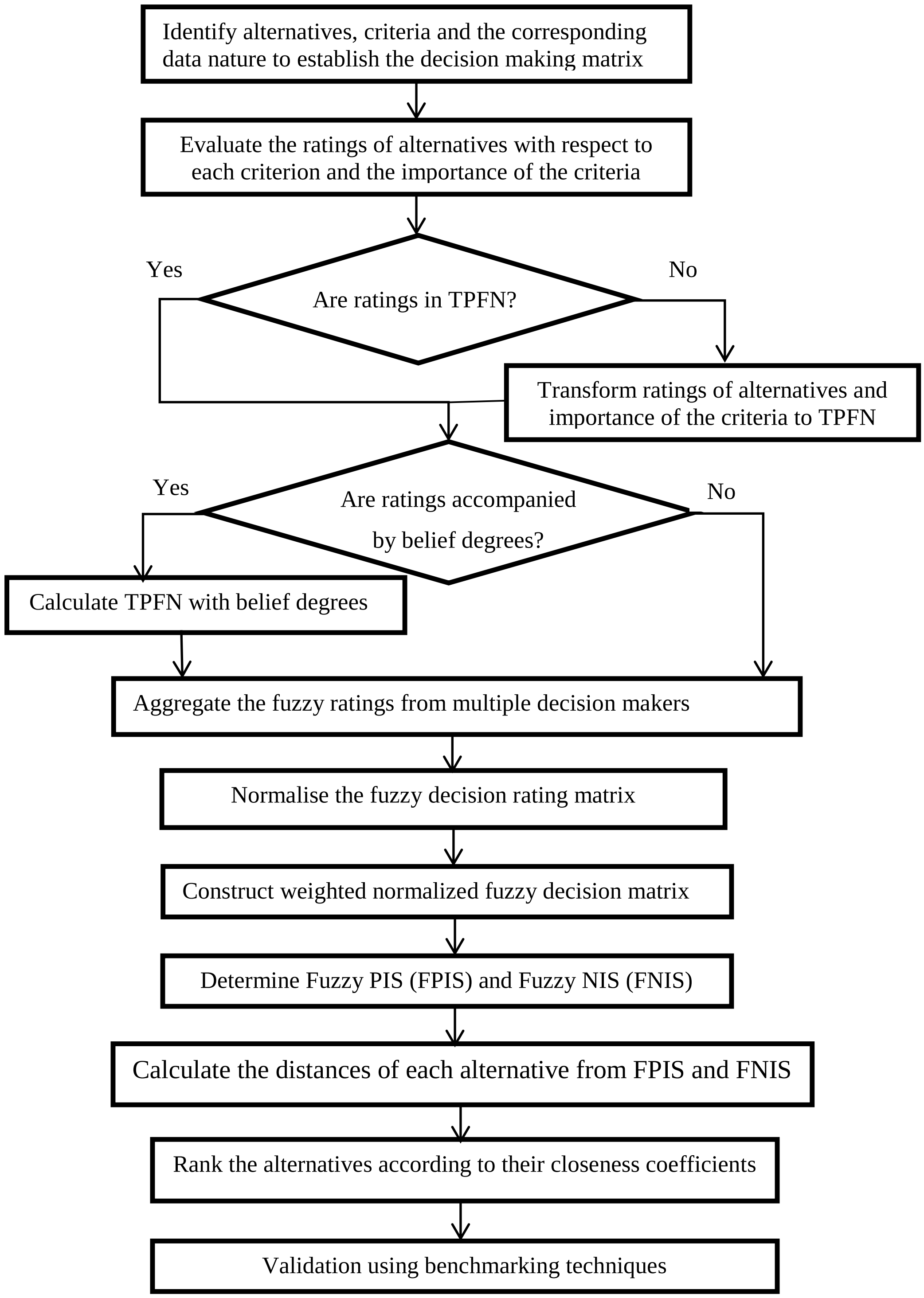

Figure 4.1 Framework of revised fuzzy TOPSIS

4.4.1 Identify Alternatives and Criteria to Establish the Decision Making Matrix Format with the Presentation of All Alternatives and Criteria

In order to capture raw data, the matrix D can be established to include various data types and it can be expressed as below:

$$D = \begin{array}{c} \\ A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_j & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11} & \cdots & x_{12} & \cdots & x_{1n} \\ \vdots & & \vdots & & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & & \vdots & & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \end{array} \tag{4.1}$$

$W = [\widetilde{w}_1 \ldots \widetilde{w}_j \ldots \widetilde{w}_n]$,

where each A_i represent alternative i considered; C_j is the criterion used to measure the performance of each alternative; and x_{ij} is the rating of the i^{th} alternative with respect to the j^{th} criterion and can be described by a TPFN, $x_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$, a triangular fuzzy number $x_{ij} = (a_{ij}, b_{ij}, d_{ij})$, a crisp number $x_{ij} = a_{ij}$, a range number $x_{ij} = (a_{ij}, d_{ij})$ or a pre-defined linguistic variable with belief degree. The TPFNs of the linguistic variables are pre-defined and presented in Table 4.1. $\widetilde{w}_j$ is the subjective importance estimation of the j^{th} criterion and can be assessed using linguistic variables, which are described by TPFNs in Table 4.2.

4.4.2 Evaluate the Ratings of Alternatives with Respect to Each Criterion and the Importance of the Criteria, $\widetilde{w}_j$

It is often difficult for experts to give a confident assessment of the alternatives by only using single linguistic terms. They might not be able to establish a strong correlation between the evaluations and the pre-defined linguistic variables. There are assessors who prefer to give a range of numerical values or a precise numerical value especially when objective information is known to support their evaluations. Therefore, in order to collect raw data as comprehensively as possible, four options can be used in assessing the alternatives in this method. They are:

- Objective data - a crisp numerical value. For instance, the human resource needed in a project could be “3 persons”.
- Range data - a range of numerical values. For instance, the duration of a project could be between “3 to 4 months”.
- Fuzzy data - a range of numerical values with likelihood. For instance, the cost of a project could be between“£35k to £40k” with the highest likelihood of “£37k” (a triangular fuzzy number) or with the highest likelihood of “£37k to £38k” (a TPFN).
- Linguistic data - multiple linguistic variables with belief degrees. For instance, management commitment to a project could be “Very good” with 80% belief degree and “Good” with 10% belief degree. The definitions of linguistic variables are given in Table 4.1, which is developed on the basis of fuzzy membership functions in Chen’s (Chen, 2000)’s work.

Table 4.1 Linguistic variables for the ratings alternatives

Very poor (VP)	(0, 0, 0, 1)
Poor (P)	(0, 1, 1, 3)
Medium poor (MP)	(1, 3, 3, 5)
Fair (F)	(3, 5, 5, 7)
Medium good (MG)	(5, 7, 7, 9)
Good (G)	(7, 9, 9, 10)
Very good (VG)	(9, 10, 10, 10)

The importance of the criteria $\tilde{w}_j$ can be assessed by using pre-defined linguistic variables in Table 4.2. It is created by extending the triangular fuzzy membership functions in Chen (2000)’s study into TPFNs in this study.

Table 4.2 Linguistic variables for the importance weight of each criterion

Very low (VL)	(0, 0, 0, 0.1)
Low (L)	(0, 0.1, 0.1 0.3)
Medium low (ML)	(0.1, 0.3, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.5, 0.7)
Medium high (MH)	(0.5, 0.7, 0.7, 0.9)
High (H)	(0.7, 0.9, 0.9, 1)
Very high (VH)	(0.9, 1, 1, 1)

4.4.3 Transform Ratings of Alternatives to TPFN

Traditional fuzzy TOPSIS is not capable of handling different types of data simultaneously. In this new fuzzy TOPSIS method, a data transformation mechanism is developed based on TPFNs to unify the various data formats into a TPFN form as follows.

- Objective data, $x_{ij} = a_{ij}$ can be transformed to $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$, where $a_{ij} = b_{ij} = c_{ij} = d_{ij}$.
- Range data, $x_{ij} = (a_{ij}, b_{ij})$ can be transformed to $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$, where $a_{ij} = b_{ij},\ c_{ij} = d_{ij}$.
- Fuzzy data, a triangular fuzzy number $x_{ij} = \left(a_{ij}, b_{ij}, d_{ij}\right)$ can be transformed to $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$, where $b_{ij} = c_{ij}$. There is no need to transform any TPFN data.
- Linguistic data, if the input data is presented by a single linguistic term with 100% belief degree, then it can be presented by the TPFN of the term in Table 4.1. If the input data is described by multiple linguistic terms with partial belief degrees to each, then its TPFN can be calculated as follows.

If the belief degree is complete ($\sum_{h=1}^{7} \beta_{ij}^{h} = 1$), then the TPFN of the input evaluation is:

$$\tilde{x}_{ij} = \sum_{h=1}^{7} \beta_{ij}^{h} \tilde{f}_h \tag{4.2}$$

where β_{ij}^{h} stands for the degree of belief for the h^{th} linguistic variable in Table 4.1 used to describe the fuzzy rating of the i^{th} alternative with respect to the j^{th} criterion; and $\tilde{f}_h$ represents the TPFN of the h^{th} linguistic variable.

If the belief degree is incomplete ($\sum_{h=1}^{7} \beta_{ij}^{h} < 1$), the remaining degrees of belief ($1 - \sum_{h=1}^{7} \beta_{ij}^{h}$) need to be re-assigned to both grades of the first/lowest and the last/highest ratings. Let $\tilde{x}_{ij}^{L}$ *and* $\tilde{x}_{ij}^{H}$ stand for the evaluations when the remaining degree of belief is re-assigned to the first/lowest rating and last/highest rating, respectively. When assigning the remainder to the lowest grade, the TPFN for the evaluation $\tilde{x}_{ij}^{L}$ can be calculated as:

$$\tilde{x}_{ij}^{L} = \left(a_{ij}^{L}, b_{ij}^{L}, c_{ij}^{L}, d_{ij}^{L}\right) = \sum_{h=1}^{7} \beta_{ij}^{h} \tilde{f}_h + \left(1 - \sum_{h=1}^{7} \beta_{ij}^{h}\right)\tilde{f}_1 \tag{4.3}$$

When assigning the remaining to the highest rating, the TPFN for the evaluation $\tilde{x}_{ij}^{H}$ can be calculated as:

$$\tilde{x}_{ij}^{H} = \left(a_{ij}^{H}, b_{ij}^{H}, c_{ij}^{H}, d_{ij}^{H}\right) = \sum_{h=1}^{7} \beta_{ij}^{h} \tilde{f}_h + \left(1 - \sum_{h=1}^{7} \beta_{ij}^{h}\right)\tilde{f}_7 \tag{4.4}$$

The two TPFNs can be combined into one set of TPFN to cover the membership ranges of the highest and lowest ratings using:

$$\tilde{x}_{ij} = \left(a_{ij}, b_{ij}, c_{ij}, d_{ij}\right) = \left[\min\left(a_{ij}^{L}, a_{ij}^{H}\right), \min\left(b_{ij}^{L}, b_{ij}^{H}\right), \max\left(c_{ij}^{L}, c_{ij}^{H}\right), \max\left(d_{ij}^{L}, d_{ij}^{H}\right)\right] \tag{4.5}$$

4.4.4 Aggregate the Fuzzy Ratings and Weights from Multiple Decision Makers

Assume that K experts are in a decision group. The importance of the criteria and the ratings of the alternatives with respect to each criterion can be calculated as[2]:

$$\tilde{x}_{ij} = \frac{1}{K}\left[x_{ij}^{1}(+)\ldots(+)x_{ij}^{K}\right] \tag{4.6}$$

$$\widetilde{w}_j = \frac{1}{K}\left[\widetilde{w}_j{}^{1}(+)\ldots(+)\widetilde{w}_j{}^{K}\right] \tag{4.7}$$

where $\tilde{x}_{ij}$ stands for the final evaluation for i^{th} alternative with respect to the j^{th} criterion and $\widetilde{w}_j$ is denoted as the final evaluation of the importance of criteria. x_{ij}^{K} is the evaluation given by the Kth expert which has been transformed to TPFN in the previous step. $\widetilde{w}_j{}^{K}$ represents the evaluation of the importance of criteria provided by the Kth expert in section 4.4.2.

4.4.5 Normalise the Fuzzy Decision Rating Matrix

The linear scale transformation is used to transform the various criteria scales into a comparable scale. The normalised fuzzy decision matrix $\tilde{R}$ can be obtained as follows:

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m\times n} \tag{4.8}$$

where if B and C indicate the sets of benefit and cost criteria respectively, then:

[2] Although having wide applications in fuzzy TOPSIS, averaging experts' fuzzy evaluations is based on the assumption that they have the same importance to make the decision. If some experts obviously play more important roles than the others in a Six Sigma project selection process, their individual weights in decision making should be taken into account.

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{d_j^*}, \frac{b_{ij}}{d_j^*}, \frac{c_{ij}}{d_j^*}, \frac{d_{ij}}{d_j^*}\right), \qquad j \in B$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{d_{ij}}, \frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \qquad j \in C$$

$$d_j^* = \max d_{ij} \;\; if\; j \in B$$

$$a_j^- = \min a_{ij} \;\; if\; j \in C$$

4.4.6 Constructed Weighted Normalized Fuzzy Decision Matrix

The weighted normalized fuzzy decision matrix can be constructed by multiplying the normalized fuzzy decision matrix $\tilde{R}$ with the aggregated weights $\tilde{w}_j$ as follows:

$$\tilde{V} = [\tilde{v}_{ij}]_{m\times n} \qquad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n \tag{4.9}$$

where $\tilde{v}_{ij} = \tilde{r}_{ij}(\times)\tilde{w}_j$. $\tilde{V}$ is the weighted normalized fuzzy decision matrix. $\tilde{v}_{ij}$ are normalized positive trapezoidal fuzzy numbers with the value ranges belonging to the close interval [0, 1].

4.4.7 Determine FPIS and FNIS

From the weighted normalised fuzzy decision matrix $\tilde{V}$, it can be clearly seen that each element $\tilde{v}_{ij}$ represents a normalised TPFN with a value range belonging to the close interval [0, 1]. Therefore, FPIS A^* and FNIS A^- can be separately defined as:

$$A^* = (\tilde{v}_1^*, \ldots, \tilde{v}_j^*, \ldots, \tilde{v}_n^*)$$

$$A^- = (\tilde{v}_1^-, \ldots, \tilde{v}_j^-, \ldots, \tilde{v}_n^-) \tag{4.10}$$

where $\tilde{v}_j^* = (1, 1, 1, 1)$ and $\tilde{v}_j^- = (0, 0, 0, 0)$, $j = 1, 2, \ldots, n$.

4.4.8 Calculate the Distances of Each Alternative from FPIS and FNIS

The distances of each alternative from A^* and A^- can be calculated using Euclidean distance measurement between two fuzzy numbers as follows:

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*) = \sum_{j=1}^{n} \sqrt{\frac{1}{4}\left[\left(a_{ij}^v - 1\right)^2 + \left(b_{ij}^v - 1\right)^2 + \left(c_{ij}^v - 1\right)^2 + \left(d_{ij}^v - 1\right)^2\right]}$$

$i = 1, 2, \dots, m$ (4.11)

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) = \sum_{j=1}^{n} \sqrt{\frac{1}{4}\left[\left(a_{ij}^v - 0\right)^2 + \left(b_{ij}^v - 0\right)^2 + \left(c_{ij}^v - 0\right)^2 + \left(d_{ij}^v - 0\right)^2\right]}$$

$i = 1, 2, \dots, m$ (4.12)

where $i = 1, 2, \dots, m$; $\tilde{v}_{ij} = (a_{ij}^v, b_{ij}^v, c_{ij}^v, d_{ij}^v)$.

4.4.9 Calculate the Distance Closeness Coefficient of Each Alternative

The distance closeness coefficient of each alternative can be obtained by using Equation (4.13)

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-} \qquad i = 1, 2, \dots, m \qquad (4.13)$$

4.4.10 Rank the Alternatives According to their Closeness Coefficients

Obviously, an alternative A_i is closer to the FPIS A^* and further from the FNIS A^- as CC_i approaches 1. Therefore, the larger the value CC_i, the more preferred the alternative it represents. The best alternative can be identified as the one with the largest CC_i value.

4.4.11 Validation using Benchmarking Techniques

In this study, a benchmarking technique is used to compare the new fuzzy TOPSIS method with the approximate TOPSIS by Yang *et al*. (2011) A case analysis is first carried out to demonstrate the feasibility of the new method through the Six Sigma project selection of a world leading shipping company. Second, Yang *et al.*'s method is used with the same input data to test the soundness of the new method. While the new method is validated by obtaining similar outputs as those from an established model, it also shows the superiority over the established one in simplifying calculation and improving the accuracy of results.

4.5 Six Sigma Project Selections Using the Revised TOPSIS

An illustrative example is given in this section to demonstrate the use of the new fuzzy TOPSIS in Six Sigma project selection. A world leading shipping company started a Six Sigma programme in order to reduce costs and increase customer satisfaction. At an initial stage, four Six Sigma projects were identified. However, due to the limitation of resources, the management team would like to select one to start with which will maximally benefit the company within a short period.

4.5.1 Identify Alternatives, Criteria and the Corresponding Data Nature to Establish the Decision Making Matrix Format

The case was to select the best project to suit the current needs of the company for cost savings in a short term. Four identified projects (alternatives) were A_1: Reduce the number of incorrect invoices, A_2: Reduce the number of wasted journeys, A_3: Reduce unbilled charges and A_4: Reduce lead-time in query resolving.

The selection of Six Sigma needs to align with the strategic objectives and priorities of an organization. It is a very important decision to make for organizations as Six

Sigma projects require different resources (capital, time and labour etc.). Studies show that during the project selection process, companies overemphasise financial savings and the applicability of Six Sigma (Nonthaleerak and Hendry, 2008). Researchers have proposed different criteria in Six Sigma project selection in the form of generic criteria. Table 4.3 displays some typical criteria from previous studies.

Table 4.3 Six Sigma project selection criteria overview

Author	**Proposed criteria**
Pande *et al*. (2000)	• Business benefits criteria • Feasibility criteria • Organization impact criteria
Harry and Schroeder (2006)	• Defects per million opportunities • Net cost savings • COPQ • Cycle time • Customer satisfaction • Capacity • Internal performance
Banuelas *et al*. (2006)	• Customer impact • Financial impact • Top management commitment • Measurable and feasible • Learning and growth • Connected to business strategy and core competence
Bilgen and Sen (2012)	• Resources (Cost, Time, Labour) • Benefits (Saving, Productivity, Scrap yield decrease) • Effects (Quality, Capacity, Energy)

Pande *et al*. (2000) indicated that there should not be too many factors in project selection. Though different projects may have different targets to achieve depending on industrial requirements and company needs, there is no doubt that every project requires multiple resources (e.g. capital and labour, etc.) and aims to achieve certain benefits (e.g. cost saving) at a manageable risk level. Therefore, in this case, three main criteria – Cost, Benefit and Risk, with sub-criteria (shown in Figure 4.2) are identified by a team of senior managers of the shipping company using a brainstorming technique. The identified criteria and sub-criteria could vary subject to the development strategies of different companies. From Figure 4.2, the project selection criteria are denoted by C_1: Financial expenses, C_2: Project duration, C_3: Human resources, C_4: Cost savings, C_5: Increase productivity, C_6: Increase customer satisfaction, C_7: Applicability of the project, C_8: Connect to business strategy, C_9: Top management commitment.

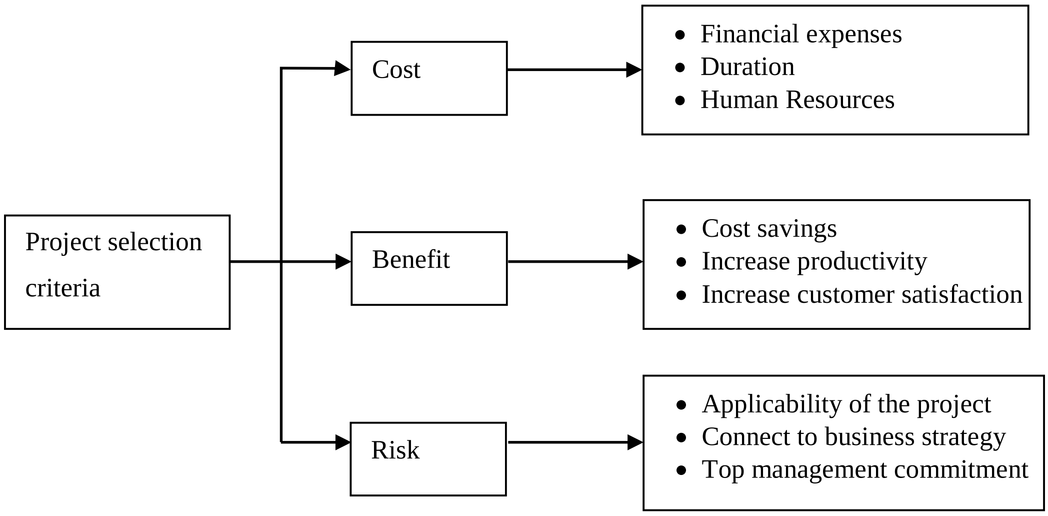

Figure 4.2 Project selection criteria with sub-criteria

4.5.2 Evaluate the Ratings of Alternatives with Respect to Each Criterion and the Importance of the Criteria, $\tilde{w}_j$

The selected criteria need to be prioritised as the ones most critical to the overall success of the organisation will have the most impact on the project selection. Three decision makers (DM_1, DM_2 *and* DM_3) including the chief operation officer, the chief finance officer and a Six Sigma MBB participated in the project selection process. They used Table 4.2 to provide their evaluations of the importance of the criteria and Table 4.1 for rating each alternative against every criterion. The evaluations are presented in Table 4.4 and Table 4.5 respectively, in which some descriptions (e.g. 90% MG evaluation of A_1 with respect to C_9 from DM_1) reveal the incomplete knowledge of the decision makers.

Table 4.4 The importance weight of the criteria given by decision makers

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
DM1	H	VH	H	VH	MH	H	H	MH	H
DM2	MH	VH	H	VH	MH	H	VH	MH	VH
DM3	H	VH	H	VH	MH	MH	VH	H	H
VL – Very low, L – Low, ML – Medium low, M – Medium, MH – Medium high, H – High, VH – Very high									

Table 4.5 The rating of alternatives by decision makers under all criteria

	c	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	DM1	G	5M	3	G	G	VG	G	G	90%MG
	DM2	G	5-6M	5	MG	G	VG	90%G	G	F
	DM3	G	5-6M	4-5	MG	G	G	MG	G	F
A_2	DM1	F	6M	5-6	G	F	MG	G	G	90%G
	DM2	F	6-7M	6-8	VG	MG	G	G	G	G
	DM3	F	6M	6	G	F	G	G	G	G
A_3	DM1	G	3M	3	F	MP	80%F,20%MP	VG	VG	VG
	DM2	G	2-3M	3	MG	F	F	VG	G	G
	DM3	G	3M	3	F	F	F	VG	G	G
A_4	DM1	G	4M	4	MP	MG	VG	G	VG	90%MG
	DM2	G	5-6M	4-5	MP	G	G	MG	G	MG
	DM3	G	5M	4-5	P	MG	VG	G	G	G
VP – Very poor, P – Poor, MP – Medium poor, F – Fair, MG – Medium good, G – Good, VG – Very good *M under C2 stands for" Month"*										

4.5.3 Transform Ratings of Alternatives to TPFN and Aggregate the Fuzzy Ratings from Multiple Decision Makers

Once the assessments from decision makers are obtained, they can all be transformed to TPFNs to establish a fuzzy decision matrix. Based on information in Table 4.5, different types of data can be converted into a common form using the fuzzy transformation mechanism in Section 4.4.3.

- Objective data. For instance, the evaluation from DM_1 for alternative A_1 regarding criterion C_2 is 5M. It can be transformed to a TPFN of (5, 5, 5, 5).
- Range data. For instance, the evaluation from DM2 for alternative A_1 regarding criterion C_2 is 5-6M. It can be transformed to a TPFN of (5, 5, 6, 6).
- Linguistic data. For instance, the evaluation from DM1 for alternative A_3 regarding criterion C_6 was provided with a complete belief degree and the TPFN can be calculated by using Equation (4.2).

$$\tilde{x}_{3,6} = \sum_{h=1}^{h_j} \beta_{3,6}^{h} \tilde{f}_h = 0.8 \times \ (3, 5, 5, 7) + 0.2 \times (1,3,3,5) = (2.6,4.6,4.6,6.6)$$

The evaluations from DM_1 for alternatives A_1, A_2 and A_4 with regards to criterion C_9 and from DM_2 for alternative A_1 with regards to criterion C_7 were provided with incomplete belief degrees and the TPFNs can be calculated by using Equations (4.3), (4.4) and (4.5). Taking DM_1, for alternative A_1 against C_9 as an example where the evaluation is 90% MG.

$$\tilde{x}_{1,9}^{L} = \left(a_{1,9}^{L}, b_{1,9}^{L}, c_{1,9}^{L}, d_{1,9}^{L}\right) = \sum_{h=1}^{7} \beta_{1,9}^{h} \tilde{f}_h + (1 - \sum_{h=1}^{7} \beta_{1,9}^{h}) \tilde{f}_1$$
$$= 0.9 \times (5,7,7,9) + 0.1 \times (0,0,0,1) = (4.6, 6.3, 6.3, 8.2)$$
$$\tilde{x}_{ij}^{H} = \left(a_{ij}^{H}, b_{ij}^{H}, c_{ij}^{H}, d_{ij}^{H}\right) = \sum_{h=1}^{7} \beta_{ij}^{h} \tilde{f}_h + (1 - \sum_{h=1}^{h_j} \beta_{ij}^{h}) \tilde{f}_7$$
$$= 0.9 \times (5,7,7,9) + 0.1 \times (9, 10, 10, 10) = (5.4, 7.3, 7.3, 9.1)$$
$$\tilde{x}_{ij} = \left(a_{ij}, b_{ij}, c_{ij}, d_{ij}\right) =$$
$$[\min\left(a_{ij}^{L}, a_{ij}^{H}\right), \min\left(b_{ij}^{L}, b_{ij}^{H}\right), \max\left(c_{ij}^{L}, c_{ij}^{H}\right), \max\left(d_{ij}^{L}, d_{ij}^{H}\right)]$$
$$= (4.6, 6.3, 7.3, 9.1)$$

In a similar way, all the other input data in Table 4.5 can be transformed in TPFNs. All the TPFNs are then aggregated by using Equations (4.6) and (4.7). The results are shown in Table 4.6 and Table 4.7

4.5.4 Normalise the Fuzzy Decision Rating Matrix

The transformed ratings are normalized by using Equation (4.8). Taking alternative A_1 with regards to criterion C_2 as an example, C_2 is a cost criterion and $a_2^- = \min a_{i2}$ = 2.67. Consequently, the normalized rating can be calculated as:

$$\tilde{r}_{12} = \left(\frac{a_2^-}{d_{12}}, \frac{a_2^-}{c_{12}}, \frac{a_2^-}{b_{12}}, \frac{a_2^-}{a_{12}}\right) = \left(\frac{2.67}{5.67}, \frac{2.67}{5.67}, \frac{2.67}{5}, \frac{2.67}{5}\right) = (0.47,0.47,0.53,0.53)$$

The same can be calculated for all the other ratings. The results of the normalised matrix are shown in Table 4.8.

4.5.5 Constructed Weighted Normalized Fuzzy Decision Matrix

The weights of criteria are built in the matrix by using Equation (4.9) and the results are listed in Table 4.9. For example, the weighted normalised fuzzy evaluation of alternative A_1 with regards to criterion C_2 can be computed as

$$\tilde{v}_{1,1} = \tilde{r}_{i1,1}(\times)\tilde{w}_1 = (0.7,0.9,0.9,1) \times (0.63,0.83,0.83,0.97) = (0.44,0.75,0.75,0.97)$$

4.5.1 Determine FPIS and FNIS

From Equation (4.10), the following are obtained.

$$A^* = [(1,1,1,1),(1,1,1,1),(1,1,1,1),(1,1,1,1),(1,1,1,1),(1,1,1,1),(1,1,1,1),(1,1,1,1),(1,1,1,1)]$$
$$A^- = [(0,0,0,0),(0,0,0,0),(0,0,0,0),(0,0,0,0),(0,0,0,0),(0,0,0,0),(0,0,0,0),(0,0,0,0),(0,0,0,0)]$$

Table 4.6 The importance weight of the criteria in TPFN

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
DM1	(0.7,0.9,0.9,1.0)	(0.9,1.0,1.0,1.0)	(0.7,0.9,0.9,1.0)	(0.9,1.0,1.0,1.0)	(0.5,0.7,0.7,0.9)	(0.7,0.9,0.9,1.0)	(0.7,0.9,0.9,1.0)	(0.5,0.7,0.7,0.9)	(0.7,0.9,0.9,1.0)
DM2	(0.5,0.7,0.7,0.9)	(0.9,1.0,1.0,1.0)	(0.7,0.9,0.9,1.0)	(0.9,1.0,1.0,1.0)	(0.5,0.7,0.7,0.9)	(0.7,0.9,0.9,1.0)	(0.9,1.0,1.0,1.0)	(0.5,0.7,0.7,0.9)	(0.9,1.0,1.0,1.0)
DM3	(0.7,0.9,0.9,1.0)	(0.9,1.0,1.0,1.0)	(0.7,0.9,0.9,1.0)	(0.9,1.0,1.0,1.0)	(0.5,0.7,0.7,0.9)	(0.5,0.7,0.7,0.9)	(0.9,1.0,1.0,1.0)	(0.7,0.9,0.9,1.0)	(0.7,0.9,0.9,1.0)
$\widetilde{w}$	(0.63,0.83,0.83,0.97)	(0.9,1.0,1.0,1.0)	(0.7,0.9,0.9,1.0)	(0.9,1.0,1.0,1.0)	(0.5,0.7,0.7,0.9)	(0.63,0.83,0.83,0.97)	(0.83,0.97,0.97,1)	(0.57,0.77,0.77,0.93)	(0.7,0.9,0.9,1.0)

Table 4.7 The rating of alternatives by decision makers under all criteria in TPFN

	c	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	DM1	(7,9,9,10)	(5,5,5,5)	(3,3,3,3)	(7,9,9,10)	(7,9,9,10)	(9,10,10,10)	(7,9,9,10)	(7,9,9,10)	(4.6,6.3,7.3,9.1)
	DM2	(7,9,9,10)	(5,5,6,6)	(5,5,5,5)	(5,7,7,9)	(7,9,9,10)	(9,10,10,10)	(6.3,8.1,9.1,10)	(7,9,9,10)	(3,5,5,7)
	DM3	(7,9,9,10)	(5,5,6,6)	(4,4,5,5)	(5,7,7,9)	(7,9,9,10)	(7,9,9,10)	(5,7,7,9)	(7,9,9,10)	(3,5,5,7)
	A_{1j}	(7,9,9,10)	(5,5,5.67,5.67)	(4,4,4.33,4.33)	(5.67,7.67,7.67, 9.33)	(7,9,9,10)	(8.33,9.67,9.67,10)	(5.67,7.67,7.67,9.33)	(7,9,9,10)	(3.67,5.67,5.67,7.67)
A_2	DM1	(3,5,5,7)	(6,6,6,6)	(5,5,5,5)	(7,9,9,10)	(3,5,5,7)	(5,7,7,9)	(7,9,9,10)	(7,9,9,10)	(6.3,8.1,9.1,10)
	DM2	(3,5,5,7)	(6,6,7,7)	(6,6,8,8)	(9,10,10,10)	(5,7,7,9)	(5,7,7,9)	(7,9,9,10)	(7,9,9,10)	(7,9,9,10)
	DM3	(3,5,5,7)	(6,6,6,6)	(6,6,6,6)	(9,9,10,10)	(3,5,5,7)	(7,9,9,10)	(7,9,9,10)	(7,9,9,10)	(7,9,9,10)
	A_{2j}	(3,5,5,7)	(6,6,6.33,6.33)	(5.67,5.67,6.33,6.33)	(8.33,9.67,9.67,10)	(3.67,5.67,5.67,7.67)	(5.67,7.67,7.67, 9.33)	(7,9,9,10)	(7,9,9,10)	(7,9,9,10)
A_3	DM1	(7,9,9,10)	(3,3,3,3)	(3,3,3,3)	(3,5,5,7)	(1,3,3,1)	(2.6,4.6,4.6,6.6)	(9,10,10,10)	(9,10,10,10)	(9,10,10,10)
	DM2	(7,9,9,10)	(2,2,3,3)	(3,3,3,3)	(5,7,7,9)	(3,5,5,7)	(3,5,5,7)	(9,10,10,10)	(7,9,9,10)	(7,9,9,10)
	DM3	(7,9,9,10)	(3,3,3,3)	(3,3,3,3)	(3,5,5,7)	(3,5,5,7)	(3,5,5,7)	(9,10,10,10)	(7,9,9,10)	(7,9,9,10)
	A_{3j}	(7,9,9,10)	(2.67,2.67,3,3)	(3,3,3,3)	(3.67,5.67,5.67,7.67)	(2.33,4.33,4.33,6.33)	(3,5,5,7)	(9,10,10,10)	(7.63,9.33,9.33,10)	(7.63,9.33,9.33,10)

A_4	DM1	(7,9,9,10)	(4,4,4,4)	(4,4,4,4)	(1,3,3,5)	(5,7,7,9)	(9,10,10,10)	(7,9,9,10)	(9,10,10,10)	(4.6,6.3,7.3,9.1)
	DM2	(7,9,9,10)	(5,5,6,6)	(4,4,5,5)	(1,3,3,5)	(7,9,9,10)	(7,9,9,10)	(5,7,7,9)	(7,9,9,10)	(5,7,7,9)
	DM3	(7,9,9,10)	(5,5,5,5)	(4,4,5,5)	(0,1,1,3)	(5,7,7,9)	(9,10,10,10)	(7,9,9,10)	(7,9,9,10)	(7,9,9,10)
	A_{4j}	(7,9,9,10)	(4.67,4.67,5,5)	(4,4,4.67,4.67)	(0.67,2.33,2.33,4.33)	(5.67,7.67,7.67, 9.33)	(8.33,9.67,9.67,10)	(6.33,8.33,8.33,9.67)	(7.67,9.33,9.33,10)	(5.67,7.67,7.67, 9.33)

Table 4.8 Normalized fuzzy decision matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	(0.7,0.9,0.9,1)	(0.47,0.47,0.53,0.53)	(0.69,0.69,0.75,0.75)	(0.57,0.77,0.77,0.93)	(0.7,0.9,0.9,1)	(0.83,0.97,0.97,1)	(0.61,0.8,0.84,0.97)	(0.7,0.9,0.9,1)	(0.35,0.54,0.58,0.77)
A_2	(0.3,0.5,0.5,0.7)	(0.42,0.42,0.44,0.44)	(0.47,0.47,0.53,0.53)	(0.83,0.97,0.97,1)	(0.37,0.57,0.57,0.77)	(0.57,0.77,0.77,0.93)	(0.7,0.9,0.9,1)	(0.7,0.9,0.9,1)	(0.68,0.87,0.9,1)
A_3	(0.7,0.9,0.9,1)	(0.89,0.89,1,1)	(1,1,1,1)	(0.37,0.57,0.57,0.77)	(0.23,0.43,0.43,0.63)	(0.29,0.49,0.49,0.69)	(0.9,1,1,1)	(0.77,0.93,0.93,1)	(0.77,0.93,0.93,1)
A_4	(0.7,0.9,0.9,1)	(0.53,0.53,0.57,0.57)	(0.64,0.64,0.75,0.75)	(0.07,0.23,0.23,0.43)	(0.57,0.77,0.77,0.93)	(0.83,0.97,0.97,1)	(0.63,0.83,0.83,0.97)	(0.77,0.93,0.93,1)	(0.55,0.74,0.78,0.94)

Table 4.9 Weighted normalized fuzzy decision matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	(0.44,0.75,0.75,0.97)	(0.42,0.47,0.53,0.53)	(0.48,0.62,0.68,0.75)	(0.51,0.77,0.77,0.93)	(0.35,0.63,0.63,0.9)	(0.53,0.81,0.81,0.97)	(0.51,0.78,0.81,0.97)	(0.4,0.69,0.69,0.93)	(0.27,0.51,0.54,0.77)
A_2	(0.19,0.42,0.42,0.68)	(0.38,0.42,0.44,0.44)	(0.33,0.43,0.48,0.53)	(0.75,0.97,0.97,1)	(0.18,0.4,0.4,0.69)	(0.36,0.64,0.64,0.9)	(0.58,0.87,0.87,1)	(0.4,0.69,0.69,0.93)	(0.52,0.81,0.84,1)
A_3	(0.44,0.75,0.75,0.97)	(0.8,0.89,1,1)	(0.7,0.9,0.9,1)	(0.33,0.57,0.57,0.77)	(0.12,0.3,0.3,0.57)	(0.18,0.41,0.41,0.66)	(0.75,0.97,0.97,1)	(0.43,0.72,0.72,0.93)	(0.59,0.87,0.87,1)
A_4	(0.44,0.75,0.75,0.97)	(0.48,0.53,0.57,0.57)	(0.45,0.58,0.68,0.75)	(0.06,0.23,0.23,0.43)	(0.28,0.54,0.54,0.84)	(0.53,0.81,0.81,0.97)	(0.53,0.81,0.81,0.97)	(0.43,0.72,0.72,0.93)	(0.42,0.69,0.72,0.94)

4.5.2 Calculate the Distances of Each Alternative from FPIS and FNIS

The distances from alternatives to FPIS and FNIS are calculated using Equations (4.11) and (4.12). For example, the distances from A_1 to FPIS and FNIS with respect to C_4 can be computed as:

$$d_{1,4}^{\ *} = d(\tilde{v}_{1,4}, \tilde{v}_4^{\ *}) = \sqrt{\frac{1}{4}[(0.51-1)^2 + (0.77-1)^2 + (0.77-1)^2 + (0.93-1)^2]} = 0.3$$

$$d_{1,4}^{\ -} = d(\tilde{v}_{1,4}, \tilde{v}_4^{\ -}) = \sqrt{\frac{1}{4}[(0.51-0)^2 + (0.77-0)^2 + (0.77-0)^2 + (0.93-0)^2]} = 0.76$$

Similarly, the individual distances from A_1 to FPIS and FNIS with respect to the other criteria can be obtained, respectively. The total distances from A_1 to FPIS and FNIS can then be computed by adding all the obtained individual distances together. Consequently, the distances from all alternatives to FPIS and FNIS with regard to all the criteria are obtained and shown in Table 4.10.

Table 4.10 Distances of each alternative from FPIS and FNIS

	A^*	A^-
A_1	3.41	6.09
A_2	3.75	5.74
A_3	3.08	6.45
A_4	3.7	5.8

4.5.3 Calculate the Distance Closeness Coefficient of Each Alternative

By using Equation (4.13) in section 4.4.9, the distance closeness coefficient can be calculated as:

$$CC_1 = \frac{d_1^-}{d_1^* + d_1^-} = 0.64$$

Similarly, $CC_2 = 0.6$, $CC_3 = 0.68$ and $CC_4 = 0.61$ can be obtained. According to the closeness coefficient, the ranking order of the four alternatives is $A_3 > A_1 > A_4 > A_2$. It means that based on the current needs of the organization, the best Six Sigma project to be selected is "Reduce unbilled charges", while the last choice is "Reduce lead time in query resolving".

4.5.4 Validation using Benchmarking Techniques

In order to validate the soundness and reliability of the new fuzzy TOPSS approach, the original input in terms of alternative rating and the importance of criteria in Table 4.4 and Table 4.5 are used in Yang *et al*. (2011)'s approximate TOPSIS. If the new fuzzy TOPSIS is reliable, the output from the approximate TOPSIS should be kept in harmony with the above result to a significant extent. Furthermore, to demonstrate the superiority of the new method, the main calculation processes of the approximate TOPSIS by Yang *et al.* are provided as follows.

The PBR and PWR matrices are presented in Table 4.11 and Table 4.12. The results of the normalized matrix are shown in Table 4.13 and Table 4.14. Because of the possible best and worst rating matrices, the calculation demands twice the effort and time compared with the new fuzzy TOPSIS method in this study.

The results from the approximate TOPSIS are obtained and presented in intervals as:

$CC_1 = (0.57, 0.59)$ with average value 0.58

$CC_2 = (0.47, 0.48)$ with average value 0.475

$CC_3 = (0.69, 0.7)$ with average value 0.695

$CC_4 = (0.56, 0.57)$ with average value 0.565

It is not possible to compare the range data to draw a definite conclusion (unless the upper boundary of one range is lower than the lower boundary of the other). Therefore, although it may contain inaccuracy, the averages of the range values have to be used for ranking purposes. Consequently, $A_3 > A_1 > A_4 > A_2$. While the consistency between the two results validates the new method, the drawbacks of Yang *et al*. (2011)'s method also demonstrate the advantages of this study.

4.6 Discussion and Conclusion

For many companies, how to implement a successful Six Sigma project is still a question to be addressed. One of the critical factors of successful implementation of Six Sigma projects is to select the right project at the right time. Six Sigma project selection has therefore attracted intensive attention from researchers. Various methods, such as AHP in a MCDM process, have been proposed in literature. While showing some attractiveness in taking into account multiple criteria, they also reveal critical problems in addressing uncertainties in data. Conventional fuzzy TOPSIS methods use fuzzy numbers to provide an effective framework of dealing with fuzziness, thus capable of ranking competing alternatives with respect to multiple criteria under uncertainties. However, only tackling imprecise evaluation using single linguistic terms exposes their incapability of accommodating any incompleteness or ignorance in subjective evaluations. A novel fuzzy TOPSIS method was proposed through the development of a new fuzzy transformation mechanism, enabling different types of data to be analysed simultaneously in one TOPSIS framework. By doing so, it can provide a rational solution to MCDM under uncertainty without compromising the easiness and accuracy of traditional TOPSIS. An illustrative case analysis is conducted in a world leading shipping company to demonstrate its feasibility and soundness in selecting the best Six Sigma project in shipping quality control. Further tests of the new proposed model should make it possible to have its wider applications in other (e.g. aeronautical) sectors.

Table 4.11 The possible best rating of alternatives by decision makers under all criteria

	c	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	DM1	(7,9,10)	(5,5,5)	(3,3,3)	(7,9,10)	(7,9,10)	(9,10,10)	(7,9,10)	(7,9,10)	(5.4,7.3,9.1)
	DM2	(7,9,10)	(5,5,5)	(5,5,5)	(5,7,9)	(7,9,10)	(9,10,10)	(7.2,9.1,10)	(7,9,10)	(3,5,7)
	DM3	(7,9,10)	(5,5,5)	(4,4,4)	(5,7,9)	(7,9,10)	(7,9,10)	(5,7,9)	(7,9,10)	(3,5,7)
	A_{1j}	(7,9,10)	(5,5,5)	(4,4,4)	(5.67,7.67,9.33)	(7,9,10)	(8.33,9.67,10)	(5.67,7.67,9.33)	(7,9,10)	(3.67,5.67,7.67)
A_2	DM1	(3,5,7)	(6,6,6)	(5,5,5)	(7,9,10)	(3,5,7)	(5,7,9)	(7,9,10)	(7,9,10)	(7.2,9.1,10)
	DM2	(3,5,7)	(6,6,6)	(6,6,6)	(9,10,10)	(5,7,9)	(5,7,9)	(7,9,10)	(7,9,10)	(7,9,10)
	DM3	(3,5,7)	(6,6,6)	(6,6,6)	(9,10,10)	(3,5,7)	(7,9,10)	(7,9,10)	(7,9,10)	(7,9,10)
	A_{2j}	(3,5,7)	(6,6,6)	(5.67,5.67,5.67)	(8.33,9.67,10)	(3.67,5.67,7.67)	(5.67,7.67, 9.33)	(7,9,10)	(7,9,10)	(7,9,10)
A_3	DM1	(7,9,10)	(3,3,3)	(3,3,3)	(3,5,7)	(1,3,5)	(2.6,4.6,6.6)	(9,10,10)	(9,10,10)	(9,10,10)
	DM2	(7,9,10)	(2,2,2)	(3,3,3)	(5,7,9)	(3,5,7)	(3,5,7)	(9,10,10)	(7,9,10)	(7,9,10)
	DM3	(7,9,10)	(3,3,3)	(3,3,3)	(3,5,7)	(3,5,7)	(3,5,7)	(9,10,10)	(7,9,10)	(7,9,10)
	A_{3j}	(7,9,10)	(2.67,2.67,2.67)	(3,3,3)	(3.67,5.67,7.67)	(2.33,4.33,6.33)	(3,5,7)	(9,10,10)	(7.63,9.33,10)	(7.63,9.33,10)
A_4	DM1	(7,9,10)	(4,4,4)	(4,4,4)	(1,3,5)	(5,7,9)	(9,10,10)	(7,9,10)	(9,10,10)	(5.4,7.3,9.1)
	DM2	(7,9,10)	(5,5,5)	(4,4,4)	(1,3,5)	(7,9,10)	(7,9,10)	(5,7,9)	(7,9,10)	(5,7,9)
	DM3	(7,9,10)	(5,5,5)	(4,4,4)	(0,1,3)	(5,7,9)	(9,10,10)	(7,9,10)	(7,9,10)	(7,9,10)
	A_{4j}	(7,9,10)	(4.67,4.67,4.67)	(4,4,4)	(0.67,2.33,4.33)	(5.67, ,7.67, 9.33)	(8.33,9.67,10)	(6.33, 8.33,9.67)	(7.67,9.33,10)	(5.67, 7.67, 9.33)

Table 4.12 The possible worst rating of alternatives by decision makers under all criteria

	c	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	DM1	(7,9,10)	(5,5,5)	(3,3,3)	(7,9,10)	(7,9,10)	(9,10,10)	(7,9,10)	(7,9,10)	(4.6,6.3,8.2)
	DM2	(7,9,10)	(6,6,6)	(5,5,5)	(5,7,9)	(7,9,10)	(9,10,10)	(6.3,8.1,9.1)	(7,9,10)	(3,5,7)
	DM3	(7,9,10)	(6,6,6)	(5,5,5)	(5,7,9)	(7,9,10)	(7,9,10)	(5,7,9)	(7,9,10)	(3,5,7)
	A_{1j}	(7,9,10)	(5.67, 5.67, 5.67)	(4.33,4.33,4.33)	(5.67,7.67,9.33)	(7,9,10)	(8.33,9.67,10)	(5.67,7.67,9.33)	(7,9,10)	(3.67,5.67,7.67)
A_2	DM1	(3,5,7)	(6,6,6)	(6,6,6)	(7,9,10)	(3,5,7)	(5,7,9)	(7,9,10)	(7,9,10)	(6.3,8.1,9.1)
	DM2	(3,5,7)	(7,7,7)	(8,8,8)	(9,10,10)	(5,7,9)	(5,7,9)	(7,9,10)	(7,9,10)	(7,9,10)
	DM3	(3,5,7)	(6,6,6)	(6,6,6)	(9,10,10)	(3,5,7)	(7,9,10)	(7,9,10)	(7,9,10)	(7,9,10)
	A_{2j}	(3,5,7)	(6.33,6.33,6.33)	(6.67,6.67,6.67)	(8.33,9.67,10)	(3.67,5.67,7.67)	(5.67,7.67, 9.33)	(7,9,10)	(7,9,10)	(7,9,10)
A_3	DM1	(7,9,10)	(3,3,3)	(3,3,3)	(3,5,7)	(1,3,5)	(2.6,4.6,6.6)	(9,10,10)	(9,10,10)	(9,10,10)
	DM2	(7,9,10)	(3,3,3)	(3,3,3)	(5,7,9)	(3,5,7)	(3,5,7)	(9,10,10)	(7,9,10)	(7,9,10)
	DM3	(7,9,10)	(3,3,3)	(3,3,3)	(3,5,7)	(3,5,7)	(3,5,7)	(9,10,10)	(7,9,10)	(7,9,10)
	A_{3j}	(7,9,10)	(3,3,3)	(3,3,3)	(3.67,5.67,7.67)	(2.33,4.33,6.33)	(3,5,7)	(9,10,10)	(7.63,9.33,10)	(7.63,9.33,10)
A_4	DM1	(7,9,10)	(4,4,4)	(4,4,4)	(1,3,5)	(5,7,9)	(9,10,10)	(7,9,10)	(9,10,10)	(4.6,6.3,8.2)
	DM2	(7,9,10)	(6,6,6)	(5,5,5)	(1,3,5)	(7,9,10)	(7,9,10)	(5,7,9)	(7,9,10)	(5,7,9)
	DM3	(7,9,10)	(5,5,5)	(5,5,5)	(0,1,3)	(5,7,9)	(9,10,10)	(7,9,10)	(7,9,10)	(7,9,10)
	A_{4j}	(7,9,10)	(5,5,5)	(4.67,4.67,4.67)	(0.67,2.33,4.33)	(5.67, ,7.67, 9.33)	(8.33,9.67,10)	(6.33, 8.33,9.67)	(7.67,9.33,10)	(5.67, 7.67, 9.33)

Table 4.13 Normalized possible best rating matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	(0.571,0.86,1)	(0.7,0.7,0.7)	(0.38,0.38,0.38)	(0.54,0.75,0.93)	(0.61,0.87,1)	(0.77,0.95,1)	(0.02,0.55,0.91)	(0,0.67,1)	(0,0.32,0.63)
A_2	(0,0.29,0.57)	(1,1,1)	(1,1,1)	(0.82,0.96,1)	(0.17,0.43,0.7)	(0.39,0.67,0.9)	(0.18,0.73,1)	(0,0.67,1)	(0.53,0.84,1)
A_3	(0.571,0.86,1)	(0,0,0)	(0,0,0)	(0.32,0.54,0.75)	(0,0.26,0.52)	(0,0.28,0.56)	(0.73,1,1)	(0.22,0.78,1)	(0.63,0.89,1)
A_4	(0.571,0.86,1)	(0.6,0.6,0.6)	(0.38,0.38,0.38)	(0,0.18,0.39)	(0.43,0.7,0.91)	(0.77,0.95,1)	(0,0.55,0.91)	(0.22,0.78,1)	(0.32,0.64,0.9)

Table 4.14 Normalized possible worst rating matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	(0.571,0.86,1)	(0.8,0.8,0.8)	(0.36,0.36,0.36)	(0.54,0.75,0.93)	(0.61,0.87,1)	(0.77,0.95,1)	(0,0.5,0.84)	(0,0.67,1)	(0,0.29,0.6)
A_2	(0,0.29,0.57)	(1,1,1)	(1,1,1)	(0.82,0.96,1)	(0.17,0.43,0.7)	(0.39,0.67,0.9)	(0.23,0.74,1)	(0,0.67,1)	(0.5,0.8,0.95)
A_3	(0.571,0.86,1)	(0,0,0)	(0,0,0)	(0.32,0.54,0.75)	(0,0.26,0.52)	(0,0.28,0.56)	(0.74,1,1)	(0.22,0.78,1)	(0.64,0.9,1)
A_4	(0.571,0.86,1)	(0.6,0.6,0.6)	(0.45,0.45,0.45)	(0,0.18,0.39)	(0.43,0.7,0.91)	(0.77,0.95,1)	(0.06,0.57,0.91)	(0.22,0.78,1)	(0.31,0.6,0.86)

Chapter 5. Revised FMEA Model to Facilitate Six Sigma in Shipping Companies

5.1 Introduction

The existing literature indicates that effectively identifying failures is a common problem encountered in many industrial sectors when applying Six Sigma. This reveals a significant research challenge as to how advanced techniques are utilised to improve the failure identification in Six Sigma thus facilitating its wide application especially in service industries such as shipping management.

FMEA ranks possible failure modes based on three criteria: Severity (*S*), Occurrence (*O*) and Detection (*D*). Each failure mode is assigned scores against each of these three criteria on an ordinal scale. In traditional FMEA, an RPN is then computed for each failure mode by multiplying the three ordinal scores. FMEA was originally evolved at the National Aeronautics and Space Administration, an environment where the interest in preventing failures is extremely high. It was later popularized in the automobile industry. Today, FMEA is frequently used in service industries and various function areas of companies including operations, sales and marketing, accounting and information technology (Bradley and Guerrero, 2011). Due to its visibility and easiness, FEMA has become an integral tool in Six Sigma process improvement projects (Antony *et al.*, 2005; Sokovic *et al.*, 2005). Different from the application of FMEA in the manufacturing industry, its adaptation for the service sector requires appropriately addressing the challenges of insufficient quantified information, non-linear interrelationship and different weights associated with the three criteria of *S*, *O* and *D*.

A careful literature review reveals that the computation of RPN values and the score assigning method in traditional FMEA have been questioned in many previous studies. Various methods have been proposed to overcome the inherent drawbacks exposed in the traditional FMEA. Fuzzy logic is one of the most widely used methods among them (Yang *et al.*, 2008). Bowles and Pelaez (1995) described a fuzzy logic based approach for prioritizing failures in Failure Mode, Effects and Criticality Analysis (FMECA), which used linguistic terms, min-max method and defuzzification in criticality analysis for FMEA. Based on this approach, Xu *et al.* (2002) presented a fuzzy-logic based method to address the question of the composition of the original RPN. However, using fuzzy min-max operation, the approach may result in the loss of useful information in the process of inference (Yang *et al*., 2008). Pillay and Wang (2003) used a fuzzy logic approach together with grey theory where FMEA attributes were evaluated directly by linguistic terms and grey theory was applied to obtain an RPN by assigning relative weighting coefficients. Although it simplified a complex rule base by combining similar rules, the method did not consider the uncertainties of fuzzy output in evaluation. Liu *et al.* (2011) proposed the use of a fuzzy evidential reasoning (FER) approach together with grey theory in FMEA. Belief structures were built into the model in the assessment to address the presentation of uncertainties in assessment. It overcomes the weakness of the loss of useful information in fuzzy risk inference. However, the complex calculation involved may not be friendly to mathematically unsophisticated users. Braglia *et al.* (2003) presented a fuzzy TOPSIS method where the risk factors are set as criteria and failure modes as alternatives. This method was further developed by Kutlu and Ekmekcioglu (2012) by combining a fuzzy AHP and a fuzzy TOPSIS to take into consideration the importance of risk factors. Based on fuzzy distances to the best and worst ideal solutions, the results of failure evaluations cannot reflect the "goodness" of their risks and thus be used to conduct effectiveness evaluation of risk control measures. While many approaches comprised the visibility of the RPN method in order to improve the accuracy of failure prioritisation, they ignored the fact that it is the simplicity of the traditional FMEA that largely contributes to its wide applications in practice. To tackle this problem, Yang *et al*. (2008) developed a Fuzzy Rule-Based Bayesian Reasoning (FuRBaR) approach through combining fuzzy logic and Bayesian reasoning to take advantage of their ability to model incompleteness and randomness of failure information. While it provides a potential solution for the trade-off between simplicity and accuracy of FMEA, it struggles to rationalise the belief degree distribution in the fuzzy rule base (FRB) establishment and take into account the impact of different weights of *S*, *O* and *D* in failure prioritization, which need to be dealt with in order to facilitate the adaption of FMEA in general and its application in Six Sigma quality control in particular.

To address the above challenges, this chapter aims to develop a feasible FMEA model in service based quality control through revisiting the FuRBaR approach. In the new model, AHP and Fuzzy Bayesian Reasoning (FBR) are combined in a complementary way, in which the AHP is used to deal with the different weights among the three criteria, while FBR is applied to tackle the non linear relationship among the three criteria. More importantly, the new approach uniforms the linguistics terms used to describe the IF (the three FMEA criteria) and THEN (the risk level) parts of a rule base and realise the rational distribution of belief degrees in fuzzy rules. To achieve the aim, this chapter is organised as follows. Section 2 reviews the literature of FMEA with respect to the development of FMEA modelling. Section 3 describes a new FMEA method by taking into account the failure characteristics of service industries. In section 4, a real case of improving accounting management procedure of shipping lines is given. Section 5 concludes the chapter.

5.2 Literature Review

5.2.1 Use FMEA in Six Sigma

One of the success factors of Six Sigma is its ability to integrate different statistical tools and techniques within the DMAIC framework in a systematic and disciplined manner. FMEA as an effective tool for failure ranking and risk identification is used by Six Sigma organizations as one of the quality tools. In the survey carried out by Antony *et al*. (2005), FMEA is one of the commonly used and most useful tools in Six Sigma application with high familiarity to Six Sigma practitioners. The widespread adoption of Six Sigma in industry implies the frequent use of FMEA in many industries. Some typical examples of using FMEA in Six Sigma are reported through academic publications. Sokovic *et al*. (2005) used FMEA in a Six Sigma project for process design. It was used to identify root causes in the Six Sigma project in Cheltenham based Kohler Mira (Lee-Mortimer, 2006). Kumi and Morrow (2006) recorded the use of FMEA to prioritise failures by using RPN and identify possible actions in a Six Sigma project in Newcastle University Library. Su and Chou (2008) used FMEA to carry out project risk evaluation and the traditional RPN approach was used to assist Six Sigma project generation. Wei *et al.* (2010) documented the use of FMEA in a Six Sigma project in a direct selling company to identify failure modes and RPN was calculated by multiplying the *S*, *O* and *D*. Garland (2011) applied FMEA as a primary tool in the analysis phase of a Six Sigma project in Eastman Chemical Company to identify failures, estimate the associated risks and prioritise actions to be taken by using RPN. Nooramin *et al.* (2011) utilized FMEA to identify and prioritize the root causes in Six Sigma application in maritime container terminals. It is evidenced that the current use of FMEA in Six Sigma is mainly based on the traditional RPN approach. Its principle and main disadvantages in practical applications are analysed in the ensuing section.

5.2.2 Traditional FMEA

One of the main purposes of FMEA in Six Sigma is to prioritize the RPN of the failures to assign the limited resources to the most serious risk item. A key element of FMEA is analysing three characteristics of failures:

- Severity (*S*) - severity of the potential effects of the failure.
- Occurrence (*O*) - likelihood that the failure will occur.

- Detection (*D*) - likelihood that the problem will be undetected before it reaches the end-user/customer.

Typically, the project team scores each failure mode on a scale of 1 to 10 (with 1 being the best and 10 being the worst case) in each of these three areas and an RPN is then calculated

$$RPN = S \times O \times D \quad (5.1)$$

The RPN value is used to rank each failure in terms of their risk levels.

The traditional FMEA has shown its visibility and easiness in many applications. However, it has some disadvantages when being applied in a wide context. They include (Ben-Daya and Raouf, 1996; Braglia *et al.*, 2003; Chang *et al.*, 2001; Gilchrist, 1993; Pillay and Wang, 2003; Sankar and Prabhu, 2001; Sharma *et al.*, 2005; Wang *et al.*, 2009; Yang *et al*., 2008; Liu *et al*., 2011):

(i) The mathematical formula for calculating RPN is questionable and debatable. Multiplication is an arbitrary choice for combining three criteria scores.

(ii) It is usually difficult and inaccurate to give precise point evaluations of intangible quantities associated with *S*, *O* and *D*.

(iii) The same value of RPN may indicate totally different risk implications.

(iv) It neglects relative importance among *S*, *O* and *D*; and presumes that three attributes have the same weight in determining the priority of the failures.

Considering the subjective nature of failure data in service industries such as shipping management, there is a great need for developing a new FMEA method to tackle the associated uncertainties. Among all the mentioned shortcomings for FMEA, some have been well addressed in the literature while the others have received little attention such as the above iii and iv, which motivates this study to fill in the research gap of FMEA and its application in Six Sigma projects in the shipping industry.

5.2.3 AHP

Psychologists argue that it is easier and more accurate to express one's opinion on only two alternatives than simultaneously on all the alternatives. It also allows consistency and cross checking between different pair-wise comparisons. One of the purposes of using AHP in this chapter is to provide weights for each criterion of *S*, *O* and *D* by pair-wise comparisons.

AHP was developed by Saaty (Saaty, 1980) and it has been identified as an important approach to solve complex MCDM problems involving multiple qualitative and quantitative criteria. It has been widely used across various industries in many applications such as project selection (Mustafa and Albahar, 1991), allocating resources and setting priorities (Nepal *et al.*, 2010; Barbarosoglu and Pihas, 1995). It can also be used as an effective tool for assessing the weight of each criterion in FMEA (Braglia, 2000).

5.2.4 Fuzzy Bayesian Reasoning

Among all the new methods developed for overcoming shortcomings of traditional FMEA, the most widely applied is to use fuzzy logic theory to manipulate the linguistic terms (Yang *et al.*, 2008). The use of fuzzy logic theory contributes to the development of more precise failure critical analysis; however, it renders an important factor for traditional FMEA application – simplicity. Furthermore, fuzzy if-then rules have been criticised due to their incapability of effectively incorporating different weights of risk factors into the fuzzy inference system itself (Yang *et al.*, 2008). Bayesian networks (BN) are a powerful risk analysis tool and are used in a range of real applications concerned with predicting properties of safety critical systems (Lee and Lee, 2006; Liu *et al.*, 2005; Hanninen and Kujala, 2012). However, a common criticism of the Bayesian approach is that it requires too much information in the form of prior probabilities, and that this information is often difficult or impossible to obtain in risk assessment (Yang *et al.*, 2008).

Consequently, earlier work has indicated that it is beneficial to combine fuzzy logic and Bayesian reasoning for the purpose of compensating their individual disadvantages. The combination of Fuzzy-Bayesian in safety and reliability studies can be found in many previous studies (Bott *et al.*, 2002; Huang *et al.*, 2005; Huang *et al.*, 2006; Li *et al.*, 2012).

A Rule based Inference Methodology using the Evidential Reasoning algorithm (RIMER) has been proposed (Yang *et al.*, 2006) and successfully applied to engineering system safety analysis (Li and Liao, 2007; Liu *et al.*, 2004). The model is designed on the basis of a FRB with a belief structure. The rules include various belief degrees distributed into the multiple linguistic variables of the conclusion attribute. The main advantage of using belief degrees is to capture uncertainty and non-linear causal relationships in assessment. However, the corresponding complex uncertainty inference may be not friendly enough to mathematically unsophisticated users. A FuRBaR approach was developed to simplify the uncertainty inference of belief rule bases (Yang *et al*., 2008). However, this approach, like RIMER, still needs to construct and establish the complex rule bases, which may be error-prone. There is a possibility to assign incompatible belief degrees in a FRB when a large scale scheme with hundreds of rules is defined entirely subjectively. "Incompatible" means contradictory belief degree distributions in two/more relevant rules, in which one rule which should have a better risk evaluation has actually been assigned belief degrees presenting a worse safety level. For example, in the safety rule base developed by Liu *et al*. (2004), Rule 85 and Rule 86 with their IF parts as the sets of {"reasonable low" failure occurrence likelihood (L), "moderate" failure consequence severity (C), "highly unlikely" failure consequence probability (P)} and {"reasonable low" L, "moderate" C, "unlikely" P} have been assigned their THEN parts as the sets of {(0.5, "good"), (0.5, "average"), (0, "fair"), (0, "poor")} and {(0.6, "good"), (0.4, "average"), (0, "fair"), (0, "poor")}. Furthermore, when new attributes are identified in the IF parts, it may be difficult to update the original rule base and to produce the output without the re-establishment of the whole FRB system.

In this chapter, the FuRBaR approach is revisited to provide a powerful tool with the capability of assigning compatible belief degrees in traditional fuzzy IF-THEN rule based risk assessment methods, while making subjective risk assessment more rational and visible. The new method is generated by extending the FurBaR approach on the basis of the AHP approach and utility theory, showing its superiority in modelling incompleteness of subjective judgement and accommodating additional attributes compared to the RIMER and FurBaR. It will therefore improve FMEA and its application in Six Sigma quality control.

5.3 A Revised FMEA Methodology using AHP and FRB

In this section, AHP and FRB are used to overcome the shortcomings of the traditional FuRBaR. AHP is used to assess the weights of the three criteria in FMEA and FRB with a belief structure which is applied to transfer belief degrees in rule bases into subjective conditional probabilities in BN. The necessary steps are outlined in Figure 5.1.

5.3.1 Assessing the Weights of the Three Criteria in FMEA (S, O, D) Using AHP Method

Step 1: Establish a pair-wise comparison decision matrix (M).

A pair-wise comparison 3-by-3 matrix (M) is constructed for the three criteria (*S*, *O* and *D*). a in the matrix represents a quantified judgement on a pair of criteria (e.g. a_{SO} represents the importance of S over *O*). A scale of "1" to "9" is adopted to conduct non-quantitative pair-wise comparisons of two elements (Saaty, 1980) (Table 5.1).

$$M = \begin{array}{c} \\ S \\ O \\ D \end{array} \begin{array}{c} \begin{array}{ccc} S & O & D \end{array} \\ \begin{bmatrix} a_{SS} & a_{SO} & a_{SD} \\ a_{OS} & a_{OO} & a_{OD} \\ a_{DS} & a_{DO} & a_{DD} \end{bmatrix} \end{array}$$

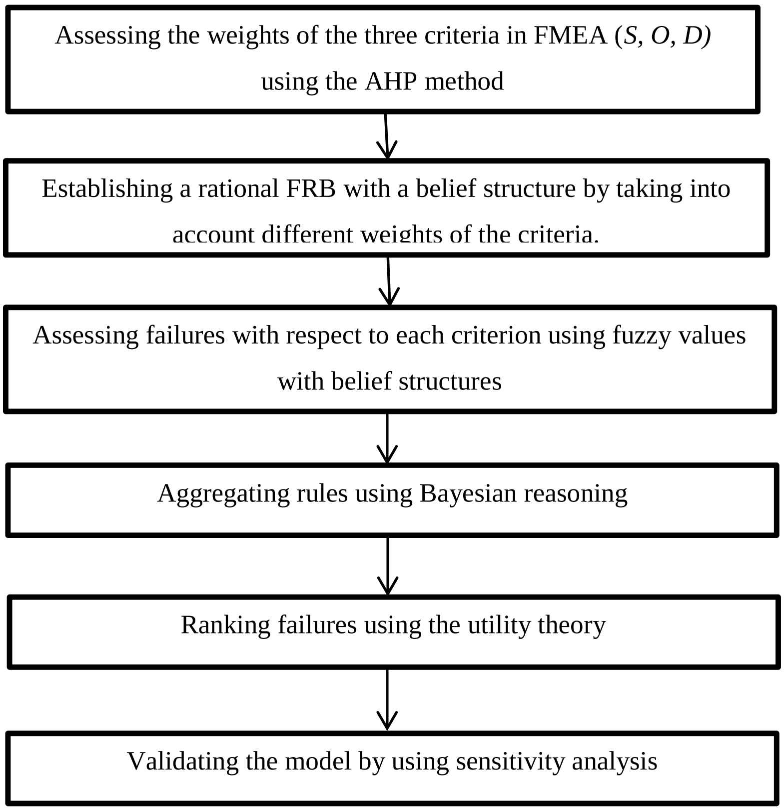

Figure 5.1 Steps for revised FMEA methodology using AHP and FRB

Table 5.1 Judgement scores in AHP (Saaty, 1980)

Score	Judgment	Explanation
1	Equally	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly favour one activity over another
5	Strongly	Experience and judgment strongly favour one activity over another
7	Very strongly	An activity is strongly favoured and its dominance demonstrated in practice
9	Extremely	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Step 2: Normalize the decision matrix and calculate the priorities of this matrix to obtain the weights of criteria $w_S, w_O \ and \ w_D$.

In order to calculate the weight of each criterion, the comparison matrix has to be normalized. This can be done by summing each set of column values; then each value is divided by the corresponding summed value. The relative weights of criteria w_S, w_O and w_D are obtained through averaging each row. This can be presented by using Equation (5.2).

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \qquad k = (1, 2, 3) \tag{5.2}$$

where, a_{ij} is the entry of row i and column j in a comparison matrix of order n and w_k is the weight of a specific criterion k in the pairwise comparison matrix. In this case, criterion 1 is *S*, 2 refers to *O* and 3 stands for *D*. The number of criteria / alternatives in the matrix, $n = 3$.

Step 3: Consistency check

In order to derive meaningful weights, a minimal consistency is required and a test must be done. The consistency of the comparison matrices is tracked by a Consistency Ratio (CR). CR index in AHP is used in order to maintain consistency in decision making of the responders. CR can be defined as follows:

$$CR = \frac{CI}{RI} \tag{5.3}$$

CI is the consistency index and RI is the random index. CI can be defined as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5.4}$$

where λ_{max} defined as the largest eigenvalue is approximately calculated in Equation (5.5).

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \qquad j = (1, 2, 3), k = (1, 2, 3) \tag{5.5}$$

where w_j and w_k are the weights of criteria obtained in Step 2**.**

RI is generated by Saaty's team and the values are shown in Table 5.2. According to Saaty (1995), the consistency ratio (CR) should be less than 5%, 8%, and 10% for a 3 × 3 matrix, a 4 × 4 matrix, and matrices of higher orders, respectively. If the CR value is too high, then it is deemed that there is no reliability in the decision on the chosen preference (Saaty, 1980).

Table 5.2 Random index (RI) for the factors used in the decision making process.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

5.3.2 Establishing a FRB with a Rational Belief Structure

In this method, both the three criteria and risk level are defined on the same plane of a grade set of {very low, low, average, high, very high} and relevant weights are assigned to the three criteria. The belief degrees associated with each grade of the risk level for all rules are then calculated by using Equation (5.6).

$$\beta_{Ri}^{j} = \beta_{Si}^{j} \cdot w_S + \beta_{Oi}^{j} \cdot w_O + \beta_{Di}^{j} \cdot w_D \tag{5.6}$$

where i = (1, 2, …, 5) means a grade in the set of {very low, low, average, high, very high}; j is the j^{th} rule in the rule base; β_{Ti}^{j} (T ∈ (*S*, *O*, *D*)) equals one when *Ti* is presented in the j^{th} rule and otherwise it is zero. Consequently, the development of the rule base with a belief structure can be standardised and rationalised. For example, a particular rule can be developed as follows.

Rule 2: IF *S* is very low, *O* is very low and *D* is low, THEN the risk level is very low with a belief degree of "(w_S+w_O)", low with a belief degree of " w_D", average with a belief degree of "0", high with a belief degree of "0" and very high with a belief degree of "0".

By using Equation (5.6), the FRB with belief structures together with the weights of FMEA criteria can be established as shown in Table 5.3.

Table 5.3 *FRB* with belief structures and weights of criteria in FMEA

Rules	**Antecedent attributes**			**Risk Level**				
	Severity of failure (*S*)	Frequency of occurrence (*O*)	Difficulty of detection (*D*)	Very Low	Low	Average	High	Very High
Weight	w_S	w_O	w_D	β_{R1}	β_{R2}	β_{R3}	β_{R4}	β_{R5}
1	Very low	Very low	Very Low	$w_S + w_O + w_D$	0	0	0	0
2	Very low	Very low	Low	$w_S + w_O$	w_D	0	0	0
3	Very low	Very low	Average	$w_S + w_O$	0	w_D	0	0
…	…	…	…	…	…		…	…
123	Very high	Very high	Average	0	0	w_D	0	$w_S + w_O$
124	Very high	Very high	High	0	0	0	w_D	$w_S + w_O$
125	Very high	Very high	Very high	0	0	0	0	$w_S + w_O + w_D$

By doing so, the complex work of constructing fuzzy rule bases with belief structures in FMEA can be replaced through establishing relatively straightforward linear calculation. This generic method is examined by a case study of failure prioritisation of accounting management of a shipping line in Section 5.4.

5.3.3 Assessment of Failures Using Fuzzy Belief Structures

The three criteria (*S*, *O*, *D*) for every failure mode can be evaluated numerically or linguistically. Both of them have been extensively applied and have their merits and demerits. However, the evaluation involves a high level of uncertainty since it is a group decision behaviour and the assessment information for risk factors mainly based on experts' subjective judgments may be incomplete and imprecise. In addition, many experts are willing to express their opinions by belief degrees (or possibility measures) based on a set of evaluation grades, i.e., {Very Low, Low, Moderate, High, and Very High} in reality (Liu *et al.*, 2011), when no any single grade can be individually used to describe risk parameters by them with full confidence. From Section 5.3.2, it is known that the linguistic terms used to describe variables (T_i, T ∈ (*S, O, D*); *i*=1, 2, …, 5), are set as "Very low", "Low", "Average", "High", and "Very high". The risk level of a particular failure is also described using such linguistic variables (R_i, *i* = 1, …, 5) as "Very low", "Low", "Average", "High", and "Very high". Each grade associated with the three criteria can be described with respect to real observations. Furthermore, based on the experts' opinions, it is possible to represent all the five individual assessment grades by trapezoidal fuzzy numbers. To simplify the discussion and without loss of generality, their membership function values are developed based on Liu *et al*. (2011)'s work (Figure 5.2 and Table 5.4). It is obviously possible to have some flexibility in the definition of membership functions to suit different situations.

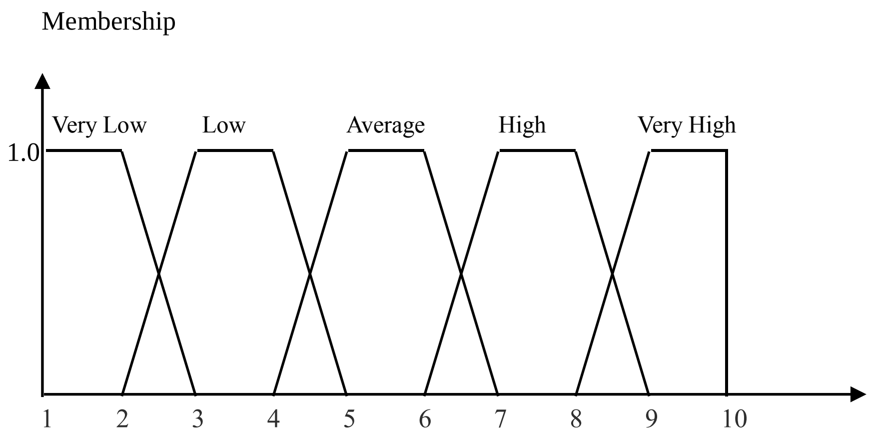

Figure 5.2 Fuzzy membership functions for linguistic terms

Table 5.4 Fuzzy ratings for linguistic terms.

Linguistic terms	**Fuzzy number**
Very Low	(1, 1, 2, 3)
Low	(2, 3, 4, 5)
Average	(4, 5, 6, 7)
High	(6, 7, 8, 9)
Very High	(8, 9, 10, 10)

Subjective judgements from Six Sigma project teams can then be collected using the linguistic terms with belief degrees or any utility values. For example, the "*O*" of one failure mode is judged by *k* experts as "O_i" with β_{Oi}^n belief degrees. Then the belief degree of *O* belonging to O_i is calculated as follows.

$$\beta_{Oi} = \frac{\sum_{n=1}^{k} \beta_{Oi}^{n}}{k} \qquad (n = 1,2, \ldots\ldots k), (i = 1, 2, \ldots, 5) \tag{5.7}$$

In the same way, the belief degree for *S* and *D* at different grades (*i*) evaluated by *k* experts can be calculated by using Equation (5.8).

$$\beta_{Ti} = \frac{\sum_{n=1}^{k} \beta_{Ti}^{n}}{k} \qquad (n = 1,2, \ldots\ldots k), (i = 1, 2, \ldots, 5), \mathrm{T} \in (S, O, D) \tag{5.8}$$

It may sometimes be difficult for the experts to directly give the evaluations using linguistic terms. If the evaluation is presented as other forms such as (i) a crisp numerical value, (ii) a range of numerical value, (iii) a triangular fuzzy number and (iv) a trapezoidal fuzzy number, it can be converted into linguistic terms with fuzzy memberships using fuzzy mapping techniques such as the fuzzy similarity calculation (Yang *et al*., 2009). Let u_E be the fuzzy membership functions of a fuzzy estimation *E* and u_{T_i} (T ∈ (*S*, *O*, *D*); *i*=1, 2, …, 5) be the trapezoidal fuzzy numbers of linguistic terms T_i, respectively. The similarity degrees between u_E and u_{T_i} can be calculated as follows (Li and Liao, 2007).

$$S(u_E, u_{T_i}) = \frac{\int_{-\infty}^{+\infty} \left(\min\{u_E(x), u_{T_i}(x)\}\right) \mathrm{dx}}{\int_{-\infty}^{+\infty} u_E(x) \mathrm{dx}} \qquad (5.9)$$

If two membership functions are the same, that is $u_E = u_{T_i}$, then $S\left(u_E, u_{T_i}\right) = 1$. If two membership functions do not have any overlap, the similarity degree is zero. For other situations, the higher the percentage of the overlap is, the higher the similarity degree. After all the similarity degrees between u_E and u_{T_i} are computed, the belief degree B_{T_i}, can be computed as follows:

$$B_{u_E}^{T_i} = \frac{S\left(u_E, u_{T_i}\right)}{\sum_{i=1}^{5} S\left(u_E, u_{T_i}\right)} \qquad (T \in (S, O, D);\ i=1, 2, \ldots, 5) \qquad (5.10)$$

For example, the similarity degree between a fuzzy estimation u_E and u_{T_i} (T ∈ (*S*, *O*, *D*); *i*=1, 2, …, 5) in Figure 5.3 is calculated by using Equation (5.9) as follows:

$$S\left(u_E, u_{T_1}\right) = \frac{0}{area\ 1 + area\ 2 + area\ 3 + area\ 4} = 0$$
$$S\left(u_E, u_{T_2}\right) = \frac{area\ 1 + area\ 2}{area\ 1 + area\ 2 + area\ 3 + area\ 4} = 0.33$$
$$S\left(u_E, u_{T_3}\right) = \frac{area\ 2 + area\ 3}{area\ 1 + area\ 2 + area\ 3 + area\ 4} = 0.75$$
$$S\left(u_E, u_{T_4}\right) = \frac{0}{area\ 1 + area\ 2 + area\ 3 + area\ 4} = 0$$
$$S\left(u_E, u_{T_5}\right) = \frac{0}{area\ 1 + area\ 2 + area\ 3 + area\ 4} = 0$$

Furthermore, using Equation (5.10), $B_{u_E}^{T_i}$ can be normalised as follows:

$$B_{u_E}^{T_1} = \frac{S\left(u_E, u_{T_1}\right)}{\sum_{i=1}^{5} S\left(u_E, u_{T_1}\right)} = 0$$
$$B_{u_E}^{T_2} = \frac{S\left(u_E, u_{T_2}\right)}{\sum_{i=1}^{5} S\left(u_E, u_{T_2}\right)} = 0.31$$
$$B_{u_E}^{T_3} = \frac{S\left(u_E, u_{T_3}\right)}{\sum_{i=1}^{5} S\left(u_E, u_{T_3}\right)} = 0.69$$

$$B_{u_E}^{T_4} = \frac{S(u_E, u_{T_4})}{\sum_{i=1}^{5} S(u_E, u_{T_4})} = 0$$

$$B_{u_E}^{T_5} = \frac{S(u_E, u_{T_5})}{\sum_{i=1}^{5} S(u_E, u_{T_5})} = 0$$

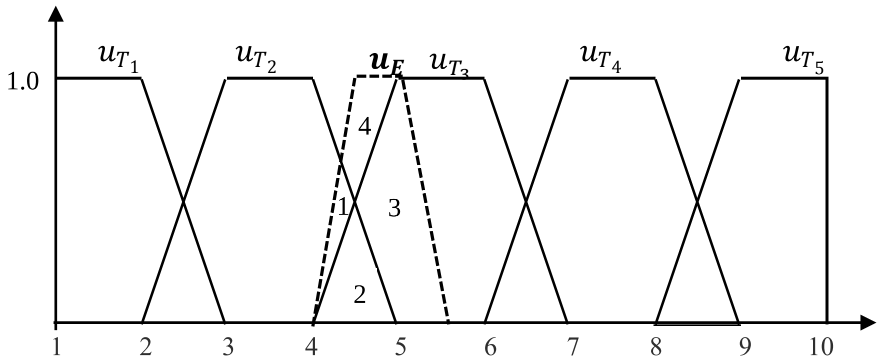

Figure 5.3 Example of similarity degree between u_E and u_{T_i}(T ∈ (*S, O, D*); *i*=1, 2, …, 5)

In this way, the fuzzy estimation for *E* can be transformed into the belief structure and shown in the following form:

u_E = {(0, “Very Low”), (0.31, “Low”), (0.69, “Average”), (0, “High”), (0, “Very High”)}

Consequently, raw data regarding the failure evaluation with respect to each criterion can be presented in various formats to avoid useful information loss at an initial stage. The obtained belief degrees can be converted and presented as the subjective probabilities of a failure as:

$$p(T_i) = \beta_{Ti} \tag{5.11}$$

5.3.4 Rule Aggregation with the Weights of FMEA Criteria Using Bayesian Reasoning

The principle of the FurBaR approach is used in this step. The kernel of the approach is to appropriately transform belief degrees in rule bases into subjective conditional probabilities in *BN*. The transformation makes it possible to take the advantages of both fuzzy and Bayesian inference. Taking rule 2 in Table 5.3 *FRB* with belief structures and weights of criteria in FMEA as an example, it can be symbolised as:

IF $S = S_1, O = O_1$, and $D = D_2$, THEN $R_1 = (w_S + w_O)$, $R_2 = w_D$, $R_3 = 0$, $R_4 = 0$ and $R_5 = 0$.

It can be further transformed and presented by conditional probabilities as:

$$p(R_i|S_1, O_1\ and D_2) = ((w_S + w_O), w_D, 0, 0, 0) \tag{5.12}$$

Using a *BN* technique, the FRB constructed in FMEA can be modelled and converted into a four-node converging connection. It includes three parent nodes, N_O, N_S, and N_D (Nodes *O*, *S* and *D*); and one child node N_R (Node *R*) (Yang *et al*., 2008). Having transferred the rule base into a *BN* framework (see Equation (5.12)), the rule-based risk inference for the failure criticality analysis will be simplified as the calculation of the marginal probability of the node N_R. The rule base in Table 5.3 denotes a 5×5×5×5 conditional probability table (CPT) (see Table 5.5).

Table 5.5 The Conditional Probability Table of N_R

S	S_1								S_5						
O	O_1				O_5				O_1				O_5		
D / R	D_1		D_5		D_1		D_5		D_1		D_5		D_1		D_5
R_1	$w_S + w_O + w_D$		$w_S + w_O$		$w_S + w_D$		w_S	…	$w_O + w_D$		w_O		w_D		0
R_2	0	…	0	…	0	…	0		0	…	0	…	0	…	0
R_3	0		0		0		0		0		0		0		0
R_4	0		0		0		0		0		0		0		0
R_5	0		w_D		w_O		$w_O + w_D$		w_S		$w_S + w_D$		$w_S + w_O$		$w_S + w_O + w_D$

Subjective probabilities for each node of N_O, N_S *and* N_D are expressed as $p(O_i)$, $p(S_j)$, and $p(D_k)$ using Equation (5.11) respectively. Having analysed all the probabilities of the four nodes, the probability of N_R can be calculated as (Jensen, 2001):

$$p(R_h) = \sum_{j=1}^{5}\sum_{i=1}^{5}\sum_{k=1}^{5} p(R_h| S_j, O_i, D_k)p(S_j)p(O_i)p(D_k) \qquad (h = 1, \dots \dots, 5) \qquad (5.13)$$

where *h*, *i*, *j* and *k* all represent evaluation grades.

5.3.5 Failure Ranking

In order to prioritize failures, the appropriate utility values U_{Rh} for R_h $(h = 1 \dots \dots 5)$ need to be assigned using the utility theory. They can be obtained by using the centroid defuzzification method (Mizumoto, 1995). Consequently, the utility values of R_h $(h = 1 \dots \dots 5)$ can be calculated as below.

U_{R1} = Very low = 1.778

U_{R2} = Low = 3.5

U_{R3} = Average = 5.5

U_{R4} = High = 7.5

U_{R3} = Very high = 9.222

Then the failure priority/ranking index can be developed as:

$$RI = \sum_{h=1}^{5} p(R_h)U_{Rh} \qquad (5.14)$$

where the smaller the value of RI is, the lower the risk level of the potential failure mode. The effects (EI) to RI values when input changes can be computed as:

$$EI = RI' - RI = \sum_{h=1}^{5} p(R_h)' U_{Rh} - \sum_{h=1}^{5} p(R_h)U_{Rh} \qquad (5.15)$$

where RI' and $p(R_h)'$ represent the RI value and the probability of N_R after changes of inputs, respectively.

The calculation process can be simplified by using a *Hugin* software package (Andersen *et al*., 1990).

5.3.6 Validation

Validation is an important aspect of this methodology. It requires a careful test to ensure its soundness. It is particularly important and desirable when subjective elements are involved in the proposed methodology. In this study, sensitivity analysis for partial validation of the model has been developed. If the methodology is sound and its inference reasoning is logical, then the sensitivity analysis must at least follow the following three axioms (Yang *et al*., 2008; Jones *et al.*, 2010).

Axiom 1. A slight increment/decrement in the degrees of belief associated with any linguistic variables of the three criteria will certainly result in the effect of a relative increment/decrement in the degrees of belief of the linguistic variables of the Risk Level.

Axiom 2. Given the same variation of belief degree distributions of the three criteria, its influence magnitude to the Risk Level will keep consistency with their weight distributions.

Axiom 3. The total influence magnitudes of the combination of the probability variations from x criteria (evidence) on the values should always be greater than the one from the set of x-y ($y \in x$) criteria (sub-evidence).

5.4 A Case Analysis of Accounting Management in Shipping Lines

In this section, the new FMEA method is illustrated through the failure analysis process in a Six Sigma project for improving the accounting management of a world leading container shipping company. It aims at reducing the amount of unmatched payment for non-credit customers. The project has followed the DMAIC methodology and FMEA is used in the measure phase to identify failures of high risk.

There are generally two types of customers in accounting in shipping lines' operations: credit customer and non-credit customer. Credit customers are given the right to make a lump sum payment for the service received from the shipping company within a certain period (e.g. every 30 days). Non-credit customers are required to make payments for every service before completion (delivery or release of containers). It is found that very often the payments made by non-credit customers cannot be or are wrongly allocated to the service provided. This has led to delays, reworks and sometimes, loss of payments. Prior to the introduction of Six Sigma, although much effort was put in to reduce the amount of unmatched payment, continuous errors occurred without a systemic examination of relevant work processes. The effort turned out to be insufficient. A Six Sigma project team of 4 members from both accounting and operational departments in a shipping company was formed and led by this research. They include two senior managers and two operational supervisors from different operational departments. At the early stage of the measure phase, three process steps were identified, namely, "Charge input", "Invoice sending" and "Instruction from customers". From the three steps, the project team identified ten failure modes for key process inputs which are shown in Table 5.6. The presented FMEA method in this work was then used to identify the failure modes with high risk scores.

5.4.1 Establish a Pair-wise Comparison Decision Matrix and Calculate the Weight for Each Criterion

A brainstorming technique was used to evaluate the relative pair-wise comparison scores of the three criteria (S, O and D) from the team. The aggregate pair-wise comparison matrix is established in Table 5.7. The weight of each criterion is then calculated using Equation (5.2). The consistency of the judgements is checked. CR of the aggregate pair-wise comparison matrix is 0.0158 (below 5%), indicating a satisfactory degree of consistency (Table 5.7).

Table 5.6 Failure modes identified

No of Failures	Key Process Input	Failure Modes
1	Experience level of operator	inexperienced operator
2	Accurate quotation	wrong quotation
3	Wellbeing of operator	not well / personal problems
4	Clear information from port of loading (POL)	late/no information from POL
5	Working machine	fax machine break down
6	Volume of work of operator	too much work to do
7	Time of sending request	request sent after payment
8	Working machine	system break down
9	Accurate information from customers	wrong information from customer
10	Accurate tariff	wrong tariff

Table 5.7 Comparison matrix for FMEA criteria

	S	O	D	w_i
S	1	1.5	2	0.454
O	0.67	1	2	0.347
D	0.5	0.5	1	0.199

λ_{max} = 3.018, CI = 0.0091, CR =0.0158

5.4.2 Rule Establishment with a Rational Belief Structure

The belief degrees relating to each rule have been calculated using Equation (5.6). It is then further transformed into a subjective probability form using Equation (5.12). Consequently, a new rule base with a rational belief structure by taking into account different weights of the FMEA criteria is established and expressed in Table 5.8. The completed rule base is presented in Appendix 3.

Table 5.8 Sample of a new FMEA rule base with a rational belief structure

Failure	S 45.4%	O 34.7%	D 19.9%	Risk Level				
				VL	L	A	H	VH
F1	VL	VL	VL	100.00%	0.00%	0.00%	0.00%	0.00%
F2	VL	VL	L	80.10%	19.90%	0.00%	0.00%	0.00%
F3	VL	VL	A	80.10%	0	19.90%	0	0
F4	VL	VL	H	80.10%	0	0	19.90%	0
F5	VL	VL	VH	80.10%	0	0	0	19.90%
F6	VL	L	VL	65.30%	34.70%	0	0	0
…	…	…	…	…	…	…	…	…
F123	VH	VH	A	0.00%	0.00%	19.90%	0.00%	80.10%
F124	VH	VH	H	0.00%	0.00%	0.00%	19.90%	80.10%
F125	VH	VH	VH	0.00%	0.00%	0.00%	0.00%	100.00%

5.4.3 Use Subjective Judgements to Estimate the Failure Modes

To facilitate the failure evaluation data collection, the meaning of each grade/linguistic term used to describe the three FMEA criteria is defined in Table 5.9. It is noted that the numerical ranking values can be used to collect crisp estimations from the team members. The members participated in identifying the process inputs and assessing them against each criterion (*S, O, D*). Each member provided his/her individual assessment to the failure modes against each criterion. Four types of evaluations were received, including a single crisp number, a triangular fuzzy number, a trapezoidal fuzzy number and an interval. Taking one failure mode "inexperienced operator" as an example, the evaluations given by four members are listed in Table 5.10. The evaluations were then transferred to linguistic terms with belief degrees by using Equations (5.9) and Equation (5.10). The final belief degrees for each risk level of this failure were calculated by using Equation (5.8) in Table 5.11. As each member plays the same role in the process and they had similar working background, an equal weight was given to them in this study.

Table 5.9 Ratings for *S*, *O* and *D*.

Rank	**Grade**	**S**	**O**	**D**
10	Very high	Hazardous without warning	Failure is almost inevitable	Cannot detect
9		Hazardous with warning		Very remote chance of detection
8	High	Loss of primary function	Repeated failures	Remote chance of detection
7		Reduced primary function performance		Very low chance of detection
6	Average	Loss of secondary function	Occasional failures	Low chance of detection
5		Reduced secondary function performance		Moderate chance of detection
4	Low	Minor defect noticed by most customers	Relatively few failures	Moderately high chance of detection
3		Minor defect noticed by some customers		High chance of detection
2	Very low	Minor defect noticed by discriminating customers	Failure is unlikely	Very high chance of detection
1		No effect		Almost certain detection

Table 5.10 Expert subjective input for *S*, *O* and *D*

	S	*O*	*D*
Exp. 1	(6, 7, 8)	(6, 7, 8)	(6, 7, 8)
Exp. 2	100% High	50% High, 50% Av.	100% High
Exp. 3	(6, 7, 8)	(5, 6, 7)	(6, 7, 8)
Exp. 4	50% High, 50% Av.	100% Av.	100% High

Table 5.11 Belief degrees transformed from expert evaluations

	S	*O*	*D*
Exp. 1	(0, 0, 0.2, 0.8, 0)	(0, 0, 0.2, 0.8, 0)	(0, 0, 0.2, 0.8, 0)
Exp. 2	(0, 0, 0, 1, 0)	(0, 0, 0.5, 0.5, 0)	(0, 0, 0, 1, 0)
Exp. 3	(0, 0, 0.2, 0.8, 0)	(0, 0, 0.2, 0.8, 0)	(0, 0, 0.2, 0.8, 0)
Exp. 4	(0, 0, 0.5, 0.5, 0)	(0, 0, 1, 0, 0)	(0, 0, 0, 1, 0)
Final BD	$p(S_j) = (0, 0, 0.225, 0.775, 0)$	$p(O_i) = (0, 0, 0.475, 0.525, 0)$	$p(D_k) = (0, 0, 0.1, 0.9, 0$

5.4.4 Conduct the Risk Inference

Having transformed evaluation into the format of probabilities, the risk level of "in-experienced operator" can be calculated by using Equation (5.13) as:

$$p(R_h) = \sum_{j=1}^{5}\sum_{i=1}^{5}\sum_{k=1}^{5} p(R_h \mid S_j, O_i, D_k)p(S_j)p(O_i)p(D_k)$$

$$= p(Rh|S_3, O_3, D_3)p(S_3)p(O_3)p(D_3) + p(Rh|S_3, O_3, D_4)p(S_3)p(O_3)p(D_4) +$$

$$p(Rh|S_3, O_4, D_3)p(S_3)p(O_4)p(D_3) + p(Rh|S_3, O_4, D_4)p(S_3)p(O_4)p(D_4) +$$

$$p(Rh|S_4, O_3, D_3)p(S_4)p(O_3)p(D_3) + p(Rh|S_4, O_3, D_4)p(S_4)p(O_3)p(D_4) +$$

$$p(Rh|S_4, O_4, D_3)p(S_4)p(O_4)p(D_3) + p(Rh|S_4, O_4, D_4)p(S_4)p(O_4)p(D_4)$$

$$= (0, 0 ,1, 0, 0) \times 0.225 \times 0.475 \times 0.1 + (0, 0, 0.801, 0.199, 0) \times 0.225 \times 0.475 \times 0.9 +$$

$$(0, 0, 0.653, 0.347, 0) \times 0.225 \times 0.525 \times 0.1 + (0, 0, 0.454, 0.546, 0) \times 0.225 \times 0.525 \times 0.9$$

$$+$$

$$(0, 0, 0.546, 0.454, 0) \times 0.775 \times 0.475 \times 0.1 + (0, 0, 0.347, 0.653, 0) \times 0.775 \times 0.475$$

$$\times 0.9 +$$

$$(0, 0, 0.199, 0.801, 0) \times 0.775 \times 0.525 \times 0.1 + (0, 0, 0, 1, 0) \times 0.775 \times 0.525 \times 0.9$$

$$= (0, 0, 0.287, 0.713, 0)$$

The result shows that the risk level associated with the failure mode "inexperienced operator" is (0, 0, 0.287, 0.713, 0). It can be interpreted as that the risk level of "inexperienced operator" is very low with a subjective probability of 0, low with a subjective probability of 0, average with a subjective probability of 0.287, high with a subjective probability of 0.713 and very high with a subjective probability of 0.

The above calculation can be modelled using *Hugin* software, which is a general purpose tool for probabilistic graphical models such as Bayesian networks and influence diagrams (Madsen *et al.*, 2003). Taking the failure mode "inexperienced operator" as an example, the risk level has been modelled as shown in Figure 5.4.

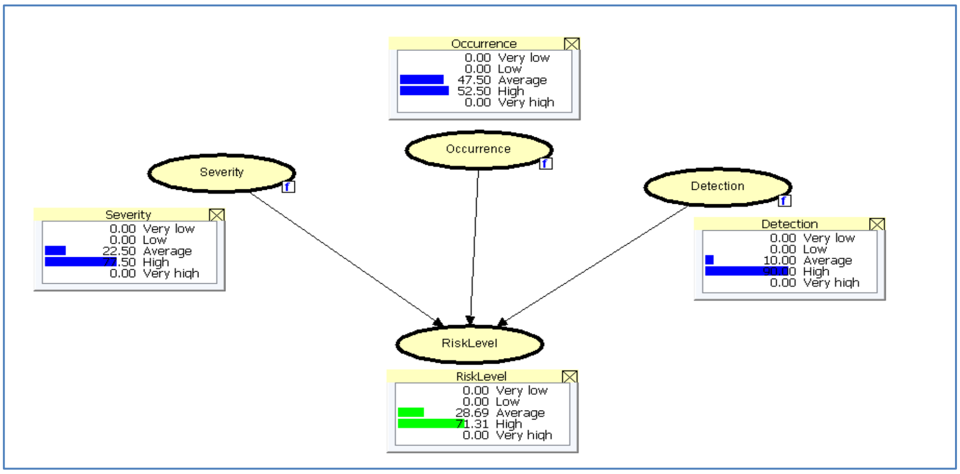

Figure 5.4 *Hugin* example

5.4.5 Prioritization of the Failures

For the purpose of prioritization of the failures, the risk level expressed by linguistic variables requires further analysis by assigning them appropriate utility values using Equation (5.14). For example, the failure priority/ranking index for "inexperienced operator" can be calculated as:

$$RI = \sum_{h=1}^{5} p(R_h) U_{Rh}$$

$$= 0 \times 1.788 + 0 \times 3.5 + 0.287 \times 5.5 + 0.713 \times 7.5 + 0 \times 9.222$$

$$= 6.93$$

In a similar way, the risk levels and RI values for all the other failure modes are calculated and shown in Table 5.12. The result shows that the failure modes of the highest risk levels are "inexperienced operator", "request sent after payment" and "too much work to do". Thus, appropriate quality improvement measures can be developed to reduce the unmatched payment effectively[3].

[3] This FMEA analysis was a part of a Six Sigma project for improving accounting management. The final result from the project proved the cost effectiveness of the developed improvement measures

Table 5.12 RI values for the failure modes identified

Failure Modes	**RI value**	**Risk ranking**
inexperienced operator	6.93	1
wrong quotation	6.14	4
not well / personal problems	6.03	6
late/no information from POL	6.06	5
fax machine break down	6.02	7
too much work to do	6.34	3
request sent after payment	6.52	2
system break down	5.47	9
wrong information from customer	5.71	8
Wrong tariff	5.45	10

Due to the fact that the failure modes identified in this FEMA study were the ones related to key inputs that were screened by C&E matrix prior to the FMEA study, the RI values are therefore close.

5.4.6 Validation of the Result

The accuracy of the result of the above analysis can be tested using sensitivity analysis described in Section 5.3.6. First, it is required to clarify the relationship between the risk levels of failure modes and the three criteria. The relationship, as shown in Table 5.3, can be described as that the risk level is higher if the levels of its *S*, *O* and *D* are higher. Next, a 10% (0.1) subjective probability is reassigned to each criterion, and moved toward the increment/decrement of the risk level of a failure mode. If the model reflects the logical reasoning, the risk level and RI values of the mode should increase/decrease accordingly. For example, if the 10% subjective probability of the Severity of the failure mode "in-experienced operator"

based on the successful identification of the failure modes of high risk levels.

decreasingly moves from “High” to “Very low”, then the RI value of the failure mode decreases from 6.93 to 6.18. Similar studies have been conducted for all the other failure modes and all the results obtained are in line with **Axiom 1** in Section 5.3.6.

From the above analysis, the effects of the minor input variation of the three criteria reveal that the RI values (output) are sensitively changed in a logical manner. However, the study does not well disclose the influence magnitude of the subjective probability changes with reference to the weights of criteria. To investigate such an influence magnitude, the change of a subjective probability with a step of 0.05 is given to test the influence magnitude of the corresponding RI values for each criterion. The result is observed and presented in a graphical form in Figure 5.5. It is clearly seen that the influence magnitudes of the subjective probability changes of each criterion to the RI values are significantly different and closely follow their individual assigned weights. If the rule base structure is reliable, then the influence magnitude to the RI values will follow the same weight ratio among the three criteria *S*, *O* and *D* which is 9:7:4 (45.4% : 34.7% : 19.9%). For example, 0.05 subjective probability changes from “High” to “Very low” in *S*, *O* and *D* for failure mode “inexperienced operator” produce the effects to RI values as 0.13 (=6.93-6.80), 0.1 (=6.93-6.83) and 0.06 (=6.93-6.87), respectively. It shows that the influence magnitude keeps harmony with the weight ratio. This is consistent with **Axiom 2** introduced in Section 5.3.6.

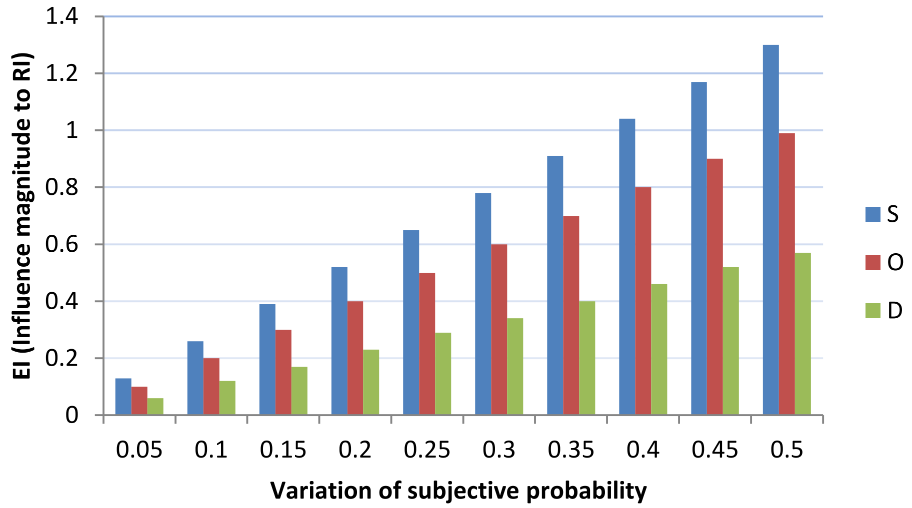

Figure 5.5 Sensitivity analysis

The rest of this section will analyse the effect of the combined variations from the three criteria to RI values. The combinations of the variations can be categorised in the following three groups.

1) Subjective probability variation of *S*, the subjective probability variation of *O*, and the subjective probability variation of *D*.

2) The combination of the subjective probability variations of *S* and *O*, the combination of the subjective probability variations of *S* and *D*, and the combination of the subjective probability variations of *O* and *D*.

3) The combination of the subjective probability variations of *S*, *O* and *D*.

The tests for this investigation are carried out by changing subjective probabilities for the failure mode of "inexperience operators" as an example. The change is 0.05 subjective probability variations from "High" to "Very Low" for all the criteria. The results of RI and associated EI (using Equation (5.15)) are shown as follows.

1) Variations from individual criteria

0.13 (=6.93-6.81) for variation of *S*

0.1 (=6.93-6.83) for variation of *O*, and

0.06 (=6.93-6.87) for variation of *D*

2) Variations from two criteria
   0.23 (=6.93-6.7) from combination of *S* and *O*.
   0.19 (=6.93-6.74) from combination of *S* and *D*.
   0.16 (=6.93-6.77) from combination of *O* and *D*.
3) Variations of three criteria
   0.29 (=6.93-6.64) from combination of *S*, *O* and *D*.

According to **Axiom 3**, if the model reflects the reality, then the influence magnitude of the combined variations of the three criteria to RI values will always be greater than the one of any two criteria, which in turn is greater than the one of each individual criterion. Comparing all the relevant inference magnitudes to RI values above (0.29 > any of (0.23, 0.19, 0.16), 0.29 > any of (0.13, 0.1, 0.06), 0.23> any of (0.13, 0.1), 0.19> any of (0.13, 0.06) and 0.16> any of (0.1, 0.06)), it is clear that for the investigation of this example, the model is sound. Furthermore, in a similar way, more investigations are conducted to prove the reliability of the model in a comprehensive manner.

5.5 Conclusion

FMEA is an important and popular tool used in Six Sigma. In view of its difficulties in application in the shipping industry, a revised FMEA using FuRBaR approach is proposed in this research. It can not only capture FMEA team members' diverse opinions under different types of uncertainties, but also consider the different weights of the criteria of FMEA. In this approach, fuzzy logic is combined with Bayesian reasoning in a complementary way where belief degrees are assigned to subjective judgement of linguistic variables. The Bayesian marginalization algorithm is used to conduct risk inference taking into considerations of the three criteria in FMEA (*S*, *O* and *D*). It therefore, not only improves the accuracy of FMEA but also, very importantly, maintains the easiness of FMEA.

The application of the proposed FMEA method was examined and illustrated through a real case study in a container shipping company. It showed that the proposed method provided a practical, effective and flexible way for risk evaluation in FMEA. For a particular unmatched payment scenario in accounting management, it has been identified that the failure modes of the highest risk levels are “too much work to do”, “inexperienced operator” and “request sent after payment”. The proposed method also offers great potential to be applied in other industries, especially those sectors in which failure data is unavailable or unreliable.

Chapter 6. Evaluating KPIs in Shipping Management by Using DEMATEL, ANP and ER

6.1 Introduction

Measuring performance in every aspect becomes an important part of today's business management. As one of the performance measurement instruments, KPIs are widely used in practice as a freestanding tool or a part of process improvement methodologies, such as Six Sigma.

KPIs are measures used to assess process performance in an organization which provides useful information for measuring progress towards the company goals, facilitating internal or external benchmarking and identifying inefficiencies in core business operations. Well defined KPIs also enable an organization to be able to measure the successes of projects and obtain data for future analysis.

It is found through the relevant literature review that KPIs are often defined as quantitative measures (Ahmad and Dhafr, 2002; Bose, 2006; Cheng *et al.*, 2011) and those used in the service functions of shipping companies are mostly presented by numerical data with a liner distribution. However, intangible performances with non-liner distributions also need to be measured where quantitative KPIs become inadequate, especially when human activities take a great part in the business performance. In the service industries, the most important dimensions for quality include: Time, Timelines, Completeness, Courtesy, Consistency, Accessibility and Convenience, Accuracy and Responsiveness (Radovic *et al.*, 2012). It is impossible to define all of them by using quantitative measures. Furthermore, qualitative KPIs can help managers to concentrate on an organisation's objectives rather than what can actually be measured. It is argued by many experienced consultants that an organization should deploy qualitative KPIs on starting a performance management process and add quantitative ones over time as more information is gathered and the process is being understood better. To measure qualitative performances, experts' subjective judgements based on linguistic terms are often used, which inevitably involve uncertainties and vagueness. It is difficult, if not impossible, to use a single score or ratio for capturing imprecision and vagueness inherent in a subjective assessment (Yang and Xu, 2002a). This is the main restriction for KPIs to be used for measuring qualitative performance.

KPIs are commonly presented in a hierarchical structure with the lower level indicators being grouped by their upper indicators or attributes (e.g. performance of teams, tasks and functions, etc.) and all indicators are presumed to bear the same weights without considering any interdependency in the evaluation process. In reality, KPIs measure performances that carry different priorities to the business objective. KPI accomplishment is a highly iterative process. It is common for accomplishment of one KPI to cause extra cost or effort for other KPIs, due to various reasons, such as incomplete information, limited resources, or communication barriers. It is difficult but necessary to identify the inter-relationships among different KPIs and the order of priorities for accomplishment of individual KPIs (Cai *et al.*, 2009). The management at a higher level makes decisions based on the high level attribute(s) which is/are assessed through the associated lower level indicators. In practice, qualitative data obtained from experts can be presented by any given linguistic grades, such as, (good, bad) or (low, high). Even quantitative data collected for KPIs may be measured in incomparable units, such as, "number of staff trained" may be presented as "10 per month" and the "rate of wrong invoices" could be "12%". In order to use KPIs as an effective tool for benchmarking purposes, outcomes from KPIs from different function areas or organizations need to be presented in a comparable way, which means the KPIs need to be synthesized into the same unit. It is commonly seen with quantitative KPIs that the average scores of lower level KPIs are used to obtain value to measure their upper level KPIs' performance in hierarchical structures. One of the drawbacks of scoring a subjective judgement as an average number is the possible loss of linkage between assessment and business-planning activities in complex decision situations (Yang *et al.*, 2001). Furthermore, different indicators may have different priorities or importance in the evaluation process, which is also affected by the existence of the interdependence among them. For example, cost may be considered to be more important than safety in the service functions of a shipping company, but the cost is affected by the safety. As safety precautions and measurements increase due to the change of legislation, the cost will increase. Therefore, to obtain a rational result from KPIs to assist decision making, weights of indicators need be defined to reflect their priorities in the whole system with consideration of interdependency among them, and the results of KPIs can be transformed into compatible units. The lack of studies in this subject has revealed a significant research gap to be filled.

This study therefore aims at developing a rigorous methodology for evaluating and synchronizing both qualitative and quantitative KPIs. In this method, DEMATEL and ANP methods are combined to produce the weights of indicators taking into consideration the existence of interdependence. Fuzzy logic and Evidential Reasoning (ER) are combined in a complementary way to synthesize both qualitative and quantitative data. In order to achieve this purpose, the DEMATEL, ANP methods and fuzzy ER approach are reviewed in section 2. The rest of the chapter is organized as follows. Section 3 describes the development of the new research methodology, followed by a case study in Section 4. Finally, the chapter is concluded in Section 5.

6.2 Literature Review

6.2.1 KPIs in the Shipping Industry

In order to ensure that the predetermined goal of a company can be achieved, monitoring is needed not only for the end results, but most importantly, inputs and every step of each process. KPIs provide a useful tool to serve such a purpose for organizations. They are most commonly utilized to measure actual performances against key success factors.

Shipping management has engaged in very limited systematic studies on standardization of KPIs. KPIs are developed within an organization without industry standardisation. Realizing the issue, InterManager initialized a shipping KPI project aiming to develop a standard industry measurement tool. The project received a great amount of support from the shipping industry. In 2011, shipping KPIs were officially launched. The applications of the results from standardising the performance measurements within the shipping industry are the Internal Improvement, Benchmarking, Performance Based Contracting and Building of Public awareness (Konsta and Plomaritou, 2012). However, all indicators identified have been quantified even for the ones of qualitative features, crisp numbers are used for the KPIs and average values are calculated to obtain final values. This method could cause loss of information during data collection and make it difficult to reflect true subjective evaluation in practice. Furthermore, the KPIs are not assigned associated weights to reflect their importance, nor given any consideration of interdependence within them which may have great impact on the outcome of final performance evaluation.

6.2.2 DEMATEL

The DEMATEL method, developed by the Geneva Research Centre of the Battelle Memorial Institute (Fontela and Gabus, 1976; Fontela and Gabus, 1973) is an effective tool to model and quantify the causal relations within a set of criteria. It has the ability to identify the interdependence among the factors within a system and determine the level of interdependence between them. It has therefore been used in many areas, to identify different factors for business needs (Shieh *et al.*, 2010; Fan *et al.*, 2012), analyse interrelated relationships within business (Wang and Tzeng, 2012), select suppliers (Dey *et al.*, 2012) and define relationships between KPIs (Cheng *et al*., 2011).

6.2.3 ANP

ANP is an attractive MCDM tool, which was proposed by Saaty in 1996. It is an extension of Analytical Hierarchy Process (AHP) and allows the consideration of interdependence among and between levels of attributes and alternatives. Different from AHP, ANP uses a network without the need to specify levels as in hierarchy. Figure 6.1 presents the differences between the structures of hierarchy and network. Hierarchy structure is a special case of a network system where weights are determined independently. ANP focuses on dependency among elements within the same cluster (inner dependency) and between different clusters (outer dependency) (Saaty, 2008) and provides a way to input judgments and measurements to derive ratio scale priorities for the distribution of influences among the factors and groups of factors in the decision. Outer dependence is the dependence between clusters but in a way to allow for feedback circuits. Inner dependence is the interdependence within a cluster combined with feedbacks between clusters (Saaty and Takizawa, 1986). ANP provides a tool to evaluate all the relationships systematically by adding all interactions, interdependences, and feedbacks in decision making systems (Zaim *et al.*, 2014).

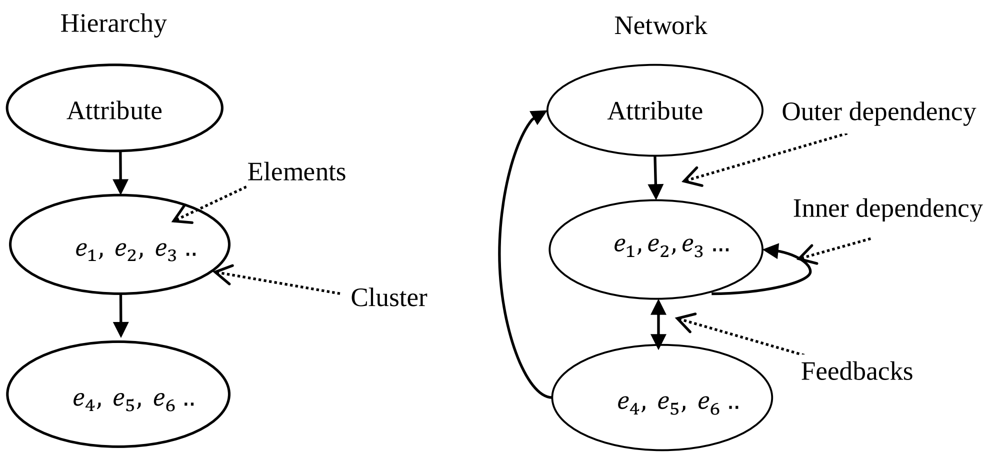

Figure 6.1 Hierarchy and Network

ANP has been highly appreciated due to the fact that many decision problems cannot be presented by a hierarchical structure because of the existence of interdependence. Its application can be found in a wide range of areas, such as analysing organizational project alternatives (Meade and Sarkis, 1999), R&D project selection (Meade and Presley, 2002), supplier selection (Gencer and Guerpinar, 2007), resource allocation in transportation (Wey and Wu, 2007), strategic e-business decision analysis (Raisinghani *et al.*, 2007) and many more. Literature also shows that ANP has often been used together with DEMATEL to determine the influencing weights for criteria (Chen, 2012; Vujanovic *et al*., 2012; Tsai and Hsu, 2010; Lee *et al*., 2011).

KPIs in organizations are not independent but highly influencing and with feedback relationships among them. The use of DEMATEL and ANP provides a path to effectively evaluate the importance of indicators and address the existence of inter-relationships. In an ANP method, not all indicators need to be pairwise compared, but only those that have a non-zero influence. For the others that do not have any interdependency, a zero value will be assigned. Therefore, the use of DEMATEL performs an accurate initial assessment for the upper level KPIs to identify their relationship of interdependency which can then be further narrowed down for the ANP analysis.

6.2.4 Fuzzy Logic and Evidential Reasoning (ER) Algorithm

Fuzzy logic was designed to deal with fuzziness in data. It is mostly applied using fuzzy *IF-THEN* rules (fuzzy rule-based system) derived from human knowledge. A fuzzy rule-based system allows the modelling of language-related uncertainties by providing a systematic procedure to transfer human knowledge and the reasoning process without the need of precise quantitative analysis. It uses a collection of fuzzy *IF-THEN* rules from human experts or domain knowledge and combines them into a single system. Many studies have combined the fuzzy rule-based system with other methodologies, such as neural network (Lin and Lee, 1991; Lee and Teng, 2000;

Mitra and Hayashi, 2000), generic algorithms (Ishibuchi *et al.*, 1995; Phillips *et al.*, 1996) and ER (Liu *et al.*, 2004; Dymova *et al.*, 2010) to take their combined advantages in dealing with uncertainty.

ER is a process of drawing plausible conclusions from uncertain or incomplete information (Yang *et al*., 2009b). It was developed based on Dempster-Shafer (D-S) theory in 1994 for dealing with multiple attribute decision analysis (MADA) problems (Yang and Singh, 1994). The kernel of the ER approach is an evidential reasoning algorithm developed on the basis of a multi-attribute evaluation framework and evidence combination rule of the D-S theory. The algorithm can be used to aggregate attributes of a multilevel structure (Yang and Xu, 2002b). It has been applied to many decision making problems, such as, vessel selection (Yang *et al*., 2009b), organizational self-assessment (Yang *et al*., 2001), roadside hazard severity indicator evaluation (Ayati *et al*., 2012) and general cargo ship design (Sen and Yang, 1995).

FER combines the two approaches, fuzzy logic and ER. It has developed itself as an established MADA method and is widely used to solve complex decision problems in various applications. For example, Yang *et al*. (2009c) used FER to synthesize evaluations for decision attributes in selecting security control options; Liu *et al*. (2011) applied FER in capturing and aggregating the diversified, uncertain assessment information given by team members during data collection for failure mode and effects analysis. FER is therefore adopted in this study to synthesise KPI evaluations in a meaningful way so that they can be confidently used to make decisions.

6.3 KPIs Management in the Shipping Industry by Using DEMATL, ANP and FER

The functionalities of KPIs can be fully utilized through systematic management.

KPIs are indicators measuring performances that need to be measured without considering the types of the data presenting them. A KPI tree is normally in a hierarchical structure. The top levels contain the KPIs that can assist top management to obtain a clear view of company overall performance and make decisions. The sub-levels KPIs or PIs are those used to measure the performances contributing to the attributes that are measured by the top level KPIs. A KPI tree contains as many levels as necessary until it reaches a point where users are confident to obtain and use adequate information or experience to provide the inputs for the indicators. In order to assess performances confidently through KPIs, their importance to the objective need to be determined and the information they provide are to be transformed into compatible units and subsequently synthesised. This can be achieved by the application of DEMATEL, ANP and FER methods. The proposed framework is presented in Table 6.2 and described as below.

6.3.1 Identify KPIs and PIs to Build a KPI Tree

Putting performance measurement in place could be a time and effort consuming task, especially when there is a lack of incentives and top management support. Many service functions of shipping companies may already have a certain number of indicators such as financial and sales indicators. There were no standard shipping KPIs that have been widely adopted in the industry. The shipping KPI project initiated by InterManager has provided an opportunity to develop standard industry measurements. However, those indicators are mainly focusing on the measurement of vessel operations instead of service functions. For shipping management companies, it is a crucial task to identify indicators that can be used to effectively measure their service performance.

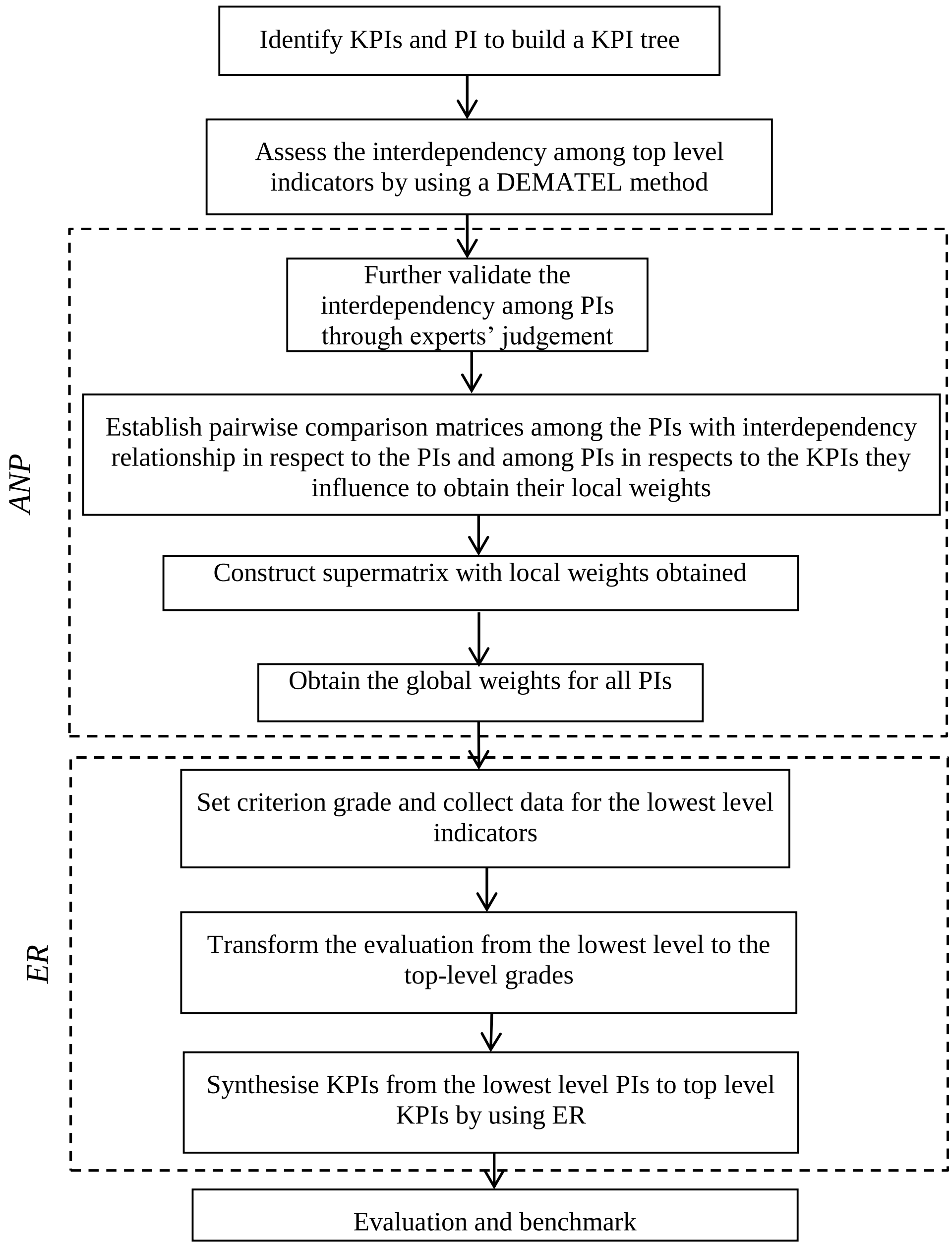

Figure 6.2 Proposed framework for KPI management

A vast number of studies in KPI identification and selection can be found in the literature. Hubner-Bloder and Ammenwerth (2009) used Delphi to gather experts' opinions to select the most suitable KPIs for hospital information systems benchmarking; Alwaer and Clements-Croome (2010) chose the most appropriate indicators for assessing sustainable intelligent buildings by carrying out literature reviews and surveys with a number of professionals; Zheng *et al.* (2009) developed a performance measurement indicator system by adopting a framework from previous studies and validate the KPIs through surveys and interviews for technological innovation of a firm; Cheng *et al*. (2011) applied the Delphi method to obtain KPIs and their dimensions and mind map to draw a KPI framework for new product development; McCance *et al.* (2012) identified KPIs for nursing and midwife care by using workshop and consensus. All those methods can be used to effectively identify indicators and construct KPI trees.

6.3.2 Assess the Interdependencies of the Top Level Indicators using DEMATEL

The application of DEMATEL is to identify interdependencies among the top level indicators to narrow down the amount of pairwise comparison that needs to be conducted in the ANP method when prioritising KPIs. The method can be summarized as follows:

Step 1: Compute the average matrix (*M*)

Suppose there are *n* indicators under the same objective or another indicator on a KPI tree and there are *G* experts who provide evaluation of the direct influence between any two indicators. Respondents are asked to indicate the degree of direct influence one indicator *i* exerts on another indicator *j*. The evaluation is based on the scale of 0, 1, 2, 3, 4, which represent "no influence", "low influence", "medium influence", "high influence" and "extremely high influence" respectively. A higher score from a respondent indicates a belief that insufficient involvement in the problem of indicator *i* exerts a stronger possible direct influence on the inability of indicator *j*, or, in positive terms, that greater improvement in indicator *i* is required to improve indicator *j* (Tzeng *et al.*, 2007). The notation of $x_{(ij)}$ indicates the degree to which the expert believes the *i*th indicator affects the *j*th indicator. For $i = j$, the diagonal elements are set to zero. A $n \times n$ matrix for the evaluation of each expert (x_{ij}^{g}) can be established as $X^{g} = [x_{ij}^{g}]$, where g is the *g*th of the expert with $1 \leq$ g

≤G. Thus, X^1, $X^2, X^3 \ldots X^G$ are the matrices from *G* experts. The average matrix $M = [m_{ij}]$ can be constructed as below.

$$M = \left[m_{ij}\right] = [\frac{1}{G}\sum_{g=1}^{G} x_{ij}^{g}] \qquad i = (1, 2, \ldots n), j = (1, 2, \ldots n)$$

Step 2: Normalize the average matrix (*M*) and obtain the normalized direct relation matrix (*D)*

The normalized direct-relation matrix *D* can be obtained by equation (6.1).

$$D = M \times S \tag{6.1}$$

where $S = Min[\frac{1}{max_{1 \le i \le n} \sum_{j=1}^{n} m_{ij}}, \frac{1}{max_{1 \le i \le n} \sum_{i=1}^{n} m_{ij}}]$. Each element in matrix *D* falls between zero and one.

Step 3: Calculate the total relation matrix (*T*)

The total relation matrix *T* is obtained by using Equation (6.2).

$$T = \left[t_{ij}\right]_{n \times n} = \lim_{m=\infty}(D^1 + D^2 + \cdots + D^m) \\ = \sum_{m=1}^{\infty} D^i = D(I - D)^{-1} \tag{6.2}$$

where *I* is the identity matrix and total relation matrix can be presented as below.

$$\left[t_{ij}\right]_{n \times n} = \begin{bmatrix} t_{11} \cdots & t_{1j} & \cdots & t_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ t_{i1} \cdots & t_{ij} & \cdots & t_{in} \\ \vdots & \vdots & \vdots & \vdots \\ t_{n1} \cdots & t_{nj} & \cdots & t_{nn} \end{bmatrix}$$

Step 4: Calculate the sums of rows and columns of the total relation matrix (*T*)

Let *r* and c be the sum of rows and sum of columns of the total relation matrix *T*, respectively. Suppose that r_i represents the sum of *i*th row and c_j denotes the sum of *j*th column, then the value of r_i indicates the effects given by indicator *i* to the other indicators (Equation (6.3)) and c_j shows effects received by indicator j from the other indicators (Equation (6.4)) both directly and indirectly. When $i = j$, the sum $(r_i + c_j)$ illustrates the total effects given and received by indicator i, and $(r_i - c_j)$ indicates the net effect that indicator *i* contributes to the system. $(r_i + c_j)$ indicates the degree of importance that factor *i* plays in the system. Moreover, if $(r_i - c_j)$ is positive, indicator *i* is a net cause, while indicator *i* is a net receiver or result if $(r_i - c_j)$ is negative (Liou *et al*., 2007).

$$r_i = \sum_{j=1}^{n} t_{ij} \qquad (i = 1,2, \ldots\ldots, n) \tag{6.3}$$

$$c_j = \sum_{i=1}^{n} t_{ij} \qquad (j = 1, 2, \ldots\ldots, n) \tag{6.4}$$

Step 5: Set threshold value *(α)* and obtain the impact relations-map (IRM).

Setting a threshold value *(α)* is to filter out those indicators that only have negligible effects so that the indicators bearing considerable effects can be clearly identified for effective decision making. Only factors with effect greater than the threshold value should be chosen and shown in an impact-relations-map (IRM) or causal diagram (Tang *et al*., 2007). The values that are lower than the threshold will be set to zero in the total relation matrix (*T*). The threshold value can be obtained through either subjective judgement from experts (Gwo-Hshiung *et al.*, 2007) or mathematical calculation (Wu and Tsai, 2012). The mathematical method is adapted to obtain the threshold value in this study, which is calculated by the average value of t_{ij} in matrix T (Equation (6.5))

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij}}{N} \tag{6.5}$$

where *N* is the total number of elements $(n * n)$ in the matrix *T*. Any value lower than α in matrix T is considered to be zero to construct the matrix T^{α}.

The IRM is constructed and presents the relationship based on the matrix T^{α}**.** The IRM visualizes the interdependency relationship among indicators.

The same processes start with the top level indicators so that only those lower level indicators which have been identified with the possibility of influencing or being influenced by other indicators need to be further analysed.

6.3.3 Obtain Lower Level Indicator Weights by using the ANP Method

After the interdependencies among the top level indicators are identified by DEMATEL, the indicators in the group of those top level indicators need to be reviewed to identify the interdependency relationship among them. This can be done by group discussion with experts. Through this activity, the lowest level indicators with interdependency can be confirmed. ANP calculation can then be utilized to analyse their interdependencies and obtain the local weights for indicators.

Step 1: Establish pairwise comparisons matrices (*A*) for all indicators and obtain local weights

The relative importance values for all indicators with interdependencies need to be obtained through pairwise comparisons. The pairwise comparison matrices are constructed among the top level indicators and indicators under the same top level indicator. The respondents need to answer the questions such as: "Given an indicator and its upper level indicator or objective, which of the two indicators influences the given indicator more with respect to the upper level indicator or objective, and how much more than another indicator?". The responses are presented numerically, scaled on the basis of Saaty's 1-9 scale where 1 presents indifference between the two indicators and 9 stands for overwhelming dominance of the indicator under consideration (row indicator) over the comparison indicator (column indicator) in a pairwise comparison matrix. Suppose there are *m* indicators to be compared in a matrix, let $e_1, e_2, \dots, e_m$ denote the different indicators, where $a_{(ij)}$ represents the level of influences that the respondent believes when indicator e_i is compared with e_j. When scoring is conducted for a pair, a reciprocal value is automatically assigned to the reverse comparison within the matrix.

$$A = a_{(ij)} = \begin{array}{c} \\ e_1 \\ e_2 \\ \vdots \\ e_i \\ \vdots \\ e_m \end{array} \begin{array}{c} \begin{array}{cccccc} e_1 & e_2 & \cdots & e_j & \cdots & e_m \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2j} & \cdots & a_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} & \cdots & a_{im} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mj} & \cdots & a_{mm} \end{bmatrix} \end{array} \qquad (6.6)$$

where $a_{(ij)} = 1$ if $i = j$; $a_{(ij)} = \frac{1}{a_{ji}}$, $i = (1, 2, \dots m)$ and $j = (1, 2, \dots m)$

Once the pairwise comparisons are completed, the local priority vectors can be obtained by dividing each element in a column by the sum of the column elements and then summing the elements in each row of the resultant matrix and dividing by the number of elements in the row (Meade and Sarkis, 1999). This is presented by Equation (6.7).

$$w_k = \frac{1}{m} \sum_{j=1}^{m} \frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \qquad k = (1, 2, \dots m) \qquad (6.7)$$

where, w_k is the priority vector of a specific indicator k in the pairwise comparison matrix. Its value is a part of the supermatrix in the later steps.

Step 2: Form unweighted supermatrix

ANP uses supermatrix for a resolution of the effects of the interdependence that exists between the elements of the system (Meade and Sarkis, 1999). The elements of the supermatrix are imported from the pairwise comparison matrices of interdependencies (step 1). A supermatrix with an example of one of its general entry matrices is shown as Equation (6.8)

$$
W = \begin{array}{c c} & \begin{array}{c c c c c} C_1 & \cdots & C_j & \cdots & C_n \\ e_{11} \cdots e_{1m_1} & \cdots & e_{j1} \cdots e_{jm_j} & \cdots & e_{n1} \cdots e_{nm_n} \end{array} \\ \begin{array}{c c} C_1 & \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ e_{1m_1} \end{array} \\ \vdots & \\ C_i & \begin{array}{c} e_{i1} \\ e_{i2} \\ \vdots \\ e_{im_i} \end{array} \\ \vdots & \\ C_n & \begin{array}{c} e_{n1} \\ e_{n2} \\ \vdots \\ e_{nm_n} \end{array} \end{array} & \begin{bmatrix} W_{11} & \cdots & W_{1j} & \cdots & W_{1n} \\ \vdots & & \vdots & & \vdots \\ W_{i1} & \cdots & W_{ij} & \cdots & W_{in} \\ \vdots & & \vdots & & \vdots \\ W_{n1} & \cdots & W_{nj} & \cdots & W_{nn} \end{bmatrix} \end{array} \tag{6.8}
$$

where C_n denotes the *n*th cluster (top level indicator or objective), e_{nm} represents the *m*th indicator in the *n*th cluster, and W_{ij} is the principal eigenvector of the influence of the indicators in the *j*th cluster compared to the *i*th cluster. If *j*th cluster has no influence on the *i*th cluster, then $W_{ij} = 0$. W_{ij} (Figure 6.3) represents the values of priority vectors of indicators from the cluster C_i in relation to elements from the cluster C_j which were derived from step 1.

$$
W_{ij} = \begin{vmatrix} w_{i1}^{j1} & w_{i1}^{j2} & \dots & w_{i1}^{jm_j} \\ w_{i2}^{j1} & w_{i2}^{j2} & \dots & w_{i2}^{jm_j} \\ \vdots & \vdots & \vdots & \vdots \\ w_{im_i}^{j1} & w_{im_i}^{j2} & \dots & w_{im_i}^{jm_j} \end{vmatrix}
$$

Figure 6.3 i, j block of a supermatrix in ANP

Step 3: Obtain weighted supermatrix

The weighted supermatrix can be obtained through multiplying the priority vectors of each element in the un-weighted supermatrix with the priority vectors of the corresponding clusters (both were calculated in step 1).

Step 4: Calculate the global weights with the limiting supermatrix

The super-matrix is made to converge to obtain a long-term stable set of weights. This is achieved by multiplying the weighted suprematrix itself multiple times to obtain the limiting supermatrix (limiting weighted supermatrix). In other words, the weighted supermatrix is raised to the *k*th power, where *k* is an arbitrarily large number, until it becomes a stable supermatrix in order to obtain the global priority-influential vectors, also called the global weights.

The lengthy and complex calculation of ANP can be eased by the use of the computer software - “Super decisions”. By creating relationships among indicators and inputting the original evaluations from the pairwise comparison matrices in the software, the global weight can be obtained directly.

6.3.4 Set Criterion Grade and Collect Data for the Lowest Level Indicators

Before data collection, corresponding grades are required to be given to all indicators for experts’ assessments using either objective data or subjective judgement. For indicators with qualitative data input, various sets of linguistic terms are defined to reflect the nature of the criteria. For example, a set of linguistic terms (Very satisfied, satisfied, average, unsatisfied, extremely unsatisfied) can be used to categorize the evaluation of the indicator “customer satisfaction”. For those indicators with quantitative data, numerical grades can be used, For instance, the evaluation grades for the percentage of late deliveries per week could be described as “Very poor” if the rate is more than 20%, “Poor” if the rate is 15%, “Average” if the rate is 10%, “Good” if the rate is 5% and “Very Good” if the rate is “0%”. The setting of the grades can be based on experts’ opinion, historical data and/or organizations’ objectives/expectations. When utilizing historical data for the grade setting, values for the two grades (i.e. the most and least prepared) need to be firstly determined through the data available. The values for the most preferred rating and the least preferred rating are represented by the best and worst records among the data. The grade setting can also be conducted by any other grade that is known or can be determined, e.g. a target value or average value. Suppose there are N evaluation grades to assign the numerical values to and the values for the already known two grades are presented by v_h and v_l, where $1 \leq l < h \leq N$. The values for the in-between grades (v_n) can then be calculated by using a linear distribution in Equations (6.9) and (6.10).

$$v_n = v_{n+1} - \left(\frac{v_h - v_l}{h - l}\right) \quad if\, v_l < v_n < v_h \quad 1 \leq n \leq N - 1 \tag{6.9}$$

$$v_n = v_{n-1} + \left(\frac{v_h - v_l}{h - l}\right) \quad if\, v_l > v_n > v_h \quad 2 \leq n \leq N \tag{6.10}$$

6.3.5 Transform the Evaluation from the Lowest Level to Top Level Grades

Raw data collected for indicators could be in different formats and grades. In order to execute further analysis and assessment, the grades defined need to be transformed into the same form. The transformation is carried out by establishing fuzzy rule bases based on experts' experience and/or organization objectives/expectations.

For example, assume that the indicator "Elapsed time between shipping instruction & Bill of Lading issue" has its upper level indicator "Team performance" and top level KPI "company competitiveness" in a KPI tree. The top level KPI "Company competitiveness (C)" can be described linguistically in terms of "Very competitive (C1)", "Fairly competitive (C2)", "Average (C3)" and "Not competitive (C4)". The indicator "Team efficiency (T)" can be expressed using linguistic terms as "Very Good (T1)", "Good (T2)", "Average (T3)", "Poor (T4)" and "Very poor (T5)". The linguistic terms used to assess the indicator "Elapsed time between shipping instruction & Bill of Lading issue (E)" are "less than 2 days (E1)", "3 days (E2)", "4 days (E3)" and "more than 5 days (E4)". A fuzzy rule base belief structure between the linguistic terms expressing the indicators at three levels can be generated for the transformation from fuzzy input to output as shown below.

R_1: IF "Elapsed time between shipping instruction & Bill of Lading issue (E)" is "less than 2 days (E1)", then "team performance (T)" is "Very Good (T1)" with 100% degree of belief.

It can be simplified as:

R_1: IF *E1, then 100% T1.*

Similarly,

R_2: IF *E2, then75% T2 and 25% T3.*

R_3: IF *E3, then 50% T3 and 50% T4.*

R_4: IF *E4, then 25% T4 and 75% T5.*

R_5: IF *T1, then 100% C1.*

R_6: IF *T2, then 25% C1 and 75% C2.*

R_7: IF *T3, then 15% C2 and 85% C3.*

R_8: IF *T4, then 15% C3 and 85% C4.*

R_9: IF *T5, then 100% C4.*

Through this method, the "Elapsed time between shipping instruction & Bill of Lading issue" can be transformed onto "Company competitiveness". For example, if the Elapsed time between shipping instruction & Bill of Lading issue for a company is 4 days, according to R_3, it can be described as 50% T3 and 50% T4. Based on R_7 and R_8, It can then be converted into (7.5% C2 and 42.5% C3) and (7.5% C3 and 42.5% C4), respectively. Consequently, it equals to 7.5% C2, 50% C3 and 42.5% C4.

6.3.6 Synthesise Indicators from the Lowest Level PIs to Top Level KPIs by using an ER Algorithm

Once the transformation from the lowest level to the top level indicators is completed, the information can then be utilized in the ER algorithm which can be explained as follows (Yang and Xu, 2002b).

Suppose there is a two level hierarchy structure - a parent level KPI E consists of L indicators at the children level which include all the indicators influencing the assessment of the KPI E. Indicators can be represented as

$E = (e_1, e_2, \ldots e_i, \ldots e_L)$.

The weight of each indicator was obtained in section 6.3.3 and can be expressed as $w = (w_1, w_2, \ldots w_i \ldots w_L)$. w_i is the normalized relative weight for indicator i where $0 \leq w_i \leq 1$ and $\sum_{i=1}^{L} w_i = 1$.

Let N present the number of evaluation grades, Each H_n $(n = 1,2, \ldots N)$ is a standard grade for assessing an indicator for a top level KPI. Evaluations for all the indicators obtained in section 6.3.4 were transformed to the standard grades through the technique in section 6.3.5. Let A_i represent the transformed evaluation for indicator e_i. The evaluations can then be presented as follows:

$$A_i = [(H_n, \beta_{n,i}), n = 1,2, \ldots N] \tag{6.11}$$

where $\beta_{n,i}$ is the degree of belief associated with the evaluation grade H_n for the indicator e_i and $\sum_{i=1}^{L} \beta_{n,i} \leq 1$. When all H_n are defined by crisp numbers, an evaluation given in the format of a crisp number can be transformed into the relevant grades with the associated belief degrees through Equation (6.12).

$$\beta_{n,i} = \frac{v_{g,i} - v_{m,i}}{v_{n,i} - v_{m,i}}$$
$$\beta_{m,i} = 1 - \beta_{n,i} \tag{6.12}$$
$$(v_{n,i} \geq v_{g,i} \geq v_{m,i}), (n = 1,2, \ldots N), (m = 1,2, \ldots N)$$

where $\beta_{m,i}$ denotes to the degree of belief associated with the evaluation grade H_m for the indicator e_i; $v_{g,i}$ represents the evaluation given to the indicator e_i; $v_{n,i}$ is the grade value that is higher than or equal to the evaluation ($v_{g,i}$) and $v_{m,i}$ stands for the grade value that is lower or equal to the evaluation ($v_{g,i}$).

The basic probability assignments for each indicator can then be calculated as below.

Let $m_{n,i}$ be a basic probability mass representing the degree to which the *i*th indicator supports the hypothesis that the parent level indicator is assessed to the *n*th evaluation grade. Then $m_{n,i}$ can be obtained as follows:

$$m_{n,i} = w_i \beta_{n,i} \qquad (n = 1,2, \dots N) \tag{6.13}$$

Let $m_{H,i}$ be the remaining probability mass unassigned to any individual grade after e_i has been assessed. $m_{H,i}$ can be calculated as follows:

$$m_{H,i} = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - w_i \sum_{n=1}^{N} \beta_{n,i} \qquad (i = 1,2 \dots L) \tag{6.14}$$

$m_{H,i}$ can be decomposed into $\bar{m}_{H,i}$ and $\tilde{m}_{H,i}$, where $\bar{m}_{H,i}$ represents the remaining probability mass that other indicators (apart from *i*th indicator) can play in the assessment. $\tilde{m}_{H,i}$ is the unassigned probability mass due to the possible incompleteness in the assessment. They can be expressed as follows:

$$\bar{m}_{H,i} = 1 - w_i \text{ and } \tilde{m}_{H,i} = w_i(1 - \sum_{n=1}^{N} \beta_{n,i}) \tag{6.15}$$

$m_{H,i}$ can therefore be presented as:

$$m_{H,i} = \bar{m}_{H,i} + \tilde{m}_{H,i} \tag{6.16}$$

The probability assignment for an indicator can be combined by using the following. Let $m_{n,I(1)} = m_{n,1}$ $(n = 1,2, \dots N)$, $\bar{m}_{H,I(1)} = \bar{m}_{H,1}$, $\tilde{m}_{H,I(1)} = \tilde{m}_{H,1}$ and $m_{H,I(1)} = m_{H,1}$. A factor $K_{I(i+1)}$ is used to normalize $m_{n,I(i+1)}$ and $m_{H,I(i+1)}$ so that $\sum_{n=1}^{N} m_{n,i} + m_{H,I(i+1)}$ =1.

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq t}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1} \quad (i = 1,2 \ldots L-1) \tag{6.17}$$

The combined probability assignments $m_{n,I(L)}$ $(n = 1,2, \ldots N)$, $\bar{m}_{H,I(L)}$, $\tilde{m}_{H,I(L)}$ and $m_{H,I(L)}$ can be generated as follows.

$\{H_n\}$:

$$m_{n,I(i+1)} = K_{I(i+1)}[m_{n,I(i)} m_{n,i+1} + m_{H,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1}] \tag{6.18}$$

$\{H\}$:

$$\begin{aligned} m_{H,I(i)} &= \tilde{m}_{H,I(i)} + \bar{m}_{H,I(i)} \\ \tilde{m}_{H,I(i+1)} &= K_{I(i+1)}[\tilde{m}_{H,I(i)} \tilde{m}_{H,i+1} + \bar{m}_{H,I(i)} \tilde{m}_{H,i+1} + \tilde{m}_{H,I(i)} \bar{m}_{H,i+1}] \\ \bar{m}_{H,I(i+1)} &= K_{I(i+1)}[\bar{m}_{H,I(i)} \bar{m}_{H,i+1}] \end{aligned} \tag{6.19}$$

The combined degrees of belief of all the indicators for the assessment to the KPI E can then be calculated. Let β_n denote a degree of belief that the KPI is assessed to the grade H_n, which is generate by combining the assessments for all the associated indicators e_i, $(i = 1,2 \ldots L)$. β_n can be calculated by:

$$\begin{aligned} \{H_n\}&: \beta_n = \frac{m_{n,I(L)}}{1 - \bar{m}_{H,I(L)}} \quad (n = 1,2, \ldots N) \\ \{H\}&: \beta_H = \frac{\tilde{m}_{H,I(L)}}{1 - \bar{m}_{H,I(L)}} \end{aligned} \tag{6.20}$$

The overall assessment for the KPI E can be represented by Equation (6.21)

$$S(E) = (H_n, \beta_n) \quad (n = 1,2, \ldots N) \tag{6.21}$$

Suppose the utility of an evaluation grade H_n is denoted by $u(H_n)$ and $u(H_{n+1}) > u(H_n)$ if H_{n+1} is preferred to H_n (Yang and Xu, 2002a). The expected utility of the top level KPI, $u(E)$ can be calculated as:

$$u(E) = \sum_{n=1}^{N} \beta_n u(H_n) \tag{6.22}$$

The utility value of each linguistic term $u(H_n)$ is obtained in a linear manner through using Equation (6.23).

$$u(H_n) = \frac{V^n - V_{min}}{V_{max} - V_{min}} \tag{6.23}$$

where V_{max} is the ranking value of the most preferred linguistic term, V_{min} is the ranking value of the least preferred linguistic term and V^n is the ranking value of the linguistic term considered.

When several parent level KPIs need to be compared, the above process can be repeated to obtain the estimates for those parent level performance indicators. Once the utility values for the top level KPIs are calculated, they can then be benchmarked. E_l is said to be preferred to E_k if $u(E_l) > u(E_k)$.

The whole process of ER calculation can be performed by using an ER calculation software package which is called Intelligent Decision System via Evidential Reasoning, or IDS (Yang and Xu, 2002b).

6.4 A Case Study of KPI Tree Management in a Shipping Management Company

A world leading shipping management company established a performance monitoring programme by using KPIs in order to monitor and measure its current performance, and to compare performances between different function areas and different periods of time. The indicators that are important to the company objective are identified. Table 6.1 displays the pre-established KPI tree structure containing all the indicators at the KPIs (upper) and PIs (lower) levels.

Table 6.1 KPI tree structure

Objective	KPI	PI
Company overall performance	(A) Health and Safety Management & Performance	A1) Lost time injury rate
		A2) Total recordable case frequency
		A3) Near miss reports received
	(B) Quality Assurance	B1) Overdue NCNs
		B2) Overdue NCNs longer than 1 month
		B3) Overdue audits - office
		B4) Overdue SHEQ audits - ships
	(C) Environmental Performance	C1) Contained spillage
		C2) Pollution incidents
		C3) Port authority environmental violations
		C4) Suppliers with ISO 14001 accreditation
	(D) HR Management Performance	D1) Crew retention
		D2) Office staff retention
	(E) Operational Performance	E1) Unscheduled downtime. Out of service - offshore
		E2) Unscheduled downtime. Out of service - marine
		E3) Overdue vessel technical inspections
		E4) Port state detentions
	(F) Technical Performance	F1) Outstanding PM items
	(G) Purchasing & Accounting Performance	G1) Outstanding invoices not approved for payment (NAPS)
		G2) Purchasing feedback reports

6.4.1 Assess the Interdependencies of the KPIs Using DEMATEL

A questionnaire was designed for the evaluation of influencing levels among all KPIs. The questionnaire contains seven comparison tables. Each comparison table requires the appraiser to provide the judgement of the degree of influence of each KPI listed in the column to the target KPI list on the top row of the table. Table 6.2 is a table from the questionnaire to investigate the degree of influences that all other KPIs have in regards to the target KPI (A) Health and Safety Management & Performance. The same questionnaire tables are designed for the rest of KPIs. The detailed questionnaire can be found in Appendix 4.

Table 6.2 Evaluation table for the degree of influences

Degree of influence that each of the following KPI directly has on the target KPI: (A)Health and Safety Management & Performance					
KPI	**Degree of influence** 0: No influence, 1:Low influence 2:Medium influence: 3: High influence 4:Very high influence				
	0	1	2	3	4
(B) Quality Assurance					
(C) Environmental Performance					
(D) HR Management Performance					
(E) Operational Performance					
(F) Technical Performance					
(G) Purchasing & Accounting Performance					

Data is gathered through the responses of the questionnaires for the DEMATEL study.

Step 1: Compute the average matrix (*M*)

The matrix $M = [m_{ij}]$ is constructed based on the data collected as below:

$$M = [m_{ij}] = \begin{bmatrix} 0 & 2 & 2 & 2 & 4 & 2 & 1 \\ 2 & 0 & 4 & 3 & 4 & 3 & 3 \\ 2 & 3 & 0 & 2 & 2 & 4 & 1 \\ 1 & 2 & 0 & 0 & 1 & 2 & 2 \\ 2 & 4 & 3 & 0 & 0 & 2 & 1 \\ 2 & 3 & 3 & 1 & 2 & 0 & 1 \\ 1 & 3 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

Step 2: Normalize the average matrix (*M*) and obtain the normalized direct relation matrix (*D)*

$$S = Min\left[\frac{1}{max_{1\le i\le n}\sum_{j=1}^{n} m_{ij}}, \frac{1}{max_{1\le i\le n}\sum_{i=1}^{n} m_{ij}}\right] = Min\left[\frac{1}{17}, \frac{1}{19}\right] = 0.0526$$

The relation matrix (D) can then be calculated by using Equation (6.1).

$$D = M \times S = \begin{bmatrix} 0 & 2 & 2 & 2 & 4 & 2 & 1 \\ 2 & 0 & 4 & 3 & 4 & 3 & 3 \\ 2 & 3 & 0 & 2 & 2 & 4 & 1 \\ 1 & 2 & 0 & 0 & 1 & 2 & 2 \\ 2 & 4 & 3 & 0 & 0 & 2 & 1 \\ 2 & 3 & 3 & 1 & 2 & 0 & 1 \\ 1 & 3 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \times 0.0526$$

$$= \begin{bmatrix} 0 & 0.105 & 0.105 & 0.105 & 0.211 & 0.105 & 0.053 \\ 0.105 & 0 & 0.211 & 0.158 & 0.211 & 0.158 & 0.158 \\ 0.105 & 0.158 & 0 & 0.105 & 0.105 & 0.211 & 0.053 \\ 0.053 & 0.105 & 0 & 0 & 0.053 & 0.105 & 0.105 \\ 0.105 & 0.211 & 0.158 & 0 & 0 & 0.105 & 0.053 \\ 0.105 & 0.158 & 0.158 & 0.053 & 0.105 & 0 & 0.053 \\ 0.053 & 0.158 & 0.053 & 0.053 & 0.053 & 0.053 & 0 \end{bmatrix}$$

Step 3: Calculate the total relation matrix (*T*)

The total relation matrix *T* is obtained by following Equation (6.2).

$$T = D(I - D)^{-1} = \begin{bmatrix} 0.178 & 0.377 & 0.333 & 0.247 & 0.421 & 0.335 & 0.205 \\ 0.337 & 0.386 & 0.499 & 0.35 & 0.501 & 0.467 & 0.351 \\ 0.289 & 0.438 & 0.26 & 0.267 & 0.358 & 0.442 & 0.221 \\ 0.158 & 0.267 & 0.152 & 0.098 & 0.199 & 0.238 & 0.197 \\ 0.278 & 0.46 & 0.389 & 0.172 & 0.253 & 0.345 & 0.21 \\ 0.268 & 0.407 & 0.373 & 0.208 & 0.334 & 0.239 & 0.203 \\ 0.168 & 0.321 & 0.211 & 0.16 & 0.214 & 0.211 & 0.11 \end{bmatrix}$$

Step 4: Calculate the sums of rows and columns of the total relation matrix (*T*)

The degree of importance for each KPI is calculated through Equations (6.3) and (6.4) and is shown in Table 6.3.

Table 6.3 Degree of importance through DEMATEL

	r + c	***r - c***
A	3.773	0.42
B	5.545	0.236
C	4.492	0.057
D	2.808	-0.19
E	4.387	-0.17
F	4.308	-0.24
G	2.89	-0.1

With the highest $(r_i + c_j)$ value, KPI B plays higher importance than the others in the whole KPI system where KPI D is least important with the lowest $(r_i + c_j)$ value. KPI A, B and C are act as net causes ($(r_i - c_j)$ >0), while KPI D, E, F and G are net receivers ($\left(r_i - c_j\right) < 0$).

Step 5: Set threshold value *(α)* and obtain the impact relations-map (IRM).

By using Equation (6.5), the threshold value is obtained as $\alpha = 0.28778$. The values below α are set to zero and the total relation matrix T with α cut is changed to matrix T^{α} and is shown as below:

$$T^{\alpha} = \begin{bmatrix} 0 & 0.377 & 0.333 & 0 & 0.421 & 0.335 & 0 \\ 0.337 & 0.386 & 0.499 & 0.35 & 0.501 & 0.467 & 0.351 \\ 0.289 & 0.438 & 0 & 0 & 0.358 & 0.442 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.46 & 0.389 & 0 & 0 & 0.345 & 0 \\ 0 & 0.407 & 0.373 & 0 & 0.334 & 0 & 0 \\ 0 & 0.321 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The IRM is derived from DEMATEL and is shown in Figure 6.4.

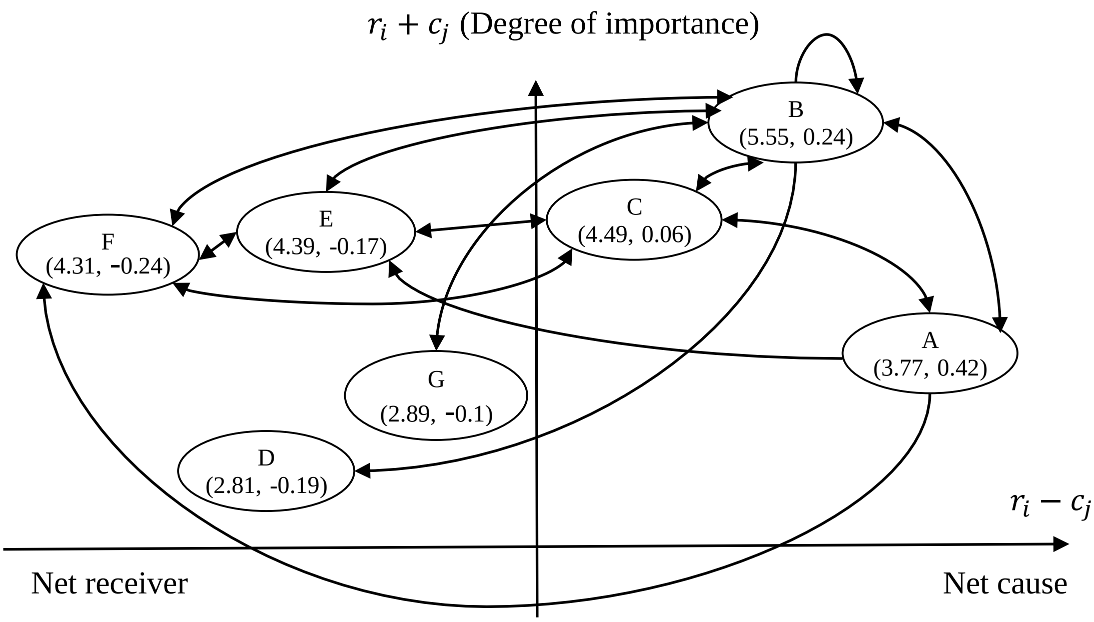

Figure 6.4 impact relations-map from DEMATEL

6.4.2 Obtain the Weights for the Lower Level Indicators by using the ANP method

Through experts' judgements, the existence of interdependency among the lower level indicators is identified based on the results from DEMATEL. This activity clarifies the interdependency between lower level indicators which can also adjust the interdependency relationship among KPIs. By doing this, the number of pairwise comparisons that need to be carried out is significantly reduced. In our case, without the experts' judgement, pairwise comparisons need to be conducted for all the lower level indicators whose upper level KPIs were identified as interdependent through DEMATEL analysis. The number of such comparisons is 360. However, experts have filtered those lower level indicators down to the ones that actually affect each other and the pairwise comparisons need only to be conducted among them. This activity has reduced the number of pairwise comparison to 60.

To obtain the local weights, questionnaires with pairwise comparison matrices for indicators with interdependency relationships are created. Table 6.4 is a pairwise comparison table for the evaluation of influences among PIs in regards to PI (A2). Similar comparison matrices are established for all the KPIs and PIs that have been identified with interdependency. The detailed questionnaire is attached in Appendix 5 and Appendix 6.

The evaluations obtained are used to calculate the priority vector of an indicator through Equation (6.7). For example, the evaluations given for the pairwise comparison matrix in Table 6.4 are presented in Table 6.5.

Table 6.4 Pairwise comparison table for the evaluation of influences

Which indicator in the pair (on the same row) influences **A2) Total Recordable Case Frequency** more with respect to the **(A) Health and Safety Management & Performance**, and how much more than the other indicator																			
No.	PI	**(Extreme Influence: 9、Substantial Influence: 7、Essential or Strong Influence: 5、Moderate Influence: 3、Equal Influence: 1)**																	PI
1	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C2)Pollution Incidents ( )
2	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environmental Violations ( )
3	(C2)Pollution Incidents ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environmental Violations ( )

Table 6.5 Evaluations for the level of influences among C1, C2 and C3 in regards to indicator A1

A1	C1	C2	C3	Priorities
C1	1	5	5	0.7143
C2	0.2	1	1	0.1429
C3	0.2	1	1	0.1429

The priority vector for C1 is calculated as below:

$$w_{c1} = \frac{1}{m}\sum_{j=1}^{m}\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} = \frac{1}{3}\left(\frac{1}{1+0.2+0.2}+\frac{5}{1+1+5}+\frac{5}{1+1+5}\right) = 0.7143$$

The priority vectors for C2 and C3 in regards to A1 are obtained in the same way and listed in Table 6.5. The unweighted supermatrix (Table 6.6) is constructed by using the priority vectors for all the indicators, where "0" is given when there is no interaction between any two indicators. The cluster weight matrix (Table 6.7) is generated containing the priority vectors for all the KPIs, which are obtained by using the same method. To build the weighted supermatrix (Table 6.8), priority vectors in the unweighted supermatrix are multiplied by the priority vectors of the corresponding clusters. For example, the priority vector for KPI C in regards to KPI A is 1. Each priority vector for PIs under KPI C in regards to PIs under KPI A is to be multiplied by 1. Therefore, all priority vectors in Table 6.5 are multiplied by 1 to achieve the values in the weighted supermatrix. The supermatrix is then converged to a limiting supermatrix (Table 6.9) and the global weights for all the lower level indicators are listed in Table 6.10.

The calculation process can be performed by the computer software – "SuperDecisions". "SuperDecisons" is decision making software based on the AHP and ANP. It is a simple easy-to-use package for constructing decision models with dependence and feedback and computing results using the supermatrices of the ANP (Adams and Saaty, 2003). Figure 6.5 is the relation map produced by the software.

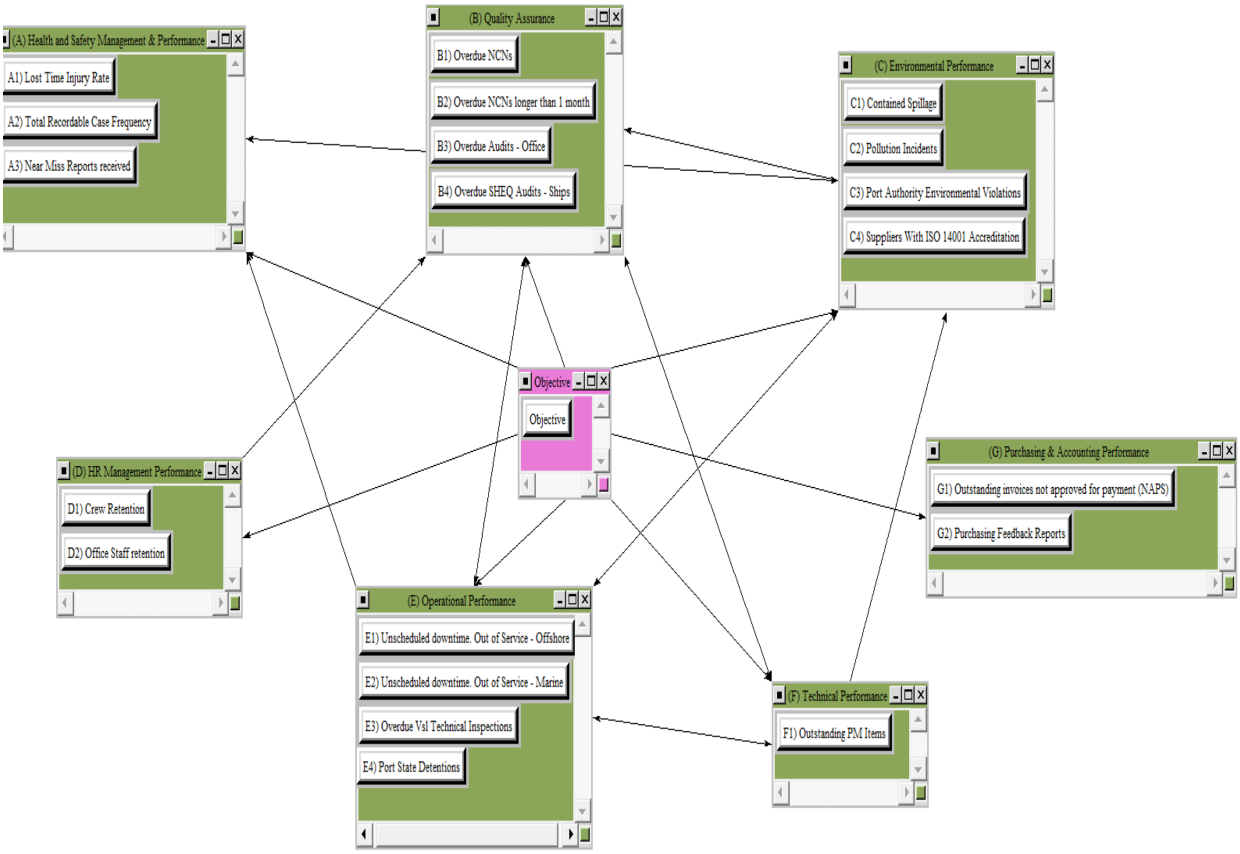

Figure 6.5 Relationship diagram created in “Super decisions” software

Table 6.6 Unweighted supermatrix

	A1	**A2**	**A3**	**B1**	**B2**	**B3**	**B4**	**C1**	**C2**	**C3**	**C4**	**D1**	**D2**	**E1**	**E2**	**E3**	**E4**	**F1**	**G1**	**G2**	**Objective**
A1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2897	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8000	0.0000	0.0000	0.0000	0.0660
A2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6554	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2000	0.0000	0.0000	0.0000	0.3187
A3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0549	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6153
B1	0.0000	0.0000	0.0000	0.0000	0.1250	0.0000	0.0000	0.0626	0.1265	0.1095	0.0000	0.3333	0.0000	0.0000	0.0000	0.2493	0.0000	0.0836	0.0000	0.0000	0.2190
B2	0.0000	0.0000	0.0000	0.8571	0.0000	0.0000	0.0000	0.4791	0.1865	0.3090	0.0000	0.3333	0.0000	0.0000	0.0000	0.5936	0.0000	0.4443	0.0000	0.0000	0.0502
B3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2190
B4	0.0000	0.0000	0.0000	0.1429	0.8750	0.0000	0.0000	0.4583	0.6870	0.5816	0.0000	0.3333	0.0000	0.0000	0.0000	0.1571	0.0000	0.4721	0.0000	0.0000	0.5119
C1	0.0000	0.7143	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0556	0.0540	0.1939	0.1158	0.1991	0.0000	0.0000	0.1028
C2	0.0000	0.1429	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4815	0.5891	0.7429	0.4417	0.0675	0.0000	0.0000	0.5881
C3	0.0000	0.1429	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4629	0.3568	0.0633	0.4057	0.7334	0.0000	0.0000	0.2578
C4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0368	0.0000	0.0000	0.0000	0.0512
D1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000
D2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000
E1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.0000	0.0000	0.1581
E2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.0000	0.0000	0.1680
E3	0.0000	0.0000	0.0000	0.1250	0.0000	0.0000	0.0000	0.0000	0.1111	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0411
E4	0.0000	0.0000	0.0000	0.8750	0.0000	0.0000	0.0000	0.0000	0.8889	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8000	0.0000	0.0000	0.6327
F1	0.0000	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
G1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8750
G2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1250
Objective	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 6.7 Cluster weight matrix

	A	**B**	**C**	**D**	**E**	**F**	**G**	**Objective**
A	0.0000	0.0000	0.7891	0.0000	0.7890	0.0000	0.0000	0.5389
B	0.0000	0.6885	0.1031	1.0000	0.1031	0.7641	0.0000	0.2298
C	1.0000	0.0000	0.0000	0.0000	0.1078	0.1210	0.0000	0.0685
D	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0363
E	0.0000	0.1148	0.1078	0.0000	0.0000	0.1149	0.0000	0.0521
F	0.0000	0.1967	0.0000	0.0000	0.0001	0.0000	0.0000	0.0327
G	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0416
Objective	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 6.8 Weighted supermatrix

	A1	**A2**	**A3**	**B1**	**B2**	**B3**	**B4**	**C1**	**C2**	**C3**	**C4**	**D1**	**D2**	**E1**	**E2**	**E3**	**E4**	**F1**	**G1**	**G2**	**Objective**
A1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2563	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7038	0.0000	0.0000	0.0000	0.0356
A2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5796	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1760	0.0000	0.0000	0.0000	0.1717
A3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0486	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3316
B1	0.0000	0.0000	0.0000	0.0000	0.0972	0.0000	0.0000	0.0626	0.0619	0.0127	0.0000	0.3333	0.0000	0.0000	0.0000	0.1218	0.0000	0.0639	0.0000	0.0000	0.0503
B2	0.0000	0.0000	0.0000	0.5902	0.0000	0.0000	0.0000	0.4791	0.0912	0.0357	0.0000	0.3333	0.0000	0.0000	0.0000	0.2901	0.0000	0.3395	0.0000	0.0000	0.0115
B3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0503
B4	0.0000	0.0000	0.0000	0.0984	0.6806	0.0000	0.0000	0.4583	0.3358	0.0672	0.0000	0.3333	0.0000	0.0000	0.0000	0.0767	0.0000	0.3607	0.0000	0.0000	0.1176
C1	0.0000	0.7143	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0556	0.0540	0.0991	0.0139	0.0241	0.0000	0.0000	0.0070
C2	0.0000	0.1429	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4815	0.5891	0.3795	0.0531	0.0082	0.0000	0.0000	0.0403
C3	0.0000	0.1429	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4629	0.3568	0.0323	0.0488	0.0887	0.0000	0.0000	0.0177
C4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0044	0.0000	0.0000	0.0000	0.0035
D1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0182
D2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0182
E1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0115	0.0000	0.0000	0.0082
E2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0115	0.0000	0.0000	0.0088
E3	0.0000	0.0000	0.0000	0.0143	0.0000	0.0000	0.0000	0.0000	0.0568	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0021
E4	0.0000	0.0000	0.0000	0.1004	0.0000	0.0000	0.0000	0.0000	0.4543	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0919	0.0000	0.0000	0.0330
F1	0.0000	0.0000	0.0000	0.1967	0.2222	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000	0.0000	0.0000	0.0000	0.0327
G1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0364
G2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0052
Objective	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 6.9 Limiting supermaterix

	A1	**A2**	**A3**	**B1**	**B2**	**B3**	**B4**	**C1**	**C2**	**C3**	**C4**	**D1**	**D2**	**E1**	**E2**	**E3**	**E4**	**F1**	**G1**	**G2**	**Objective**
A1	0.0000	0.0724	0.0000	0.0724	0.0724	0.0000	0.0000	0.0724	0.0724	0.0724	0.0000	0.0724	0.0000	0.0724	0.0724	0.0724	0.0724	0.0724	0.0000	0.0000	0.0724
A2	0.0000	0.0497	0.0000	0.0497	0.0497	0.0000	0.0000	0.0497	0.0497	0.0497	0.0000	0.0497	0.0000	0.0497	0.0497	0.0497	0.0497	0.0497	0.0000	0.0000	0.0497
A3	0.0000	0.0030	0.0000	0.0030	0.0030	0.0000	0.0000	0.0030	0.0030	0.0030	0.0000	0.0030	0.0000	0.0030	0.0030	0.0030	0.0030	0.0030	0.0000	0.0000	0.0030
B1	0.0000	0.0543	0.0000	0.0543	0.0543	0.0000	0.0000	0.0543	0.0543	0.0543	0.0000	0.0543	0.0000	0.0543	0.0543	0.0543	0.0543	0.0543	0.0000	0.0000	0.0543
B2	0.0000	0.1812	0.0000	0.1812	0.1812	0.0000	0.0000	0.1812	0.1812	0.1812	0.0000	0.1812	0.0000	0.1812	0.1812	0.1812	0.1812	0.1812	0.0000	0.0000	0.1812
B3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
B4	0.0000	0.3667	0.0000	0.3667	0.3667	0.0000	0.0000	0.3667	0.3667	0.3667	0.0000	0.3667	0.0000	0.3667	0.3667	0.3667	0.3667	0.3667	0.0000	0.0000	0.3667
C1	0.0000	0.0698	0.0000	0.0698	0.0698	0.0000	0.0000	0.0698	0.0698	0.0698	0.0000	0.0698	0.0000	0.0698	0.0698	0.0698	0.0698	0.0698	0.0000	0.0000	0.0698
C2	0.0000	0.0246	0.0000	0.0246	0.0246	0.0000	0.0000	0.0246	0.0246	0.0246	0.0000	0.0246	0.0000	0.0246	0.0246	0.0246	0.0246	0.0246	0.0000	0.0000	0.0246
C3	0.0000	0.0342	0.0000	0.0342	0.0342	0.0000	0.0000	0.0342	0.0342	0.0342	0.0000	0.0342	0.0000	0.0342	0.0342	0.0342	0.0342	0.0342	0.0000	0.0000	0.0342
C4	0.0000	0.0004	0.0000	0.0004	0.0004	0.0000	0.0000	0.0004	0.0004	0.0004	0.0000	0.0004	0.0000	0.0004	0.0004	0.0004	0.0004	0.0004	0.0000	0.0000	0.0004
D1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
E1	0.0000	0.0019	0.0000	0.0019	0.0019	0.0000	0.0000	0.0019	0.0019	0.0019	0.0000	0.0019	0.0000	0.0019	0.0019	0.0019	0.0019	0.0019	0.0000	0.0000	0.0019
E2	0.0000	0.0019	0.0000	0.0019	0.0019	0.0000	0.0000	0.0019	0.0019	0.0019	0.0000	0.0019	0.0000	0.0019	0.0019	0.0019	0.0019	0.0019	0.0000	0.0000	0.0019
E3	0.0000	0.0039	0.0000	0.0039	0.0039	0.0000	0.0000	0.0039	0.0039	0.0039	0.0000	0.0039	0.0000	0.0039	0.0039	0.0039	0.0039	0.0039	0.0000	0.0000	0.0039
E4	0.0000	0.0449	0.0000	0.0449	0.0449	0.0000	0.0000	0.0449	0.0449	0.0449	0.0000	0.0449	0.0000	0.0449	0.0449	0.0449	0.0449	0.0449	0.0000	0.0000	0.0449
F1	0.0000	0.0914	0.0000	0.0914	0.0914	0.0000	0.0000	0.0914	0.0914	0.0914	0.0000	0.0914	0.0000	0.0914	0.0914	0.0914	0.0914	0.0914	0.0000	0.0000	0.0914
G1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
G2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Objective	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 6.10 Weights of lowest level indicators

Indicators	Weights
A1	0.0724
A2	0.0497
A3	0.0030
B1	0.0543
B2	0.1812
B3	0.0000
B4	0.3667
C1	0.0698
C2	0.0246
C3	0.0342
C4	0.0004
D1	0.0000
D2	0.0000
E1	0.0019
E2	0.0019
E3	0.0039
E4	0.0448
F1	0.0914
G1	0.0000
G2	0.0000

6.4.3 Set Criterion Grades and Collect Data for the Lowest Level Indicators

The linguistic terms that are used to describe the grades for both the company's overall performance and KPIs are defined as (Very Poor, Underperformed, On target, Good, Excellent). These grades can also be used to define most of the indicators. Due to the fact that all current indicators used in the company are quantitative measures, values for grades are generated based on historical data and using Equations (6.9) and (6.10). Take the indicator A3 as an example, the best performance is 20.1 and the target is 18. The value for the in-between grade "Good" can be calculated as follows:

$$v_4 = v_5 - \left(\frac{v_5 - v_3}{h - l}\right) = 20.1 - \left(\frac{20.1 - 18}{5 - 3}\right) = 19.05$$

The in-between grade "under performed" is calculated by using the value of worst performance 12 and the target value 18.

$$v_2 = v_1 + \left(\frac{v_3 - v_1}{h-l}\right) = 18 - \left(\frac{18-12}{3-1}\right) = 15$$

Indicators that are assessed by either "0 value" or "over 0", such as B3 and B4, are defined by the grades ">0" and "0". These grades are transformed into the grades defining the upper level KPIs by using the fuzzy rule base belief structure. Take B3 as an example, the fuzzy rule base belief structure can be constructed as:

R1: IF "Overdue Audits – Office" is "0", then "Quality Assurance" is "Excellent".
R2: If ""Overdue Audits – Office" is ">0", then "Quality Assurance" is "Very poor".

In a similar way, the scores for the other grades are obtained and listed in Table 6.11.

6.4.4 Transform the Evaluation and Synthesis Indicators from the Lowest Level to Top Level by using an ER Algorithm

The evaluations are obtained for all indicators, which are then transformed into the associated linguistic terms with belief degrees based on the scores of the evaluation grades in Table 6.11. Take the evaluation associated with indicator A1 in month 2 as an example. The value was given as 0.39 per 1,000,000 man hours. By using Equation (6.12), the value can be transformed and presented as the associated belief degrees of the evaluation grades as follows:

$$\beta_{4,A1} = \frac{v_{g,A1} - v_{5,A1}}{v_{4,A1} - v_{5,A1}} = \frac{0.39-0.2}{0.475-0.2} = 0.691$$
$$\beta_{5,A1} = 1 - \beta_{4,A1} = 0.309$$

Table 6.11 Indicator evaluations and grades associated with linguistic terms

KPI	PI	Units	Very Poor	Underperformed	On Target	Good	Excellent
(A) Health and Safety Management & Performance	**A1) Lost time injury rate**	Per 1,000,000 man hrs	1.3	1.025	0.75	0.475	0.2
	A2) Total recordable case frequency	Per 1,000,000 man hrs	3.6	2.75	1.9	1.05	0.2
	A3) Near miss reports received	Av. No. / Vsl / month	12	15	18	19.05	20.1
(B) Quality Assurance	**B1) Overdue NCNs**	Number of NCNs	15	14	13	12.5	12
	B2) Overdue NCNs longer than 1 month	OD > 1 mth	16	14.5	13	11.5	10
	B3) Overdue audits - office	Number	>0				0
	B4) Overdue SHEQ audits - ships	Number	>0				0
(C) Environmental Performance	**C1) Contained spillage**	No. / year	8	5.5	3	2	1
	C2) Pollution incidents	Number	>0				0
	C3) Port authority environmental violations	Number	>0				0
	C4) Suppliers with ISO 14001 accreditation	% on supplier list	0.14	0.145	0.15	0.155	0.16
(D) HR Management Performance	**D1) Crew retention**	% retention	85.13	88.565	92	95.435	98.87
	D2) Office staff retention	% retention	96	97	98	99	100
(E) Operational Performance	**E1) Unscheduled downtime. Out of service - offshore**	% days per year	0.0673	0.05115	0.035	0.01885	0.0027
	E2) Unscheduled downtime. Out of service - marine	% days per year	0.0666	0.0508	0.035	0.0192	0.0034
	E3) Overdue Vsl technical inspections	Number	>0				0
	E4) Port state detentions	No. / vessel	>0				0
(F) Technical Performance	**F1) Outstanding PM items**	% outstanding	0.03	0.025	0.02	0.015	0.01
(G) Purchasing & Accounting Performance	**G1) Outstanding invoices not approved for payment (NAPS)**	No. / month	581	490.5	400	309.5	219
	G2) Purchasing feedback reports	No. / month	4	7	10	11	12

The results from the evaluation of A1 can then be expressed as (0% Very poor, 0% Underperformed, 0% On target, 69.1% Good, 30.9% Excellent). Similarly, all the evaluations are transformed and listed in Table 6.12.

The results are synthesised by following Equations (6.13) to (6.21). Take A1 and A2 in month 2 as examples. The weights for A1 and A2 were obtained in section 6.4.2, which are 0.0724 and 0.0497, respectively. To synthesise the two indicators, their weights are normalized to the unit 1. The normalized weights are: $w_{A1} = 0.593$ and $w_{A2} = 0.407$. The two indicators can then be synthesised as below.

1) Obtain probability mass by using Equation (6.13)

$m_{1,1} = w_1\beta_{1,1} = 0.593 \times 0 = 0$
$m_{2,1} = w_1\beta_{2,1} = 0.593 \times 0 = 0$
$m_{3,1} = w_1\beta_{3,1} = 0.593 \times 0 = 0$
$m_{4,1} = w_1\beta_{4,1} = 0.593 \times 0.691 = 0.409$
$m_{5,1} = w_1\beta_{5,1} = 0.593 \times 0.309 = 0.184$

$m_{1,2} = w_2\beta_{1,2} = 0.407 \times 0 = 0$
$m_{2,2} = w_2\beta_{2,2} = 0.407 \times 0 = 0$
$m_{3,2} = w_2\beta_{3,2} = 0.407 \times 0 = 0$
$m_{4,2} = w_2\beta_{4,2} = 0.407 \times 0.288 = 0.117$
$m_{5,2} = w_2\beta_{5,2} = 0.407 \times 0.712 = 0.29$

2) Calculate the remaining probability mass by using Equation (6.15) and (6.16).

$\bar{m}_{H,1} = 1 - w_1 = 1 - 0.593 = 0.407$
$\tilde{m}_{H,1} = w_1\left(1 - \sum_{n=1}^{5} \beta_{n,1}\right) = 0.593(1 - 1) = 0$
$m_{H,1} = \bar{m}_{H,1} + \tilde{m}_{H,1} = 0.407 + 0 = 0.407$

$\bar{m}_{H,2} = 1 - w_2 = 1 - 0.407 = 0.593$

$\tilde{m}_{H,2} = w_2\left(1 - \sum_{n=1}^{5} \beta_{n,2}\right) = 0.407(1 - 1) = 0$

$m_{H,2} = \bar{m}_{H,2} + \tilde{m}_{H,2} = 0.593 + 0 = 0.593$

3) Obtain the combined probability assignments by following Equations (6.17), (6.18) and (6.19).

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq t}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1}$$

$$= [1 - (m_{1,1} \times m_{2,2} + m_{1,1} \times m_{3,2} + m_{1,1} \times m_{4,2} + m_{1,1} \times m_{5,2} + m_{2,1} \times m_{1,2} + m_{2,1} \times m_{3,2} + m_{2,1} \times m_{4,2} + m_{2,1} \times m_{5,2} + m_{3,1} \times m_{1,2} + m_{3,1} \times m_{2,2} + m_{3,1} \times m_{4,2} + m_{3,1} \times m_{5,2} + m_{4,1} \times m_{1,2} + m_{4,1} \times m_{2,2} + m_{4,1} \times m_{3,2} + m_{4,1} \times m_{5,2} + m_{5,1} \times m_{1,2} + m_{5,1} \times m_{2,2} + m_{5,1} \times m_{3,2} + m_{5,1} \times m_{4,2})]^{-1}$$

$$= [1 - (0.409 \times 0.289 + 0.184 \times 0.117)]^{-1} = 1.163$$

$$m_{1,I(i+1)} = K_{I(i+1)}\left[m_{1,I(i)} m_{1,i+1} + m_{H,I(i)} m_{1,i+1} + m_{1,I(i)} m_{H,i+1}\right]$$

$$m_{1,I(2)} = 1.163\left[m_{1,1} \times m_{1,2} + m_{H,1} \times m_{1,2} + m_{1,1} \times m_{H,2}\right]$$

$$= 1.163[0 \times 0 + 0.407 \times 0 + 0 \times 0.593] = 0$$

$$m_{2,I(i+1)} = K_{I(i+1)}\left[m_{2,I(i)} m_{1,i+1} + m_{H,I(i)} m_{2,i+1} + m_{2,I(i)} m_{H,i+1}\right]$$

$$m_{2,I(2)} = 1.163\left[m_{2,1} \times m_{2,2} + m_{H,1} \times m_{2,2} + m_{2,1} \times m_{H,2}\right]$$

$$= 1.163[0 \times 0 + 0.407 \times 0 + 0 \times 0.593] = 0$$

$$m_{3,I(i+1)} = K_{I(i+1)}\left[m_{3,I(i)} m_{3,i+1} + m_{H,I(i)} m_{3,i+1} + m_{3,I(i)} m_{H,i+1}\right]$$

$$m_{3,I(2)} = 1.163\left[m_{3,1} \times m_{3,2} + m_{H,1} \times m_{3,2} + m_{3,1} \times m_{H,2}\right]$$

$$= 1.163[0 \times 0 + 0.407 \times 0 + 0 \times 0.593] = 0$$

$$m_{4,I(i+1)} = K_{I(i+1)}\left[m_{4,I(i)}m_{4,i+1} + m_{H,I(i)}m_{4,i+1} + m_{4,I(i)}m_{H,i+1}\right]$$

$$m_{4,I(2)} = 1.163\left[m_{4,1} \times m_{4,2} + m_{H,1} \times m_{4,2} + m_{4,1} \times m_{H,2}\right]$$

$$= 1.163[0.409 \times 0.117 + 0.407 \times 0.117 + 0.409 \times 0.593] = 0.394$$

$$m_{5,I(i+1)} = K_{I(i+1)}\left[m_{5,I(i)}m_{5,i+1} + m_{H,I(i)}m_{5,i+1} + m_{5,I(i)}m_{H,i+1}\right]$$

$$m_{5,I(2)} = 1.163\left[m_{5,1} \times m_{5,2} + m_{H,1} \times m_{5,2} + m_{5,1} \times m_{H,2}\right]$$

$$= 1.163[0.184 \times 0.289 + 0.407 \times 0.289 + 0.184 \times 0.593] = 0.325$$

$$\tilde{m}_{H,I(i+1)} = K_{I(i+1)}\left[\tilde{m}_{H,I(i)}\tilde{m}_{H,i+1} + \bar{m}_{H,I(i)}\tilde{m}_{H,i+1} + \tilde{m}_{H,I(i)}\bar{m}_{H,i+1}\right]$$

$$\tilde{m}_{H,I(2)} = 1.163\left[\tilde{m}_{H,1}\tilde{m}_{H,2} + \bar{m}_{H,1}\tilde{m}_{H,2} + \tilde{m}_{H,1}\bar{m}_{H,2}\right]$$

$$= 1.163(0 \times 0 + 0.407 \times 0 + 0 \times 0.593) = 0$$

$$\bar{m}_{H,I(i+1)} = K_{I(i+1)}[\bar{m}_{H,I(i)}\bar{m}_{H,i+1}]$$

$$\bar{m}_{H,I(2)} = K_{I(i+1)}\left[\bar{m}_{H,1}\bar{m}_{H,2}\right] = 1.163(0.407 \times 0.593) = 0.28$$

4) Calculate the combined degree of belief of the indicators through applying Equation (6.20)

$$\beta_1 = \frac{m_{1,I(2)}}{1-\bar{m}_{H,I(2)}} = \frac{0}{1-0.28} = 0$$

$$\beta_2 = \frac{m_{1,I(2)}}{1-\bar{m}_{H,I(2)}} = \frac{0}{1-0.28} = 0$$

$$\beta_3 = \frac{m_{3,I(2)}}{1-\bar{m}_{H,I(2)}} = \frac{0}{1-0.28} = 0$$

$$\beta_4 = \frac{m_{4,I(2)}}{1-\bar{m}_{H,I(2)}} = \frac{0.394}{1-0.28} = 0.548$$

$$\beta_5 = \frac{m_{4,I(2)}}{1-\bar{m}_{H,I(2)}} = \frac{0.325}{1-0.28} = 0.452$$

The overall assessment for A1 and A2 can then be expressed as (0% Very poor, 0% underperformance, 0% on Target, 54.8% Good, 45.2% Excellent).

5) Generate the utility value of the top level KPI by using Equations (6.22) and (6.23).

Firstly, the utility values associated with each linguistic term are as below:

Very Poor	Under Performance	On Target	Good	Excellent
(1)	(2)	(3)	(4)	(5)

$$u(H_1) = \frac{V^1 - V_{min}}{V_{max} - V_{min}} = \frac{1-1}{5-1} = 0$$

$$u(H_2) = \frac{V^2 - V_{min}}{V_{max} - V_{min}} = \frac{2-1}{5-1} = 0.25$$

$$u(H_3) = \frac{V^3 - V_{min}}{V_{max} - V_{min}} = \frac{3-1}{5-1} = 0.5$$

$$u(H_4) = \frac{V^4 - V_{min}}{V_{max} - V_{min}} = \frac{4-1}{5-1} = 0.75$$

$$u(H_5) = \frac{V^5 - V_{min}}{V_{max} - V_{min}} = \frac{5-1}{5-1} = 1$$

The utility value for the upper level KPI can then be calculated as follows.

$$u(E) = \sum_{n=1}^{5} \beta_n u(H_n) = 0.548 \times 0.75 + 0.452 \times 1 = 0.863$$

In a similar way, all the indicators can be synthesised. This lengthy calculation can be by performed in the Software IDS (Yang and Xu, 2002b).

Figure 6.6 presents an outcome from IDS in regards to the company overall performance over a four months period, where the utility value for each month are: Month 1= 0.7991, Month 2 = 0.9690, Month 3 = 0.9594, and Month 4 = 0.9368.

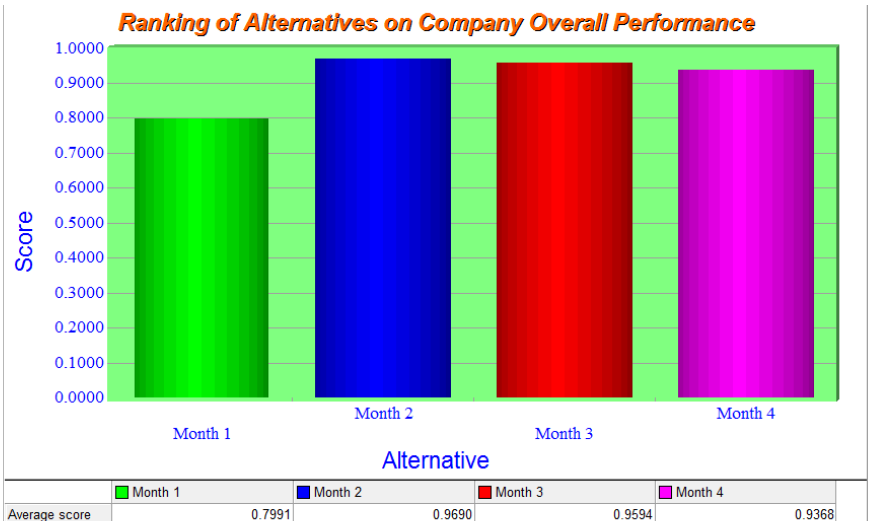

Figure 6.6 Ranking for the company overall performance over four-month period

Similar comparisons can be conducted for various other purposes, such as, visualize the comparison of KPIs for the given time frame (Figure 6.7)

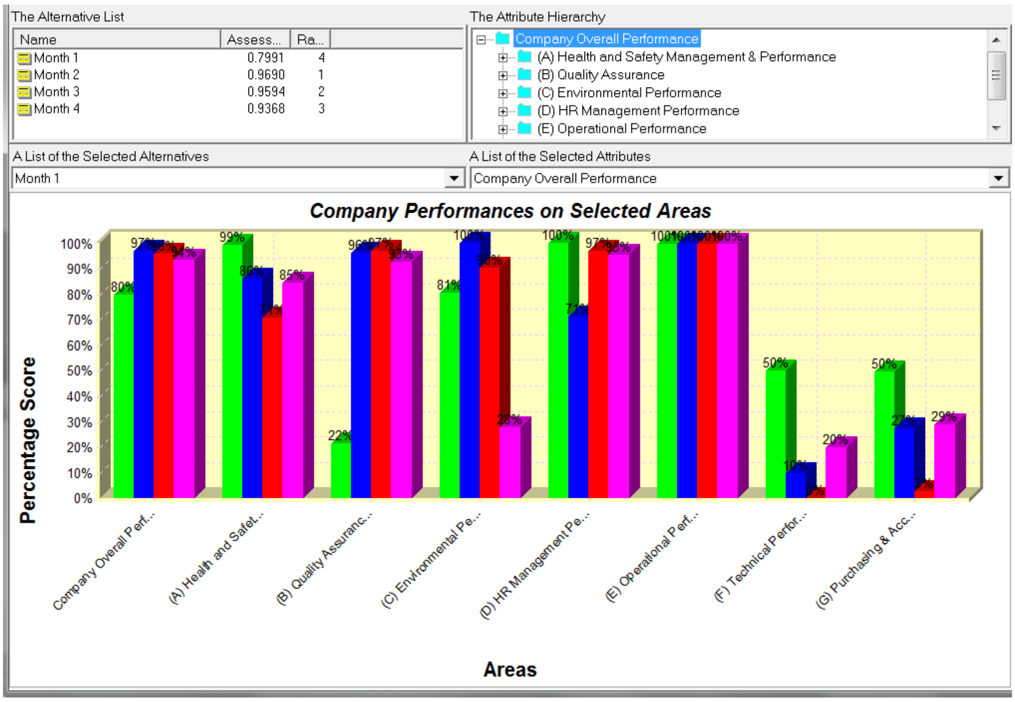

Figure 6.7 Comparison of KPIs over four-month period

6.5 Conclusion

As a performance measurement tool, KPIs have shown their great popularity in practice. It helps identify existing issues, monitor performance and enable performance comparison between different function areas. Like many other industries, in shipping industry, the majority of current practitioners apply KPIs with only quantitative data and without considering the importance of different indicators or their interdependencies, which have restricted their applicability and caused biases in results. This study developed a systematic method in KPI measurement to overcome those issues and therefore, provided reliable and comparable results for management to make rational decisions. In this research, DEMATEL and ANP were used to obtain weights of indicators. The marriage of DEMATEL and ANP enabled the calculation of weights for indicators by taking into consideration interdependency among them. The use of the FER approach enabled the handling of both quantitative and qualitative data and synthesizing indicators on a KPI tree from the bottom to the top level in a meaningful way.

Table 6.12 Belief degrees transformed from the evaluations form all indicators

KPI	PI	Month 1					Month 2					Month 3					Month 4				
		Very Poor	Under Performance	On Target	Very Good	Excellent	Very Poor	Under Performance	On Target	Very Good	Excellent	Very Poor	Under Performance	On Target	Very Good	Excellent	Very Poor	Under Performance	On Target	Very Good	Excellent
(A)	A1	0	0	0	0	1	0	0	0	0.691	0.309	0	0	0.418	0.582	0	0	0	0	0.509	0.491
	A2	0	0	0	0	1	0	0	0	0.288	0.712	0	0	0	0.68	0.32	0	0	0	0.682	0.318
	A3	0	1	0	0	0	0.733	0.267	0	0	0	0	0	0	0	1	1	0	0	0	0
(B)	B1	0	1	0	0	0	1		0	0	0	0	0	0	0	1	1	0	0	0	0
	B2	0	0	0	0	1	0	0	0	0	1	0	0	0	0.667	0.333	0	0	0	0.667	0.333
	B3	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
	B4	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
(C)	C1	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0
	C2	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
	C3	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
	C4	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0
(D)	D1	0	0	0	0	1	0	0	0	0.39	0.61	0	0	0	0.39	0.61	0	0	0	0.472	0.528
	D2	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
(E)	E1	0	0	0	0	1	0	0	0	0	1	0	0	0	0.22	0.78	0	0	0	0.248	0.752
	E2	0	0	0	0.11	0.89	0	0	0.64	0.32	0	0	0	0	0.468	0.532	0	0	0	0	1
	E3	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
	E4	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
(F)	F1	0	0	1	0	0	0.6	0.4	0	0	0	1	0	0	0	0	0.2	0.8	0	0	0
(G)	G1	1	0	0	0	0	0	0.729	0.27	0	0	0.702	0.298	0	0	0	0.315	0.685	0	0	0
	G2	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0.333	0.667	0	0

Chapter 7. Discussion and Conclusion

7.1 Introduction

Since its first application in Motorola, Six Sigma has been widely used by many world-leading companies with significant quality improvement achieved. Given its effectiveness and uniqueness in providing quantitative analysis results, Six Sigma has always been one of the most popular quality improvement methodologies in modern manufacturing and service industries. However, there are very few studies in the application of Six Sigma in the shipping industry, especially its service functions where there are a high number of uncertainties and qualitative measures due to the involvement of extensive human activities. The aim of this research was to enhance the ability of Six Sigma methodology in handling uncertainties and qualitative data, so that it can be effectively applied in the OSFs of shipping companies. Strong research needs were identified when a generic framework for implementing Six Sigma in a shipping company was newly developed. Advanced techniques such as AHP, TOPSIS, BN, fuzzy logic, DEMATEL, ANP and ER were combined in an innovative way to improve the abilities of Six Sigma tools in uncertainty treatment. The new hybrid methods are:

1) A novel conceptual fuzzy TOPSIS using trapezoidal fuzzy numbers for Six Sigma project selection.
2) A revised FMEA model by applying AHP and fuzzy Bayesian reasoning for failure identification and prioritisation throughout the DMAIC framework.
3) A novel KPI management method by combining DEMATEL, ANP and FER for quality monitoring and improvement.

This chapter summarizes the key findings of this research. The research contributions with reference to the research objectives are discussed. It also addresses the limitation of this research and suggestions for further research are proposed towards the end of this chapter.

7.2 Key Findings and Contributions from the Research

7.2.1 Findings on the Issues regarding the Implementation of Six Sigma in OSFs of Shipping Companies

The literature recorded extensive applications of Six Sigma in service industries. The CSFs are recognized by academics and practitioners for the successful implementation of Six Sigma. A P-DMAIC-R model was therefore newly proposed for the implementation of Six Sigma in OSFs of shipping companies. While the new model was validated through a real Six Sigma project in a world leading ship company, the following issues were identified during the implementation:

- It appeared that there was lack of an effective method in assisting the decision making process of project selection. Due to the fact that much information was unknown or ambiguous at the start of a project, a decision on project selection was often made by taking an educated guess. An effective method that can handle the uncertainties and subjective judgements during a project selection process is needed to assist in making rational decisions. This issue was tackled by using the Fuzzy TOPSIS method in Chapter 4.

- During the application of FMEA, it was found that it was difficult to use the classical scoring mechanism based on crisp numbers to make a confident judgement. There were situations where an expert was not entirely certain about an evaluation and the judgement tended to be distributed across different grades. This could not be handled by the traditional method where a single score is assigned to a failure mode against each criterion. Furthermore, the final results obtained for ranking the failures (RPN) did not consider the different weights among the three criteria (S, O, D). These can affect FMEA's applicability in an environment where extensive uncertainties exist and data is largely generated from subjective judgements. Chapter 5 of this thesis adopted AHP, FRB and BN methods in a complimentary manner to equip the classical FMEA with new features. AHP was used to determine the different weights of the three criteria, while FRB made it possible to make judgement by linguistic terms with rational belief degrees which were aggregated by the application of the BN method.

- In the KPI selection process, instead of focusing on the process inputs that need to be measured, people tend to select the ones that can only be measured quantitatively with available data. This is due to the widely believed definition that KPIs are quantitative measures. It has constrained the usability of KPIs for the measurement of intangible performances which are often present in the service environment with human activities involved. In addition, it is very difficult, if not impossible, to compare the measurement results generated from the KPIs used to monitor different process points for the benchmarking purpose across different departments and periods. Such an issue was addressed in Chapter 6 in which DEMATEL-ANP and fuzzy ER were combined to rationalise the weight assignments among interdependent KPIs and to synthesise both qualitative and quantitative KPIs in a logical way.

7.2.2 Findings and Contributions of the New Fuzzy TOPSIS for Project Selection

There is not a lack of research in the subject of project selection in the literature. However, the information required for selecting projects during Six Sigma implementation is from both objective databases and subjective judgements from experts which are often presented in various formats with ambiguity and incompleteness. Consequently, to a very large extent, the existing MCDMs are not fully suitable to modelling the associated uncertainties.

A new approximate TOPSIS method was developed in this thesis to assist in decision making during the Six Sigma project selection process. Different from the traditional fuzzy TOPSIS methods, the new method used trapezoidal fuzzy numbers with belief degrees to accommodate various types of data including objective information, interval data, fuzzy numbers and linguistic variables. Minimum restrictions were set for the evaluation during the project selection process which means more raw information can be directly captured and the alternatives and criteria can be evaluated with confidence. This new approximate TOPSIS method was also capable of handling the fuzziness and incompleteness in the input data and transforming and aggregating them through a new fuzzification mechanism in the TOPSIS inference process. Different types of data were converted into the trapezoidal fuzzy numbers by taking into account the associated belief degrees. Those trapezoidal fuzzy numbers formed the basis for the calculation of the distance closeness coefficient. The outcomes were presented as crisp numbers which can be used to prioritise alternative projects.

7.2.3 Findings and Contributions regarding the Revised FMEA Model

The simplicity of FMEA has made it a popular tool in failure ranking. However, its mechanism has received a large number of criticisms including:

1) The calculation of RPN is questionable by using multiplication;
2) It is difficult to give a precise point evaluation for the failures associated with the criteria;
3) The same RPN values may indicate different risk implications; and
4) It ignores the different importance among the three criteria.

Different methods were proposed in previous studies attempting to address these issues with fuzzy logic being one of the most widely used methods. However, those methods employing advanced techniques to provide more accurate results compromised the easiness and visibility of the traditional FMEA.

A modified FMEA was required which can deal with the uncertainties existing in OSFs in shipping companies and rationally ranking failures while maintaining its easiness for the project team to use with confidence. The new FMEA approach could properly address the challenges received in FMEA application and enhanced the applicability of FMEA by using the hybrid of AHP and FBR approaches. The marriage of fuzzy logic theory and BN took advantages of their individual advantages which are easy to use and capable of effectively incorporating different weights of risk factors into the fuzzy inference system for the fuzzy logic. This enabled the evaluations to be expressed both in crisp numbers and linguistic terms when safety analysts in shipping companies are required to rank the identified failure modes. The new method improved the accuracy and applicability of FMEA under uncertainty, and very importantly, maintains its easiness during the application.

7.2.4 Findings and Contributions regarding the KPIs Management Method

Being a widely used tool in today's business performance measurement, KPIs have received a large amount of attention. KPIs must be aligned with the business strategy taking into account both qualitative or quantitative measurements. The traditional view on the KPIs - quantitative measures, however, has constrained its applicability in qualitative measures. This tends to drive a company either to ignore the qualitative measures or convert them into quantitative data which may lead to incorrect or lost information. Apart from performance measurement, KPIs are often expected to be used as a tool for benchmarking among different function areas within an organization or with outside competitors in the open market. Being expressed by different units or measurement scales, KPIs cannot be helpful in any types of comparison and benchmarking. Furthermore, top management frequently makes decisions based on the information generated from base level KPIs. The performance measured by indicators often carry different importance towards the company strategy and have a certain degree of interdependency. Identifying their importance by taking into account the existence of interdependency is important in synthesising those indicators rationally to the top level KPIs for management to base decisions upon.

The methodology proposed in Chapter 6 enabled KPIs to be used for measuring both qualitative and quantitative data, and to assess and benchmark performances within service functions of shipping companies or between competitors. The interdependency among indicators was identified by using a DEMATEL method. The results obtained contribute to the application of an ANP approach which was for the first time to determine the interdependent weights of all indicators in the shipping context. The well-known fuzzy rule-based system handles uncertainties using a systematic procedure without the need of precise quantitative data. Consequently, the involved stakeholders and industrial practitioners could easily carry out their evaluation using the predefined lingusitcs grades without the need of knowing the mechanism on KPI transformation.

7.3 Limitations of the Research and Suggestions for Future Research

7.3.1 Limitations of the Research

This research explores the application of Six Sigma in OSFs of shipping companies. Six Sigma in OSFs of shipping companies was analysed for the first time. While showing immediate benefits and capabilities in the shipping OSFs, the successful delivery of Six Sigma projects in leading companies also reveals potentials and concerns yet to be identified. There was only limited data and information available to support the research. It therefore led to the use of illustrative case studies in the model developments. During the case study for the KPIs management model, questionnaires had to be revisited several times in order to achieve consistent results. Interviews were also arranged for data collection. Personal interview was rather time-consuming and the success depended on the willingness of respondents to collaborate. Furthermore, the questionnaire consisted of over 200 pairwise comparisons and it was difficult to complete the questionnaire in one interview. Due to the time constraint, it was difficult to conduct multiple interviews with participants of this research. Some of the questions were therefore dealt with by emails and telephone conversations. The focus of this research was not only to test the applicability of Six Sigma in OSFs of shipping companies, but very importantly, to enhance its tools for dealing with uncertainties. However, no attempt had yet made to test the models in other sectors of service industries. Moreover, tools in the extensions and derivatives of Six Sigma, such as DFSS and Lean Six Sigma were not discussed in this study. All the aforementioned issues could contribute to more relevant studies in future to make this research a sustainable topic under investigation.

7.3.2 Suggestions for Future Research

In the study of Six Sigma, most research is focusing on its application in different industry sectors. Very limited research, if any, is investigating the possibility of improving its tool sets in order to handle uncertainties. It is necessary to address the existence of uncertainties in the service industries in general and in OSFs of shipping companies in specific. The involvement of a large number of assumptions, subjective judgements and opinions needs to be dealt with carefully and effectively during the Six Sigma implementations. Several areas of further research based on the outcome of this thesis are listed as follows:

- Implement the developed framework and models in more OSFs of shipping companies so that the findings from this study could be generalised. Such a process will also help verify the capabilities and difficulties of the newly developed framework and methods.

- Increase the research scope across a wider range of service industries.
  The capability of new Six Sigma toolsets in terms of tackling uncertainties will be useful to facilitate the implementation of the DMAIC framework in the sectors where qualitative features of quality control could not be easily ignored. It to some extent opens a new horizon in Six Sigma research and with time, will possibly provide a paradigm shift in the Six Sigma methodology and its implementation

- Enhance other Six Sigma related methodologies with more powerful toolsets and methods.
  The applicability of the newly developed models and methods in DFSS and Lean-Six Sigma can be investigated to enhance their abilities of accommodating uncertainties in input data.

- Use the advanced techniques and methods to enhance the uncertainty treatment capability of the other classical tools in Six Sigma.
  This study only proposed the improved methods for a few tools highly demanded in the projects/case studies being undertaken during this research. It will be beneficial to further conduct the similar studies to see how the other tools such as C&E matrix can benefit from the use of advanced techniques and methods.

The shipping industry is paying an increasing attention to improvement of service quality. The methodology and mechanism of Six Sigma in process improvement make it attractive in terms of both research reach and significance. By improving its ability in uncertainty treatment, Six Sigma can be significantly enhancing its impact in width (across different sectors) and in depth (involving more projects of qualitative features). This PhD study formulates a platform for future research to be conducted in the subject of enhancing the applicability of Six Sigma under different uncertain environments.

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Appendices

Appendix 1 C&E matrix for non-recovered wasted journey

Rating of Importance to Customer		8	10	7	7	
Process Step	**Process Inputs**	No. of Recoverable wasted Journeys (WJ)	No. of none recoverable WJ	Customer Satisfaction	Cost of WJ	Total
Notification to transport team	Time of day	9	9	9	9	288
Haulage collected/not collected	Container suitability	9	9	9	9	288
Haulage arranged	Accuracy of info	9	9	9	9	288
Receive instruction from customer	Type of instructions	9	9	9	9	288
Input data into system	Operator experience	9	9	9	3	246
Input data into system	Type of cargo	9	9	9	3	246
Charge recovery from customer and notify	Quality of notification of failure	9	9	9	1	232
Haulage arranged	Time of job	9	9	9	1	232
Receive instruction from customer	Timing of instruction	9	3	9	9	228
Receive instruction from customer	Timing of cancellation	9	3	9	9	228
Receive instruction from customer	Accuracy of information	9	9	9	0	225
Receive instruction from customer	Number booking reference ability	9	9	9	0	225
Receive instruction from customer	Customer service quality	9	9	9	0	225
Haulage collected/not collected	Inaccessible load place	9	9	9	0	225
Charge recovery from customer and notify	Customer notification period	9	9	9	0	225
Charge recovery from customer and notify	Customer (acceptance/rejection)	9	9	9	0	225
Charge recovery from customer and notify	Customer querying notification	9	9	9	0	225
Haulage arranged	Accuracy of info transmitted to haulier	9	9	9	0	225
Haulage arranged	Time of year (bank Holidays)	9	9	9	0	225
Raise invoice	Transport confirmation POD	9	9	3	3	204
Receive instruction from customer	Availability of specialist equipment	3	9	9	3	198
Notification to transport team	No. of orders	3	9	1	9	184
Input data into system	Collection reference accuracy	9	9	3	0	183
Booking confirmed with customer/agent	Acknowledgement from customer (y/n)	9	9	3	0	183
Raise invoice	Data accuracy in system	9	9	3	0	183
Raise invoice	Freight invoices timing on credit customers	9	9	3	0	183
Raise invoice	Cancelled booking	9	9	3	0	183
Haulage collected/not collected	Number of jobs	3	3	9	9	180
Notification to transport team	Availability of transport team	3	9	0	9	177
Receive instruction from customer	Time of day (peak booking period)	3	9	9	0	177
Notification to transport team	Accuracy of Information	3	9	9	0	177
Haulage collected/not collected	Equipment availability	0	9	9	3	174
Haulage collected/not collected	Cargo weight	9	9	1	0	169
Haulage collected/not collected	Out of gauge cargo	9	9	1	0	169
Haulage collected/not collected	Undeclared hazard	9	9	1	0	169

Raise invoice	Port of discharge agent	9	9	1	0	169
Receive instruction from customer	Equipment functionality (fax email)	9	3	9	0	165
Receive instruction from customer	Number of customer points of contact	1	9	9	0	161
Haulage collected/not collected	Depot delay	0	9	9	0	153
Cost versus Recovery	Linkage of cost code with revenue code	3	3	9	3	138
Haulage collected/not collected	Weather conditions/ vehicle breakdown/traffic conditions	3	3	3	9	138
Receive instruction from customer	Customer	9	3	3	0	123
Receive instruction from customer	Amendments of instructions	9	3	3	0	123
Haulage collected/not collected	Hazardous labels (present/not present)	9	3	3	0	123
Notification to transport team	Response time	3	3	9	0	117
Receive instruction from customer	System setup/functionality	0	9	3	0	111
Input data into system	Data accuracy	0	9	3	0	111
Input data into system	Number of orders	0	9	3	0	111
Input data into system	Staff availability	0	9	3	0	111
Transport re-booked	Warehouse availability	9	1	1	0	89
Haulage arranged	Mode of transport	1	1	1	9	88
Haulage arranged	Availability of Haulier	3	3	3	1	82
Transport re-booked	Vessel cut off time	1	1	9	0	81
Transport re-booked	Space on vessel	1	1	9	0	81
Transport re-booked	Time of notification	1	1	9	0	81
Haulage collected/not collected	Customer contact details (yes/no)	3	3	3	0	75
Transport re-booked	Number of amendments	3	3	3	0	75
Raise invoice	Credit customer (y/n)	3	3	3	0	75
Raise invoice	Information on credit	3	3	3	0	75
Haulage arranged	Operator availability	3	3	3	0	75
Haulage arranged	Operator training	3	3	3	0	75
Haulage collected/not collected	No paper work	0	3	3	3	72
Haulage collected/not collected	Driver hour allocations	0	3	3	3	72
Receive instruction from customer	Availability of vessel space	0	0	9	0	63
Haulage collected/not collected	Haulier error	0	0	9	0	63
Cost versus Recovery	Accuracy of info from haulier	1	1	1	1	32
Cost versus Recovery	Accuracy of log	1	1	1	1	32
Transport re-booked	Hazardous acceptance	0	0	3	0	21

Appendix 2 FMEA analysis for non-recovered wasted journey

Key Process Input	Failure Modes - What can go wrong?	Effects	SEV	Causes	OCC	Current Controls	DET	RPN
Container suitability	Customer did not request specific container details	Wasted journey (customer or company liability)	10	Customer makes assumptions that container will be suitable	8	No current control	9	720
Container suitability	Information not put on booking	Wasted Journey not recoverable	10	Human error	7	No current control	9	630
accuracy of info	Wrong date or time relayed	Wasted Journey company liable	10	Human error	7	No current control	9	630
accuracy of info	Wrong size container	Wasted journey company liable	10	Operator error, info not put on	6	No current control	9	540
accuracy of info	Load Reference not given	Wasted journey or detention	8	Customer does not give reference	7	No current control	9	504
Time of day	Cancellation received close to midday and relayed to transport after 12	Wasted Journey liable to company	10	Cut off of 12 and customers utilise every second.	5	No formal controls	9	450
Quality of notification of failure	Conflicting info from different departments	Difficulty in wasted journey recovery	10	Wrong info relayed (transport)	7	Unknown	6	420
Operator experience	Wrong data inputted	Wasted journeys	10	Lack of supervisory time	8	No current control	5	400
Container suitability	Box not available	Wasted Journey due to either company or Depot	6	Unknown damage to box's and equipment	7	Depot controls /container control	9	378
Accuracy of info	Special trailer requirements missed	Wasted Journey customer	8	Information not given by customer	5	No controls	9	360
Accuracy of info	Special trailer requirements missed	Wasted journey to company	10	Operator error info not put on	4	No current control	9	360
Accuracy of info	No special requirements	Wasted Journey company liable	10	Customer assumes company knowledge for repeat business	4	No current control	9	360
Type of Instructions	Email and fax not functioning	Delays cancellation causing wasted journey	10	Server issues/ failures	4	No current control	9	360
Operator experience	Wrong data inputted	Wasted journeys	10	Staff Shortages	7	No current control	5	350
Container suitability	Box not available	wasted Journey due to either company or Depot	8	Box not released (data accuracy)	4	Depot controls /container control	9	288
Time of job	Late for pick up	Dispute with customer (accepted or rejected)	5	Late on previous job	8	No current control	7	280
Container suitability	Depot releases box not to request standard	Wasted journey fault of depot	6	Data accuracy and stock control	5	Depot controls /container control	9	270
Accuracy of info	Wrong pick up point info	Wasted Journey company liable	10	Repeat bookings with changed address	3	No current control	9	270
Accuracy of info	Wrong pick up point info	Wasted Journey company liable	10	Places with same name, transport do not book on postal code	3	No current control	9	270

Accuracy of info	Wrong size container	Wasted Journey Customer	6	Customer error (wrong info)	5	No current control	9	270
Time of job	Late for pick up	Dispute with customer (accepted or rejected)	5	Collecting empty from depot due to opening hours/ or in stack	7	No current control	7	245
Container suitability	Customer did not request specific container details	Wasted journeys	8	Lack of customer knowledge	3	No current control	9	216
Accuracy of info	Undeclared out of gauge	Wasted journey to customer	8	Customer does not declare or give accurate measurements	3	No current control	9	216
Operator experience	Wrong data inputted	Wasted journeys	10	Lack of training	5	Limited training	4	200
Container suitability	Information not put on booking.	Wasted Journey not recoverable	10	Lack of Knowledge of Customer Service	2	No current control	9	180
Quality of notification of failure	Delay in customer notification	Difficulty in wasted journey recovery	8	Delayed info from transport (costs)	4	No current control	4	128
Quality of notification of failure	Delay in customer notification	Difficulty in wasted journey recovery	8	Lack of time in customer service department	4	No current control	4	128
Accuracy of info	Un-booked Hazard and/or no stickers	Wasted journey to customer	6	customer does not declare as hazard	2	Responsibili ty of customer	9	108
Accuracy of info	Un-booked Hazard and/or no stickers	Wasted journey to company	10	Operator error info not put in system	1	No current control	9	90
Accuracy of info	Undeclared out of gauge	Wasted journey to company	10	Operator error info not put in system	1	No current control	9	90

Appendix 3 FRB with Belief Structures and Weights of Criteria in FMEA from Case Study

Failure	S 45.40%	O 34.70%	D 19.90%	Risk Level				
				VL	L	A	H	VH
F1	VL	VL	VL	100.00%	0.00%	0.00%	0.00%	0.00%
F2	VL	VL	L	80.10%	19.90%	0.00%	0.00%	0.00%
F3	VL	VL	A	80.10%	0	19.90%	0	0
F4	VL	VL	H	80.10%	0	0	19.90%	0
F5	VL	VL	VH	80.10%	0	0	0	19.90%
F6	VL	L	VL	65.30%	34.70%	0	0	0
F7	VL	L	L	45.40%	54.60%	0	0	0
F8	VL	L	A	45.40%	34.70%	19.90%	0	0
F9	VL	L	H	45.40%	34.70%	0	19.90%	0
F10	VL	L	VH	45.40%	34.70%	0	0	19.90%
F11	VL	A	VL	65.30%	0.00%	34.70%	0.00%	0.00%
F12	VL	A	L	45.40%	19.90%	34.70%	0.00%	0.00%
F13	VL	A	A	45.40%	0.00%	54.60%	0.00%	0.00%
F14	VL	A	H	45.40%	0.00%	34.70%	19.90%	0.00%
F15	VL	A	VH	45.40%	0.00%	34.70%	0.00%	19.90%
F16	VL	H	VL	65.30%	0.00%	0.00%	34.70%	0.00%
F17	VL	H	L	45.40%	19.90%	0.00%	34.70%	0.00%
F18	VL	H	A	45.40%	0.00%	19.90%	34.70%	0.00%
F19	VL	H	H	45.40%	0.00%	0.00%	54.60%	0.00%
F20	VL	H	VH	45.40%	0.00%	0.00%	34.70%	19.90%
F21	VL	VH	VL	65.30%	0.00%	0.00%	0.00%	34.70%
F22	VL	VH	L	45.40%	19.90%	0.00%	0.00%	34.70%
F23	VL	VH	A	45.40%	0.00%	19.90%	0.00%	34.70%
F24	VL	VH	H	45.40%	0.00%	0.00%	19.90%	34.70%
F25	VL	VH	VH	45.40%	0.00%	0.00%	0.00%	54.60%
F26	L	VL	VL	54.60%	45.40%	0	0	0
F27	L	VL	L	34.70%	65.30%	0	0	0
F28	L	VL	A	34.70%	45.40%	19.90%	0	0
F29	L	VL	H	34.70%	45.40%	0	19.90%	0
F30	L	VL	VH	34.70%	45.40%	0	0	19.90%
F31	L	L	VL	19.90%	80.10%	0	0	0
F32	L	L	L	0.00%	100.00%	0	0	0
F33	L	L	A	0.00%	80.10%	19.90%	0	0
F34	L	L	H	0.00%	80.10%	0	19.90%	0
F35	L	L	VH	0.00%	80.10%	0	0	19.90%
F36	L	A	VL	19.90%	45.40%	34.70%	0.00%	0.00%
F37	L	A	L	0.00%	65.30%	34.70%	0.00%	0.00%
F38	L	A	A	0.00%	45.40%	54.60%	0.00%	0.00%
F39	L	A	H	0.00%	45.40%	34.70%	19.90%	0.00%
F40	L	A	VH	0.00%	45.40%	34.70%	0.00%	19.90%
F41	L	H	VL	19.90%	45.40%	0.00%	34.70%	0.00%
F42	L	H	L	0.00%	65.30%	0.00%	34.70%	0.00%
F43	L	H	A	0.00%	45.40%	19.90%	34.70%	0.00%
F44	L	H	H	0.00%	45.40%	0.00%	54.60%	0.00%
F45	L	H	VH	0.00%	45.40%	0.00%	34.70%	19.90%
F46	L	VH	VL	19.90%	45.40%	0.00%	0.00%	34.70%
F47	L	VH	L	0.00%	65.30%	0.00%	0.00%	34.70%
F48	L	VH	A	0.00%	45.40%	19.90%	0.00%	34.70%
F49	L	VH	H	0.00%	45.40%	0.00%	19.90%	34.70%
F50	L	VH	VH	0.00%	45.40%	0.00%	0.00%	54.60%
F51	A	VL	VL	54.60%	0	45.40%	0	0
F52	A	VL	L	34.70%	19.90%	45.40%	0	0
F53	A	VL	A	34.70%	0	65.30%	0	0
F54	A	VL	H	34.70%	0	45.40%	19.90%	0
F55	A	VL	VH	34.70%	0	45.40%	0	19.90%
F56	A	L	VL	19.90%	34.70%	45.40%	0	0
F57	A	L	L	0.00%	54.60%	45.40%	0	0
F58	A	L	A	0.00%	34.70%	65.30%	0	0
F59	A	L	H	0.00%	34.70%	45.40%	19.90%	0
F60	A	L	VH	0.00%	34.70%	45.40%	0	19.90%
F61	A	A	VL	19.90%	0.00%	80.10%	0.00%	0.00%

F62	A	A	L	0.00%	19.90%	80.10%	0.00%	0.00%
F63	A	A	A	0.00%	0.00%	100.00%	0.00%	0.00%
F64	A	A	H	0.00%	0.00%	80.10%	19.90%	0.00%
F65	A	A	VH	0.00%	0.00%	80.10%	0.00%	19.90%
F66	A	H	VL	19.90%	0.00%	45.40%	34.70%	0.00%
F67	A	H	L	0.00%	19.90%	45.40%	34.70%	0.00%
F68	A	H	A	0.00%	0.00%	65.30%	34.70%	0.00%
F69	A	H	H	0.00%	0.00%	45.40%	54.60%	0.00%
F70	A	H	VH	0.00%	0.00%	45.40%	34.70%	19.90%
F71	A	VH	VL	19.90%	0.00%	45.40%	0.00%	34.70%
F72	A	VH	L	0.00%	19.90%	45.40%	0.00%	34.70%
F73	A	VH	A	0.00%	0.00%	65.30%	0.00%	34.70%
F74	A	VH	H	0.00%	0.00%	45.40%	19.90%	34.70%
F75	A	VH	VH	0.00%	0.00%	45.40%	0.00%	54.60%
F76	H	VL	VL	54.60%	0	0	45.40%	0
F77	H	VL	L	34.70%	19.90%	0	45.40%	0
F78	H	VL	A	34.70%	0	19.90%	45.40%	0
F79	H	VL	H	34.70%	0	0	65.30%	0
F80	H	VL	VH	34.70%	0	0	45.40%	19.90%
F81	H	L	VL	19.90%	34.70%	0.00%	45.40%	0.00%
F82	H	L	L	0.00%	54.60%	0.00%	45.40%	0.00%
F83	H	L	A	0.00%	34.70%	19.90%	45.40%	0.00%
F84	H	L	H	0.00%	34.70%	0.00%	65.30%	0.00%
F85	H	L	VH	0.00%	34.70%	0.00%	45.40%	19.90%
F86	H	A	VL	19.90%	0.00%	34.70%	45.40%	0.00%
F87	H	A	L	0.00%	19.90%	34.70%	45.40%	0.00%
F88	H	A	A	0.00%	0.00%	54.60%	45.40%	0.00%
F89	H	A	H	0.00%	0.00%	34.70%	65.30%	0.00%
F90	H	A	VH	0.00%	0.00%	34.70%	45.40%	19.90%
F91	H	H	VL	19.90%	0.00%	0.00%	80.10%	0.00%
F92	H	H	L	0.00%	19.90%	0.00%	80.10%	0.00%
F93	H	H	A	0.00%	0.00%	19.90%	80.10%	0.00%
F94	H	H	H	0.00%	0.00%	0.00%	100.00%	0.00%
F95	H	H	VH	0.00%	0.00%	0.00%	80.10%	19.90%
F96	H	VH	VL	19.90%	0.00%	0.00%	45.40%	34.70%
F97	H	VH	L	0.00%	19.90%	0.00%	45.40%	34.70%
F98	H	VH	A	0.00%	0.00%	19.90%	45.40%	34.70%
F99	H	VH	H	0.00%	0.00%	0.00%	65.30%	34.70%
F100	H	VH	VH	0.00%	0.00%	0.00%	45.40%	54.60%
F101	VH	VL	VL	54.60%	0	0	0	45.40%
F102	VH	VL	L	34.70%	19.90%	0	0	45.40%
F103	VH	VL	A	34.70%	0	19.90%	0	45.40%
F104	VH	VL	H	34.70%	0	0	19.90%	45.40%
F105	VH	VL	VH	34.70%	0	0	0	65.30%
F106	VH	L	VL	19.90%	34.70%	0.00%	0.00%	45.40%
F107	VH	L	L	0.00%	54.60%	0.00%	0.00%	45.40%
F108	VH	L	A	0.00%	34.70%	19.90%	0.00%	45.40%
F109	VH	L	H	0.00%	34.70%	0.00%	19.90%	45.40%
F110	VH	L	VH	0.00%	34.70%	0.00%	0.00%	65.30%
F111	VH	A	VL	19.90%	0.00%	34.70%	0.00%	45.40%
F112	VH	A	L	0.00%	19.90%	34.70%	0.00%	45.40%
F113	VH	A	A	0.00%	0.00%	54.60%	0.00%	45.40%
F114	VH	A	H	0.00%	0.00%	34.70%	19.90%	45.40%
F115	VH	A	VH	0.00%	0.00%	34.70%	0.00%	65.30%
F116	VH	H	VL	19.90%	0.00%	0.00%	34.70%	45.40%
F117	VH	H	L	0.00%	19.90%	0.00%	34.70%	45.40%
F118	VH	H	A	0.00%	0.00%	19.90%	34.70%	45.40%
F119	VH	H	H	0.00%	0.00%	0.00%	54.60%	45.40%
F120	VH	H	VH	0.00%	0.00%	0.00%	34.70%	65.30%
F121	VH	VH	VL	19.90%	0.00%	0.00%	0.00%	80.10%
F122	VH	VH	L	0.00%	19.90%	0.00%	0.00%	80.10%
F123	VH	VH	A	0.00%	0.00%	19.90%	0.00%	80.10%
F124	VH	VH	H	0.00%	0.00%	0.00%	19.90%	80.10%

F125	VH	VH	VH	0.00%	0.00%	0.00%	0.00%	100.00%

Appendix 4 Questionnaire for DEMATEL Study Among KPIs

School of Engineering
Section of Maritime Studies

Liverpool John Moores University
Byrom Street

L3 3AF

UK

Phone : 0044 (0)151 231 2028

Fax : 0044 (0)151 298 2624

Email : z.qu@ljmu.ac.uk

08 October 2014

Dear Sir/Madam,

With the ever increasing customer requirements level and global market competition, companies are paying increasing attention to enhance their performance in order to retain customers. Profitability along is not sufficient to discriminate excellence. Therefore, measuring company performance in every aspect becomes an important part of today's business management. As one of the performance measurement tools, Key Performance Indicators (KPIs) are widely used in practice as a freestanding tool or part of process improvement methodology.

A research project at Liverpool John Moores University is currently being carried out with regard to KPIs management in shipping industry. The necessity for this investigation is that at the moment, most companies that uses KPIs only use them to measure numerical inputs, but not or very limited where qualitative information presents. This has made KPIs become measures for what can be measured instead of what needs to be measured. Furthermore, if effectively used, KPIs can be used as great bases for performance benchmarking and comparisons.

This research aims at develop a KPIs management method using techniques that can effectively handle qualitative data and take into account of the weights and relationship of different KPIs so that they can be eventually synthesized into comparable units.

Our research now needs to test if the newly developed method can serve the research aims. Thus this survey sets out for collecting information to be used in the method. For the purpose of this research, existing KPIs in your company are adopted.

I should be most grateful if I could ask you to spare some of your very valuable time to complete the accompanying questionnaire and to email or post it to myself at the address as shown above. Your vital feedback will greatly benefit and contribute in the formulation of an industry wide opinion. I can assure you that the confidentiality of your response will be honoured and respected.

Yours faithfully,

Zhuohua Qu
Lead Researcher
MSc, B.Eng (Hons) Maritime Operations

Introductory of the questionnaire survey

The questionnaire will be about first of all comparing the interdependency among KPIs, secondly comparing relative importance of KPIs and thirdly, the influencing weight of PIs.

KPI and PI list

	KPI	PI
Company overall performance	Health and Safety Management & Performance	➢ Lost time injury rate ➢ Total recordable case frequency ➢ Near miss reports received
	Quality Assurance	➢ Overdue NCNs ➢ Overdue NCNs longer than 1 month ➢ Overdue audits – office ➢ Overdue SHEQ audits - ships
	Environmental Performance	➢ Contained spillage ➢ Pollution incidents ➢ Port authority environmental violations ➢ Suppliers with ISO 14001 accreditation
	HR Management Performance	➢ Crew retention ➢ Office staff retention
	Operational Performance	➢ Unscheduled downtime. Out of service - offshore ➢ Unscheduled downtime. Out of service - marine ➢ Overdue vsl technical inspections ➢ Port state detentions
	Technical Performance	➢ Outstanding PM items
	Purchasing & Accounting Performance	➢ Outstanding invoices not approved for paym (NAPS) ➢ Purchasing feedback reports

The objective of this questionnaire is to identify any interdependency among KPIs.

Description on how to fill up the Questionnaire

The evaluation scale of interdependency between indicators ranges from 0 to 3 as show in the table below.

Evaluation scale and its corresponding degree of agree

0	No influence
1	Low influence
2	Medium influence
3	High influence
4	Very high influence

Example - how to evaluate the interdependency of indicators and fill the blanks of the Evaluation Forms for indicators

This Evaluation Form attempts to draw your evaluation on the level of influence among KPIs. For example, among 7 KPIs, if you think that the performance of PIs in **KPI B (Quality Assurance)** has **high influence** on the performance of target **KPI A (Health and Safety Management & Performance)**, your evaluation scale is “3” so that you should mark “X” in “3” against KPI B on the evaluation form as below.

Sample Form:

Target KPI: (A) Health and Safety Management & Performance					
KPI	Degree of influencing				
	0	1	2	3	4
(B) Quality Assurance				X	

However, if you think that the performance of PIs in **KPI B (Quality Assurance)** has **no influence** on the performance of targeting **KPI A (Health and Safety Management & Performance)**, your evaluation scale is “0” so that you should mark “X” in “0” against KPI B on the evaluation form as below.

Sample Form:

Target KPI: (A) Health and Safety Management & Performance					
KPI	Degree of influencing				
	0	1	2	3	4
(B) Quality Assurance	X				

Evaluation form of the influence level between KPIs (Questionnaire to be filled)

Degree of influence that each of the following KPI directly has on the target KPI: (A)Health and Safety Management & Performance					
KPI	**<u>Degree of influencing</u> 0: No influence, 1:Low influence 2:Medium influence: 3: High influence 4:Very high influence**				
	0	1	2	3	4
(B)Quality Assurance					
(C)Environmental Performance					
(D)HR Management Performance					
(E)Operational Performance					
(F)Technical Performance					
(G)Purchasing & Accounting Performance					

Degree of influence that each of the following KPI directly has on the target KPI: (B)Quality Assurance					
KPI	**<u>Degree of influencing</u> 0: No influence, 1:Low influence 2:Medium influence: 3: High influence 4:Very high influence**				
	0	1	2	3	4
(A)Health and Safety Management & Performance					
(C)Environmental Performance					
(D)HR Management Performance					
(E)Operational Performance					
(F)Technical Performance					
(G)Purchasing & Accounting Performance					

Degree of influence that each of the following KPI directly has on the target KPI: (C)Environmental Performance					
KPI	**<u>Degree of influencing</u>** **0: No influence, 1:Low influence** **2:Medium influence: 3: High influence** **4:Very high influence**				
	0	1	2	3	4
(A)Health and Safety Management & Performance					
(B)Quality Assurance					
(D)HR Management Performance					
(E)Operational Performance					
(F)Technical Performance					
(G)Purchasing & Accounting Performance					

Degree of influence that each of the following KPI directly has on the target KPI: (D)HR Management Performance					
KPI	**<u>Degree of influencing</u>** **0: No influence, 1:Low influence** **2:Medium influence: 3: High influence** **4:Very high influence**				
	0	1	2	3	4
(A)Health and Safety Management & Performance					
(B)Quality Assurance					
(C)Environmental Performance					
(E)Operational Performance					
(F)Technical Performance					
(G)Purchasing & Accounting Performance					

Degree of influence that each of the following KPI directly has on the target KPI: (E)Operational Performance					
KPI	**Degree of influencing** **0: No influence, 1:Low influence 2:Medium influence: 3: High influence** **4:Very high influence**				
	0	1	2	3	4
(A)Health and Safety Management & Performance					
(B)Quality Assurance					
(C)Environmental Performance					
(D)HR Management Performance					
(F)Technical Performance					
(G)Purchasing & Accounting Performance					

Degree of influence that each of the following KPI directly has on the target KPI: (F)Technical Performance					
KPI	**Degree of influencing** **0: No influence, 1:Low influence 2:Medium influence: 3: High influence** **4:Very high influence**				
	0	1	2	3	4
(A)Health and Safety Management & Performance					
(B)Quality Assurance					
(C)Environmental Performance					
(D)HR Management Performance					
(E)Operational Performance					
(G)Purchasing & Accounting Performance					

Degree of influence that each of the following KPI directly has on the target KPI: (G)Purchasing & Accounting Performance					
KPI	**Degree of influencing** **0: No influence, 1:Low influence 2:Medium influence: 3: High influence** **4:Very high influence**				
	0	1	2	3	4
(A)Health and Safety Management & Performance					
(B)Quality Assurance					
(C)Environmental Performance					
(D)HR Management Performance					
(E)Operational Performance					
(F)Technical Performance					

Appendix 5 Questionnaire for ANP Study to Obtain the Evaluation for the Importance of Indicators in Relation to the Upper Level Indicators

The objective is to identify the importance of KPIs and PIs in relation to their upper-level indicators.

Description on how to fill up the Questionnaire

The evaluation scale of weights of criteria ranges from 1 to 9 depending on the degree of relative importance as shown in the table below.

Evaluation scale and its corresponding degree of importance

Evaluation scale	Degree of importance
1	Equally Important to the objective
3	Slightly more important to the objective
5	Moderately more important to the objective
7	Strongly more important to the objective
9	Absolutely more important to the objective

2, 4, 6, 8 are intermediate values between the two adjacent judgements

Example - how to evaluate the relative importance of criteria and fill the blanks of the Evaluation Form for KPIs

Our Evaluation Form attempts to draw your evaluation on relative importance of KPIs and PIs between the first left hand and the last right hand columns. In other words, it aims to identify how much more relatively important the KPIs or PIs in the first left hand column are compared to those in the last right hand column for every row to the objective, and vice versa.

For example, if you think **KPI A (Health and Safety Management & Performance)** in the first LEFT hand column is more important than **KPI B (Quality Assurance)** in the last RIGHT hand column in contributing to the **objective** - company overall performance, then please tick "X" in "A" (as below in blue). After that, if you think that A is **moderately more important** than B, your evaluation scale is "5" so that you should circle the 5:1 column of the Evaluation Form below. (See our Sample Form below)

Sample Form:

KPI	**(Absolutely more important：9、Strongly more important:7、 Moderately more important：5、Slightly more important: 3、 Equally Important：1)**																		KPI
	In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale								Equally important	In case that KPI in last RIGHT hand column are relatively more important than the KPI in the first LEFT hand column, circle an appropriate column according to your importance evaluation scale									
(A) Health and Safety Management & Performance (X)	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	**1:1**	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9		(B) Quality Assurance ( )

On the contrary, if you think **KPI B (Quality Assurance)** in the last RIGHT hand column is more important than **KPI A (Health and Safety Management & Performance)** in the first LEFT hand column in contributing to the **objective** - company overall performance, then please tick “X” in “B” (as below in blue). After that, if you think that B is **Strongly more important** than A, your evaluation scale is “7” so that you should circle the 1:7 column of the Evaluation Form below. (See our Sample Form below)

Sample Form:

KPI	**(Absolutely more important：9、Strongly more important:7、 Moderately more important：5、Slightly more important: 3、 Equally Important：1)**																		KPI
	In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale								Equally important	In case that KPI in last RIGHT hand column are relatively more important than the KPI in the first LEFT hand column, circle an appropriate column according to your importance evaluation scale									
(A) Health and Safety Management & Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	**1:1**	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9		(B) Quality Assurance (X)

Next, if you think the importance of any KPI or PI is located between “Strongly more important (the scale 7)” and “Absolutely more important (the scale 9)” to the objective, compared to other KPI or PI, your evaluation scale is 8 so that please circle the 8:1 or 1:8 column. This logical scale evaluation is applied to evaluation scales, 2, 4, 6, and 8.

Finally, if your think that the importance of KPIs between A in the first left hand column and B in the last right hand column are the same ("Equally Important") to the objective, your evaluation scale is 1, please circle only in the 1:1 column in the middle of the Evaluation Form. (See our Sample Form below)

Sample Form:

<table>
<tr><td rowspan="2">KPI</td><td colspan="17">(Absolutely more important：9、Strongly more important:7、Moderately more important：5、Slightly more important: 3、Equally Important：1)</td><td rowspan="2">KPI</td></tr>
<tr><td colspan="8">In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale</td><td>Equally important</td><td colspan="8">In case that KPI in last RIGHT hand column are relatively more important than the KPI in the first LEFT hand column, circle in an appropriate column according to your importance evaluation scale</td></tr>
<tr><td>(A) Health and Safety Management & Performance ( )</td><td>9:1</td><td>8:1</td><td>7:1</td><td>6:1</td><td>5:1</td><td>4:1</td><td>3:1</td><td>2:1</td><td>1:1</td><td>1:2</td><td>1:3</td><td>1:4</td><td>1:5</td><td>1:6</td><td>1:7</td><td>1:8</td><td>1:9</td><td>(B) Quality Assurance ( )</td></tr>
</table>

In the same way as explained above, **<u>all the comparison on each row SHOULD be filled with one of the evaluation scale numbers ranging from 1 to 9 according to your judgment of weights between each pair of criteria.</u>**

Evaluation form of the importance of all indicators in relation to the upper level indicators (Questionnaire to be filled)

Objective - Company overall performance																		
KPI	**(Absolutely more important：9、Strongly more important:7、Moderately more important：5、Slightly more important: 3、Equally Important：1)**																	KPI
	In case that KPI in first LEFT hand column is relatively more important than the KPI in the last right hand column, circle an appropriate column according to your evaluation scale								Equally important	In case that KPI in last RIGHT hand column is relatively more important than the criteria in the first LEFT hand column, circle an appropriate column according to your evaluation scale								
(A)Health and Safety Management & Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(B)Quality Assurance ( )
(A)Health and Safety Management & Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(C)Environmental Performance ( )
(A)Health and Safety Management & Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(D)HR Management Performance ( )
(A)Health and Safety Management & Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E)Operational Performance ( )
(A)Health and Safety Management & Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(F)Technical Performance ( )
(A)Health and Safety Management & Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(G)Purchasing & Accounting Performance ( )
(B)Quality Assurance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(C)Environmental Performance ( )
(B)Quality Assurance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(D)HR Management Performance ( )
(B)Quality Assurance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E)Operational Performance ( )
(B)Quality Assurance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(F)Technical Performance ( )
(B)Quality Assurance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(G)Purchasing & Accounting Performance ( )
(C)Environmental Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(D)HR Management Performance ( )
(C)Environmental Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E)Operational Performance ( )
(C)Environmental Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(F)Technical Performance ( )
(C)Environmental Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(G)Purchasing & Accounting Performance ( )

(D)HR Management Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E)Operational Performance ( )
(D)HR Management Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(F)Technical Performance ( )
(D)HR Management Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(G)Purchasing & Accounting Performance ( )
(E)Operational Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(F)Technical Performance ( )
(E)Operational Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(G)Purchasing & Accounting Performance ( )
(F)Technical Performance ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(G)Purchasing & Accounting

KPI (A) Health and Safety Management & Performance																		
PI	**(Absolutely more important：9、Strongly more important:7、Moderately more important：5、Slightly more important: 3、Equally Important：1)**																	PI
	In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale								Equally important	In case that KPI in last RIGHT hand column are relatively more important than the criteria in the first LEFT hand column, circle an appropriate column according to your importance evaluation scale								
(A1)Lost Time Injury Rate ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(A2)Total Recordable Case Frequency ( )
(A1)Lost Time Injury Rate ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(A3)Near Miss Reports received ( )
(A2)Total Recordable Case Frequency ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(A3)Near Miss Reports received ( )

KPI (B) Quality Assurance																		
PI	**(Absolutely more important：9、Strongly more important:7、 Moderately more important：5、Slightly more important: 3、 Equally Important：1)**																	PI
	In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale								Equally important	In case that KPI in last RIGHT hand column are relatively more important than the criteria in the first LEFT hand column, mark circle an appropriate column according to your importance evaluation scale								
(B1)Overdue NCNs ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(B2)Overdue NCNs longer than 1 month ( )
(B1)Overdue NCNs ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(B3)Overdue Audits - Office ( )
(B1)Overdue NCNs ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(B4)Overdue SHEQ Audits - Ships ( )
(B2)Overdue NCNs longer than 1 month ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(B3)Overdue Audits - Office ( )
(B2)Overdue NCNs longer than 1 month ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(B4)Overdue SHEQ Audits - Ships ( )
(B3)Overdue Audits - Office ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(B4)Overdue SHEQ Audits - Ships ( )

KPI (C) Environmental Performance																		
PI	**(Absolutely more important：9、Strongly more important:7、 Moderately more important：5、Slightly more important: 3、 Equally Important：1)**																	PI
	In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale								Equally important	In case that KPI in last RIGHT hand column are relatively more important than the criteria in the first LEFT hand column, circle an appropriate column according to your importance evaluation scale								
(C1)Contained Spillage ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(C2)Pollution Incidents ( )
(C1)Contained Spillage ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(C3)Port Authority Environmental Violations ( )
(C1)Contained Spillage ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(C4)Suppliers With ISO 14001 Accreditation ( )
(C2)Pollution Incidents ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(C3)Port Authority Environmental Violations ( )
(C2)Pollution Incidents ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(C4)Suppliers With ISO 14001 Accreditation ( )
(C3)Port Authority Environmental Violations ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(C4)Suppliers With ISO 14001 Accreditation ( )

KPI (D) HR Management Performance																		
PI	**(Absolutely more important：9、Strongly more important:7、 Moderately more important：5、Slightly more important: 3、 Equally Important：1)**																	PI
	In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale								Equally important	In case that KPI in last RIGHT hand column are relatively more important than the criteria in the first LEFT hand column, circle an appropriate column according to your importance evaluation scale								
(D1)Crew Retention ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(D2)Office Staff retention ( )

KPI (E) Operational Performance																		
PI	**(Absolutely more important：9、Strongly more important:7、 Moderately more important：5、Slightly more important: 3、 Equally Important：1)**																	PI
	In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale								Equally important	In case that KPI in last RIGHT hand column are relatively more important than the criteria in the first LEFT hand column, circle an appropriate column according to your importance evaluation scale								
(E1)Unscheduled downtime. Out of Service - Offshore ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E2)Unscheduled downtime. Out of Service - Marine ( )
(E1)Unscheduled downtime. Out of Service - Offshore ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E3)Overdue Vsl Technical Inspections ( )
(E1)Unscheduled downtime. Out of Service - Offshore ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E4)Port State Detentions ( )
(E2)Unscheduled downtime. Out of Service - Marine ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E3)Overdue Vsl Technical Inspections ( )
(E2)Unscheduled downtime. Out of Service - Marine ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E4)Port State Detentions ( )
(E3)Overdue Vsl Technical Inspections ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(E4)Port State Detentions ( )

KPI (G) Purchasing & Accounting Performance																		
PI	**(Absolutely more important：9、Strongly more important:7、 Moderately more important：5、Slightly more important: 3、 Equally Important：1)**																	PI
	In case that KPI in first LEFT hand column are relatively more important than the KPI in the last right hand column, circle an appropriate column according to your importance evaluation scale								Equally important	In case that KPI in last RIGHT hand column are relatively more important than the criteria in the first LEFT hand column, circle an appropriate column according to your importance evaluation scale								
(G1)Outstanding invoices not approved for payment (NAPS) ( )	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	(G2)Purchasing Feedback Reports ( )

Appendix 6 Questionnaire for ANP Study to Obtain the Evaluation for the Level of Influences among Lower Level Indicators

This questionnaire will be about finding interdependencies weights among all indicators.

Description on how to fill up the Questionnaire

The evaluation scale of influencing level of indicators ranges from 1 to 9. The followings describe the used scale of **Relative Influence** level of two elements with respect to another given element:

Evaluation scale and its corresponding degree of influence

Evaluation scale	Degree of importance
1	Equal Influence
3	Moderate Influence
5	Essential or Strong Influence
7	Substantial Influence
9	Extreme Influence

2, 4, 6, 8 are intermediate values between the two adjacent judgements

Example - how to evaluate the relative influence level of indicators and fill the blanks of the Evaluation Forms

For example, if you think **KPI B (Quality Assurance)** is more influential than **KPI C (Environmental Performance)** on a common given criteria "**KPI A (Health and Safety Management & Performance)"** in achieving the **objective – better company performance,** then please tick "X" in "B" (as below in blue). Next, if you think "KPI B" influences **"**KPI A**" 5 times more** than the unselected **KPI C –** then circle or highlight "5" in any colour at the side of selected KPI B.

Sample Form:

which of the two indicator influences **<u>(A) Health and Safety Management & Performance</u>** more with respect to the **Company Performance**, and how much more than another indicator																		
KPI	**(Extreme Influence：9、Substantial Influence:7、 Essential or Strong Influence：5、Moderate Influence: 3、 Equal Influence：1)**																	KPI
(B) Quality Assurance (X)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C) Environmental Performance

On the contrary, if you think **KPI C (Environmental Performance)** is more influential than **KPI B (Quality Assurance)** on a common given criteria "**KPI A (Health and Safety Management & Performance)"** in achieving the **objective – better company performance,** then please tick "X" in "C" (as below in blue). Next, if you think "KPI C" influences **"**KPI A**" 9 times more** than the unselected **KPI B –** then circle or highlight "9" in any colour at the side of selected KPI A.

Sample Form:

which of the two indicator influences **<u>(A) Health and Safety Management & Performance</u>** more with respect to the **Company Performance**, and how much more than another indicator																		
KPI	**(Extreme Influence：9、Substantial Influence:7、 Essential or Strong Influence：5、Moderate Influence: 3、 Equal Influence：1)**																	KPI
(B) Quality Assurance ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C) Environmental Performance (X)

Finally, you might notice that there are situations where the indicators to be compared are the same as the common given criteria. For example, compare **KPI B (Quality Assurance)** with **KPI C (Environmental Performance)** to decide which one is more influential on **KPI B (Quality Assurance)** in achieving the objective – better company performance**.** In such situation, if KPI C has little influence on KPI B in respect to the objective and the performance of KPI B in regards to the objective is highly influenced by its own performance, then, KPI B might be 7 or 8 times more influential than KPI C (depending on your judgement). However, If KPI C has strong influence on KPI B than KPI B itself in regards to the objective , then the score to choose will be “5”for KPI C.

In the same way as explained above, **all the comparison on each row SHOULD be filled with one of the evaluation scale numbers ranging from 1 to 9 according to your judgment of the level of influence between each two criteria.**

Evaluation form of the influence level among indicators (Questionnaire to be filled)

Which indicator in the pair (on the same row) influences **A2) Total Recordable Case Frequency** more with respect to the **(A) Health and Safety Management & Performance**, and how much more than the other indicator																			
No.	PI	**(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)**																	PI
1	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C2)Pollution Incidents ( )
2	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environmental Violations ( )
3	(C2)Pollution Incidents ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environmental Violations ( )

Which indicator in the pair (on the same row) influences **B1) Overdue NCNs** more with respect to the **(B) Quality Assurance**, and how much more than the other indicator																			
No.	PI	**(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)**																	PI
4	(B2)Overdue NCNs longer than 1 month ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
5	(E3)Overdue Vsl Technical Inspections ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(E4)Port State Detentions ( )

Which indicator in the pair (on the same row) influences **B2) Overdue NCNs longer than 1 month** more with respect to the **(B) Quality Assurance**, and how much more than the other indicator																			
No.	PI	**(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)**																	PI
6	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )

Which indicator in the pair (on the same row) influences **C1) Contained Spillage** more with respect to the **(C) Environmental Performance**, and how much more than the other indicator																			
No.	PI	**(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)**																	PI
7	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B2)Overdue NCNs longer than 1 month ( )
8	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
9	(B2)Overdue NCNs longer than 1 month ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )

Which indicator in the pair (on the same row) influences **<u>C2) Pollution Incidents</u>** more with respect to the **(C) Environmental Performance**, and how much more than the other indicator																			
No.	PI	**(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)**																	PI
10	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B2)Overdue NCNs longer than 1 month ( )
11	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
12	(B2)Overdue NCNs longer than 1 month ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
13	(E3)Overdue Vsl Technical Inspections ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(E4)Port State Detentions ( )

Which indicator in the pair (on the same row) influences **<u>C3) Port Authority Environmental Violations</u>** more with respect to the **(C) Environmental Performance**, and how much more than the other indicator																			
No.	PI	**(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)**																	PI
14	(A1)Lost Time Injury Rate ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(A2)Total Recordable Case Frequency ( )
15	(A1)Lost Time Injury Rate ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(A3)Near Miss Reports received ( )
16	(A2)Total Recordable Case Frequency ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(A3)Near Miss Reports received ( )
17	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B2)Overdue NCNs longer than 1 month ( )
18	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
19	(B2)Overdue NCNs longer than 1 month ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )

Which indicator in the pair (on the same row) influences **<u>D1) Crew Retention</u>** more with respect to the **(D) HR Management Performance**, and how much more than the other indicator																			
No.	PI	**(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)**																	PI
20	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B2)Overdue NCNs longer than 1 month ( )
21	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
22	(B2)Overdue NCNs longer than 1 month ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )

Which indicator in the pair (on the same row) influences **E1) Unscheduled downtime. Out of Service – Offshore** more with respect to the **(E) Operational Performance**, and how much more the than other indicator

No.	PI	(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)																	PI
23	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C2)Pollution Incidents ( )
24	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environnemental Violations ( )
25	(C2)Pollution Incidents ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environnemental Violations ( )

Which indicator in the pair (on the same row) influences **E2) Unscheduled downtime. Out of Service – Marine** more with respect to the **(E) Operational Performance**, and how much more than the other indicator

No.	PI	(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)																	PI
26	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C2)Pollution Incidents ( )
27	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environnemental Violations ( )
28	(C2)Pollution Incidents ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environnemental Violations ( )

Which indicator in the pair (on the same row) influences **E3) Overdue Vsl Technical Inspections** more with respect to the **(E) Operational Performance**, and how much more than the other indicator

No.	PI	(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence: 3、Equal Influence：1)																	PI
29	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B2)Overdue NCNs longer than 1 month ( )
30	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
31	(B2)Overdue NCNs longer than 1 month ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
32	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C2)Pollution Incidents ( )
33	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environnemental Violations ( )
34	(C2)Pollution Incidents ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environnemental Violations ( )

Which indicator in the pair (on the same row) influences **<u>E4) Port State Detentions</u>** more with respect to the **(E) Operational Performance**, and how much more than the other indicator

No.	PI	(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence:3、Equal Influence：1)																	PI
35	(A1)Lost Time Injury Rate ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(A2)Total Recordable Case Frequency ( )
36	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C2)Pollution Incidents ( )
37	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environmental Violations ( )
38	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C4)Suppliers With ISO 14001 Accreditation ( )
39	(C2)Pollution Incidents ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environmental Violations ( )
40	(C2)Pollution Incidents ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C4)Suppliers With ISO 14001 Accreditation ( )
41	(C3)Port Authority Environmental Violations ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C4)Suppliers With ISO 14001 Accreditation ( )

Which indicator in the pair (on the same row) influences **<u>F1) Outstanding PM Items</u>** more with respect to the **F) Technical Performance**, and how much more than the other indicator

No.	PI	(Extreme Influence：9、Substantial Influence:7、Essential or Strong Influence：5、Moderate Influence:3、Equal Influence：1)																	PI
42	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B2)Overdue NCNs longer than 1 month ( )
43	(B1)Overdue NCNs ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
44	(B2)Overdue NCNs longer than 1 month ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(B4)Overdue SHEQ Audits - Ships ( )
45	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C2)Pollution Incidents ( )
46	(C1)Contained Spillage ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environmental Violations ( )
47	(C2)Pollution Incidents ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(C3)Port Authority Environmental Violations ( )
48	(E1)Unscheduled downtime. Out of Service - Offshore ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(E2)Unscheduled downtime. Out of Service - Marine ( )
49	(E1)Unscheduled downtime. Out of Service - Offshore ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(E4)Port State Detentions ( )
50	(E2)Unscheduled downtime. Out of Service - Marine ( )	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	(E4)Port State Detentions ( )