Thesis for the Degree of Doctor of Philosophy

An Improvement Strategy Based on the Failure Risk and Corrective Action Prioritization in Service FMEA

By

Agung Sutrisno

Department of Systems Management and Engineering

The Graduate School

Pukyong National University

August, 2012

An Improvement Strategy Based on the Failure Risk and Corrective Action Prioritization in Service FMEA

Advisor: Prof. Hyuck Moo Kwon, PhD

By

Agung Sutrisno

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

In Department of Systems Management and Engineering,

Pukyong National University

August 2012

An Improvement Strategy Based on the Failure Risk and Corrective Action Prioritization in Service FMEA

A dissertation

By

Agung Sutrisno

Approved by:

(Prof. Young Seok Ock, PhD)

(Prof. Young Jin Kim, PhD)

(Prof. Pyung –Hoi Koo,PhD)

(Prof. Seung Hoon Lee,PhD)

(Prof. Hyuck Moo Kwon,PhD)

Agustus 25, 2012

Table of Contents

List of Tables

List of Figure

List of Symbols

O_k : Occurrence of Failure Mode k, $k = 1,2,\ldots..l$.

D_k : Detect ability of Failure Mode k, $k = 1,2,\ldots.l$.

S_k : Severity Effect of Failure Mode k, $k = 1,2,\ldots l$.

PF : Probability of failure.

CF : Consequence of Failure.

C : Cause of failure.

E : Failure Effect.

l : Number of failure modes.

$P(C_{ki})$:Probability of the failure cause i causing occurrence of failure mode k, $k = 1,2,\ldots,l$ and $i=1, 2, \ldots n_k$.

$P(F_k|C_{ki})$:Conditional probability of failure mode k given the failure cause i already occurred, $k = 1,2,\ldots,l$ and $i=1,2,\ldots n_k$.

$P(E_{kj}|F_k)$: Conditional probability of the failure effect j given the failure mode k. already occurred, $k=1,2,\ldots l$ and $j = 1,2,\ldots.n$..

$P(F_k)$:Probability occurrence of failure mode k, $k = 1,2,\ldots l$.

$E(L_k|F_k)$:The Expected Loss k given the failure mode k already occurred, $k=1,2,\ldots l$.

L_{kj} : The loss score of failure effect j due to failure mode k, $k=1,2,..l$ and $j=1,2,..m_k$.

$E(L_k)$:The expected loss due to occurrence of failure mode k, $k=1,2,\ldots l$.

$P(C_{ki}|F_k)$:Posterior probability of failure cause i give failure mode k already occurred, k = $1,2,\ldots l$ and $i = 1,2,\ldots.n_k$..

CIF_k	: The internal failure cost due to occurrence of failure mode *k*, *k = 1,2,..l.*
CEF_k	: The external failure cost due to occurrence of failure mode *k*, *k = 1,2,..l.*
CO_k	: The opportunity cost due to occurrence of failure mode *k*, *k = 1,2,..l.*
QPO	: Total units solicited by a purchase order.
QRD	: Real quantity of unit delivered.
S	: Selling price of service process.
L_{ki}	: Loss function of failure mode *k* due to cause *i*, *k = 1,2,...,l.and i = 1,2,...*n_k.
α_k	:Severity of the effect of failure mode *k*, *k = 1,2,...,l.*
W_{ki}	:Elapsed time span of failure mode *k* due to cause *i*, *k = 1,2,...,l* and *i=1,2,...,*n_k.
T	: Total System mission time span.
X_{ki}	:Elapsed time span of failure cause *i* of failure mode *k* counted from the beginning of system mission, *k= 1,2,....1.* and *i=1,2,...,*n_k.
Y_{ki}	:Elapsed time span of failure mode *k* due to failure cause *i*, *k= 1,2,....1, and i=1,2,...,*n_k.
$f_{x_{ki}}$	: Probability density function of X_{ki}.
$f_{Y_{ki}}$	: Probability density function of Y_{ki}.
λ_{ki}	:The occurrence rate of failure cause *i* of failure mode *k*, *k=1,2,...l.* and *i*= i= *1,2,...*n_k.
μ_{ki}	:Occurrence rate of failure mode *k* due to cause *i*, *k=1,2,...l* and *i*= *1,2,...*n_k.
W_{ki}	:The elapsed time of failure mode *k* due to cause *i*, *k=1,2,...l,* and *i=1,2,...*n_k.
$f_{w_{ki}}(w)$	: Probability density function of W_{ki}.

$F_{W_{ki}}(w)$: Distribution function of W_{ki}.

U_{ki} :The elapsed failure occurrence time of failure mode *k* due to cause *i*, *k=1,2,...l. and i=1,2,...n$_k$.*

$f_{U_{ki}}(u)$: Probability density function of U_{ki}.

τ_{ki} : Detection rate of failure mode *k* due to cause *i*, *k=1,2,....l* and *i=1,2,...n$_k$.*

D_{ki} : Detect ability of failure mode *k* due to cause *i*, *k=1,2,...l* and *i=1,2,...n$_k$.*

IFO_k : Impact factor of opportunity variables *k*, *k= 1,2,....o.*

MVO_k :Estimated monetary benefit due occurrence of opportunity variable *k*, *k=1,2...o.*

IFT_k : Impact factor of threat variable *k*, *k = 1,2,...t.*

MVT_k : Estimated monetary loss due to possibility occurrence of threat variable *k*, *k = 1, 2... t.*

IFS_k : Impact factor of the strength variable *k*, *k = 1, 2...s.*

Y_k : Weight of strength variable *k*, *k = 1, 2...s.*

W_k : Importance rating of internal variable *k*, *k = 1, 2...w.*

IFW_k : Impact factor of weakness variable *k*, *k = 1, 2...w.*

X_k : Weight of weakness variable *k*, *k = 1, 2...w.*

Z_k : The importance rating of external variable *k*, *k = 1, 2...w.*

FM_k : Failure mode *k*, *k = 1, 2....l.*

CA_{ik} : Corrective action *i* for failure mode *k*, $i= 1, 2, ...n_k$, $k = 1,2,...l$

PS_{ik} : Preference score of corrective action *i* for failure mode *k*, $i=1,2,...,n_k$, $k=1, 2, ...l$.

IC_{ik} : Implementing cost of the corrective action *i* for failure mode *k*, i= 1, 2, …n_k, $k=1,2,....l$.

CE_{ik} : Cost efficiency of corrective action *i* for failure mode *k*, i = 1, 2, 3…..n_k,

$k = 1,2,..l.$

SED_i : Scope of the expected deviation of corrective action i, $i = 1,2,....l$.

Chapter 1

Introduction

1.1 Review and Classification of Previous Works on Risk Evaluation and Strategy Selection in FMEA

Driven by increasing customers' expectation for error free service provision, improving quality of failure assessment tool by using FMEA is an important research issues in business. In addition, FMEA is also becoming a strategic approach toward operational cost reduction. Since introduced in 1950s for military purposes, the FMEA utilization is widely spread into automotive, manufacturing and as well as service sector. The ultimate goal in implementing FMEA to business operation is for improving quality, which in turn will lead to customers' satisfaction. The strategic role of FMEA in business process improvement is undeniable as the FMEA is becoming the backbone of modern business management standard such as ISO 9000, QS 9000 and ISO 39000 (Ponds,[92]).

Among other quality improvement tools such as QFD (Quality Function Deployment) and Quality Control Chart, the merits of FMEA are due to its ability to rank criticality of service failure by metric named the risk priority number (RPN) and accessing the effectiveness of risk response by another metric called the reliability improvement ratio (RIR) (Devadasan *et al*. [33]). The reliability improvement ratio can be defined as the RPN ratio which counted by comparing the RPN reduction after and before implementing corrective action. According to Seyedhosseini and Hatefi [106], for both metrics, the RPN and RIR are having equal importance in FMEA methodology. The former is used to indicate criticality of specific failure occurrence and used as basis for resource allocation in responding risk occurrence and the latter indicates the effectiveness of implementing corrective actions to specific root cause of failure.

Driven by above importance, in this thesis, classification and review on references pertaining two above aspects in FMEA are undertaken. The goal to perform literature survey is on reviewing previous works for obtaining any research gaps which still warrants for further investigations. The literature database such as Emerald, Springer, Ebscohost, Hindawi, Sage, Ingenta, Sciencedirect, and Directory of Open access journal (DOAJ) are used. The periodical is chosen among other type of literature, since it is perceived as the source of knowledge which has the most of up to date information and elaborating on very specific issue (Ngai *et al.* [87]). The time span of initial survey is started from 1990-2010. The key words used in the literature search are “FMEA” and “FMECA”. All obtainable literature is then analyzed based on its content following to the two criteria, RPN estimation and corrective action issue. References which are written in non English language are excluded and the results from the papers’ content analysis are then depicted in table 1.1.

Table 1.1 Classification of Failure Risk and Corrective Action Reprioritization Model in FMEA References

		Application Area	
		Manufacturing	**Service**
FMEA Aspect	**Failure Risk Prioritization by RPN Estimation**	Bowles and Pelaez [15], Dong [31], Puente *et al.* [94], Sharma *et al.* [73], Sharma *et al.*[115] Sharweney *et al.*[105], Shankar and Prabhu [103] Ben Daya and Raouf [14], Sharma and Sharma [111], Tay and Lim [123], Chang *et al.*[28], Chang and Chen [17], Braglia [9], Braglia *et al.*[13], Franceschini and Galeto [45], Ahsen[5], Chang and Sun[20], Senol[113], Sachdeva *et al.* [112]	Keskin and Ozkan[70], Jeegadeshan *et al.* [63], **Chapter 3 and Chapter 4 of this thesis**
	Corrective Action Prioritization	Bluvband *et al.* [12], Yadav *et al.* [133], Davidson and Labib [32], Childs[21], Kumar and Chaturvedhy[68], Hekmapatnah *et al.* [56], Carmignani [19], Niu *et al.*[86], Karuppuswamy *et al.*[71], Eismailian *et al.* [35], Zammori and Gabrielli [142], Chen[27]	Seyedhosseini and Hatefi[102], Shahin[101], **Chapter 5 of this thesis**

1.2 Some Comments on Failure Risk Evaluation and Strategy Selection in FMEA

Based on the result of literature survey as presented in table 1.1, it is obvious that many methodologies have proposed to improve quality of failure risk and corrective action prioritization in FMEA. For example, dealing with fuzziness in RPN ratings as based on MIL STD 1629A; fuzzy logic –base RPN estimation methods have been presented by Bowles and Pelaez [15] and other scholars. In attempt to quantify severity of failure effects, cost –based failure criticality assessments have been proposed by Ahsen [5], Carmignani [19], and Jeegadeshan *et al.* [63]. Also, besides Fuzzy Logic; Chang *et al.* [28] presented the use of Grey Theory, Braglia[9] introduced the use of Analytical Hierarchy Process (AHP), and Sachdeva [112] presented on utilization of TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to enhance RPN estimation.

Similarly, regarding FMEA-based strategy selection aspect, many methodologies have been proposed to rank competing improvement efforts. For example, to estimate the effectiveness of corrective action implementation, the RPN reduction ratio is proposed by Bluvband *et al.* [12], Seyedhosseini and Hatefi [106] introduced the Risk - Response ratio. Niu *et al.* [86] exemplified on the use grey theory on ranking corrective actions. Hekmatpanah *et al.* [56] presented the use of scrap reduction ratio as basis to select corrective action. Chen [27] and Zammori and Gabbrielli [142] presented the use of ANP (Analytical Network Priority) for selecting risk-based corrective actions selection. In addition, it is also obvious that previous studies on above mentioned aspects in FMEA are mostly dedicated in non service oriented sectors.

Referring to FMEA classification as given in table 1.1, the 1-10 scale is the mostly used as basis to estimate the rank of RPN index. The versatility on the use of such scale is possibly due to ease of use in industrial practice. Among other methodology to rank criticality of failure risk, Fuzzy Logic is the mostly used as means to estimated the RPN in FMEA utilization and followed by cost-oriented failure risk prioritization.

The survey on previous works in FMEA is also indicating that most of previous FMEA-based corrective action selection models are still practiced on single company and not yet practiced in collaborative operation with tiers. In other words, utilization of corrective action reprioritization methodology is not practiced within supply chain environment. The literature survey on risk-based strategy selection is also revealing that the Iron Triangles (cost, time, and quality) are the mostly used basis to determine the corrective action prioritization.

1.3 Observable Research Gaps and Research Directions

From table 1.1, it is obvious that many endeavors have been dedicated to improve quality of failure risk and corrective action prioritization in FMEA literature. However, driven by the importance on considering impact of uncertainty from business environments (Wielle *et al.*[127]), growing contribution of service sector (Zaman and Anjalin,[139]) and uniqueness of service system (Hashim, [60]); from the thesis perspective, there are still some research discrepancies demanding further investigations to improve perform ability of FMEA as strategic quality improvement tool. The observable research gaps which become the motivation to perform further investigations regarding to failure risk prioritization and corrective action issues in FMEA are elaborated in the following:

- ✓ Although some amount of studies have been presented to improve quality in estimating the RPN, the basis to estimate the RPN is still using 1-10 scale with seemed overlooking the nature of failure occurrences and using no scientific basis. The use of 1-10 scale to represent probability rating may also yield varying interpretations among organizations. The implication of neglecting on the use of probability theory in estimating the RPN is that the RPN from such estimation might be inappropriate and may lead to erroneous decision making. Also, the utilization of 1-10 ordinal scale in quantifying criticality of failure occurrence will vary among practitioners in varying industries. There is a need to use a “universal language” as surrogate on description of the probability of failure occurrence rate in the FMEA rating guidance.

- ✓ Even though failure phenomenon has time aspect in its occurrence, previous FMEA studies are still seemed overlooking to incorporate failure cause and failure time occurrence. Negligence on incorporating time occurrence aspect in failure risk evaluation is not appropriate since failure event is having three attributes; its type (mode), time occurrence and consequences. Ignorance of one of those attributes is not appropriate in failure attribution for practical purpose. Furthermore, the possibility on loss escalation during system mission time span should be taken into consideration. In addition, considering system operation's mission, every failure mode may have different occurrence time and need different appropriate recovery timing.
- ✓ Although having growing contribution to global economy as stated by Zaman and Anjalin [132] and also due to its unique characteristics if compare to product and manufacturing operation, previous FMEA studies are mostly still focusing to non service operations. Numerous characteristics of service as elaborated by Hashim [58] imply to the need of special endeavors in applying FMEA in service operations. For instance, the influence of interaction between service system and its environment must be taken into consideration in proposing improvement efforts. Ignorance to consider impact of business environments is not appropriate since that may disadvantageous to company if sudden threat or opportunity occur and company did not make any preparation in facing such situation.
- ✓ Even though failure interaction between internal failure events and threats can possibly occur, RPN estimation in previous FMEA studies are overlooking endeavor to incorporate such interaction. Ignorance to failure interaction is not appropriate since the magnitude of loss may incur is possibly greater than magnitude of loss due to internal failure occurrence only.
- ✓ Estimation of the failure severity which is still based on 1-10 ordinal scale in

conventional FMEA is overlooking the situation that although faulty service already occurred, customers may still have tolerability against such occurrence.

- ✓ Although having equal importance in risk-based quality improvement efforts, studies to select and rank competing corrective actions are still based on brainstorming which may very time consuming and heavily depend of decision makers' experiences. There is a need to innovate on finding better way to discover appropriate corrective actions in a relatively short time and more systematically manner.
- ✓ The determination of the failure probability component in the RPN in conventional FMEA is seemed based on technical perspective only and overlooking situation that organizational and its environments may have contribution to probability of failure occurrences. In other words, physiological and social aspects of the system under study are not considered. According to Bea *et al*. [7], the perspective on viewing the risk from company's operation as a representation of socio-technical system should follow to the illustration as depicted in figure 1.1.

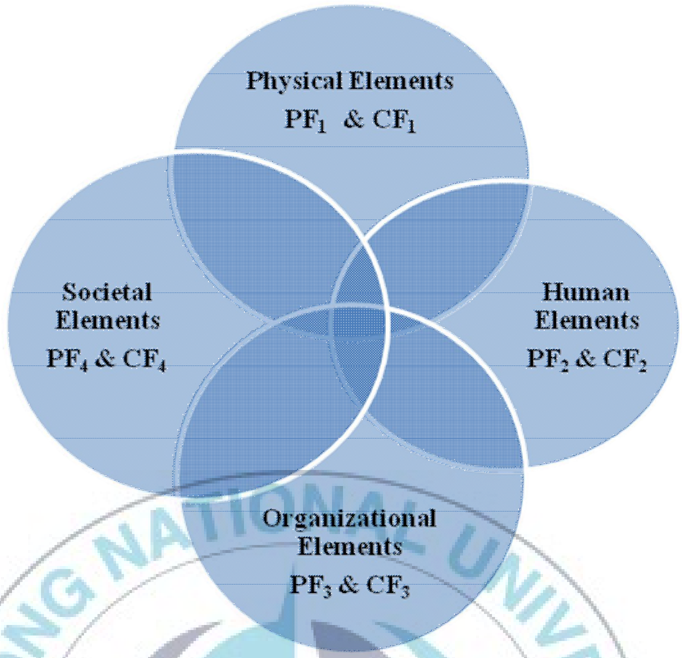

Figure 1.1 Evaluating and Managing Risk of Company as a Socio-Technical System (Bea *et al.* [7])

Evaluation and management on the risk of socio-technical system is based on the overall probability of system failure occurrence and its composite consequences. In mathematical model, it is formulated as,

Risk of faulty socio-technical system = overall likelihood of system failure occurrence (PF) x overall consequences (CF) (1.1.)

Where

$PF = PF_1 + PF_2 + PF_3 + PF_4$

$CF = CF_1 + CF_2 + CF_3 + CF_4$

- ✓ Even though enable to pinpoint critical failures, the RPN provides nothing to determine what appropriate tools are needed to rectify and prevent the occurrence of critical failure modes. In other words, RPN provides the estimation on the loss score, but it does not provide a solution to curb the root cause of the problem. There is a need to develop appropriate decision support systems as complimentary improvement tool to solve the problems based on the characteristics of failure cause.

- ✓ Upon observing the scale used in estimating the severity of failure effect in the conventional FMEA, it is still based on the assumption than the loss occurrence is constant over time in terms of its score and did not consider the time span of its exposure. Such assumption is inappropriate to be applied in real situation since the loss incur may escalate over time. In addition, upon observing different failure occurrence, when decide to focus to failure rectification, decision makers usually also consider the estimated time span of loss exposure.
- ✓ Having observed to previous studies in FMEA-based corrective action prioritization model, studies to select improvement strategy are implemented to solve quality problem in the first of life cycle of business operation. In other words, corrective action reprioritization methods are still limited to first business operation's deviation. Regarding possibility that business system has multiple life cycles and may experience on multiple deviations; endeavors to select corrective actions for multiple service delivery deviation are almost overlooked by previous literature.
- ✓ The RPN estimation in previous FMEA studies is seemed still accomplished in reactively manner. It is important to develop a predicted RPN based on past failure occurrences. Furthermore, as failures modes are occurring with different occurrence rate and loss scale, there is a need to develop a predictive RPN model based on such situation. The advantage on utilizing predicted RPN in predicting the loss is invaluable to avoid the occurrence of critical failures in future business operation.

- ✓ Although implementation of corrective action has uncertain outcome, the degree of uncertainty on its outcome is not considered in previous FMEA-based improvement strategy selection models. Since improvement effort is not always ending with success, the degree of uncertainty on the outcome of improvement strategy should be taken into consideration when appraising competing strategies.

1.4 Research Contribution

As can be seen in table 1.1, endeavors for improving some research discrepancies of conventional FMEA are already proposed by many studies. Nevertheless, previous studies are still focused on manufacturing operations. And very few are dedicated in service sector. In addition, the reality that the business environments are affecting endeavor for improving business improvement effort is overlooked. Compare to previous studies, the main distinction of this thesis with previous studies is in the application area. Related to thesis goal to present scientific contribution, this thesis attempts to contribute to the body of knowledge in the some aspects as elaborated in the followings.

- Provision of an improved model on determining probability component in RPN quantification as one of the main part of FMEA methodology. This will enable for decision makers in estimating probability components into more scientifically basis. Inclusion of the financial –oriented loss components will emphasize decision makers on the value of quality costs.
- Inclusion on failure time occurrence in time-dependent expected loss model will enable decision makers to estimate the escalation of quality loss from a faulty operation. Since the time dependent expected loss model utilized the three models of loss function, the possibility of loss escalation of during the

system mission time is accommodated.

- Regarding that service system is interacting with its environment, inclusion of impact of business factors is represented with the score of impact factor of SWOT Variables. By considering impact factor of SWOT variables, decision makers can select the most preferred corrective action upon scanning positive and negative impact of business environmental factors.

1.5 Research Limitations and Thesis Structure

Based on above research gaps, it is obvious that failure risk prioritization and improvement strategy selection are still becoming fertile research areas in FMEA as quality improvement tool.

Nevertheless, regarding to the vast scope in deepening investigation to above issues, in this thesis, research focus on narrowing research gaps in conventional FMEA is limited into three research issues only. In addition, motivated by growing importance of service to global economy, research issues in improving some limitations of conventional FMEA are applied in service operation.

The first research issue is pertaining to formulation of expected loss model in FMEA as surrogate of the RPN in conventional FMEA. The expected loss model which developed based on the Conditional Probability Theory and The Law of Total Probability will be presented. To evaluate severity of failure effect, quality cost and loss – based estimation model is presented. The effectiveness of corrective action prioritization is based on the expected loss reduction before and after implementing specific corrective action.

The second research issue in improving limitation of conventional service FMEA is related to consideration of failure time occurrence in estimating the loss score from a finite time span of system's operation mission. Assumption of constant failure occurrence rate and possibility on loss escalation during system operating mission are used as basis to formulate time dependent loss model. Comparison on the results between conventional FMEA and time dependent risk scores on evaluating quality loss score from faulty service operation will be showed.

The third research issue on reprioritization of corrective actions in service FMEA is related to considering impact of business environments prior selecting improvement strategy. The last issue is accomplished by incorporating SWOT analysis in FMEA-based corrective action process. The above mentioned research issues are then resolved and reported in chapter 3, 4 and 5 in this thesis.

In dealing with all above research issues, this thesis is organised from 6 chapters which are briefly described in the followings:

In chapter 1, classification of FMEA papers based on specific criteria from the survey undertaken which become the motivation to undertake the study will be revealed and elaborated. The rationales to focus on some specific research issues which become basis to undertake the study will be provided. Regarding on the vast scope of the concerned research issues, limitations on some research scopes are also presented.

In chapter 2, research problems formulation and some basic concepts pertaining to FMEA, Risk Priority Number (RPN), Corrective Action (CA), SWOT Analysis and the Analytic Hierarchy Process (AHP will be provided.

In chapter 3, an expected loss model for re-formulating the RPN estimation of conventional FMEA is presented. The expected loss model is formulated based on assumption of failure event independence and developed based on the conditional probability theory and quality loss component.

In chapter 4, reformulation of the expected loss as surrogate of the RPN considering failure time occurrences is provided. Assumption of constant failure occurrence rate is used in the model development.

In Chapter 5, SWOT Analysis is incorporated in FMEA-based improvement effort. A preference score which is obtainable by correlating corrective action with impact factor of SWOT variable is formulated. In addition, cost efficiency as basis to appraise financial feasibility of competing corrective action is presented.

In Chapter 6, conclusions and directions for further studies are remarked

The scope of the thesis and relationship among chapters resulted from the study undertaken are then given in table 1.2. Meanwhile, the relationship among chapters in the thesis is depicted in figure 1.2.

Table 1.2 Scope of study on RPN Reprioritization and Corrective Action Selection Issue in Service FMEA

FMEA Aspect	**Tool/basis**	**Chapter in The Thesis**
Failure Risk Reprioritization	Conditional Probability Theory	Chapter 3
	Homogeneous Poisson Process	Chapter 4
Corrective Action Selection	SWOT Analysis	Chapter 5

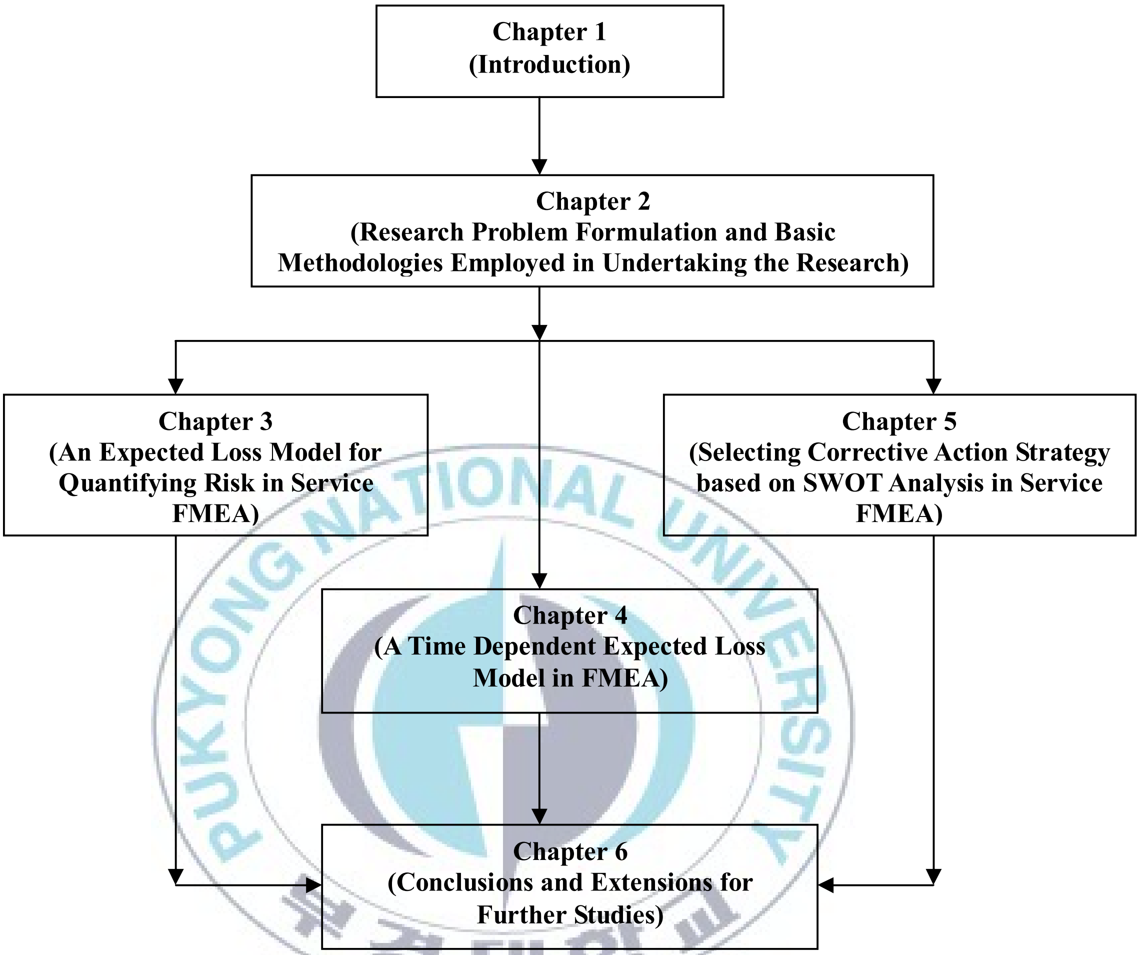

Figure 1.2 Flowchart Depicting Relationship among Chapters in the Thesis

Chapter 2

Research Problem Formulation and Basic Methodologies Employed in Undertaking the Research

In attempt for narrowing down research gaps, research problem formulation, its corresponding strategy and some basic methodologies will be used as means to undertake the research are elaborated in the following sections.

2.1 Research Problem Formulation

Research areas pertaining to FMEA are very wide. Therefore, to becoming more focused, research question which becomes starting point to undertake the investigations presented in the thesis is described as follow:

- **Research Question 1:** Probability of failure occurrence rate is important part in RPN estimation; however, its determination in conventional FMEA is having no scientific basis and still based on decision makers' subjectivity. How should we determine the RPN by considering the characteristics of failure occurrence based on probability theory? Regarding that the cost is the universal language in business to quantify the loss value in business, how to quantify the severity of failure loss using monetary term? What is the advantage on using the cost as basis to estimate the severity of failure effect using 1-10 scale as used in conventional FMEA?
- **Research Question 2:** Regarding that time is important dimension in quantifying loss incur from faulty service operation, how to incorporate

failure time occurrence in estimating the expected loss incurred? How to develop an expected loss model by considering the possibility on loss escalation during service system's mission. Is there any difference between considering and ignoring failure time occurrence in quantifying the risk of faulty service operation?

- **Research Question 3:** Following Wielle *et al.* [127], it is known that business environments are influencing endeavour to improve capability of quality improvement tool such as FMEA. Regarding the utilisation of FMEA as means to improve business based on the risk of faulty operation, how to consider the impact of business environment prior proposing FMEA-based improvement effort? What are advantages and limitations of considering the impact of business environments prior selecting corrective action from FMEA session?

2.2 Research Strategy

In attempt to reach research goals, case study by using example is employed to give illustration of the model's applicability for practical purposes. Case example is chosen as strategy to accomplish the study. According to Yin [135], typical case example is chosen as this study is aimed to demonstrate application of the new theory. It is also intended to answer the "why" and "how" research questions and the researchers have no control of the object of study. Nevertheless, regarding to some limitations, all models presented in this study are a purely theoretical.

However, to improve research validity, case example is based on the report from real application in references. All theoretical variables are proposed based on consultation to established literature.

2.3 Basic Methodologies Employed

2.3. 1 FMEA

Introduced in 1950s, FMEA is an engineering tool aimed to identify potential and or actual failure modes in a system, process, or product; rank the criticality of the failures by counting of their risk priority number, and find improvement method to avoid re-occurrence of the failure mode in future. Following Rausand and Øen [97], failure can be defined as "termination of the ability of an item to perform a required function". In real situation however, the distinction among failure mode, fault, and error is vague, thus need clarification. An error mode is defined as "any discrepancy between computed, observed or measured value or condition and the true, specified or theoretically current value." A failure mode is the description of failure. A fault is "the state of an item which characterized by inability to perform an expected function." The visual description on differentiation among failure, fault and error is depicted in figure 2.1.

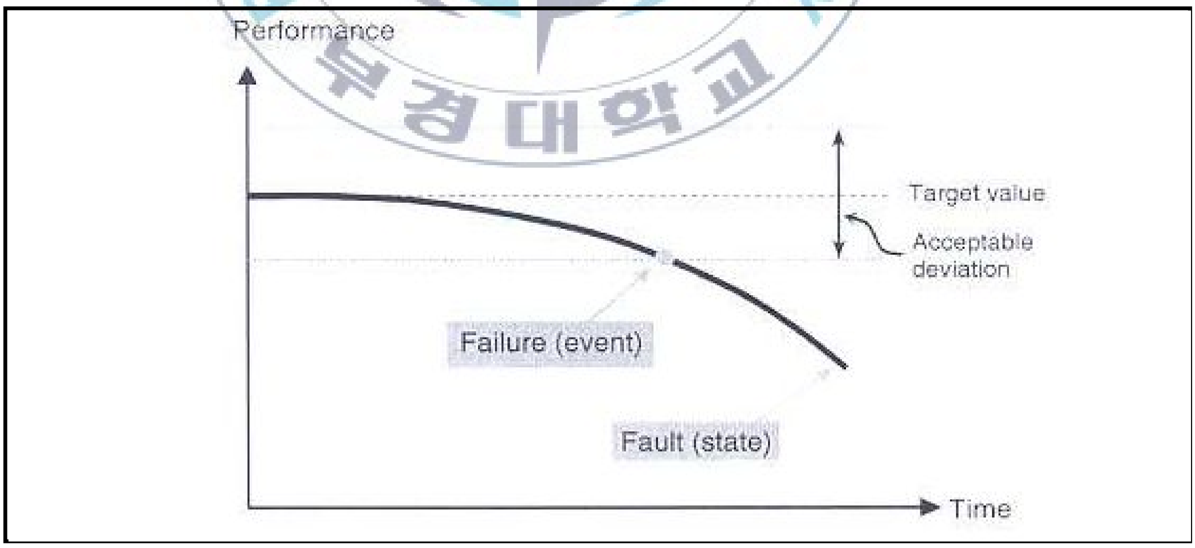

Figure 2.1 Illustration on the difference among failure, fault and error (Rausand and Oen, [97])

Referring figure 2.1, failure may be defined as termination of system performance against time until fault is occurred. Meanwhile, errors occur if system performance is beyond acceptable deviation from targeted value. In attempt to perform service failure mode and effect analysis, relationship between failure mode, its causes and effects should be understood clearly. The illustration showing relationship among root causes, failure mode and effects from a failure event is depicted in figure 2.2.

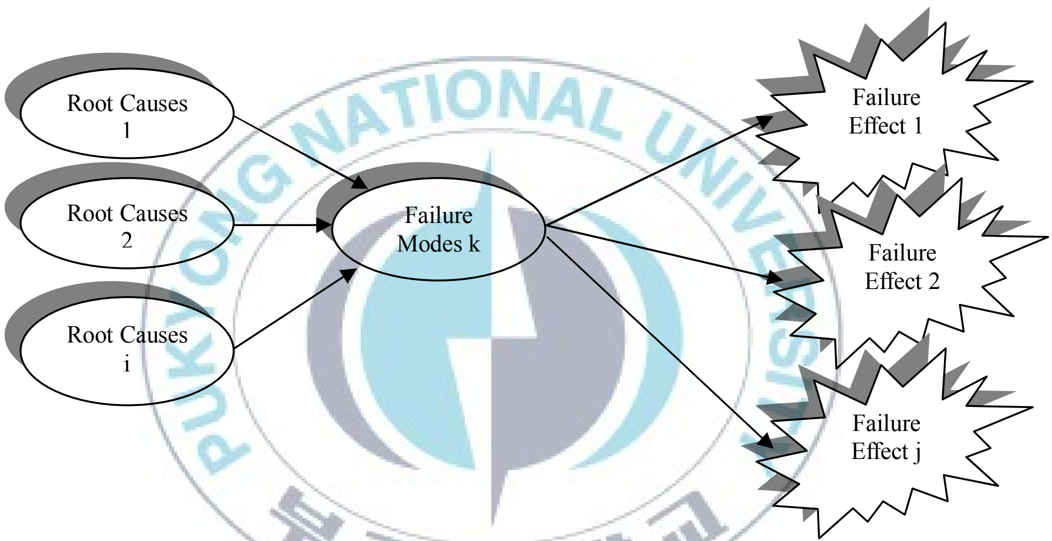

Figure 2.2 Relationship among Failure Cause, Failure Mode and Failure Effects (Adapted from Rausand and Oen, [97])

The application of FMEA is intended to improve quality and reliability requirements. Depending on its application domain, the FMEA can be classified into system, design, process and service FMEA. The occurrence of failure mode is ended with failure effect. Within conventional FMEA which based on MIL SRD 1629A, the risk of failure effect is defined as amount of loss due to the occurrence of failure effect. The criticality due to failure occurrence is represented by its RPN score.

Mathematically, the RPN (risk priority number) of FMEA is obtained by equation (2.1).

$$RPN_k = O_k D_k S_k \quad (2.1)$$

With O_k, D_k , and S_k represent the ratings of failure occurrence frequency, detect ability of failure occurrence, and severity of failure effect of failure mode k. In representing the RPN rating scale, the MILD STD 1629A provides guidance on the rating determination. Following the MILD STD 1629A, the scale and corresponding criteria of above mentioned ratings can be seen in table 2.1.

Table 2.1 The Ratings of FMEA (Chang and Sun, [20])

Failure Occurrence Frequency	Failure Detect ability	Failure Effect Severity	Rating Score
Extremely high, failure is inevitable	Control does not detect a potential cause of failure	Failure is hazardous to human life	10
Very High	Very remote chance the design control to detect a potential failure cause	Failure involves hazardous outcomes/ non compliance with governmental regulations or standards	9
Repeated failure	Remote chance the design control will detect the potential cause of failure	Product is inoperable with loss of primary function	8
High	Very low chance the design control will detect the potential cause of failure or sub sequence failure mode	Product performance is severely affected	7
Moderately High	Moderate chance that the design control will detect the potential cause of failure mode	Product Performance is degraded	6
Slightly High	Moderately high chance that the design control will detect the potential cause of failure or subsequent failure mode	Moderate effect on product performance	5
Relative Low	High chance that design control will detect the potential cause of failure or subsequent failure mode	Small effect on product performance. Product requires repair	4
Low	High chance the design control will detect the potential cause of failure or subsequent failure	Minor effect on product or system performance	3
Remote	Very high chance the design control will detect the potential cause of failure or subsequent failure mode	Very Minor effect on product or system performance	2
Nearly Impossible	Design control will almost certainly detect a potential cause of failure or subsequent failure mode	No Effect	1

Figure 2.2 shows generic procedure to perform FMEA in accessing quality of process, product design and service operation. Within real application setting, FMEA is utilized in a group oriented activity. Membership of the FMEA team is consisting of staff from every company unit. The rational to involve staff from all company units is to make a comprehensive failure assessment and make a more holistic approach in solving problem as the FMEA is intended to be applied. Usually to sharpen the analysis, an expert from outside of the company is assigned as facilitator. The results of FME session which are usually accomplished by brainstorming is then documented in FMEA sheet. The generic procedures to perform FMEA are given in figure 2.2. It can be concluded from figure 2.2 that basic procedures to perform FMEA are consisting of important steps as depicted in table 2.2. The $RPN_{revised}$ can be defined as the value of RPN which obtained upon implementing corrective actions to solve specific quality problem. The outcome of performing FMEA is the failure recovery knowledge.

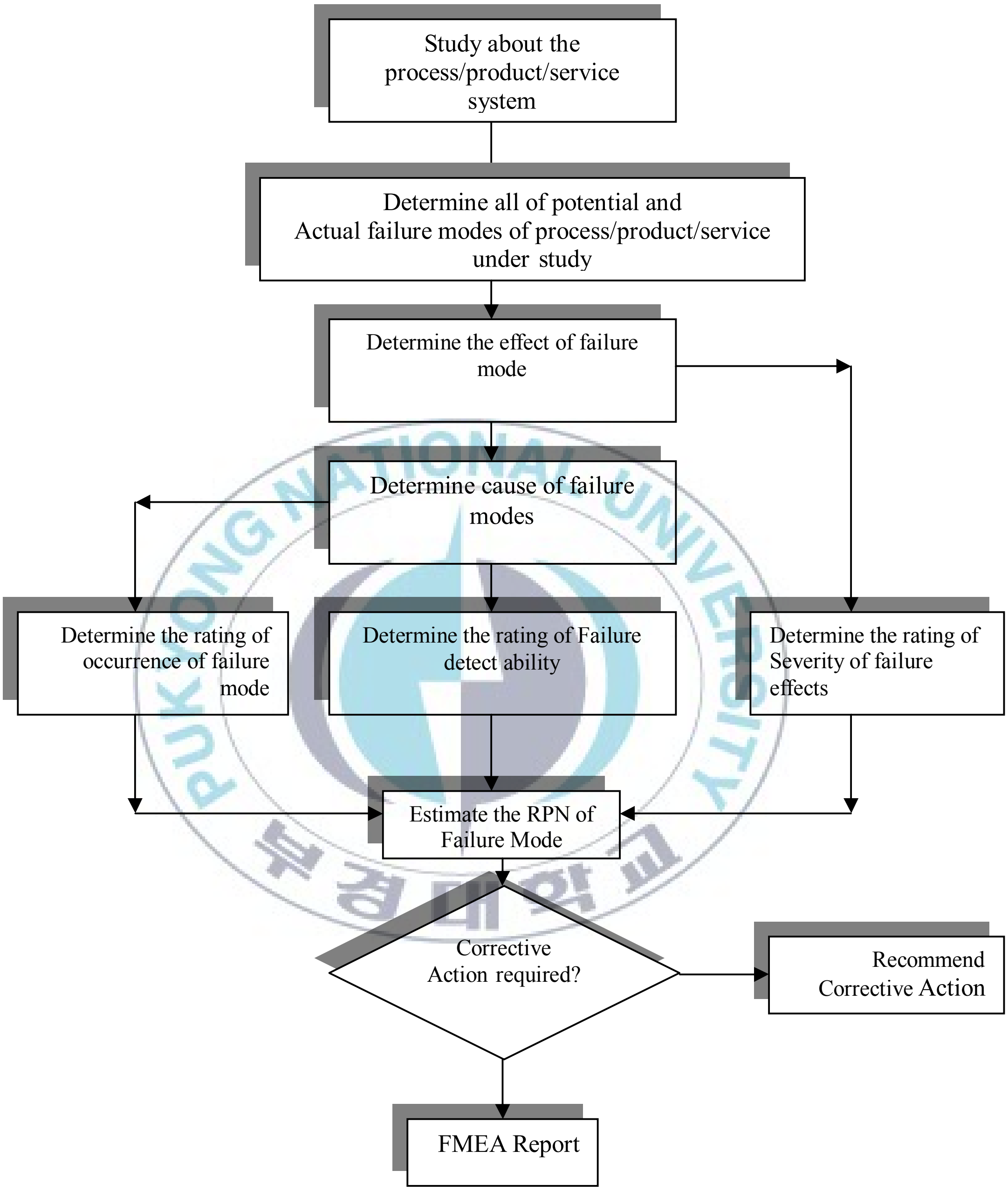

Figure 2.3 Generic Flow Chart for Performing FMEA

Table 2.2 Generic Procedures to Perform Service FMEA

Step	Questions	Outcomes
Identify service failure modes	What can go Wrong with the service systems	Failure Mode, it possible root cause, end effect
Appraise the risk of failure occurrences	What is the magnitude of the risk may incur	Risk Priority Number = Failure occurrence x failure detect ability x failure effect severity
Minimize the impact of service failure	What can be done to reduce the impact of failure occurrences?	Potential recovery efforts- change standard operating procedure, improve inspection, add personnel etc.
Verify the effectiveness of service recovery effort	Are there any reductions in risks after corrective actions are implemented?	Risk reduction Ratio = $(RPN_{Initial} - RPN_{Revised}) / RPN_{Initial}$
Archive the result of FMEA Session	What can we learn from performing FMEA in our system?	Failure Recovery Knowledge

The result of FMEA session is then tabulated in a typical table as depicted in table 2.3. For instance table 2.3 represents a FMEA table of failure mode k (FM_k) due to cause i, for $i = 1,2,3,....,n_k$ and $k = 1,2,...l$.

Table 2. 3 A Generic FMEA Sheet

Failure Cause	Failure Mode	Failure Effect	Failure Mode Detect ability	Risk Priority Number
C_{11}		E_{11}	DFM_1	RPN_1
C_{21}	FM_k	E_{21}	DFM_2	RPN_2
…		E_{31}	DFM_3	RPN_3
C_{ik}		E_{ik}	DFM_k	RPN_k

If the result of FMEA activity is well documented, it will become invaluable source of organizational learning for preventing re-occurrence of similar problem in future. For example, upon documenting the result of FMEA session, management can learn from the timing of critical failure occurrence, its severity, and what have been done to tackle the problem. Furthermore, they also can estimate on the effectiveness of the implemented corrective action and so on. By applying advance methodology, management can also forecast the timing and loss magnitude of critical failure already occurred, thus can make better anticipation.

The strategic role of FMEA in continuous quality improvement efforts is undeniable as it was definitely stated as key technique in various quality and risk management systems such as QS 9000, ISO 9001: 2008, and ISO 31000 (Pons, [92]).

2.3.2 Corrective and Preventive Action

According to the clause of ISO 9001:2000 standard [62], corrective actions can be defined as "any activities intended to eliminate the cause of non conformance have occurred from their re-occurrence". Meanwhile, preventive action is defined as "any activities aimed to eliminate the cause of potential non conformance will possibly occur". Within FMEA methodology, the priority to select corrective action to tackle the root cause of failure shall be started with the failure mode which has the largest risk priority number or to any failure which has consequences to threatening human life and or to any regulation.

After selecting certain corrective actions, the next step is to implement them for effective improvement. According to Okumus [90], Wheelen and Hunger [129], Oordobadi [88] and Al-Turki [3]; several aspects should be considered prior to strategy implementation such as:

- **Budgetary and Time Feasibility**

Budgetary feasibility and time feasibility are becoming the principal constraint since improvement effort will consume financial and time to realize its implementation.

- **Risk of Implementing Corrective Action**

Risk must be considered since uncertainty on the probability of success and outcome of implementing strategy are still unknown until it being implemented

According to Aven and Aven [4], risk can be defined as "uncertainty on achieving objective". Depending to the type, risk factors can be attributes to market risks, financial, organizational risk, and technical risk. Elaborations on typology of risk can be found in Cagno and Michaeli [18].

- **Ownership of corrective action.**

The ownership of corrective action is related to whom the responsibility to implement will belong to. Wrongly determine the ownership corrective action may lead to risk due to conflict of interest among team involved or resistance for related person(s) and possibly becoming path which lead to failure in achieving success.

- **Communication with the stakeholder and supplier(s).**

Upon achieving some planned goals and perceived strategy, determine what to inform to suppliers, stakeholder, and customer is important to prevent miss understanding and reduce the chance of errors in achieving targeted goals.

- **Key success factors and procedural aspects in implementing corrective action.**

Key success factors in this case can be defined as any important aspect which contributes to the success in gaining goals. The presence of key success factors is very critical to the success in implementing strategy. Meanwhile, procedural aspect in implementing selected strategy related to *"know how"* aspect in executing strategy.

Seyedhosseini *et al.* [107] suggested three aspects that the success criteria may be based on; the real amount of time spent, the actual costs company spent, and the real performance specification achieved upon implementing selected corrective actions. A successfully implemented corrective action should have positive effects against all these success criteria.

Some examples of business performance indicator to measure the success of implementing corrective action can be referred to Mann and Kehoe [83].

Table 2.4 Exemplary Measures to Estimate the Success of Implementing Strategy (Mann and Kehoe, [81])

Dimension	**Quantitative Measures**
Business Strategy	Market Share, Sales revenue, productivity, product quality, profitability, company growth.
Policy Deployment Measures	Quality costs, Sales forecast accuracy, target/goals.
Process Measures	Working in process, Lead Time, Process Capability

Referring to Wheelen and Hunger [127]; some causes for the failed corrective actions are due to lack of management commitment, inability to find the true root causes of the problems, and the way decision makers view the problem is still in the box. In order to make selected corrective actions are reaping success, it is important for FMEA team for understanding on what input, process, output, risk and hindrance variables to achieve desired outcome of corrective actions. Illustration which describes such relationship is depicted in figure 2.4.

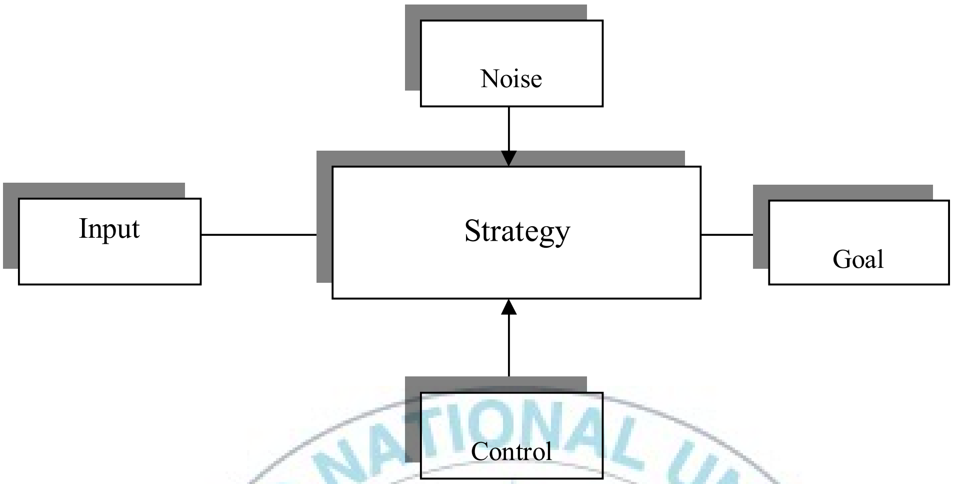

Figure 2.4 A Typical of Control Mechanism in Strategy Implementation

2.3. 3 Root Cause Analysis (RCA)

Root Cause Analysis (RCA) is defined as methodology for finding root cause which makes problems to occur. By finding root cause of quality problems, decision makers can generate various potential corrective actions. The advantage on using root cause analysis is that decision makers can formulate a systematic approach to prevent the reoccurrence of similar problem in future. Depending on the deep of analysis on problem to be solved, decision makers can choose various types of root cause analysis as represented by Mahto and Kumar [80].

The types and characteristics of various root cause analysis are presented as in table 2.5.

Table 2. 5 Typology and Characteristic of Various Root Cause Analysis (Mahto and Kumar [80])

Root Cause	Defines Problem	Define all cause relationship	Provide a causal relationship	Delineate evidence?	Explain how solutions prevent recurrence	Easy to follow Report
Cause –Effect Diagram	Tool	Yes	No	No	No	No
Interrelationship Diagram	Tool	Yes	No	No	No	No
Barrier Analysis	Tool	Yes	No	No	No	No
Current-Tree Analysis	Tool	Yes	No	No	Limited	No
Why-Why Analysis	Tool	Yes	Limited	No	No	No
Event and causal factor analysis	Method	Yes	Yes	No	No	No
Management oversight and risk tree analysis	Method	Yes	Yes	No	No	Yes
Human Performance Evaluation	Method	Yes	Yes	No	No	Yes
Kepner-Tregou Decision making	Method	Yes	Yes	No	No	Yes

The advantage of using the root cause analysis in problem solving is that the decision makers can generate more systematic solutions. The process of finding root cause is usually commenced by brainstorming among members to find many possible causes of the critical problems to be solved. For holistically and comprehensively analysis, the members of the team shall be cross functional team from every company's unit. The next step upon determining the critical failure is tracing the root cause of the critical failure by proposing assessment question by using the '4W2H' questions (What-When-Why-Who and How) and considering the 6M1I1E aspects

(Man, Machine, Material, Money, Method, Management, Information, and Environment) which may contribute to root cause occurrence. Upon identifying the most logically root cause of the critical problems; decision makers can generate some potential corrective actions to prevent their re-occurrences. Illustration showing causation to failed strategy implementation is shown in figure 2.5.

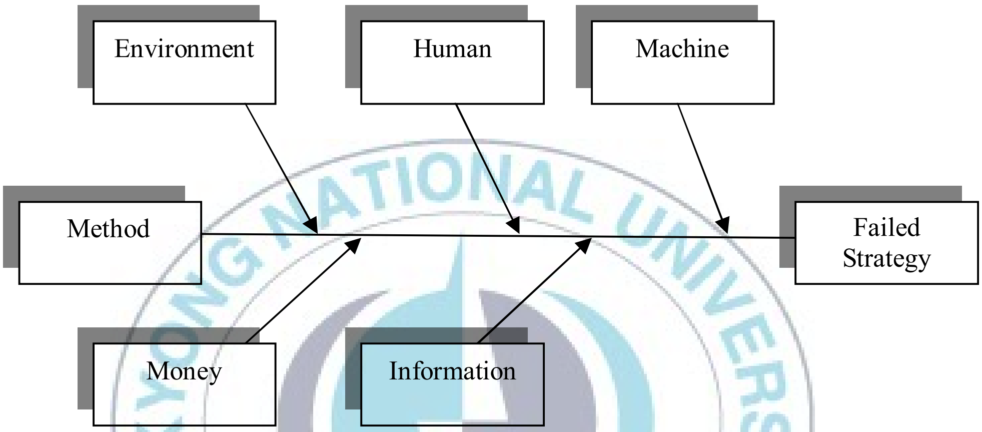

Figure 2.5 Fishbone- like Root Cause Diagram of Failed Strategy

2.4 SWOT Analysis

SWOT analysis can be defined as strategic planning tool based on scanning the Strengths, weaknesses, opportunities and threats of a firm. Initially developed by Albert Humprey in 1960s, the SWOT analysis is the probably the most versatile strategic planning tools in business practices. Setting improvement goals should be done upon identifying SWOT variables. The goal in utilizing SWOT analysis is to identify all key internal and external factors which are important in achieving company goals. The SWOT Analysis classifies two important variables of business systems:

- Internal Factors: The internal strengths and weakness of the internal company's environments.
- External factors: The opportunities and threats represented by external company's environments.

Following Al- Rausand and Qawasmeh [2], threats can be defined as any improper events or force in the external environment that harmful to business goals. Threats are also related to a set of conditions, resources and capabilities that organizations need or pressured to work with, but cannot influence or have control over it. At the other side, opportunities can be defined as a set of condition suitable for achieving goals. In other words, opportunity is a positive state that gives organizations some kind of relative advantages, or an environmental approach that positively influence to firm's profit.

Strength in SWOT Analysis can be defined as the internal power that an organization possesses to compete against its competitor. Strength also represents organizational capabilities and internal positive attitude that enable organization possess strategic power to achieve organizational goals.

Weakness in SWOT analysis can be defined as any organizational aspects which negatively impact product and or service value with regards to customers or competitive environment. It also represents shortcomings in internal capabilities that make company unable to achieve their goals or lose their competitive advantages. Usually, for further evaluation, the SWOT variables obtained from the brainstorming is then plotted in SWOT Matrix. Table 2.6 represents a typical of SWOT Matrix.

Table 2.6 A Typical of SWOT Matrix.

	Strengths (Ss)	Weaknesses (Ws)
Opportunities(Os)	SO Objectives	WO Objectives
Threats(Ts)	ST Objectives	WT Objectives

Depending to their impact on the company goals, all internal factors can be viewed as strengths or weakness, and so do the external factors. Opportunity variables which are not utilized and used by competitors can be perceived as threats and vice versa (Helms and Nixon, [54]). The impact factor of SWOT variables can be estimated based on the summation between paired positive and negative variables. Regarding to the influence type of strength and opportunity variables which gives positive impact to the company, positive sign is given. In reverse, for weakness and treat variables; since influencing negatively to company, are given negative sign. By summing up above mentioned variables, decision makers can diagnose company situational position, whether the company is in advantageous, static, or even vulnerable situation.

The benefits of employing SWOT analysis as means to formulate strategy may applicable to both profit and nonprofit- oriented organization. By using SWOT Analysis, companies may estimate what threats may occur and harmful to their businesses, thus those may take any preventative measures in advance to avoid any potential losses. In reverse, by recognizing opportunities; any preparations can be taken in advance to take potential benefits from opportunity occurrences.

2.5 Analytical Hierarchy Process (AHP)

The analytical hierarchy process (AHP) is firstly developed by Thomas Saaty which intended to facilitate structuring a complex multi-attribute problem and provides a means to decide the choice for solving the problem. According to *Liu et al.* [79], the application of AHP has been reported in various fields. Basically, the AHP is involving various aspects such as development of relative importance among the attributes suing experts' opinion, developing through algorithm a weight age for each attributes, performing similar analysis for the alternative solution strategies for each of the attributes and developing a single overall score for each of the alternative solution strategies.

The procedure to perform an AHP analysis is consisting of steps as below:

1. Develop a hierarchy structure of the decision problem in term of overall objectives.
2. Determine the relative priorities of criteria that express their relative importance in relation to the element at the higher level, on a pair-wise basis.
3. Calculate the overall rating of the decision alternatives, weighting the ratings with the relative priorities of criteria and sub-criteria.
4. Check the consistency of the decision makers' comparisons.

An illustrative chart showing the hierarchical structure of the AHP is given as in figure 2.6.

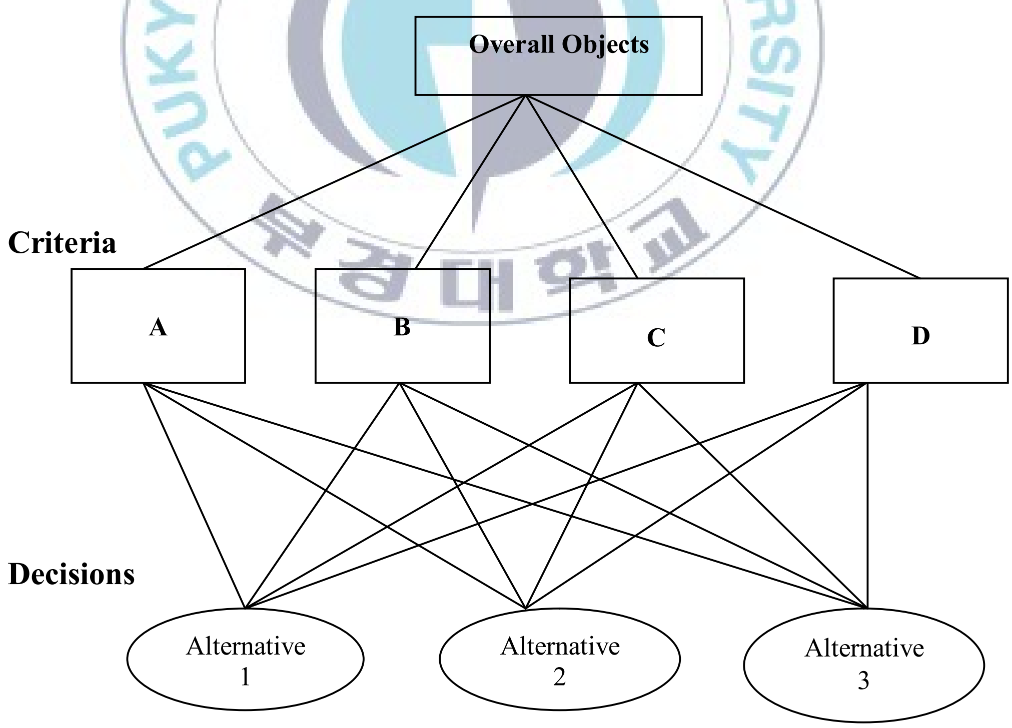

Figure 2.6 An Exemplary on Hierarchical Structure of AHP

The preference scale to estimate preference of decision makers in undertaking the AHP can be seen as depicted in table 2.7.

Table 2.7 Pair-wise Comparison Scale for AHP Preference

Verbal Judgment	Numerical Ratings
Extremely preferred	9
Very strongly preferred	7
Strongly Preferred	5
Moderately Preferred	3
Equally Preferred	1

In order to have a valid comparison, we need to check the consistency of the pair-wise matrix. According to Saaty, the procedure to check the consistency index (CI) is consisting of four-step procedures to calculate the consistency index (CI). If A represent the original pair wise comparison matrix, w denotes the weight estimate, W^T; then the steps are the following:

Step 1. Compute AW^T;

Step 2. Compute R = $\frac{1}{n}\sum_{i=1}^{n}\frac{\text{ith entry in } AW^T}{\text{ith entry in } W^T}$;

Step 3. Compute CI as follows: CI = $\frac{R-n}{n-1}$

Step 4. Compare CI to the random index (RI) from table 5. Compute $\frac{CI}{RI}$

The value of random index as basis to determine the consistency ratio is then given in table 2.8.

Table 2.8 Values of Random Index (RI)

n	Random Index
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

The small value of CI/RI represents a consistency degree of the AHP used decision making. Usually, the ratio of CI/RI is taken 0.10 as the threshold for consistency checking.

Chapter 3

An Expected Loss Model for Risk Priority in Service FMEA

3.1 Introduction

Correct evaluation of the risk of service failure is an important part toward the efficiency of a firm's resource allocation. Wrongly appraising the risk of service failure may lead to wrong resource allocation and yield to waste of resource utilization. In industrial practices, service firms utilized service FMEA (failure mode and effect analysis) as a means to estimate the risk of service failure and provide an appropriate way to minimize its impact on the end customer. FMEA in service sectors are primarily employed in various service sectors such as healthcare, education, transportation, travel, handling customer complaint, and consumer good trading. For instance, Jennifer *et al.* [64] used FMEA to reveal difficulty in accessing drug labeling error. In healthcare, Ookalkar *et al.* [89] pinpointed some critical failures and proposed improvements in *Haemodyalisis* treatments. Within transportation service, Bosch and Enriques [11] integrated FMEA with QFD (quality function deployment) in handling customer complaints. Other researchers, Zhang and Zhu [140] estimated the critical risk factors in outsourcing service. From hypermarket service, Chuang [24] combined the service blue printing and FMEA to pinpoint critical service failures in consumer goods trading. And Chuang [23] incorporated disservice analysis to enhance perceived service quality from consumer goods trading using FMEA. In conventional FMEA based on the MIL STD 1629A, prioritizing corrective actions to minimize the impact from a failure is based on the magnitude of RPN (risk priority number). The larger the RPN, the more dangerous the failure would be. And corrective actions are taken in the descending order of the magnitude of RPN. Over the years, several methods have been proposed to improve the quality of risk prioritization method in FMEA. Previous works can be classified into several categories. In attempt to consider the fuzziness of the ratings used in FMEA, fuzzy logic is used to support RPN estimation. The studies on using the fuzzy logic in FMEA is exemplified by Chang *et al.* (17), Xu *et al.* [134], Puente *et al.* [94], Tay and Lim [123], Sharma *et al.*[114]. Since the use of conventional FMEA is ignoring the impact of failure from economic perspective, cost oriented RPN estimation methodology is presented by Kmenta and Ishii [74], Karuppuswamy *et al.* [71], Ahsen [5] and Carmignani [19]. By incorporating failure effect using monetary value; the cost, the meaning of quality costs to decision makers is possibly emphasised. Moreover, it is becoming the universal language of business, the money. In attempt to consider interaction among entities in structural modelling in failure mode and effect analysis, Graph theory is incorporated by Gandhi and Agrawal [52]. In attempt to consider the failure occurrence rate in determining probability of failure occurrence rating, Poisson distribution is used by Senol [113]. And at last, considering the multi-attribute impact of failure effect, the Analytic Hierarchy Process (AHP) is proposed by Braglia [9] to weight the impact of failure effects.

For evaluating the risk priority, the previous works seem to take basically the same method as the conventional FMEA. The ratings of failure occurrence and detect ability of failure are determined intuitively without using sound statistical basis. However, in real situation, the characteristics of failure occurrences which can be in the form of dependent or independent among others are neglected in determining probability of failure occurrence score. Although it is easy to implement the 1-10 scale of FMEA in practice, the consequences of ignoring on the use of probability theory in formulating probability of failure occurrence is that it may lead to wrongly decision making and will vary among practitioners in various industrial settings in terms on its interpretation. Furthermore, the severity of failure with 1 to 10 rating is unable to reveal the magnitude of service failure effect into quantitative basis. In addition, it does not give physiological effect to managers on the meaning of quality costs incurred from faulty business operation.

In this thesis, a model on derivation of the RPN from economic perspective is proposed. The Law of Total Probability and Conditional Probability Theory are used to formulate the probability component of service failure event and the severity of failure effect is represented using failure cost and loss. Finally, the expected loss model as surrogate of the RPN in conventional FMEA is then formulated.

3.2 The Expected Loss Model

3.2.1 The Law of Total Probability

The Law of Total Probability is becoming the basis in determining the probability component in expected loss in FMEA. The law of probability is the proposition that if $B_1, B_2, \ldots, B_n$ be such events that $\bigcup_{i=1}^{n} B_i = \Omega$ and $B_i \cap B_j = \emptyset$ for $i \neq j$, with $P(B_i) > 0$ for all i. The probability for any event A, is then rewritten as equation (3.1). Derivation of equation (3.1) is given in the appendix 1.

$$P(A) = \sum_{i=1}^{n} P(A|B_i)P(B_i) \qquad (3.1)$$

Different from conventional FMEA which still based on 1-10 ordinal as scale as basis in determining probability of failure occurrence components; by using the law of total probability, the derivation on the probability of failure occurrence component in FMEA is becoming more scientifically basis and enable to consider the characteristics of failure event occurrence; whether its occurrence is independent or dependent among others.

3.2.2 Bayes Theorem for Discrete Outcomes

For a given problem, let there be *n* mutually exclusive exhaustive possible outcomes $S_1, \ldots, S_i, \ldots, S_n$ whose prior probabilities $P(S_i)$ have been established. The laws of probabilities require

$$\sum_{i=1}^{n} P(S_i) = 1, \; 0 \leq P(S_i) \leq 1, \; i=1,\ldots,n \qquad (3.2)$$

If the results of the additional study, such as sampling or further investigation, are designed as X, then where X is discrete and $P(X) > 0$, Bayes's theorem can be written as

$$P(S_i|X) = \frac{P(X|S_i)}{\sum_{j=1}^{n} P(X|S_j)P(S_j)} \qquad (3.3)$$

The posterior probability $P(S_i|X)$ is the posterior probability of outcome S_i given that additional study resulted in X. The probability of X and S_i occurring, $P(X|S_i)$ is the "joint" probability of X and S_i. The sum of all the joint probabilities is equal to the probability of X. Therefore, equation (3.3) can be written as equation (3.4).

$$P(S_i|X) = \frac{P(X|S_i)}{P(X)} \qquad (3.4)$$

3.3 Risk prioritization by expected losses

In this thesis, only the occurrence of failure over a fixed period of time is considered. In addition, independence of failure occurrence is becoming underlying assumption in developing the expected loss model. In addition, the finite time span is firstly used as basis to determine the probability component of failure occurrence. Meanwhile, some other assumptions used as basis to formulate the expected loss model are as follows:

i) All the failure modes, effects and causes are identifiable in advance.

The first assumption is the primary requirement to perform FMEA. Without holding this assumption, performing FMEA in any operation is absolutely impossible.

ii) All the causes of each failure mode can be defined into a set of mutually exclusive and exhaustive events.

For assumption ii, if the cause of failure occurrence F_k is known; they can be redefined into a set of mutually exclusive events $\{C_{k1}, C_{k2}, C_{k3,\ldots}, C_{kn_k}\}$ so that $C_{ki} \cap C_{kj} = \emptyset$ and $\bigcup_{i=1}^{n_k} C_{ki}$ covers all the causes of F_k, $k = 1, 2, \ldots, l$. If any two failure causes A and B are not mutually exclusive, redefinition to the failure causes can be stated as $C_{k1} = A - B$, $C_{k2} = B - A$ and $C_{k3} = A \cap B$.

iii) All the effects of each mode can be defined into a set of mutually exclusive and exhaustive events.

For assumption iii, a set of mutually exclusive and exhaustive effects is defined as $\{E_{k1}, E_{k2}, E_{k3,\ldots}, E_{km_k}\}$ so that $E_{ki} \cap E_{kj} = \emptyset$ and $\bigcup_{j=1}^{m_k} E_{kj}$ covers all the effects for any given failure F_k.

iv) The probability of every failure cause is known.

For assumption iv, the probability components of every failure cause can be based on decision makers knowledge which gained from his/her experience over time.

v) The failure mechanism and the conditional probabilities describing cause and effect relationships are known.

For assumption v, the use of chain model which represents a network of root cause-failure mode- effect can be used to ease in describing failure mechanism. The illustration describes above mentioned relationship is given in figure 3.1.

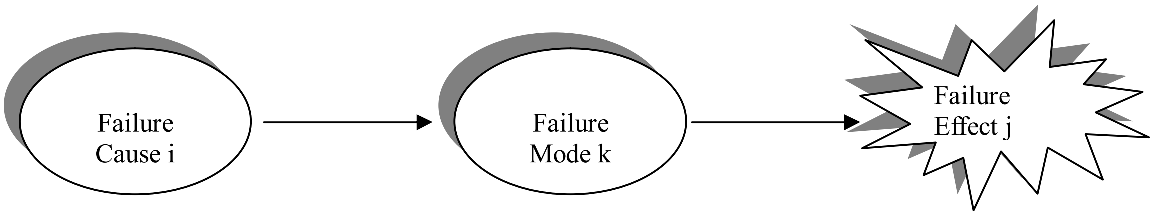

Figure 3.1 Schematic Relationship of Failure Chain

vi) The cost components corresponding to the failure effects are known.

Without knowing the cost components, the only way to determine the severity of failure effect is only be based on 1-10 scale as the same as in the conventional FMEA based on MIL STD 1629A.

Now denote that the probability of failure cause, conditional probability of failure given specific cause had occurred and conditional probability of failure effect given a specific failure mode had occurred as $P(C_{ki})$, $P(F|C_{ki})$ and $P(E_{kj}|F_k)$, $k = 1, 2, \dots, l$, $i = 1, 2, \dots, n_k$, $j = 1, 2, \dots, m_k$. And denote the cost components corresponding to the failure effects E_{k1}, E_{k2}, $E_{k3,\dots}$, E_{km_k} by L_{k1}, L_{k2}, $L_{k3,\dots}$, L_{km_k}, $k = 1, 2, \dots, l$. Then the probability of the occurrence of failure mode F_k, $k = 1, 2, \dots, l$ can be obtained by

$$P(F_k) = \sum_{i=1}^{n_k} P(C_{ki}) P(F_k|C_{ki}). \qquad (3.5)$$

Equation (3.5) represents failure occurrence probability in conventional FMEA. The probability of failure occurrence is consisting of failure cause occurrence probability and failure cause detect ability.

If the company has an established fool proof system, the value of $P(F_k|C_{ki})$ will be small. It means that the company's fool proof system enables to detect the failure cause of specific failure mode, then the occurrence of failure mode can be prevented or at least be minimized. If C_{ki} is detected before F_k occurs, $P(F_k|C_{ki})$ will take 0 as its value. In other word, the occurrence of specific failure is null. Large value of $P(F_k|C_{ki})$ indicates that the company's detect ability against occurrence of failure cause $P(C_{ki})$ is low. Thus, $P(F_k|C_{ki})$ reflects the detect ability of C_{ki}, i = 1, 2…n_k.

If the failure mode F_k can easily be detected and corrected, then $P(E_{kj}|F_k), j = 1,2,\ldots,m_k$ would be small. In reverse, if the value of $P(E_{kj}|F_k)$ is big, it indicates that related failure mode is difficult to be detected. So each score of $P(E_{kj}|F_k)$ represents the detect ability of the failure mode F_k. Large $P(E_{kj}|F_k)$ implies that the failure mode F_k is very likely to result in E_{kj}. The probability $\sum_{j=1}^{m_k} P(E_{kj}|F_k)$ can be thought to reflect the overall detect ability of the failure mode F_k. And the severity can be evaluated by losses incurred due to E_{k1}, E_{k2}, $E_{k3,\ldots}$, E_{km_k}. Thus, the conditional expected loss

$$E(L_k|F_k) = \sum_{j=1}^{m_k} L_{kj} P(E_{kj}|F_k) \qquad (3.6)$$

will represent the overall detect ability and severity of the failure mode F.

By combining Formula (3.5) and (3.6), an equation to estimated the expected loss for a given failure mode F_k is given as in equation (3.7).

$$E(L_k) = P(F_k)E(L_k|F_k). \qquad (3.7)$$

To facilitate decision makers in utilizing the expected loss model for practical purposes, a modified FMEA sheet which described the expected loss model is depicted in table 3.1. Different from the FMEA sheet of conventional FMEA which still using 1-10 scale for assigning the probability of failure occurrence, detect ability and severity rating, in the expected loss model; probability components are consisting of the 3 probability components; probability of failure cause, conditional probability of failure mode given specific failure mode has occurred, and conditional probability of failure effect given specific failure mode has occurred. In addition, if in conventional FMEA, the severity score is represented by ordinal scale, in the expected loss model the severity of failure effect is represented using cost and loss components.

By using quality cost and loss components, decision makers enable to quantify the severity of failure effects into more quantitatively basis. Indeed, those need more endeavors to collect financial data.

Table 3.1 The Modified FMEA Sheet for the Expected Loss Model

Failure Mode	Effect				Cause				Expected Loss
	E_{kj}	Severity (Loss)	detectability	Overall Effect	C_{ki}	Occurrence	detectability	Overall Occurrence	
F_1	E_{11}	L_{11}	$P(E_{11} \mid F_1)$	$E(L_1 \mid F_1)$	C_{11}	$P(C_{11})$	$P(F_1 \mid C_{11})$	$P(F_1)$	$E(L_1)$
	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$	$\vdots$		
	E_{1m_1}	L_{1m_1}	$P(E_{1m_1} \mid F_1)$		C_{1n_1}	$P(C_{1n_1})$	$P(F_1 \mid C_{1n_1})$		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
F_l	E_{l1}	L_{l1}	$P(E_{l1} \mid F_l)$	$E(L_l \mid F_l)$	C_{l1}	$P(C_{l1})$	$P(F_l \mid C_{l1})$	$P(F_l)$	$E(L_l)$
	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$	$\vdots$		
	E_{lm_l}	L_{lm_l}	$P(E_{lm_l} \mid F_l)$		C_{ln_l}	$P(C_{ln_l})$	$P(F_l \mid C_{ln_l})$		

The failure mode with the largest $E(L_k)$ should be taken care of with highest priority. In many situations, in attempt to prevent the occurrence of critical failure mode, root cause of failure must be determined. Unfortunately, the conventional FMEA is not accommodating such situation. By using the expected loss model, the expected loss attributable to a failure mode can be estimated by multiplying posterior probability of specific failure mode and its related expected loss. If $P(C_{ki}|F_k)$ represents the posterior probability of failure mode F_k and $E(L_k)$ is the expected loss due to occurrence of failure modeF_k, then, the expected loss attributable to C_{ki} can be obtained by

$$P(C_{ki}|F_k)E(L_k) = \frac{P(C_{ki})P(F_k|C_{ki})}{P(F_k)}E(L_k|F_k)P(F_k)$$
$$= P(C_{ki})P(F_k|C_{ki})E(L_k|F_k). \quad (3.8)$$

Equation (3.8) related to the expected loss due to C_{ki} in the conventional FMEA. To present mechanism to evaluate the effects and causes of certain failure mode, table 3.2 is given. Once table 3.2 is given identification of failure mechanism or root causes of critical failures are easily determined. Thus, in terms of time efficiency, this will give more benefit for practical purposes.

Table 3.2 The modified FMEA Sheet for Estimating Expected Loss Attributable to a Failure Cause

Failure Mode	Effect				Cause			Expected Loss Attributable to C_i
	E_j	Severity (Loss)	detect ability	Overall Effect	C_i	Occurrence	detect ability	
F_1	E_{11}	L_{11}	$P(E_{11}\|F_1)$	$E(L_1\|F_1)$	C_{11}	$P(C_{11})$	$P(F_1\|C_{11})$	$P(C_{11})P(F_1\|C_{11})E(L_1\|F_1)$
	⋮	⋮	⋮		⋮	⋮	⋮	⋮
	E_{1m_1}	L_{1m_1}	$P(E_{1m_1}\|F_1)$		C_{1n_1}	$P(C_{1n_1})$	$P(F_1\|C_{1n_1})$	$P(C_{1n_1})P(F_1\|C_{1n_1})E(L_1\|F_1)$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
F_l	E_{l1}	L_{l1}	$P(E_{l1}\|F_l)$	$E(L_l\|F_l)$	C_{l1}	$P(C_{l1})$	$P(F_l\|C_{l1})$	$P(C_{l1})P(F_l\|C_{l1})E(L_l\|F_l)$
	⋮	⋮	⋮		⋮	⋮	⋮	⋮
	E_{lm_l}	L_{lm_l}	$P(E_{lm_l}\|F_l)$		C_{ln_l}	$P(C_{ln_l})$	$P(F_l\|C_{ln_l})$	$P(C_{ln_l})P(F_l\|C_{ln_l})E(L_l\|F_l)$

3.4 Procedure to Perform Expected Loss Model in Service FMEA

For practical application of the expected loss model, the procedure needed can be described in the following steps:

i) Determine potential and or actual service failure modes.

Determination of potential and or actual failure modes can be based on company archival data, reports from customers' complaints and if not available; it can be based on brainstorming among FMEA teams.

ii) Access the service failure consequences.

Assessment the consequences of failure mode occurrences can be based on its impact. Depending to their types, the consequences of failure modes can be related to operational, safety, economics, non operational consequences or combination of above entities.

A failure mode is classified into operational if its occurrence is disturbing business operation, safety consequences if the failure can jeopardize customers life, and non operational consequences if even it occurs, it does not imply to any economic losses.

iii) Using Table 3.2, calculate the expected faulty loss as product of each service failure probability, detect ability, and expected cost.

The expected losses can be estimated based on information available to FMEA team. The probability components can be based on team judgments and if the data is available, the value of expected cost can be based on companies' financial reports.

iv) Compare the magnitude of expected loss of each service failure with service firm's acceptable economic criteria.

In real situation, usually company has a certain threshold of acceptable economic losses. Any incurrence of failure effect which has economic consequences beyond such threshold is then justified to take a specific corrective or preventative action.

v) If the expected loss corresponding to a failure mode is acceptable by the firm's criteria, no action is taken on the failure mode. Otherwise, go to the next step.

If the value of expected losses is still tolerable, there will be no corrective action. In reverse, if the estimated loss is beyond company tolerability, corrective and or preventative action will be taken.

vi) Using Table 3.2, find out the root causes to which the expected loss is the most attributable.

By using equation (3.8), upon performing FMEA session, decision makers can find which one among possible root causes is responsible to the occurrence of critical failure.

vii) Implement some appropriate corrective and preventive actions on the key root causes.

Considering the typical of root causes of failure modes, FMEA team can determine appropriate failure prevention measures.

viii) Verify the effectiveness of the actions.

The effectiveness of corrective action is based on the magnitude of frequency reduction of critical failures. If specific corrective action is being able to reduction frequency of occurrence in a big value, we may call that that corrective action is having high effectiveness in tackling critical problem.

ix) Document the result for organizational learning.

This step is used as basis for continual improvement. Usually, upon performing FMEA, company may obtain information on criticality of failure being observed, any workable and unworkable preventative measure and those effectiveness in solving the problem occurred.

3.5 Estimation of the Components of Expected Loss Model

3.5.1 The probability components

When using equation (3.8) as a substitute of the RPN in conventional FMEA, the three probability components $P(C_{ki})$, $P(F_k|C_{ki})$ and $P(E_{kj}|F_k)$, $k = 1, 2, \ldots, l$, $i = 1, 2, \ldots, n_k$, $j = 1, 2, \ldots, m_k$ must be known or at least estimated in advance. Indeed, without sufficient data, this can be hardly the real situation. But, as mentioned in section 3.3; practitioners usually have some knowledge on these components when use the conventional FMEA. Even if practitioners cannot obtain perfect estimates for these probabilities from the beginning, continuous updating of FMEA result in the past enables practitioners to obtain quite good estimates on the probability components.

The failure mechanism can be well established when sufficient technical information is available. In this situation, $P(F_k|C_{ki})$ and $P(E_{kj}|F_k)$ may be evaluated using this information. The technical knowledge and experiences are usually documented and maintained in most industrial organizations. And, if any kind of failure occurs, it is usually recorded with relevant information of causes attributable to. Thus, $P(F_k)$ and $P(C_{ki}|F_k)$ can be estimated using the past record of failures. Now, $P(C_{ki})$ can be estimated using the following relation

$$P(C_{ki}) = P(F_k)P(C_{ki}|F_k)/P(F_k|C_{ki}),\ k = 1, 2, \ldots, l,\ i = 1, 2, \ldots, n_k. \qquad (3.9)$$

Assuming the failure mechanism is well known, a more theoretical estimation may be possible using Bayesian estimation method. But, in this thesis; the mathematical aspect of such estimation is excluded.

3.5.2 The loss components

In completing table 3.2., the loss components $L_{k1}, L_{k2}, \ldots, L_{km_k}$, $k = 1, 2, \ldots, l$ should also be known. Note that the conventional FMEA implicitly assumes the availability of severity score for each failure effect. When the effects E_{ki}, $j = 1, 2, \ldots, m_k$ are identified for a given failure F_k together with corresponding severities, there is a good possibility to have fair estimates for L_{ki}, $j = 1, 2, \ldots, m_k$.

Let's take an illustration of estimating the loss components. Suppose a logistics firm is perceived *unreliable* in delivering its order to the customers. The *unreliability of delivery* (service failure) will cause customers' dissatisfaction, which eventually results in customers' complaint, claim or switch to another service provider. If customers claim service warranty, it directly incurs the costs to resolve service claims. If some customers switch to other service providers, it is an opportunity loss to the company. To ease on estimating the magnitude of failure effect, pictorial view representing perspective in viewing impact of service failure can be based on figure 3.2.

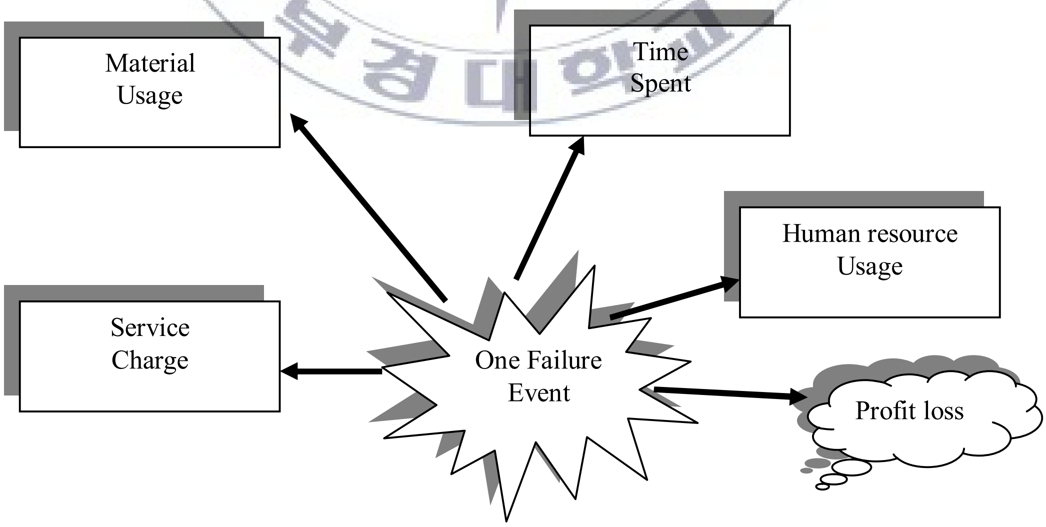

Figure 3.2 Perspective on Viewing Failure Event and Its Consequences (Krishan, [70])

From the figure 3.2., it is observable that once a failure event occurs, some consequences will follow. The occurrence of failure event will cause service charge to incur, material usage to compensate failure, some amount of time will be spent to handle customer complaint, workers will be utilized to find root cause of failures and the company also may experiencing some amount profit losses. In brief, due to the occurrence of failure event(s), company will suffered from some amount of losses.

The losses due to a service failure may be classified into three categories; internal and external failure costs, and opportunity costs. Mathematically, the quality loss components L_k can be formulated as equation (3.10).

$$L_k = CIF_k + CEF_k + CO_k \quad (3.10)$$

With CIF_k CEF_k and CO_k represent internal and external failure cost components and opportunity cost due to occurrence of failure mode k.

According to Jaju and Lakhe [64], the types of internal failure costs are as in the following; internal failure costs in the form of any cost incur to correct non conformities prior delivering products or service to customers. Exemplary of such cost are costs due to scrap, machine down time and so on. Meanwhile, external failure costs are any cost incurs after products/services are delivered to customers. The example of external failure costs are service warranty, cost to handle customers' complaints, and product liability.

The magnitude of Internal failure cost elements in the form of reworks, breakdowns, and spare and consumable costs can be estimated by following equations as depicted in table 3.3.

Table 3.3 Quantification of Internal Quality Cost Elements (Jaju and Lakhe, [64])

Cost Element		**Quantified Formula**
Internal	Rework	$\sum$[Number of Manshifts x Average Salary per Manshift]
	Breakdown	$\sum$[Machine Hours x Average Hourly Wage rate]
	Spare and Consumable costs	$\sum$[Cost of Spares and consumable used]
External		**Quantified Formula**
	Replacement done within guarantee period	$\sum$[Number of items replaced x Cost of each components]
	Administration cost to handle complaints	$\sum\left[\begin{array}{c}\text{amount of time spent to handle complaints} \\ \text{x number of person used x average person's salary}\end{array}\right]$

Based on Chavez and Beruvides [29], opportunity costs are any kind of financial profit losses due to occurrence of faulty service delivery. Estimation of opportunity costs can be accomplished by equation (3.11).

$$CO_k = (QPO - QRD)S \quad (3.11)$$

With QPO represents total units solicited by purchase order, QRD related to real quantity of unit delivered, and S related to selling price. Note that $Q_{PO} > Q_{RD}$. Next, assume that when solving failure event, some amount of money, time, and human capital are already spent. If that endeavor is failed, the amount of resources have been spent is then called cost loss.

3.6. An Example

To illustrate applicability of the expected model, an example is adopted from Chuang [23]. The example is related to hypermarket's consumers' selling service. All figures used in the case example are hypothetical and used merely for illustrative purposes. The procedure to apply the expected loss model in quantifying loss due to faulty service of case study is based on procedure presented in section 3.4.

In this case example, only 5 failure modes are used as basis of illustration instead of total 22 SERVQUAL's quality attributes. The difference between this thesis and Chuang [23] is related on endeavour to quantify effect of intangible failure effects such as customers' complaints and incorporate profitability of each proposed corrective actions. A service firm is aiming to use service FMEA to enhance reliability of their service provision by identifying the critical failure modes and their corresponding expected losses. After conducting brainstorming that supported with available data among FMEA members, the team mapped failure root causes, service failures mode, and its end effects as shown in table 3.4.

Table 3.4. Example of Modified FMEA Sheet Using Expected Loss Model (Adoption from Chuang, [23])

Failure Mode	Effect				Cause				
	Failure Effects	Severity (Loss)($)	Detect ability $P(E_j\|F)$	Overall Effect $E(L\|F)$	C_i	Occurrence $P(C_i)$	Detect ability $P(F\|C_i)$	Overall Occurrence P(F)	Expected Loss($) $E_F(L)$
Instability Of supply goods/merchandise	Short of goods Lost sales Customer complaint	1500 4000 1750	0.7 0.3 0.5	3125	Inappropriate supply forecasting Unreliable supplier Inaccurate demand forecasting	0.5 0.2 0.7	0.3 0.2 0.1	0.26	812.5
Unavailability Of goods/ merchandise	Loss sale Customers inability to find goods needed	3450 3700	0.7 0.6	4635	Inappropriate replenishment Inappropriate lay out	0.3 0.2	0.4 0.5	0.22	1019.7
Tardiness of warranty	Increasing customer warranty cost	4000	0.8	3200	Inappropriate warranty schema	0.2	0.1	0.02	64
Non conforming quality of goods	Affect food Safety against regulation Customer claims	3200 10000 200000	0.3 0.2 0.1	22960	Poor warehousing Tight less inspection Supplier error	0.1 0.1 0.05	0.3 0.2 0.1	0.055	1262.8
Inability of finding server in sales floor	Dissatisfied customers Lost sales	1000 3200	0.3 0.1	620	Poor personnel management Lack of empowerment	0.3 0.5	0.5 0.7	0.5	310

Table 3.4 illustrates the use of the expected loss model from case example. Five failure modes, root causes, end effects and their corresponding conditional probabilities are also shown. In the case example, five failure modes are “instability supply of goods/merchandise”, “unavailability of goods/merchandise”, and tardiness of warranty ”,“ non conforming quality of goods ”,“ inability of finding servers in the shop floor”.

Let us access failure mode 1, “instability of supply goods” as example. “Instability of supply goods” is caused by three causes, “inappropriate supply forecasting”, “unreliable supplier “, and “inaccurate demand”. And the end failure effects are “shortage of goods, “lost sales” and “customer complaints”. By refer to the equation (3.5); the probability of failure occurrence “instability of supply goods” is 0.26. Then, the value of severity of failure mode “instability of supply goods” is counted by using equation (3.6). Upon estimating the severity score, the severity value of failure mode 1 equals to \$ 3125. Next, the expected loss of failure mode “instability of supply goods” is estimated by multiplying the value of overall occurrence obtained by equation (3.5) and the value of overall effect of failure by equation (3.8). The equation (3.8) can be used an alternative to estimate the expected loss incurred. The expected loss caused by failure mode “instability of supply goods” accordingly is equals to \$ 812.5. The expected values of the other service failures can also be estimated with the same way. Among five failure modes of case example, “non conforming quality of goods/merchandise” is having the largest expected losses, \$1262.8.

Suppose that the threshold value of expected loss for the service firm under study is \$1000 with each failure mode. That is, the expected loss for any service failure should be no more than \$ 1000. According to this criterion, two critical failure modes are identified from Table 3.4 are as below;

i) Non conforming quality of goods
ii) Unavailability of goods/merchandise.

Before taking some remedial actions on these failure modes, the key root causes of each failure should first be identified. This can be done using Table 3.5. For instance, the value of expected loss attributable to “poor warehousing” is estimated by the use of equation (3.8). By multiplying the probability of “poor warehousing” occurrence with conditional probability of “poor warehousing” detect ability and its corresponding overall effect, we obtain the expected loss attributable to “poor warehousing” that equals to $ 688.8. The value of expected loss attributable to some other causes can be accomplished using the same way.

The estimation of the expected loss score attributable to each cause of the two critical failure modes and summarized as table 3.5. Upon performing some calculus, the root cause” poor warehousing” is being the most critical failure cause among other for failure modes “ Non Conforming quality of goods” since its estimated expected loss contribution is $688.8. By using the same idea, “inappropriate replenishment” is being the critical failure cause for failure mode “unavailability of goods/merchandise” with estimated expected loss in amount of $ 566.2.

Table 3.5 The Expected Loss Attributable to Failure Causes of Case Example

Failure		Cause			Expected Loss Attributable to C_i
mode	$E_F(L)$	C_i	**P(C_i)**	**P(F|C_i)**	
Non conforming quality of goods	1262.8	Poor warehousing	0.1	0.3	688.8
		Tight less inspection	0.1	0.2	459.2
		Supplier error	0.05	0.1	114.8
Unavailability of goods/merchandise	1019.7	Inappropriate replenishment	0.3	0.4	556.2
		Inappropriate lay out	0.2	0.5	463.5

The remedial actions may be prioritized by the expected loss attributable to each cause. In some situations, the priority may be better determined on the basis of the effectiveness of each remedial action. The effectiveness of corrective action to curb the root cause of service failure is represented by loss reduction ratio. The higher the ratio, the more effective the corrective action would be.

For illustration, suppose there is only one appropriate remedial action for each failure cause as shown in Table 3.6. If a remedial action is taken for a failure cause and it is successful, the probability of its occurrence will be decreased. The reduced value for each **P (C_i)** is also assumed as given in Table 3.6. The most effective remedial action is the one with the biggest amount of expected loss reduction. In this illustrative example, assuming the same cost for implementing every remedial action, the most effective remedial action is to establish a warehouse control system.

If profitability is considered in ranking corrective actions, the managers should reprioritize corrective actions with largest profitability. Based on Carmignani [19], the choice of the most preferred corrective action is based on its corresponding profitability index. The profitability index is estimated based on the summation between the value of advantage when specific corrective action is selected and its implementing costs. The greater the profitability of certain corrective action, the more referred it would be. However, the budget availability is also becoming determinant in choosing the most profitable corrective action as long as that is not exceeding the budget available. In this situation, the cost of implementing each remedial action should also be considered.

Table 3.6 The Effectiveness of Remedial Actions of Case Example

Failure		**P(C_i)**		**P(F|C_i)**	Expected loss		
Cause	Remedial Action	Before	After		Before	After	reduction
Poor warehousing	Establish a warehouse control system	0.1	0.01	0.3	688.8	68.9	619.9
Tightless inspection	Add new QA staff	0.1	0.05	0.2	459.2	229.6	229.6
Supplier error	Change supplier	0.05	0.04	0.1	114.8	91.8	23
Inappropriate replenishment	Change replenish method	0.3	0.1	0.4	556.2	185.4	370.8
Inappropriate lay out	Redesign store layout	0.2	0.1	0.5	463.5	231.8	231.7

Following table 3.6, among potential remedial actions to solve service failure problem of the company in case study, "establish a warehouse control system" is becoming the first priority among others since it has the biggest estimated reduction loss. The sub sequent priority is then by "change replenishment method", "redesign store layout", "add new QA staff" and "change supplier". In short, the effectiveness of competing corrective action in the expected loss model is pertaining to the loss reduction before and after implementing specific corrective action.

3.7 Discussions

3.7.1 Advantages of using the expected loss model

Improving methodology to estimate the loss due to failure occurrence is important for economic perspective. Inappropriate decision making will cause wrong decision and may lead to resource wastage. Within application of FMEA methodology in both of theoretical and practical settings, 1-10 scale of the RPNs ratings are the most widely used. Upon re-examine the ratings from probability theory's perspective, an alternative approach to estimate the RPN is presented in this thesis. The expected loss as surrogate of the RPN in conventional FMEA is presented.

The advantages of the expected loss model using the three components of failure probability $P(C_i)$, $P(F|C_i)$ and $P(E_j|F)$ for risk estimation are obvious. In the expected loss model in our study, reformulation of the probability of failure occurrences is re-constructed into a more scientific basis. Different from the formulation of the failure risk estimation in conventional FMEA which overlooked the characteristics of failure occurrences; in the expected loss model the characteristics of the failure occurrences are considered. By assuming that the occurrence of failure cause, modes and effects are mutually exclusive, the probability components of failure occurrence are determined. The advantages of re-formulating the RPN estimation using probability theory is that it will reduce the chance of inappropriate decision making and being more scientifically basis.

Using MIL STD 1629A as reference, the FMEA practitioners should follow tedious steps by brainstorming among FMEA members to estimate risk. In this situation, seniority and FMEA members' level of working experience will greatly affect the outcome of failure probability estimation. Often they have to make consensus to conclude into agreement to probability estimation. Although there is an advancement of group –based failure analysis as exemplified by Jenab and Dhillon [63], it still depends on the practitioners' subjectivity. On contrary, upon identifying the structural chain of service failures (failure causes, failure modes, and end failure effects) based on our proposed expected loss model, we can estimate the component of the three probabilities of failure in a more objective way. The attribution of the root cause of critical failure is also easier than using the conventional FMEA. Furthermore, the use of probability components in estimating the components of failure occurrence and detect ability will make consistency in implementing FMEA in almost all sectors. Different from the usage of 1-10 scale which might be vary among industries, the use of probability to represent the ratings of failure occurrence is representing uniformity for all industries.

The advantages of using our expected loss model from both academicals and industrials' perspective may be summarized as follows:

i) The proposed model provides better means to derive risk estimation using scientific basis based on conditional probability theory. While the traditional FMEA depends much on the practitioners' subjectivity in determining RPN, it will substantially improve quality of service failure risk reprioritization using FMEA approach in service field.

ii) It enables to pinpoint the part of service organization (warehouse, human resource, quality assurance, logistics, etc) that has the lowest detect ability of service failure. This will help managers to prepare better fool proofing techniques to prevent failure occurrence in future.

iii) The use of expected loss that constructed from the internal, external, and opportunity cost will raise management's awareness about the expense of service failure. Also, it enables managers to identify the key service quality attribute from the cost perspective. Furthermore, it will also useful to show the ownership of service failure cost, which in turn, will increase to the related departments' operational responsibility.

iv) It reveals capability of service firm in estimating their ability to diagnose the level of their failure detect ability power.

v) It enables management to align the most effective and profitable corrective actions to the critical service failure effects. This will not only enhance service quality improvement but also will sustain companies' long term operation as profitability is also considered in making decision.

vi) The use of probability is more universally means to articulate the scale of probability of failure occurrence in the conventional FMEA which still based on 1-10 ordinal scale.

3.7.2 Limitations of the expected loss model

There are obviously many limitations in the proposed model which must be taken into consideration for practical application. Before everything else, since based on theoretical model, validity of the model is limited and perhaps only fit to consumers' goods selling service. In addition, more refinement and articulation on estimation procedure of the probability components is obviously needed. In the expected loss model, determination of probability value is based on decision makers' intuition. Meanwhile, the probability occurrence of failure in real situation is heavily affected by explanatory variables such as services capes, the skill of workers, characteristics of service delivery and the typology of service system itself. According to Wu *et al.* [122] the probability of failure occurrence of system is affected by service system environment. The more complex service system is the more prone of service system to have failure will be.

The second limitation of the expected loss model is that the occurrence of failure event is independent of time. Since time is inseparable to characterize failure occurrence beside its consequences, negligence on time occurrence to estimate probability of failure occurrence is not appropriate since it did not consider the nature of failure attribution, its time occurrence.

The third limitation of the expected loss model is that the failure occurrence is assumed independence among others. This assumption is violating the reality that in real situation, failure event occurrence is possibly dependent one another. Assumption of single failure occurrence will cause only single failure effects is also not appropriate. As in real situation, relationship among failure cause, failure mode and failure effect may have various models. For example, single root cause may cause single failure mode but with multiple failure effects. Or multiple root causes of failure will cause multiple failure modes and multiple failure effects.

Next, estimating failure effect using monetary metrics is meaningful for practical purposes as it will also raise management awareness to the meaning of cost of quality. Beside the adagio that cost is the universal language in doing business. Nevertheless, the loss components in the expected loss model are based on economic perspective only. In real situation however, when service failure event occurs, socio-physiological –related aspects of service provision shall be taken into consideration in estimating the loss value. For instance, in applying FMEA in healthcare sector, methodology on appraising the weight of the severity of customers' aggravation or customers' worry is still less established. The other reason why using cost basis is sometimes not useful in the expected loss model is that due to difficulty to access financial data due to confidentiality.

Other limitation of the expected loss model is that it did not consider the time span of the exposure to loss occurrence. If we look carefully at the loss component of the expected loss model, it only considers the value of loss and did not consider the time span of the loss exposure. Since every failure effect has different time exposure, articulation of the magnitude of the loss components shall be related with time span of loss exposure. Suppose that there are two different failure effects with the same estimated loss values, the attention to recovery should be given to the failure mode with has the longer time exposure. Next, the occurrence of failure events is not only incurring the loss, which perceived as the something detrimental to company economy. Nevertheless, the occurrence of failure event is also creating *opportunity*. If the failure event indicating that the service system is suffering from deficiencies, it also will revealed any potential opportunity which may even making service system operates better than before.

The fifth limitation of the expected loss model is that it is only viewing service providers are doing disservice to service customers. In some situations, the occurrence of disservice events during service delivery process is possibly due to incomplete specification from customer's input. How well service providers are trying to give service delivery to customer, any uncertainty from customers input to service specification as desired by customers will possibly yield into service quality discrepancies. Moreover, interaction among internal failure and external failure events are highly possible in real service delivery practice. If the expected loss model is going to used in industrial practice, such situation must be considered carefully since the potential effects of failure interactions among internal and external failure events are possibly higher that impact due internal failure events only.

Although the SERVQUAL is possibly becoming the mostly used means to measure service quality, its dimensions is heavily affected by the North American style. The application of the SERVQUAL-based expected loss model shall also consider the cultural local settings and shall be tailored specifically to specific industry. Justification on inclusion of local cultural settings in apprising service quality is stated and exemplified by Imrie *et al.* [36]. Using research locus in Taiwan, they revealed that cultural values are influencing the hierarchy of service quality dimensions and also the SERVQUAL model of the PZB (Parasuraman, Zeitham and Berry) theory is unable to capture the breath criteria utilised by Taiwanese as representation of the Chinese culture. For instance, interpersonal relationship as one of important dimensions of service quality is not adequately addressed by SERVQUAL.

Chapter 4

A Time Dependent Expected Loss Model in FMEA

4.1 Introduction

Correct evaluation of failure risk is important part toward efficiency of a firm's resource allocation. In industrial practices, firms utilize FMEA as a means to estimate the risk of system failure and provide an appropriate way of reducing its impact on the end customer. In FMEA, severity of failure effect is measured by the Risk Priority Number (RPN). It is a metric obtained by multiplying the ratings of severity, occurrence and detect ability of every failure. The high value of the RPN gives indication the high criticality of a certain failure. And immediate attention should be pair to the failure mode which has the RPN beyond acceptable limit. Over the years, attention to take immediate corrective action is based on the RPN value. Due to its simplicity, the use of the RPN using 1-10 scale is versatile in FMEA application. For detail explanation of the conventional FMEA, the big 3 motor companies' FMEA reference manual can be referred. However, the rating on each of the three components is usually based on experience and intuition of the FMEA team. Thus, the conventional FMEA based on MIL STD 1629A provides only a rough evaluation of relative risk priority for every failure mode. In addition, since based on experience and intuition, possibility to having varying interpretation among FMEA users is inevitably occur.

Up to now, many studies have been dedicated to improve methods which complement to conventional FMEA. For example, to consider the fuzziness of the RPN ratings, fuzzy logic based RPN estimations are proposed by Bowles and Pelaez [15], Sharma and Sharma [101], and Sharma *et al.* [114]. In attempt to consider the independence of failure occurrence, Sutrisno and Kwon [103] proposed the use of expected loss model in quantifying the risk of faulty service. In brief, many studies have been presented to solve shortcomings of the RPN estimation in conventional FMEA.

Nevertheless, the previous studies seem to neglect the role of time in modeling the likelihood of failure occurrences in failure assessment process. Besides, the scales to estimate the criticality of failure effects are still based on qualitative and subjectivity of FMEA team. Furthermore, the magnitude of failure severity is assumed constant over time. Initial idea to formulate the probability of failure occurrence rating in FMEA using a more scientific approach is proposed by Senol [113]. According to her approach, the component of probability of failure occurrence in RPN estimation can be based the Poisson distribution. However, the approach used in estimating the probability of failure occurrences is neglecting the influence of failure cause occurrence time. In addition, Poisson –based FMEA of Senol [113] is still utilizing 1-10 scale rating of failure detect ability and severity. Regarding that service failure occurrence has time occurrence aspect, ignorant of failure occurrence time and assuming constant failure severity scale may inappropriate in estimating service recovery effort. Considering the strategic role of time as dimension in determining risk magnitude, an improved expected loss model which considers failure occurrence time is proposed.

In this thesis, a model for quantifying the failure risk is presented assuming that a failure can occur only after at least one of its causes has occurred in advance. Constant occurrence rates are assumed for every failure and its causes. The failure risk is evaluated by the loss that results from the failure. The loss due to every failure mode is assumed to depend on the remaining mission period of the system. To evaluate the risk of each failure mode, the expected value of its corresponding loss is obtained. In the proposed model, the expected loss of each failure mode includes the severity of failure effects and failures detect ability. The detect ability of failure effect is defined as the probability that every cause of failure actually occurs. The new risk evaluation model will facilitate FMEA team to quantify the risk of every failure mode and priorities failure modes. In addition, it accommodates possibility that the loss due to faulty operation may escalate over system mission time span.

4.2 Quantifying Risk Components in FMEA

FMEA evaluates the risk of each failure mode on the basis of three components; failure effects severity, failure occurrence frequency, and failure mode detect ability. In the conventional FMEA, every above mentioned components is determined based on 1-10 scales which largely depend on past experience and intuition of the FMEA team. There are guidelines to assign an appropriate number to every component related with a specific failure. Following MIL STD 1629A, a table which represents the ratings for RPN estimation can be refereed to chapter 2.

For practical situation the use of 1-10 scale in estimating the RPN is versatile since it is very easy in practice. But these guidelines are not precise enough and provide only a rough estimation of relative risk priority for each failure mode. Furthermore, it does not take into account the failure occurrence time and possibility that loss due to failure occurrence may escalate during a system’s mission operational time.

When sufficient information from past experience and scientific knowledge is available, a more systematic approach may be applicable. In this thesis, a scientific approach to quantification of every component of RPN estimation by considering failure time occurrence under some reasonable assumptions is proposed.

4.2.1 Failure Severity Component in Time Dependent FMEA

The severity of failure effect may reasonably be evaluated by its resultant loss. The loss will be incurred if the system or process fails during its mission time duration (0, T). If the system does not fail during (0, T), no loss is confronted. The loss function may be reasonably assumed to be a non decreasing function of the length of the remaining mission time period. Here, three different types of loss function are considered for each failure; constant, linear and quadratic loss model.

When the system suffers a fixed amount of loss if any kind of failure occurs, a constant loss function will be appropriate. If the loss due to failure k connected to its i^{th} cause is denoted by L_{ki}, the constant loss function will be given as

$$L_{ki} = \begin{cases} \alpha_k, & 0 \leq W_{ki} \leq T \\ 0, & \text{otherwise} \end{cases} \tag{4.1}$$

Where α_k is a constant reflecting the severity level of the failure k and occurs due to its i^{th} cause from the beginning time point of the system or process operation. When a failure has several effects, α_k should reflect the total aggregated effects that result from failure k.

Next, when the loss amount is proportional to the length of remaining mission time period, the linear loss function will be appropriate. In this situation, the loss function is given by

$$L_{ki} = \begin{cases} \alpha_k(T - W_{ki}), & 0 \leq W_{ki} \leq T \\ 0, & \text{otherwise} \end{cases} \tag{4.2}$$

And finally, when the unfilled mission period severely affects the loss due to the failure, the quadratic loss function will be appropriate. Under such situation, the quadratic loss function is defined by

$$L_{ki} = \begin{cases} \alpha_k (T - W_{ki})^2, & 0 \le W_{ki} \le T \\ 0, & \text{otherwise} \end{cases} \qquad (4.3)$$

The use of the three kinds of loss function model as above is advantageous since those provide more realistic articulation of loss occurrence which much fit with reality.

4.2.2 Failure Occurrence Components in Time Dependent FMEA

The occurrence of a failure may be described by the time elapsed from the beginning of the system operation to system failure. Any failure must have some causes or at least single causes which lead to the failure itself. Occurrence of every failure comes after occurrence of one or more of its cause. Thus, failure time is composed of two components; the cause occurrence time and its corresponding failure occurrence time. Extending from the original Poisson model, determination of probability density function of failure cause and failure mode component in time-dependent FMEA is determined in the following way.

Let X_{ki} be the time elapsed until the i^{th} cause, i = 1,2,3, …, *nk* of failure mode k occurs from the occurrence time point of its i-th cause. Assume that each cause occurs at a constant rate λ_{ki}, the probability density function of X_{ki} will be as in equation (4.4).

$$f_{X_{ki}} = \lambda_{ki} e^{-\lambda_{ki} x}, \qquad 0 < x, \qquad (4.4)$$

Next, let Y_{ki} be the time elapsed until failure k occurs from the occurrence time point of its i_{th} cause. Assume the occurrence rate of failure k due to its i_{th} is constant over time, say μ_{ki}. Then the probability density function of Y_{ki} will be

$$f_{Y_{ki}} = \mu_{ki} e^{-\mu_{ki} y}, 0 < y. \quad (4.5)$$

Let W_{ki} be the time elapsed until failure k occurs due to its i_{th} cause from the beginning time point of operation of the system or process. Then the W_{ki} is represented by equation (4.6).

$$W_{ki} = X_{ki} + Y_{ki} \quad (4.6)$$

Referring idea that W_{ki} is consisting of failure cause and failure mode time component, probability density function of probability of failure occurrence rate as in conventional FMEA is based on the joint probability density function of failure cause and failure mode of certain failure event. Then, the joint probability density function of failure time occurrence will follow equation (4.7)

$$f_{W_{ki}}(w) = \frac{1}{\lambda_{ki} - \mu_{ki}} \{\lambda_{ki} e^{-\mu_{ki} w} - \mu_{ki} e^{-\lambda_{ki} w}\}, 0 < w \quad (4.7)$$

And, the probability distribution function of W_{ki} is formulated as equation (4.8).

$$F_{W_{ki}}(w) = 1 - \frac{1}{\lambda_{ki} - \mu_{ki}} \{\lambda_{ki} e^{-\mu_{ki} w} - \mu_{ki} e^{-\lambda_{ki} w}\}, 0 < w \quad (4.8)$$

Derivation of equation (4.7) can be seen in appendix 2. The joint probability density function of failure occurrence as seen in equation (4.7) is the representation of probability of failure occurrence rate in conventional FMEA.

4.2.3 Failure Detect ability Components in Time Dependent FMEA.

Once a failure occurs, it takes much time and cost for remedy. But when the failure cause is detected before the failure actually occurs, it usually does not take much time and cost for correction. When the cause is detected before the corresponding failure occurs, immediate corrective action is assumed to be taken without any loss. The detect ability is determined by the probability distribution of detection time and failure occurrence time after the corresponding cause occurrence. Let U_{ki} is the time elapsed until the i^{th}cause of failure mode k is detected from its occurrence time point. Here, U_{ki} is assumed to have exponential distribution with its probability density function

$$f_{U_{ki}}(u)= \tau_{ki} e^{-\tau_{ki}\mu}, 0 < u \quad (4.9)$$

Assuming U_{ki} and Y_{ki} to be independent, the probability that the i_{th} cause of the failure mode k is detected before the corresponding failure occurs can easily be obtained as

$$P[U_{ki} < Y_{ki}]= \frac{\tau_{ki}}{\mu_{ki}+\tau_{ki}} \quad (4.10)$$

In FMEA, the detect ability component can be defined as possibility of company detect the occurrence of failure. Or it also can be defined as probability of the occurrence of failure mode due to inability to detect or prevent the occurrence of failure cause. Using above definition, the detect abilityD_{ki}, i.e. the probability of occurrence of failure k connected to its i_{th} cause is obtained by

$$D_{ki}= P[U_{ki} > Y_{ki}]= \frac{\mu_{ki}}{\mu_{ki}+\tau_{ki}} \quad (4.11)$$

Equation (4.11) is representing failure detect ability component as in that of conventional FMEA.

4.2.4 The Time Dependent Expected Loss Model

The overall risk a failure mode can be evaluated by the expected value of its resulted total loss. To get an accurate expected value of loss for failure k, the use the exact failure time distribution of failure mode k connected to its i_{th} cause is mandatory which is somewhat different from (4.7) and (4.8). It actually is far more complicated than these formulas and cannot be expressed is a simple form. Actually the component of W_{ki} depends on X_{ki}, Y_{ki}, and U_{ki}, i= 1,2,3,..,n_k.

Notice that even after the i_{th} cause of failure mode k is detected and corrected, it may reoccur after X_{ki} units of time. Thus, W_{ki} includes Y_{ki} and several random variables which are identical with X_{ki} and U_{ki}. This situation is illustrated in fig.4.1, assuming that every failure cause is detected up to the $(v\text{-}1)^{th}$ occurrence and corrected before actual failure occurs. At the v^{th} occurrence of failure cause, actual failure occurs before its cause is detected.

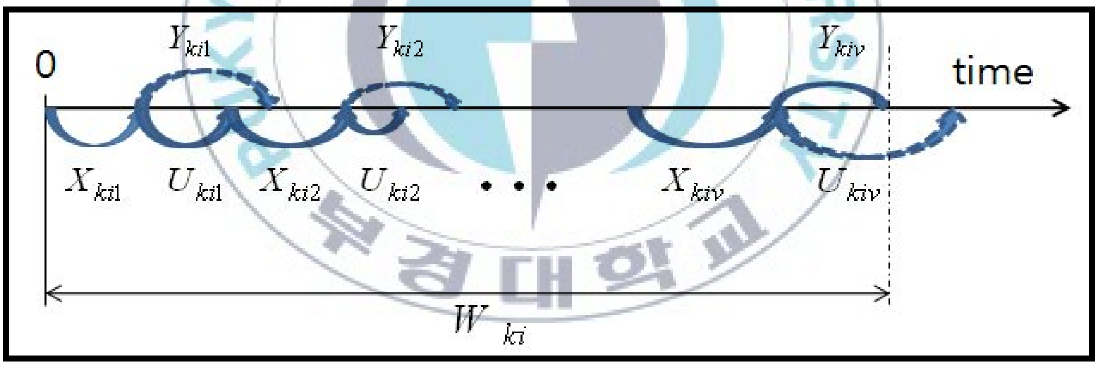

Figure 4.1 the actual components of W_{ki}

In this thesis, complexity in obtaining the expected loss is not considered. The detect ability component of failure effect is considered separately. At first, estimation of the expected loss $E[L_{ki}]$ is calculated based on the distribution of W_{ki} given by formula (4.7) and (4.8). Then, the risk of failure k due to its i^{th} cause is obtained by multiplying $E[L_{ki}]$ with detectability D_{ki} of formula (4.1). Regarding the magnitude of quality loss which can be constant and increasing over time, the three types of expected loss models are then introduced.

Regarding to the model of loss function, for constant, linear, quadratic loss function; the corresponding expected loss can be obtained by following equations respectively.

$$\mathrm{E}[L_{ki}] = \alpha_k F_{W_{ki}}(T) \tag{4.12}$$

$$\mathrm{E}[L_{ki}] = \alpha_k \int_0^T F_{w_{ki}}(w)dw \tag{4.13}$$

$$\mathrm{E}[L_{ki}] = \alpha_k \int_0^T (T-w)^2 F_{w_{ki}}(w)dw \tag{4.14}$$

The magnitude of the risk failure of failure k due to its i_{th} cause by multiplying $\mathrm{E}[L_{ki}]$ with detect ability of formula (4.11) for every i=1,2,3,…,n_k, k = 1,2,3,…,l and risk priorities of all the failure cause can be determined. To facilitate the evaluation procedure, a modified FMEA sheet of table 4.1 is presented. Different with conventional FMEA sheet which did not consider failure occurrence time components, in this thesis, regarding the failure time components, a modified FMEA sheet with two failure time components and one failure detection rate are proposed. First, is the failure cause component$(\lambda_{k_{nk}})$. Second, is the failure mode time occurrence component$(\mu_{k_{nk}})$, and third, is the failure detection rate component $(\tau_{k_{nk}})$. Each of above mentioned entity is estimated based on the initial of system's mission time span.

Note that some quantities in the sheet are not easily obtained to get directly from the given information and those are requiring some additional calculations. This means that the loss function is applicable for each failure mode. In addition, this means that the loss function should sum up all the effects corresponding to the given failure mode. The value of α_k should be taken by considering this fact into account.

Depending on the data availability, determination for the score of α_k is ideally using monetary basis since that will reflect the goal of company business as profit seeker. However, if the data is unavailable, the use of ordinal scale similar with that of conventional FMEA is sufficient.

Table 4.1 The Modified FMEA Sheet for Risk Evaluation

Failure Mode	Severity		Occurrence			Expected Loss	Detectability		Risk Measure
	Effect	Loss	Cause		Failure	E[L]	τ	D	E[L]xD
		Loss Function	Item	λ	μ				
…	…	…	…	…	…	…	…	…	…
F_k	E_{k1}	α_k $\alpha_k(T-W_k)$ $\alpha_k(T-W_k$	C_{k1}	λ_{k1}	μ_{k1}	E[L_{k1}]	τ_{k1}	D_{k1}	E [L_{ki}]D_{ki}
	E_{k2}		C_{k2}	λ_{k2}	μ_{k2}	E[L_{k2}]	τ_{k2}	D_{k2}	E[L_{ki}]D_{ki}
	…		…	…	…	…	…	…	E[L_{ki}]D_{ki}
…	E_{kmk}		C_{kn_k}	λ_{kn_k}	μ_{kn_k}	E[L_{kn_k}]	τ_{kn_k}	D_{kn_k}	E[L_{ki}]D_{ki}

Finally, considering failure occurrence time, equations to estimate the expected loss for constant, linear and quadratic models are given as in equation (4.15), (4.16) and (4.17).

$$\mathrm{E}[L_{ki}] = \alpha_k F_{W_{ki}}(T) D_{ki} \quad (4.15)$$

$$\mathrm{E}[L_{ki}] = \alpha_k \int_0^T F_{w_{ki}}(w)dw\, D_{ki} \quad (4.16)$$

$$\mathrm{E}[L_{ki}] = \alpha_k \int_0^T (T-w)^2 F_{w_{ki}}(w)\,dw\, D_{ki} \qquad (4.17)$$

By using all three models above, regarding failure occurrence time, decision makers enable to make decision into a more realistically manner.

4.3 Procedure to Perform Time Dependent Expected Loss Model in FMEA

In applying the concept of time dependent expected loss model in FMEA, the following steps can be followed:

1. Determine critical failure mode by counting its RPN. The list of critical failure modes can be based on company archival data or from customers' feedback.
2. Determine the probable root cause of each critical failure mode. This can be accomplished by brainstorming among members, and or by viewing the archival data.
3. Upon obtaining root cause of failure, estimate the time span of the failure cause occurrence, the time span of failure mode occurrence. In addition, estimate the number of undetected failure modes from corresponding cause time span. The result of this step is the time span parameters to estimate the loss value of the corresponding failure modes.
4. By using equations (4.15), (4.16), and (4.17), estimate the loss value for constant, linear and quadratic loss model.
5. Upon obtaining the result of loss function model, determine the root cause attributable to the largest or the most critical failure mode.
6. Find the appropriate way to reduce the occurrence frequency of critical failure causes.

4.4 Numerical Example

In this section, an illustrative example to explain the usage of time dependent loss model is provided. Comparison among all results from estimation with three types of loss function with that of conventional FMEA is presented. The example is related to application of FMEA in hypermarket service which is taken from Chuang [24]. The ratings of failure occurrence (O), Severity (S), and detect ability (D) are hypothetical and given just for illustrative purpose.

Table 4.1 Service FMEA Sheet of Case Example (Excerpted from Chuang [24])

Potential Failure Mode	Potential Effect	S	Potential Cause	O	Detection Method	D	RPN	Risk Rank
Unreliable Supply of goods/merchandise	Shortage of goods/merchandise	7	Poor supplier evaluative and selection	6	Suppler evaluation	7	294	1
	Lost Sale		Inappropriate supplier relationship	4	Monthly contact with customer	7	196	3
	Decreasing customers' loyalty		Insufficient inventory of suppliers	2	Three-months management meeting	2	28	4
	Customer complaint		Lack of upward communication	5	semiannual management meeting	8	280	2
	Complicating job allocation and replenishment activity		Inadequate Marketing research	3	Semiannual customers survey	1	21	5

Table 4.1 described the result of performing conventional FMEA for service system. The potential failure mode "unreliable supply of goods/merchandise" is having numerous effects ranging from "shortage of goods/merchandise" until "complicating job allocation and replenishment activity." Referring to the RPN failure, the priority to curb the failure mode is should be given to supplier evaluation

since it has the largest RPN. In reverse,” performing semiannual customers’ survey” is the least rank as it has the smallest RPN score.

Regarding to the case example, by referring to the RPN score, the most critical failure mode from table 4.1 is “unreliable supply of goods /merchandise”. Potential cause, effects and detect ability is given accordingly. To apply the time dependent model of FMEA to this example, numerical value for α, λ, μ and τ considering those numbers given in table 4.2. The mission time span taken is assumed 10 years. Table 4.2 shows the modified example fit for our model. Based on the parameter values given in table 4.2, the result of the expected loss estimation corresponding to each failure cause and summary of the result is given in table 4.3.

Next, the risk for each failure cause is evaluated is evaluated by multiplying the expected loss with its corresponding detect ability. Then, the risk priority of each failure cause is determined. The results are then displayed in table 4.5.

Table 4.2 Modified FMEA Sheet of Case Example

Potential Effect	α	Potential Failure cause	λ	μ	τ
Shortage of goods/merchandise	7	Poor supplier evaluation and selection	1/80	1/8	1/7
Lost Sale		Inappropriate supplier relationship	1/2000	1/200	1/7
Decreasing customers’ loyalty		Insufficient inventory of suppliers	1/150000	1/15000	0.50
Customer complaint		Lack of upward communication	1/15000	1/500	1
Complicating job allocation and replenishment activity		Inadequate Marketing research	1/2000	1/200	1/4

Table 4.3 The Expected Losses due to Each Failure Cause for Three Types of Loss Function

Failure Effect	α	Potential Cause	Type of loss function		
			Constant	Linear	Quadratic
Poor supplier evaluative and selection	7	Poor supplier evaluative and selection	0.35897	1.3265	7.0573
Inappropriate supplier relationship		Inappropriate supplier relationship	0.000859	0.002878	0.014424
Insufficient inventory of suppliers		Insufficient inventory of suppliers	$1.551*10^{-7}$	$5.184*10^{-7}$	$2.592*10^{-6}$
Lack of upward communication		Lack of upward communication	$1.55*10^{-5}$	$5.176*10^{-5}$	$2.589*10^{-4}$
Inadequate Marketing research		Inadequate Marketing research	0.000859	0.002878	0.014424

Next, the risk for each failure cause is then evaluated by multiplying the expected loss with each detect ability component. Referring to table 4.3, the loss function model for three types of quality loss escalation over time is presented. In general, it is observable that depending to the expected loss type used, increase in the loss magnitude is observable from constant, linear and quadratic loss model. Especially for quadratic loss model, an indication on loss escalation from the largest loss due to failure cause "poor suppliers evaluation and selection" until the lowest loss due to "inadequacy in marketing research" are shown. And for ease of handling, all results are multiplied with 1,000,000. Then the risk priority of each failure cause is determined. Table 4.4 displays the evaluated risks.

Table 4.4 The Evaluated Risk and Priority of Case Study

Potential Effects	α	Potential cause	Detection	Type of loss function			Risk Priority
				Constant	Linear	Quadratic	
Shortage of goods/merchandise	7	Poor supplier evaluative and selection	7/15	16751	619027	3293407	1
Lost Sale		Inappropriate supplier relationship	7/207	29	97	488	3
Decreasing customers' loyalty		Insufficient inventory of suppliers	7/7501	0.000145	0.000484	0.00242	5
Customer complaint		Lack of upward communication	1/6	3332	11358	57558	2
Complicating job allocation and replenishment activity		Inadequate Marketing research	1/1501	16.8	56.4	282,8	4

From table 4.1 and 4.4, it is observable that there is seemed no distinct differences in the order of the risk priority between the conventional FMEA and the time dependent expected loss model as proposed in this thesis. For example, following the calculation of the RPN based on conventional FMEA, the critical failure cause is due to "poor supplier evaluation and selection" as ranked 1. This failure cause is also the same with accomplishment using time dependent expected loss model since it is also ranked 1. However, the evaluated sizes of the corresponding risks are different. Referring to calculations of the expected loss value, a significant difference in the magnitude of expected loss among three type of loss function is evident. For example, the maximum and minimum of the RPN in conventional FMEA is 294 and 21, respectively. By considering time occurrences, the expected loss for quadratic loss function are 3293407 and 0.00242. It seems that the proposed model has yield the order of risk priority which rather different from that of the conventional FMEA. In addition, it provides more realistic information on the degree of corresponding risk. FMEA team may think that the potential cause “insufficient inventory of suppliers “cannot be neglected in table 4.2. If they refer to table 4.4., they may consider that the cause is negligible without slightest hesitation. Moreover, table 4.4 shows that how much effort should be focused on the failure cause with the highest risk priority. Based on the numerical calculation, inclusion of failure time occurrence in the failure risk estimation will give insight on how importance the time is, besides considering magnitude of the impact of failure effect.

4.5 Discussions

4.5.1 Advantages the Time Dependent Expected Loss Model in FMEA

In spite of its versatility in industrial usage, the RPN estimation in conventional FMEA is neglecting the influence of failure occurrence time and the reality that loss value is not constant over time as stated in its severity rating guidance. Ignoring failure time occurrence is not realistic since time is inevitable aspect of failure event occurrences. In this thesis, failure time occurrence is considered in estimating the expected loss within FMEA methodology. The failure time components in this thesis are consisted of the two components; failure cause and failure mode time span. Both time components are calculated from initial system mission.

By assuming the occurrence time is following the exponential probability distribution model, three types of loss function are proposed as compliment in appraising severity level of failure effect; the constant, linear, and quadratic loss function models. And also, constant failure occurrence rate is utilized in the time dependent expected loss formulation. The model provides an exemplary on how to consider the failure time occurrence in estimating the risk of failure. In addition, the proposed model facilitates decision makers in quantifying escalation of loss score during system's time span. By considering the failure occurrence time, management will have no doubt in determining the root cause of critical failure in terms of time occurrence. In addition, by utilizing the proposed model, more realistic information on managing the trend of expected losses is possible. It is also enabling management to take preventative measures of critical risk in a timely manner. Considering failure time occurrence will improve company preparedness within context of time –based business management platform.

4.5.2 Limitations of the Time Dependent Expected Loss Model in FMEA

Despite some potential benefits as described above, the time dependent expected loss model as proposed in this thesis is not free from limitations. First above all, since based on conceptual model and single service sector, the model presented by case example is lack of strong validity and cannot be generalized for all service sectors. Next, some refinements certainly needed for practical purposes. For instance, in real situation; assumption of constant failure cause occurrence rate may not appropriate. Failure events are occurring accidentally with varying occurrence rate and varying magnitude of losses. Therefore, the use of Non Homogeneous Poisson (NHPP) model as surrogate to model the varying failure occurrence rate will closer to real situation.

In addition, the model did not consider that in real situation, service system is having ability to recover from failure and may have tendency on decreasing failure occurrence rate. In other word, the "reliability growth" of the service system cannot be neglected. Moreover, the influence of service system's configuration and service environment as covariate cannot be neglected as contributing factor to possibility of failure occurrences (Wu *et al*. [128]) and Simons [108]). For example, harsh services cape and complex service system configuration are potentially greater to cause service system to have bigger failure occurrence rate. In addition, the occurrence of failure mode in real situation is also dependent among others. For example, poor suppliers' evaluation in the case example is possibly caused by "unknown suppliers' evaluation procedure" and "resistance from the suppliers." In summary, dependency among failure modes and its occurrence time cannot be not simply neglected in developing time dependent model in quality loss quantification.

Chapter 5

Selecting Corrective Action Strategy based on SWOT Analysis in Service FMEA

5.1 Introduction

As a sector that contributes to more than 70% of global domestic product, the importance of delivering reliable service operation is undeniable. Based on study of Zaman and Anjalin [132], it is evident the contribution of service sectors is continuously growing for both developed and developing countries. Nevertheless, numerous references discussing new challenges on reliability studies, such as Bhamare *et al.*[8] and Yadav and Singh [133], are still focusing on product design and manufacturing sector. Hensley and Utley [55] noted the importance on using the FMEA(failure mode and effect analysis) as a tool to assess the risk of quality problems in delivering service. Seyedhosseini and Hatefi [106] stated that determination of systematic method to rank corrective actions based on risk assessment tool is still less explored research area. In their study, within risk management platform, apprising competing corrective actions is having equal important with quantifying risk of loss occurrence. Many methodologies have been proposed to improve quality of appraising competing corrective action in risk-based improvement effort. For example, Yadav *et al*. [136] proposed to use the reduction rate of failure occurrence in ranking corrective action. Bluvband *et al.* [12] used the RPN (risk priority number) reduction ratio before and after implementing corrective action. Carmignani [19] suggested the *Priority- Profitability Diagram* as means in selecting corrective improvement strategy. Chen [27] and Zammori and Gabrielli [142] used the Analytical Network Priority as means to propose strategy evaluation.

Despite many endeavors have been dedicated to develop techniques on ranking corrective action, most ideas above are still based on impacts from inner of business system. In other word, inclusion on impact of the external business environmental factor is ignored in previous study. Furthermore, previous studies are mainly focused on the domain of product design and manufacturing. Recently, FMEA is used in service as well as manufacturing industries as an effective way of improving a system (Hesley and Utley, [55]). Based on elaboration of Hashim [60], Fitzimmons and Fitzimmons [42]; the interrelationship among service system and its environment cannot be neglected in endeavor to propose improvement effort. Thus, to improve a service system operation, the business environmental impact should also be taken into consideration. In attempt to accommodate such characteristics, the utilization of the SWOT (strength weakness opportunity threat) analysis is an effective tool that describes interrelationship between business systems with their environments.

In this thesis, an alternative approach for selecting and ranking service corrective action strategy based on SWOT analysis in Service FMEA is proposed. Employing the SWOT variables in FMEA will enable the practitioners to quantify the impact from both inner and outer business system before proposing strategic corrective actions.

5.2 Integration of SWOT Analysis in FMEA

Initially developed from military field in 1950s, FMEA (Failure mode and Effect Analysis) can be defined as a failure avoidance methodology that used to avoid the reoccurrence of the failures in the future. The end outcome of performing FMEA is the failure recovery knowledge. In spite of having capability in delineating critical and non critical failures, the use of FMEA alone is unable to estimate the impact of business environments in endeavor for solving business problem. Therefore, integration of FMEA with SWOT is expected to overcome limitation of conventional

FMEA in indicating and dealing critical business problems.

Figure 5.1 represents procedures to select and rank corrective action priority based on SWOT analysis. It also represents a model on integrating SWOT Analysis and FMEA.

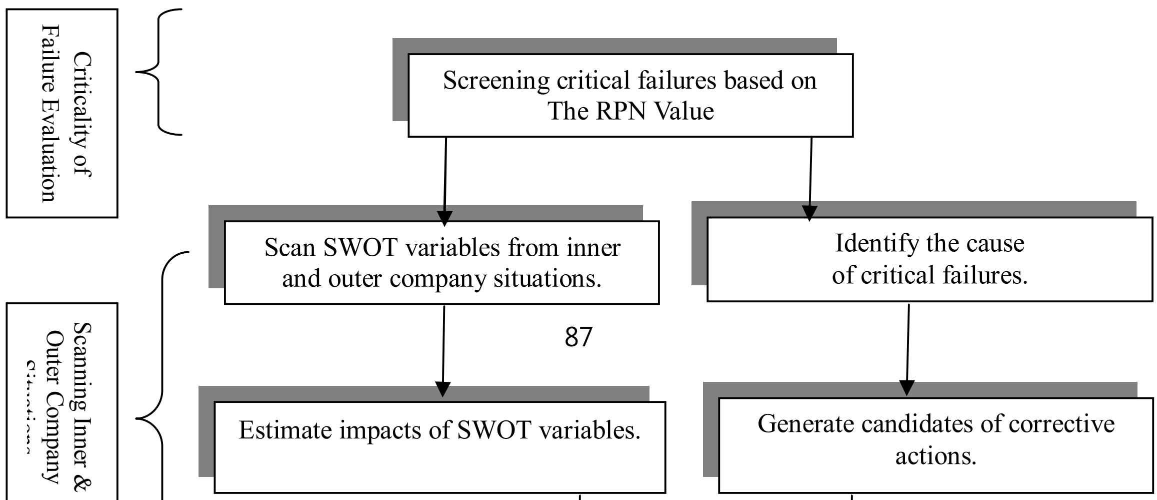

Figure 5.1 A Framework for Linking FMEA and SWOT Analysis

5.2.1 Impact Factor of SWOT Variables

The existence of SWOT variables is influencing the selection of business strategy. The possibility occurrence of opportunity variable is giving positive impact to company, and in reverse; the possibility occurrence of threat is negatively impacting to company. Meanwhile, the existence of strength variables will accelerate company business operation in reaping its goal. If strength variables are accelerating in achieving business goal, the existence of weakness variables is hindering company in achieving its goals. Regarding above elaboration, the existence of strength and opportunity variables are positively influencing company and in reverse, the threats and weakness variables are negatively impacting company. In attempt to quantify impact of SWOT variables, the impact factor (IF) is introduced in this thesis.

If IFO represents the impact of opportunity variables, the value of IFO for opportunity variable *k* is formulated as in equation 5.1. Following Lee [76], the existence of opportunity variables will give economic benefits. If the magnitude of the benefit is then represented by monetary value, MVO_k; then to quantify impact factor of opportunity variable k, equation (5.1) is used.

$$IFO_k = P(O_k)MVO_k \qquad (5.1).$$

Contrary to above situation, the existence of threat variables will give negative impact to company. Quantitatively, the impact factor of threat variable is estimated similarly with opportunity variable. And the magnitude of the loss due to possibility of threat occurrence is also assumed can be represented by financial measures, the monetary loss. The impact factor of threat variable is then given as in equation (5.2)

$$IFT_k = P(T_k)MVT_k \qquad (5.2).$$

Based on Patel and Zaveri [91], for ease of estimation, the impact of threat occurrence can be based on some amount of financial loss may incur. According to Thawengskulthai and Tannock [122], for ease of numerical handling, an ordinal scale of 1-5 can be used to quantify impact of threat and opportunity variables.

In attempt to quantify impact of weakness and strength, The Internal factor

Analysis (IFA) as initially introduced by Wheelen and Hunger [129] can be used. Let Y_k and X_k represents the weight of internal strength and weakness variables k, and W_k and Z_k represent to the ratings of importance of the internal strength and weakness variables *k* respectively; then the score of the impact factor (IF) of strength and weakness variables are given as in equation (5.3) and (5.4).

$$IFS_k = Y_k W_k \quad (5.3)$$

$$ISW_k = X_k Z_k \quad (5.4)$$

The weight of internal strengths and weaknesses variables can be estimated based on Analytical Hierarchy Priority (AHP) as exemplified by Xing and Xian [131]. Based on specific value of internal strength and weakness variables, decision makers can determine critical and non critical variables for further strategy prioritization. And so do opportunity and threat variables.

Upon completing in mapping all SWOT variables in a SWOT matrix, decision makers then can select and rank strategy which appropriate to their company goals. However, since time observation is critical in determining the SWOT variables, determination of SWOT variables must considered time observation. According to Helms and Nixon [54], it is important to note that when performing SWOT Analysis, any opportunity observed but utilized by competitors can be viewed as threats. Linked with company vision and mission and strategy deployment, the steps to identify and proposed improvement strategy based on SWOT analysis is depicted in figure 5.2. It is started with company visions and missions identifying and scanning of business system environments. After identifying core competencies and weakness from internal analysis and opportunity and threat occurrence, the goal to implement strategy is then determined. To ease of implementing selected strategy, a strategy map is then depicted. At last, to estimate perform ability of selected strategy, decision makers then determine the measurable strategy performance indicators. Usually, the Iron Triangle (cost, time and quality) is used as basis to determine strategy performance indicators.

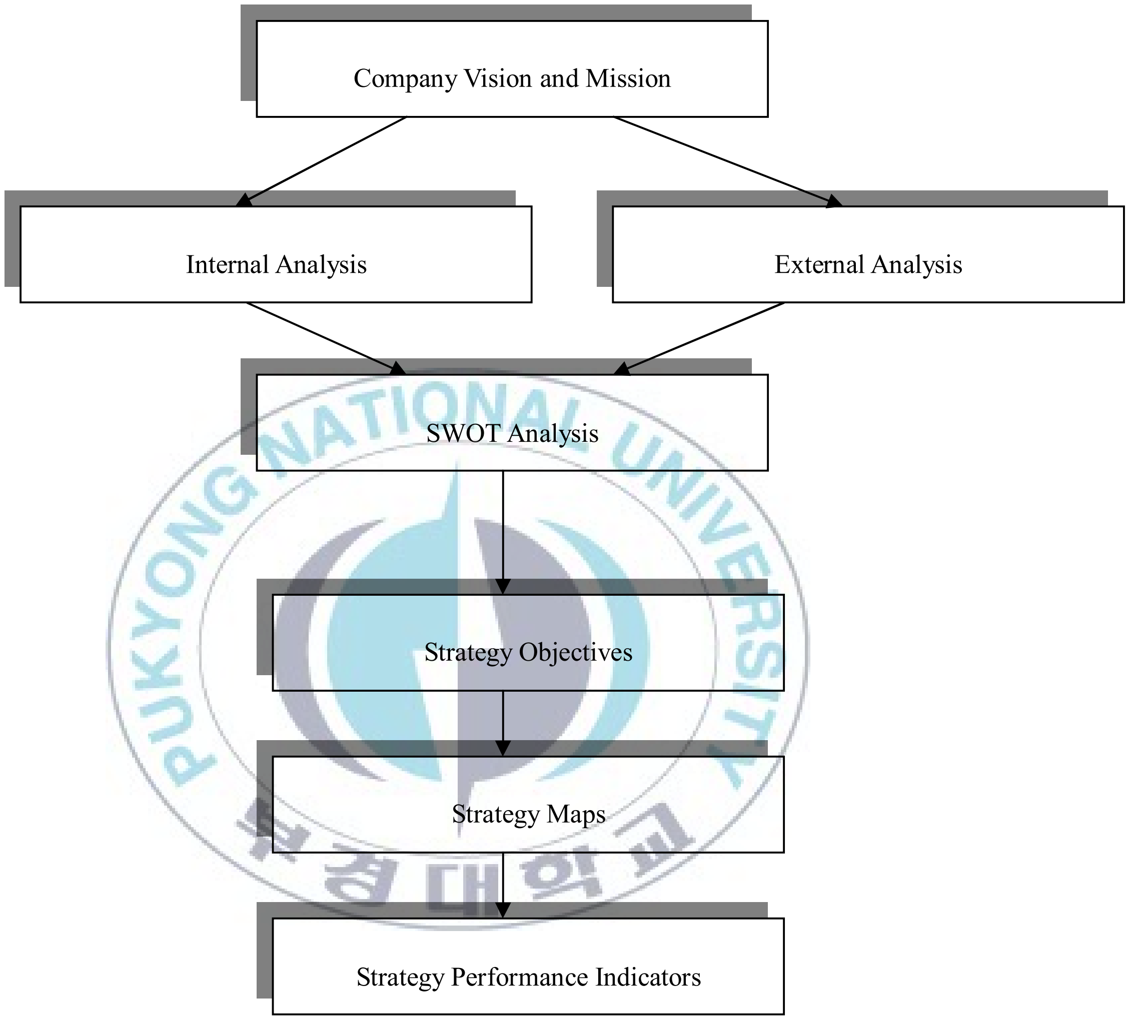

Figure 5.2 Methodologies for Identifying Strategy Maps (Quezada et al. [95])

5.2.2 Estimating Correlation Between Corrective Action and SWOT Variables

For each failure mode, there are several corrective actions possible. Suppose that there are n service failure modes, $FM_1, FM_2, \ldots, FM_n$ and r_i corrective actions $CA_{i1}, CA_{i2}, \ldots, CA_{ir_i}$ possible for FM_i. Since the customers themselves participate and play important roles in any service process, every service system is strongly interrelated with its inner and outer environments including its customers. Thus, the corrective actions inevitably have considerable correlations with at least one of the environmental variables, i.e. SWOT variables, of the service system.

The correlation between a corrective action and a SWOT variable may be positive or negative. If a corrective action increases the possibility of taking advantage of an opportunity, the correlation between the two should be positive. On the other hand, some corrective action may help prevent a threat from occurring, the correlation will be negative. Since the correlation must be between -1 and 1, the following rule to assign a number to the correlation between a corrective action and a SWOT variable are suggested:

i) If the corrective action enhances the occurrence of the SWOT variable, assign 0.9, 0.6, and 0.3 to their strong, moderate, and weak correlation, respectively.

ii) If the corrective action prevents the SWOT variable from occurring, assign -0.9, -0.6, and -0.3 to their strong, moderate, and weak correlation, respectively.

iii) If there is no relation between the two assign 0 to their correlation.

The relationship between the corrective actions and the SWOT variables can be summarized as a table. For illustration, Table 5.1 shows the correlation matrix between the corrective actions and the SWOT variables for the failure mode FM_1.

Table 5.1 Correlation Matrix between Corrective actions and SWOT Variables for FM_1

Corrective Actions	Strength			Weakness			Opportunity			Threat		
	S_1	…	S_m	W_1	…	W_p	O_1	…	O_k	T_1	…	T_l
	IFS_1	…	IFS_m	IFW_1	…	IFW_p	IFO_1	…	IFO_k	IFT_1	…	IFT_l
CA_{11}	$R_{CA_{11}S_1}$	…	$R_{CA_{11}S_m}$	$R_{CA_{11}W_1}$	…	$R_{CA_{11}W_p}$	$R_{CA_{11}O_1}$	…	$R_{CA_{11}O_k}$	$R_{CA_{11}T_1}$	…	$R_{CA_{11}T_l}$
CA_{12}	$R_{CA_{12}S_1}$	…	$R_{CA_{12}S_m}$	$R_{CA_{12}W_1}$	…	$R_{CA_{12}W_p}$	$R_{CA_{12}O_1}$	…	$R_{CA_{12}O_k}$	$R_{CA_{12}T_1}$	…	$R_{CA_{12}T_l}$
CA_{1r_1}	$R_{CA_{1r_1}S_1}$	…	$R_{CA_{1r_1}S_m}$	$R_{CA_{1r_1}W_1}$	…	$R_{CA_{1r_1}W_p}$	$R_{CA_{1r_1}O_1}$	…	$R_{CA_{1r_1}O_k}$	$R_{CA_{1r_1}T_1}$	…	$R_{CA_{1r_1}T_l}$

5.3 Estimating Preference Score as basis for Selecting corrective actions

Selecting corrective actions is a complicated task since many considerations such as benefit, and cost must be taken into accounts. Firstly calculation on the preference score for each corrective action must be accomplished. Using above mentioned example, the preference score of CA_{11} for instance is counted by the following formula;

$$= \sum_{i=1}^{m} R_{CA_{11}S_i}\, IFS_i - \sum_{i=1}^{p} R_{CA_{11}W_i}\, IFW_i + \sum_{i=1}^{k} R_{CA_{11}O_i}\, IFO_i - \sum_{i=1}^{l} R_{CA_{11}T_i} \quad (5.5)$$

The preference scores for other corrective actions can be obtained similarly. The preference score reflects the relative size of expected benefits obtained by using SWOT variables when the corresponding corrective action is implemented. The higher the value of the PS of certain action, the more preferred that corrective action to select would be.

Next, the information of costs necessary to implement corrective actions should be available. In this thesis, it is assumed that the implementation cost of every corrective action can be estimated without difficulty from the past business operation experience and influence of interest rate is neglected. Once the cost information is obtained, calculation on the cost efficiency index for each corrective action can be accomplished. For example, the cost efficiency of CA_{11} is obtained by

$$CE_{11} = (RPN_1 \times PS_{11})/IC_{11} \quad (5.6)$$

Where IC_{11} is the implementing cost for CA_{11}. The values of cost efficiency for the other corrective actions can obtained similarly. The corrective action with the largest value of cost efficiency will have the highest priority to be implemented within the budgetary limit. For clear comparison among corrective actions, table 5.2 can be used. A corrective action with implementing cost beyond the budgetary limit is infeasible and has an "X" mark in the "Feasibility" column of Table 5.2.

Table 5.2 Financial Feasibility Comparison among corrective actions

Failure Mode	RPN	Corrective Action	Preference Score	Implementing Cost	Cost Efficiency	Feasibility
FM_1	RPN_1	CA_{11}	PS_{11}	IC_{11}	CE_{11}	O
		⋮	⋮	⋮	⋮	⋮
		CA_{1r_1}	PS_{1r_1}	IC_{1r_1}	CE_{1r_1}	X
⋮	⋮	⋮	⋮	⋮	⋮	⋮
		⋮	⋮	⋮	⋮	⋮
		⋮	⋮	⋮	⋮	⋮
FM_n	RPN_n	CA_{n1}	PS_{n1}	IC_{n1}	CE_{n1}	O
		⋮	⋮	⋮	⋮	⋮
		CA_{nr_n}	PS_{nr_n}	IC_{nr_n}	CE_{nr_n}	O

5.4 Evaluating Performance of Implemented Corrective Actions

After selecting certain corrective actions, the next step is to implement them for effective improvement. According to Okumus [90], Wheelen and Hunger [127], and Al-Turki [3], several aspects should be considered prior to implementation such as budgetary feasibility, the ownership of corrective actions, communication with the stakeholder and supplier(s), key success factors and procedural aspects. Elaboration of above mentioned aspects can be seen in chapter 2. Following Seyedhosseini *et al.* [107], three aspects that the success criteria may be based on; the real amount of time spent, the actual costs company spent, and the real performance specification achieved upon implementing selected corrective actions. In mathematical model, the success measure of implementing each corrective action i is represented by its corresponding Scope Expected Deviation (SED). Details on equation to estimate SED can be referred to Seyedhosseini *et al.* [107].

If SED score is negative, it would refer to undesirable deviation; meanwhile the positive score of SED represent a desirable deviation. Regarding to desirability of SED score, the goal of decision maker is obtaining the positive SED.

5.5 Estimating Time, Quality, and Cost of Implementing Corrective Action

Regarding that the basis to appraise competing corrective action are based on the Iron Triangle measures; estimation of the time, quality and cost of implementing corrective action can be determined by breaking down activity chart by using its sub-three structures; *Activity Time Structure* (ACT), *Cost Breakdown Structure* (CBS) and *Quality Breakdown Structure* (QBS). Each activity chart has its three own factors; time, quality, and implementing cost. Activity time structure can be defined as top down hierarchical chart of task required to complete certain improvement effort. Each activity chart has three factors; completion time, quality, and implementing cost. Cost breakdown structure provides a structure for a hierarchical summation of costs and resources. The last element, quality breakdown structure represents quantification of targeted specifications of the project outputs. A chart which represents above mentioned entities is given in figure 5.3.

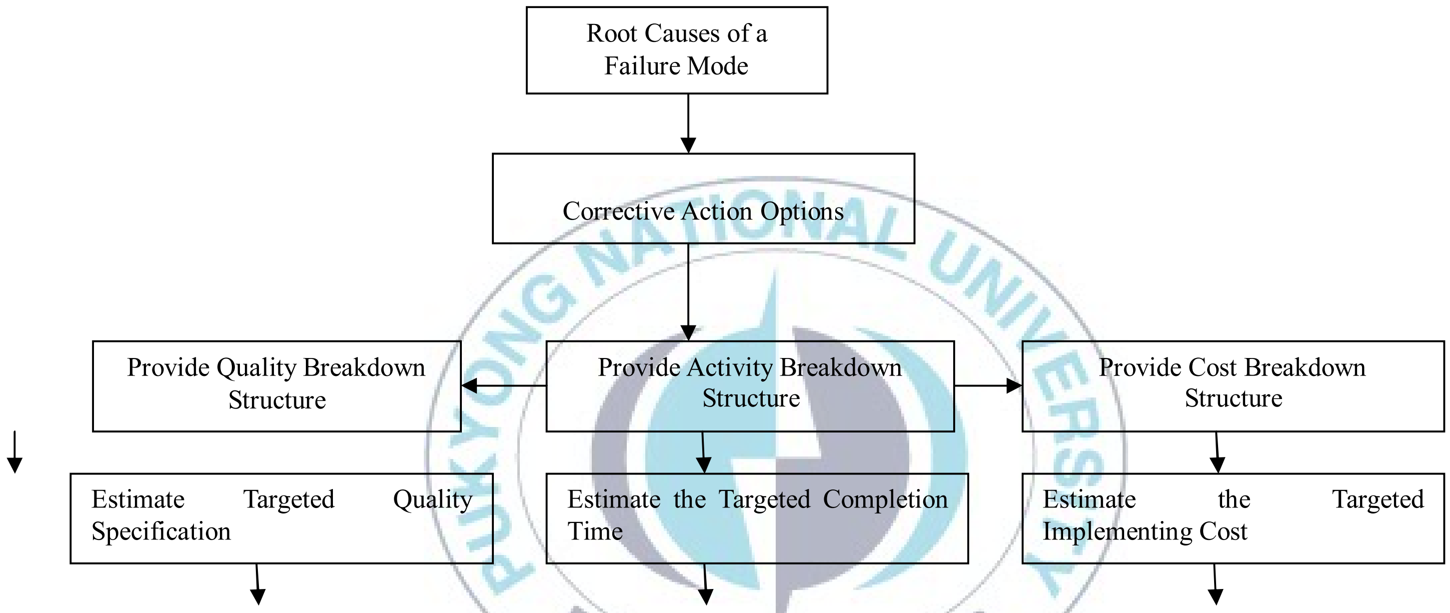

Figure 5.3 The Iron Triangle Breakdown Chart (adapted from Seyedhosseini et al., [107])

In case that the selected corrective action is failed, the root cause of failure may be traced according to flowchart as given by (Wheelen and Hunger, [121]). Following to their model, some root causes of failed corrective actions are due to low managements' commitment, erroneous strategy communication, and lack of know how to implement strategy.

5.6 Application Procedure

The application procedure to select FMEA/SWOT –based corrective action can be based on the following steps:

Step 1. Determine the list of critical failure modes based on their corresponding RPN. Information on the list of potential and actual failure modes can be obtained from company historical data, brainstorming among FMEA members, or from customers' feedbacks.

Step 2. Determine list of potential cause of critical failures with their potential corrective actions. The outcome of this stage is set of candidate solutions.

Step 3. Perform internal and external company's environmental scanning to determine list of internal and external SWOT variables, market and competitors' profiles, external resources, and also company competitive advantages. The inputs are information from customers, stakeholders, and possibly expert opinions. The outputs of this step are market situation, competition profiles, and also internal and external SWOT variables.

Step 4. Categorize, and quantify impact of SWOT variables to the company. Quantification of impact factor of SWOT variables can be accomplished by using equation (5.1), (5.2), (5.3) and (5.4).

Step 5. Determine the degree of relationship among corrective actions and all SWOT variables by estimating the values of their *correlations.* Use Delphi Method among

FMEA members. The brief procedure on how to use Delphi Method can be referred to Asadi and Daryaei [1]. The categorization of correlation coefficient value can refer to section (5.3) in this thesis.

Step 6. By obtaining the value of impact factor of SWOT variables and correlation from step 4 and 5, calculate the preference score for each corrective action. Corrective action with the highest preference score will be the first candidate to be selected besides considering its cost efficiency.

Step 7. Considering the implementing cost, calculate the cost efficiency for each corrective action. Use equation (5.6) to estimated cost efficiency of every potential corrective action.

Step 8. Rank the competing corrective action based on their cost efficiency and budgetary limit. The corrective action whose implementing cost is larger than the budgetary limit is infeasible. The corrective action with the largest cost efficiency and still within budgetary limit will be the most favorable to be chosen.

Step 9. Along with cost efficiency factor, determine the success criteria of the selected corrective action.

Step 10. Upon implementing strategy, successful and unsuccessful corrective action will be evident. Investigate the root cause of failed corrective actions. Document the results of corrective actions implementation for organizational learning.

5.7 Illustrative Example

In this study, an example from Chuang [23] is used for illustrative purpose. The case example is related to application of combination of FMEA and Service Blueprint in improving service design in hypermarket consumer goods service in Taiwan as setting. In this study, the work of Chuang [23] is used as basis to demonstrate to select corrective action from the result of FMEA assessment with an assumed set of SWOT variables. The RPN threshold for critical failures is assumed set as 24. Since this example is provided for illustration purpose, only a part of failure modes and possible causes of case study reference will be used. And evaluation of the performance of selected corrective actions is not covered.

5.8 Solution procedures

Referring to the application procedures as described section 5.7, the problem of case study is solved according to the nine steps below:

Step1. As a result of FMEA session, two critical failure modes are identified, "Unreliable supply of goods" with RPN 27.29 and "Air conditioning malfunction" with RPN 25.38. The failure effects and possible causes of failure mode "Unreliable supply of goods/merchandise" and "Air conditioning malfunction" are also depicted in table 5.3.

Table 5.3 Critical Failure Modes and RPNs of Case Study (Excerpted from Chuang [23])

Service Dimension	Failure Modes	RPN	Effects	Possible Causes
Reliability	Unreliable supply of goods/ merchandise	27.29	● Shortage of goods ● Loss sale ● Customers complaint ● Complicating job allocation and replenishment activity ● Adverse goodwill of store	● Poor supplier evaluation and relationship ● Inappropriate supplier relationship management ● Insufficient inventory of suppliers ● Inadequate marketing research ● Lack of upward communication ● Insufficient customer relationship focus ● Failure to match supply and demand
Tangible	Air conditioning Malfunction	25.38	● Food deterioration or spoil ● Customer complain ● Customer leave	● Poor maintenance of air conditioning ● Aged air- condition ● Fail to adjust the sales floor temperature based on number of customers on the sales floor ● Poor electric power design

Step2. Generate potential corrective actions to every possible failure cause.

Generating potential corrective actions is accomplished upon identifying possible failure causes. For example, the occurrence of faulty service "Unreliable supply of goods" is possibly caused by numerous causes as seen in third column of table 5.4 and potential corrective actions are also given in the fourth column. The complete possible causes and potential corrective actions for second failure mode "Air – conditioning malfunction" are also given accordingly. In term of quantity, there are 11 potential corrective actions to tackle the service quality problems of case study. For illustrative purpose, in subsequent part of this study; only first three root causes from every service failure mode will be used in model application.

Table 5.4 Potential Corrective Actions for Critical Failure Modes

Service Failure Mode	RPN	Possible Cause	Potential Corrective Actions
Unreliable supply of goods/ merchandise (FM_1)	27.29	• Poor supplier evaluation and relationship • Inappropriate supplier relationship management • Insufficient inventory of suppliers • Inadequate marketing research • Lack of upward communication • Insufficient customer relationship focus • Failure to match supply and demand	• Performing supplier evaluation (CA_{11}) • Improve supplier relationship(CA_{12}) • Add adequacy of suppliers(CA_{13}) • Improve technique of marketing research(CA_{14}) • Facilitate upward communication(CA_{15}) • Improve focus on customer relationship communication(CA_{16}) • Improve capability to perform supply and demand estimation (CA_{17})
Air conditioning Malfunction (FM_2)	25.38	• Poor maintenance of air conditioning • Aged air- condition • Fail to adjust the sales floor temperature based on number of customers on the sales floor • Poor electric power design	• Train engineering staff on air conditioning machine maintenance (CA_{21}) • Purchasing power generating equipments(CA_{22}) • Improve empowerment of operation staff on the sales floor (CA_{23}) • Re-check the air-condition configuration (CA_{24})

Step3. The list of internal and external SWOT variables is obtained by performing internal and external company's environmental scanning. Totally, 13 conceptual SWOT variables were generated for the company of case study. The theoretical criteria for weighting impact factor of SWOT variables are also presented in table 5.5. All the theoretical SWOT Variables and corresponding criteria are based on Wheelen and Hunger [129] and Foong [44].

Step4. The value of impact factor of each SWOT variable is estimated based on the summation from multiplication between the weight of every SWOT variables and its corresponding rating scale. In this study; a 1 – 5 Likert like scale is used as rating scale for simplicity and ease of use. A rating 1 is assigned to "least importance /poor/ insignificant" categories; and scale 5 is assigned to "very important /outstanding /very significant" categories. Note that the economic–based impact magnitude of threat and opportunity variables may depend on the company's situation and team judgments. The results on estimating of all SWOT variables are summarized in Table 5.5. The scores of SWOT variables' impact factors show that "High staff dedication for learning" is becoming the biggest company strength, "Lack of business facility " is the greatest company weakness, "The chance on increase on customers' demand variety" is the biggest opportunity, and "Unexpected rise in commodity prices" is the largest threat variable.

Table 5.5 SWOT Variables and Their Corresponding Criteria

SWOT Groups	Criteria	SWOT Variables
Strength	• Capability of strength variables to solve company problem • Company capability to utilize strength variables to solve the problems	Employee loyalty (S1)
		Strategic location of the hypermarket (S2)
		High staff dedication for learning (S3)
Weakness	• Capability of company in minimizing the weakness • Capability of weakness variables in disturbing company goals	Limited suppliers (W1)
		Lack of business facility (W2)
		Few chances for staff development(W3)
Opportunity	• Company capability to take advantage of opportunity occurrence • The amount of resources spent to chase the opportunity • The attractiveness of opportunity in terms of monetary value	Possibility of sales growth due to internet shopping (O1)
		Possibility of growing distribution of goods and service (O2)
		The chance on increase of customers' demand variety(O3)
Threats	• Threat capability in hindering company objective • Company capability in mitigating the negative impact • The estimated time spent for recovery when threat events occurred • The estimated negative impact when threat occur (in monetary term)	Growing number of competitor (T1)
		Unfaithful employee (T2)
		The change of supplier preference to competitors (T3)
		Unexpected rise of commodity price (T4)

Step 5. The correlation between corrective actions and SWOT variables are estimated. The guidance to categorize the value of correlation coefficient is based on section 5.3. For example, when the certain corrective actions will strongly correlate to certain SWOT variable, the coefficient correlation is assigned 0.9 and so on. The correlation matrix of all corrective actions with every quadrant of SWOT group is presented in table 5.7.

Step 6. The preference score for every potential corrective action is calculated using equation (1) and represented in the last row of table 5.7. Referring to each of the corrective action preference score of every potential corrective action, the strategy option "Improve supplier relationship (CA_{12})" is becoming the first preference to prevent reoccurrence of failure mode "Unreliable supply of goods" and followed by "Perform supplier evaluation(CA_{11})" and "Add supplier adequacy (CA_{13})". Meanwhile, for solving failure "Air condition malfunction", "Improve empowerment of Operation staff on the sales floor (CA_{23})" is firstly preferred, and followed by "Train engineering staff on air –conditioning maintenance (CA_{21}) and "Purchasing power generating equipments(CA_{22})".

Table 5.6 The Value of Impact factor of SWOT Variables

SWOT Groups	Criteria	SWOT Variables	Weight	Rating	Impact Factor (IF)
Strength	Capability of strength variables to solve company problem Company capability to utilize strength variable to solve the problems	Employee loyalty (S1)	0.262	5	1.31
		Strategic location of the hypermarket (S2)	0.328	3	0.984
		High staff dedication for learning (S3)	0.410	5	2.05
Weakness	Capability of company in narrowing down the weakness Capability of weakness variables in disrupting company goals	Limited suppliers (W1)	0.288	5	1.44
		Lack of business facility (W2)	0.565	4	2.26
		Limited opportunity for staff development(W3)	0.147	3	0.441
Opportunity	Company capability to take advantage of opportunity occurrence The amount of resources spent to chase the opportunity The attractiveness of opportunity in terms of monetary value	Possibility of sales growth due to internet shopping (O1)	0.180	4	0.720
		Possibility of growing distribution of goods and service (O2)	0.144	5	0.720
		The chance on increase of customers' demand variety(O3)	0.676	5	3.38
Threats	Threat capability in hindering company objective Capability of company in mitigating the negative impact of treat occurrence The estimated time spent for recovery when threat events occurred The estimated negative impact when threat occur (in monetary term)	Growing number of competitor (T1)	0.126	5	0.63
		Unfaithful employee (T2)	0.155	3	0.465
		The change of supplier preference to competitors (T3)	0.161	4	0.644
		Unexpected rise of commodity price (T4)	0.558	5	2.79

Step 7. Company must spend resources for funding certain preferred corrective actions. Considering the resource requirement, the implementing cost is estimated for each corrective action. And then, by using equation (5.6), the cost efficiency of each corrective action is calculated. Based on the cost-efficiency ratio, the rank of corrective actions can be assigned. The higher the cost efficiency of certain corrective action, the more favorable the corrective action would be, in condition that the implementing cost

is still below budgetary limit. The result of estimating the cost efficiency for each of potential competing corrective action is shown in table 5.8. For solving service problem “unreliable supply of goods”, the corrective action “Improve relationship with suppliers” is the first priority to be chosen and the corrective action “Improve empowerment of operation staff on the sales floor” is becoming the first choice for solving “Air conditioning malfunction”.

Table 5.8 The CA- SWOT Correlation Matrix of Case Example

		Failure Mode	**Unreliable supply of goods**			**Air conditioning malfunction**		
SWOT Variables		**Impact Factor**	**CA_{11}**	**CA_{12}**	**CA_{13}**	**CA_{21}**	**CA_{22}**	**CA_{23}**
Strength	**S1**	1.31o	0.40	0.3	0	0.52	0	0.60
	S2	0.984	0	0	0	0	0.60	0
	S3	1.44	0.70	0.60	0.30	0.864	0	0.60
Weakness	**W1**	1.44	-0.9	0.90	-0.90	0	0	0
	W2	2.26	0	0.90	0.3	0.452	-0.6	0.90
	W3	0.441	0	0	0	-0.352	0	0
Opportunity	**O1**	0.72	0.3	0.60	0.3	0.576	0.3	0.3
	O2	0.72	0.3	0.60	0.3	0.216	0	0.30
	O3	3.38	0.9	0.90	0.9	1.69	0.3	0.90
Threat	**T1**	0.630	0.60	0.6	-0.3	-0.315	-0.3	-0.30
	T2	0.465	0	0	0	0.129	0	-0.064
	T3	0.644	-0.30	-0.60	-0.3	0	0	0
	T4	2.790	0.30	0.30	0	0	0.3	0
Preference Score			**5.830**	**1.004**	**4.906**	**4.598**	**2.528**	**3.279**

Step 8. Determine the feasibility of each corrective action by considering the implementing cost and budgetary limit. Assume that the company budgetary limit is only $ 300 to cover whole potential corrective actions. Based on Table 5.8, the company of case study is possibly taking corrective action “Perform supplier evaluation (CA_{11}),”

"Improve supplier relationship(CA_{12})," "Train engineering staff on air condition maintenance(CA_{21})," and "Improve empowerment of operation staff on the sales floor(CA_{23})." However, considering both of the budgetary limit and the cost efficiency, CA_{23}, CA_{11}, and CA_{12} are selected. Since these three corrective actions will exhaust the entire budget available, CA_{21} cannot be selected.

Table 5.8 Feasibility of Implementing Corrective Actions of Case Study

Failure Mode	RPN	Potential Corrective Actions	Preference Score	Implementing Cost($)	Cost Efficiency	Feasibility
Unreliable supply of goods/ merchandise	**27.29**	Performing supplier evaluation (CA_{11})	5.830	150	1.661	O
		Improve supplier relationship(CA_{12})	1.004	100	0.274	O
		Add adequacy of suppliers(CA_{13})	4.906	350	0.383	X
Air conditioning malfunction	**25.38**	Train engineering staff on air condition maintenance (CA_{21})	4.598	180	0.648	O
		Purchase power generating equipment (CA_{22})	2.528	320	0.201	X
		Improve empowerment of operation staff on the sales floor (CA_{23})	3.279	50	1.664	O

Step 9. Determine the corrective actions' key success factors.

For getting success, some success and performance criteria should be considered prior implementing corrective actions. Those criteria may be based on previous experience, benchmarking from competitor and stakeholder input. Based on the case study; theoretical criteria for the success of implementing selected corrective actions can be depicted in table 5.9. Those criteria are adapted based on Mann and Kehoe [83]. For example, in solving service quality problem "Unreliable supply of goods/merchandise", the company of case study should adopt " Improve supplier relation" in which the responsible person to carry out that corrective action will belong to "Purchasing manager/Public Relation manager" and one of the possible performance criterion is " Reduction of the lateness frequency in goods delivery". In order to make the selected corrective action workable, "The availability of person with high communication/ negotiation skill with supplier "or "The fund to realize the stronger relationship with suppliers" should be available. In short, the success criteria are becoming the benchmark against the success in implementing selected corrective action.

Table 5.9 Key Success Factors for Implementing Corrective Action of Case Example

Service Quality Problem	Corrective Action	Ownership of Corrective Action	Performance Criteria	Key Success Factors
Unreliable supply of goods	Improve supplier relationship(CA_{12})	Purchasing Manager/ Public Relation Manager	Reduction of the lateness frequency in goods delivery	• Availability of person with high communication skill with suppliers. • Availability of incentive for strengthening business relationship with suppliers.
	Perform supplier evaluation (CA_{11})	Purchasing Manager & QA Manager	Reduction in lateness frequency in goods delivery and improvement of goods quality	• The procedure to evaluate supplier is known. • The skill to evaluate suppliers is available • Approval from top management
Air conditioning malfunction	Improve empowerment of operation staff on the sales floor(CA_{23})	Human Resource Department	Reduction in air conditioning malfunction frequency	• The existence of fund to raise awareness of customer care culture among operation staffs

5.9 Discussions

5.9.1 Advantages of the Proposed Model

The proposed model is aimed to narrow down the gaps on FMEA-based prioritization of corrective actions. To improve capability of decision makers in preparing strategic preventative measures, FMEA is combined with SWOT analysis. Impact of all internal and external business variables are scanned before proposing corrective action. To demonstrate the procedures in practice, an illustrative example is provided on implementing the proposed model to case study. Following on the theoretical procedures based on proposed model, exemplary on how to select competing CAs by considering impact of business environments are provided for practical purposes. By using the theoretical procedures, company can obtain insight on inclusion of business environmental impact prior proposing risk-based improvement efforts.

It also presents an example on how to measure financial efficiency in estimating competing corrective actions. Consideration on using financial efficiency is justifiable since company is spending its resources in implementing corrective actions. Different from corrective action determination of conventional FMEA which still based on the RPN of failure only, reliance on the RPN only is not advantageous since when sudden threats occur to company, any potential loss is inevitable. Thus, it will disadvantageous for company for long time span.

By using the model, likelihood of experiencing any potential loss can be much more avoided if compare to use the conventional FMEA which based on the RPN only. This is because prior implementing CAs, any favorable and unfavorable factors influencing implementation of CAs are firstly scanned by using SWOT Analysis. Thus, decision makers may weight which corrective actions are likely to have potential success to curb the critical problems. In reverse, any potential corrective actions which may have potential failure when implemented can be avoided in advance.

5.9.2 Limitations of the proposed model

Despite the possible benefits, the theoretical model presented in this thesis possesses some recognizable limitations if implemented in practice. First, since based on single conceptual model from single service sector, the SWOT variables presented in this study are lack of validity for generalization to other service type. Therefore, the utilization of SWOT variables from real industrial data and within various service settings needs to be used and re-tested to improve validity and appropriateness of the proposed model. Regarding time as important determinant, ignorance of time will make proposed model unusable. Following Helms and Nixon [54], time is a critical dimension in delineating opportunity and threat but it is excluded in the model development. Ignorance on time when determining SWOT variables will make corrective actions to be unrealistic since what perceived as threat today might be opportunity tomorrow and vice versa.

Next, the possibility on conflict of interest among employees or each of company business unit in implementing strategy is exist and cannot be ignored. This is because the implication of conflict of interest may lead to resistance from other group to implement the potential workable strategies. The risk due to conflicts occurrence among teams needs to be considered. Regarding that the ultimate goal in implementing strategy is to improve customers' satisfaction, any negative customers' reaction also must be taken into consideration. However, the corrective action selection model in this thesis is not covering the risk due to above mentioned situation. Considering on risk aspect, in real situation, the risk attitude of FMEA team must be considered. For the risk averters' type organization, any improvement strategy which prone to high negative risk will not be preferred. In reverse, for risk taker -oriented company, the existence of risk in implementing improvement effort will be neglected. Regarding that the criteria used to appraise the weight of SWOT variable is vague; the fuzziness of the criteria must be taken into consideration. This is because the nature of human feeling in determining the score. Methodology which based on fuzzy logic is should be used to obtain the crisp value of the rating of the SWOT variables.

Fifth, the fuzziness of the criteria on the value of rating in weighing SWOT variables is unavoidable in practice. Thus, ignorance on the fuzziness of criteria on appraising SWOT variables is not appropriate and shall be taken into consideration.

Regarding application in real setting which is characterized by uncertainty on the probability of success and intended goal will be obtained; the risk factor should be accommodated in reformulating preference score of selecting corrective action. Unfortunately, the model of corrective action ranking in this study is escaping the uncertainty aspect in implementing CAs. Next, since the strength of relationship among corrective action and SWOT variables is based on the correlation, any inaccuracies in estimating the correlation value will make corrective action ranking becomes less accurate. At last, regarding real situation where correlations between SWOTS variables are exist among themselves, consideration on such correlation cannot be neglected in refining the model for practical application.

Chapter 6

Conclusions and Extensions for Further Studies

6.1 Conclusions

This thesis is concerned with endeavor to improve two research aspcts in FMEA methodology, improvement of the RPN (risk priority number) estimation in conventional FMEA and selection of improvement strategy upon FMEA activity is accomplished. In attempt to searching for research gaps with concerned aspects, initial literature survey is undertaken. Next, improvement on some limitations of the conventional FMEA are focused on issues such as; reformulation of expected loss model as surrogate of risk priority number (RPN) in conventional FMEA, inclusion of failure occurrence time as an important dimension in estimating the expected loss of faulty service operation, formulation of a new methodology for selecting corrective action priority by considering impact of inner and outer of business environments using SWOT Analysis. All of theoretical models presented in this thesis are employed in service operation. Partial of the SERVQUAL's dimensions are used in the study. The case example from consumers' good trading service is provided to demonstrate the applicability of the model for practical purpose.

In chapter 1, research motivations on focusing RPN estimation and corrective action selection issue in conventional FMEA methodology which focus on service operation are provided. Some observable gaps which become the basis to undertake research which reported in this thesis are also discussed. The structure and relationship among chapters in this thesis is also given accordingly.

In chapter 2, research problem formulation and some basic methodologies pertaining to this thesis are provided. The basic concepts related to FMEA, RPN, Root Cause Analysis (RCA), SWOT Analysis and the Analytical Hierarchy Process (AHP) are briefly presented.

In Chapter 3, an expected loss of faulty service process is formulated based on conditional probability theory based on assumption of failure events' independence. The three components of expected loss models and service failure loss value based on economic criteria are presented. Exemplary study on the applicability of the proposed model by adopting case example on consumer good trading is given. Furthermore, estimation on the value of the quality improvement ratio by applying the model is also provided. The advantage of using the proposed model is enabling for FMEA practitioners to estimate the probability components of RPN into more scientifically basis.

In chapter 4, time as an important dimension in estimating the failure loss due to the occurrence of faulty service is considered. A three loss function models for constant, linear and quadratic loss escalation are introduced. Assumption of constant failure cause occurrence rate is used. Next, a time dependent expected loss model as surrogate of the RPN in conventional FMEA are proposed. By using the time dependent expected loss model, decision makers can take preventative measures of critical failure causes considering their time occurrences. In addition, it also provides decision makers with opportunity to consider the possibility of loss escalation during system's operation time.

In chapter 5, SWOT analysis is utilized in scanning important of inner and outer of business variables prior proposing corrective action (CA). In attempt for facilitating FMEA team in selecting suitable corrective action, a preference score which integrated the RPN of critical failures, correlation of each corrective action with SWOT variables and impact factor of SWOT variables are proposed. Evaluation of competing corrective actions' feasibility is provided by incorporating the cost efficiency factor. The advantage of using the SWOT-FMEA-based corrective action selection is that possibility to avoid the unexpected loss may incur due to threat variables occurrence and potential gain due to potential opportunities may incur.

6.2 Extensions for Further Investigation

Regarding that this thesis is still in conceptual stage, future studies in the form of the model's implementation in real operation are encouraged for its establishment. In addition, some extensions for future studies are identifiable. Elaboration on extension for future studies is given as below:

6.2.1 Inclusion of Robustness as Complimentary Criterion in FMEA based Corrective Action Selection Methodology.

The cost -benefit criterion, due to its usefulness as reflection of business goal against effort to be spent in implementing strategy; is the mostly used criterion in proposing corrective action selection in improvement effort. Nevertheless, as in real situation many unfavorable factors (noises) are exist; ignoring on their existence is not appropriate. Since they may derail improvement goals, strategy formulation upon FMEA is accomplished should also consider their existence. Inclusion of robustness of corrective action in appraising competing improvement efforts is still unknown in references.

6.2.2 Utilizing Theory of Constraint in Appraising Competing Improvement Efforts.

Upon performing FMEA session, numerous options of corrective actions are potentially executable. Since company has limited resources, the importance on using the TOC (Theory of constraint) in screening competing corrective action is undeniable. Although references on using TOC for managing business is abundantly available as elaborated by Rahman [98], the existence of study on TOC utilization in risk –based improvement selection by considering financial and non financial measures is still absent in service operation literature.

6.2.3 Selecting FMEA-based Improvement Strategy based on TRIZ Method.

Finding the root cause of service quality problem in a fast and objectively manner is important for improving business operation. Based on survey conducted by this thesis, brainstorming is the mostly used means to identify the root cause and potential solution to curb the root cause of quality problem. Nevertheless, the use of brainstorming is heavily depending on team subjectivity and experience of the members. In some situation, the new and inexperienced FMEA team will find difficulty when they have to perform root cause analysis due to their limited experiences. In attempt to bridging this discrepancy, there is a need to innovate improvement strategy selection based on TRIZ Method. Following Hua *et al.* [58], the TRIZ method is useful to solve problem in innovatively way. However, endeavor to utilize TRIZ method in rectifying quality problem in service operation is still unknown and demanding investigations.

6.2.4 Incorporating Suppliers Capability and Customer Participation in Appraising Service Quality Improvement Efforts.

As companies are collaborating among others, when non conformities occurred; in some situations, contribution of business collaborators is inevitably needed. Although study to perform FMEA in supply chain framework is already presented by Teng *et al.* [124], determination of improvement selection model which consider collaborators' capability is missing and demanding further efforts. In addition, regarding characteristics of service operation where service customers' is also acting as co-producer; extending investigations of Hesley and Utley [55] and Uzkurt [126], development of a quantitative and qualitative model for quantifying input from customers' participation in service improvement is also demanding further studies.

References

[1] Asadi, R., and Daryaei, M., (2011), Prioritization of Forms of Tourism in Iran to Formulate National Strategies, *European Journal of Scientific Research,* Vol. 65, pp. 144-152.

[2] Al-Rousan, M., and Qawasmeh, F., (2009), The Impact of SWOT Analysis on Achieving a Competitive Advantage: Evidence From Jordanian Banking Industry, *International Bulletin of Business Administration,* Iss. 6, pp. 82-92.

[3] Al-Turki, U., (2011), A Framework for Strategic Planning in Maintenance, *Journal of Quality in Maintenance Engineering*, Vol.17, Iss.2, pp. 150-162.

[4] Aven, E., and Aven, T., (2011), On How to Understand and Express Enterprise Risk, *International Journal of Business Continuity and Risk Management*, Vol.2, No.1, pp.20-34.

[5] Ahsen, A., (2008), Cost- Oriented FMEA, *International Journal of Quality and Reliability Management, Vol.* 25, no.5, pp. 466-476.

[6] Automotive Industry Action Group (1995), *Potential Failure Mode and Effect Analysis, Reference Manual.* Michigan.

[7] Bea, R., Mitroff, I., Farber, D., Foster, H., and Roberts, K.H., (2009), A New Approach to Risk: The Implication of E3, *Risk Management*, Vol.11, No.1, 30-43.

[8] Bhamare, S.S., Yadav, O.P., and Rathore,A., (2007), Evolution of Reliability Engineering Discipline over the Last Six Decades: a Comprehensive Review, *International Journal of Reliability and Safety*, Vol.1, No.4, pp. 377-410.

[9] Braglia, M., (2004), MFMEA: Multi Attribute FMEA, *International Journal of Quality and Reliability Management,* Vol. 17, no.9, pp. 1017-1033..

[10] Bullinger, H.J., Fahnrich K.J., and Meiren, T., (2003), Service Engineering-Methodical Development of New Service Products, *International Journal of Production Economics*, Vol.85, No.3, pp. 275-287.

[11] Bosch,V. G., and Enriques, F., (2005), TQM and QFD: Exploiting a Customer Complaint Management System, *International Journal of Quality and Reliability Management*, Vol.22, Iss.1, pp. 30-37.

[12] Bluvband, Z., Grabov, P., and Nakar, O., (2003), Expanded FMEA, Proceedings of the Annual Symposium on Reliability and Maintainability, pp.31-36.

[13] Braglia, M., Frosolini, M., and Montanari, R., (2003), Fuzzy Criticality Assessment model for FMEA, *International Journal of Quality and Reliability Management*, Vol.20, No.4, pp.503-524.

[14] Ben Daya, M., and Raouf, A., (1996), A Revised FMEA Model, *International Journal of Quality and Reliability Management*, Vol. 13, Iss.1, pp.43-47.

[15] Bowles, J.B., and Pelaez, C.E., (1995), Fuzzy Logic Prioritization of Failures in a System FMECA, *Reliability Engineering and Systems Safety*, Vol.50, Iss.2, pp.203-213.

[16] Chuang, P.T., (2010), Incorporating Disservice Analysis to Enhance Perceived Service Quality, *Industrial Management and Data Systems,* Vol.110, No.3, pp. 1-22.

[17] Chang, K.H., and Cheng, C.H., (2011), Evaluating the Risk of Failure Using the Fuzzy OWA and DEMATEL Method, *Journal of Intelligent Manufacturing*, vol.22, no.2, pp.113-129.

[18] Cagno, E., and Michaeli, J.L.G., (2011), Enhancing EPC Supply Chain Competitiveness through Procurement Matrix, *Risk Management*, Vol.12, pp. 147-180.

[19] Carmignani, G., (2009), An Integrated Structural Framework to Cost –Based FMEA: The Priority – Cost FMEA, *Reliability Engineering and System Safety*, vol. 94, no.4, pp.861-871.

[20] Chang, D-S., and Sun, Paul K.L., (2009), Applying DEA to Enhance Assessment Capability of FMEA, *International Journal of Quality and Reliability Management*, Vol.26, No.6, 629-643.

[21] Childs, J.A., Turning Multiple Process FMEA Results Into an Optimal Action Plan, Proceedings of the 2009 Annual Symposium on Reliability and Maintainability, Forth

Worth, Texas, pp.412-416.

[22] Chin, K.S., Wang, Y.M., Poon, G.K.K., and Yang, J.B., (2009), FMEA Using a Group Based Evidential Reasoning Approach, *Computers and Operations Research*, Vol.36, No.6, pp. 1768-1779.

[23] Chuang, P.T., (2010), Incorporating Disservice Analysis to Enhance Perceived Service Quality, *Industrial Management and Data Systems*, Vol.110, No.3, pp.1-22.

[24] Chuang, P.T., (2007), Combining Service Blueprint and FMEA for Service Design, *The Service Industries Journal*, Vol. 27, No.2, pp. 91-104.

[25] Chase, R. B., and Apte, U.M., (2007), A History of Research in Service Operations.: What is the big idea?, *Journal of Operations Management*, Vol.25, pp. 375-386.

[26] Chuan, T.K., and Raghavan, V.,(2004), Incorporating Concept of Business Priority Into QFD, *International Journal of Innovation Management*, Vol.8, No.1, pp.21-35.

[27] Chen, J.K., (2007), Utility Priority Number Evaluation for FMEA, Journal of Failure Analysis and Prevention, Vol.7, No.5, pp. 321-328.

[28] Chang, C.L., Liu, P.H., and Wei, C.C., (2001), FMEA Using Grey Theory, *Integrated Manufacturing System*, Vol.12, No.3, pp.211-216.

[29] Chauvez, S. D. A., and Beruvides, M. G., (1998), Using Opportunity Costs to Determine the Cost of Quality: A Case Study in a Continuous Process Industry, *the Engineering Economist*, Vol.43, No. 2, pp. 107-124.

[30] DIADEM, (2009), *Guidelines for FMEA for Automotive, Aerospace, and General Manufacturing Industries*, CRC Press.

[31] Dong, C., (2007), FMEA based on Fuzzy Utility Cost Estimation, *International Journal of Quality and Reliability Management*, Vol.24, No.9, pp.958-971.

[32] Davidson, G., and Labib, A.W., (2003), Learning from Failures: Design Improvement Using Multiple Criteria Decision Making Process, *Journal of Aerospace Engineering, Proceedings of the Institution of Mechanical Engineers Part G*, Vol. 217,

pp. 207-216.

[33] Devadasan,S.R., Muthu, S., Samson, N.R., and Sankaran, R.A., (2003), Design of Total FMEA Programme, International Journal of Quality and Reliability Management, Vol.20, No.5, pp. 551-568.

[34] Davis, D., and Cosenza, R.M., (1993), *Business Research for Decision Making: 3rd Edition.* Duxbury Press, California

[35] Eismailian, G., Ahmad, M.M. H., Ismail, N.,Sulaiman, S., and Hamedi, M., Particular Model for Improving FMEA by Using Overall Equipment Efficiency(OEE), in Proceedings of the 2008 International Symposium on Information Technology, Kuala Lumpur, pp.1-9.

[36] Imrie, B.C., Cadogan, J.W., and McNaughton, R.,(2002), The Service Quality Construct on a Global Stage, *Managing Service Quality*, Vol.12, No.1, 10-18.

[37] Einarsson, S., and Rausand, M., (1998), An Approach to Vulnerability Analysis of Complex Industrial Systems, *Risk Analysis*, Vol.18, Iss.5, pp.535-546.

[38] Eubank, C.F., Kmenta, S., and Ishii, K., (1996), System Behaviour Modelling as Basis for Advanced FMEA, Proceedings of the 1996, ASME DETC, Irvine, California.

[39] Eubank, C.F., Kmenta, S., and Ishii, K., (1997), Advanced FMEA Using Behaviour Modelling, In Proceedings of the 1997, ASME DETC, Sacramento, California.

[40] Flouris, T., and Yilmaz, A.K., (2010), The Risk Management Framework to Strategic Human Resource Management, *International Research Journal of Finance and Economics*, Iss.36, pp. 25-45.

[41] Finjvandraat, M., and Bouwman, H., Predicting the Unpredictable; Dealing with Risk and Uncertainty in Broadband Roll-Out, *Foresight*, Vol.12, no.6, 3-19.

[42] Fizsimmons, J.A., and Fitzsimmons, M.J., (2008), Service Management: Operations, Strategy, Information Technology, Sixth Edition, Mc Graw Hills, Boston.

[43] Fowdar, R.R., (2008), The Relative Importance of Service Dimensions in Heath Care Setting, *International Journal of Heath Care Quality Assurance*, vol. 21, no.1, pp.

104-124.

[44] Foong, L. M., (2007), *Understanding of SWOT analysis* [online]. Available online from http/ article.tqmcasestudies.com/free-tqm-ebook/swot-analysis.pdf. [Access on 29 November 2011].

[45] Franceschini, F., and Galeto, M., (2001), A New Approach for Evaluation of Risk Priority of Failure Modes in FMEA, *International Journal of Production Research*, Vol. 39, Iss.13, pp.2991-3002.

[46] Ghazinoory, S., Abdi, M., and Mehr, M. A., (2011), SWOT Methodology: a State -of -the -Art Review for the Past, A Framework for the Future, *Journal of Business Economics and Management*, Vol. 12, Iss.1,pp.24-48.

[47] Geum, Y., Cho, Y., and Park, Y., (2011), A Systemic Approach for Diagnosing Service Failure: Service Specific FMEA and Grey Relational Analysis Approach, *Mathematical and Computer Modeling*, Vol.54, Iss.11-12, pp.3126-3142.

[48] Gecky, P., Noriaki, I., and Hasida, K., (2010), Service Science, Quo Vadis? *International Journal of Service Science, Management, Engineering, and Technology*, Vol.1, No. 1, pp. 1-16.

[49] Geum, Y., Cho, Y., and Park, Y., (2011), Systematic Approach for Diagnosing Service Failure: Service Specific FMEA and Grey Relational Analysis Approach, *Mathematical and Computer Modelling*, Vol.54, No.11-12, 3126-3142.

[50] Gnikionis, N. P.,Souliotis, A.S., and Besseris, G., (2011), Six Sigma's DOE Application on the Mechanical Effect of Apple Quality in Industry-Level Storage Operations, *International Journal of Six Sigma and Competitive Advantages*, Vol.6, No.3, 197-223.

[51] Geum, Y., Shin, J., and Park, Y., (2011), FMEA-Based Portfolio to Service productivity Improvement, *The Service Industries Journal*, iFirst Edition, pp.1-23.

[52] Gandhi, O.P., and Agarwal, V.P., (2002), FMEA – A Digraph and Matrix Approach, *Reliability Engineering and System Safety*, Vol.35, No.2, pp. 147-158.

[53] Giakatis, E., and Washitani, (2001), Hidden Quality Costs and The Distinction Between Quality Costs and Quality Loss, *Total Quality Management and Business Excellence*, Vol.12, no.2, pp:179-190.

[54] Helms, M. M., and Nixon J., (2010), Exploring SWOT Analysis-Where Are We Now: A Review of Academic Research from the Last Decade, *Journal of Strategy and Management,* Vol.3, pp. 215-251.

[55] Hensley, R.L., and Utley, J.S., (2011), Using Reliability Tools in Service Operations, *International Journal of Quality and Reliability Management,* Vol.28, Iss.5, pp. 587-598.

[56] Hekmapatnah, M., Shahin, A., and Ravichandran, N., (2011), The Application of FMEA in the Oil Industry in Iran: the Case of Four Littre Oil Canning Process of Sepahan Oil Company, *African Journal of Business Management*, Vol.5, No.7, 3019-3027.

[57] Hillson, D., Grimaldi, S., and Rafale, C., (2006), Managing Project Risk Using A Cross Risk Breakdown Matrix, *Risk Management*, Iss.8, 61-67.

[58] Hua, Z., Yang, J., Coulibaly, S., Zhang, B., (2006), Integration TRIZ With Problem Solving Tools: A Literature Review From 1995-2006, *International Journal of Business Innovation and Research*, Vol.1, No.1/2, pp. 111-128.

[59] Henriksen, B., and RØstad, C.C.,(2006), Evaluating and Prioritizing Projects-Setting Targets. The Business Effect Evaluation Methodology (BEEM), *International Journal of Managing Project in Business*, Vol.3, No.2, 275-291.

[60] Hashim, M., (1984), Reliability Concepts Applied to Service Industries, *International Journal of Quality and Reliability Management*, Vol.1, No.1, pp.39-50.

[61] Ilangkumar, M.P., and Thamizhselvan, M.P., (2010), Integrated Hazard and Operability Study Using Fuzzy Linguistics Approach Using Fuzzy Linguistics Approach in Petrochemicals Industry, *International Journal of Quality and Reliability Management*, Vol. 27, No.5, pp. 541-557.

[62] International Standard Organization (ISO), (2000), ISO 9001:2000 Quality Management Systems-Vocabulary, ISO, Geneva.
[63] Jegadeshan, C., Arunachalam V.P., Devadasan, S.R., and Srinivasan, P.S.S., (2007), Design and Development of Modified Service FMEA Model, *International Journal of Services and Operations Management*, Vol.3, No.3, pp.111-126.
[64] Jennifer, J., Hyland, S., Burns, C. M., and Momtana, K., (2007), Challenges with Applying FMEA to The Process for Reading labels on Inject able Drug Containers, Proceedings on Annual Meetings of Human Factors and Ergonomics Society, pp.735-739.
[65] Jenab, K., and Dhillon, B.S., (2005), Group –based FMEA, *International Journal of Quality, Reliability, and Safety Engineering*, Vol.12, No.4, pp.291-307.
[66] Jaju, S. B., and Lakhe, R., (2009), Tracing Quality Cost in a Lugage Manufacturing Industry, *World Academy of Engineering, Science and Technology*, Vol.49, 546-549.
[67] Krishna, A., Dangayach, G.S., and Jain, R., (2011), Service Recovery: Literature Review and Research Issues, *Journal of Service Science Research,* Vol. 3, pp. 71-121.
[68] Kumar, E.V., and Chaturvedhi, K., (2011), Prioritization of Maintenance Task on Industrial Equipment for Reliability: A Fuzzy Approach, *International Journal of Quality and Reliability Management*, Vol.28, Iss.1, pp.109-126.
[69] Kwon, H.M., Hong, S.H., Lee, M.K., and Sutrisno, A., (2011) Risk Evaluation Based on the Time Dependent Expected Loss Model in FMEA, *Journal of the Korean Society of Safety*, Vol.26, No.6, pp.104-110.
[70] Keskin, G.A., and Ozkan, C., (2009), An Alternative Evaluation of FMEA: Fuzzy ART Algorithm, *Quality and Reliability Engineering International*, Vol.25, Iss.6, pp.647-661.
[71] Karuppuswamy, P., Sundararaj, G., Devadasan, S.R., Elangovan D., and Savadamuthu, L., (2006), Failure Reduction in Manufacturing System through the Risk Management Approach and the Development of A Reactive Maintenance Model,

International Journal of Risk Assessment and Management, Vol.6, no.4/5/6, pp.545-564.

[72] Krishnan, S. K., (2006), Increasing the Visibility of Hidden Failure Costs, *Measuring Business Excellence*, Vol. 10, No. 4, pp.77-101.

[73] Sharma, R.K., Kumar, D., and Kumar, P., (2005), Systematic FMEA Using Fuzzy Linguistic Modeling, *International Journal of Quality and Reliability Management*, Vol.22, Iss.9, and pp: 986-1004.

[74] Kmenta, S., and Ishii, K., (2004), Scenario-Based FMEA Using Expected Cost, *Journal .of Mechanical Design*, Vol.126, No.6, pp.1027-1035.

[75] Kmenta, S. and Ishii, K.,(1998), Advanced FMEA Using Meta Behaviour Modelling for Concurrent Design of Product and Control, Proceedings of the 1998 ASME Design Engineering Technical Conference, Atlanta, Georgia.

[76] Lee, C.T., (2010), Selecting Technologies for Constantly Changing Applications Markets, *Research -Technology Management*, Vol. 53, pp. 44-54.

[77] Lee, Amy H.I., Lin, C.Y., Wang, S.R., and Tu, Y.M., (2010), The Construction of Comprehensive Model for Production Strategy Evaluation, *Fuzzy Optimum Decision Making*, Vol.9, 187-217.

[78] Laaksolahti, A., (2005), *Measuring Organizational Capabilities in the Engineering and Consulting Industry.* Thesis (M.Sc). Lappeenranta University of Technology, Finland.

[79] Liu, D., Bishu, R.R., and Najjar, L.,(2004), Using the AHP (Analytical Hierarchy Process) as a Tool for Assessing Service Quality, *Industrial Engineering and Management Systems Journal*, Vol.4, 129-135.

[80] Mahto, D., and Kumar, A., (2008), Application of Root Cause Analysis in Improvement of Product Quality and Productivity, *Journal of Industrial Engineering and Management System*, Vol.1, No.2, pp.16-53.

[81] Mahdavi, I., Fazlollahtabar, H., Paydar, M. M., and Heidarzade, A., (2008), Applying Multi Criteria Decision Methods and SWOT Factors to Analyze the Role of Information Technology in Industry Development in Iran, *Journal of Applied Sciences,* Vol.8, Iss.17, pp. 2983-2990.

[82] Michael, S., (2001), Analyzing Service Failures and Recoveries: A Process Approach, *International Journal of Service Industries Management*, Vol.12, Iss.1, 20-33.

[83] Mann, R. and Kehoe, D., (1994). An Evaluation of The Effects of Quality Improvement Activities on Business Performance, *International Journal of Quality and Reliability Management*, Vol.11, Iss.4, pp.29-44.

[84] Narayanagounder, S., and Gurusami, K., (2009), A New Approach for Prioritizing of Failure Modes in Design FMEA Using ANOVA, *Proceedings of World Academy of Science, Engineering, and Technology*, Vol. 49, pp. 524-531.

[85] Nouri, J., Mansouri, N.,, Abbaspour, M., Karbassi A.R., Omidvari, M., (2011.), Designing a Developed Model for Assessing the Disaster Induced Vulnerability Value in Educational Centers, *Safety Science*, Vol.49,pp: 679-685.

[86] Niu, Y.M., He, Y.Z., Hong, J. L., and Zhao, X. J., (2009), The Optimization of RPN Criticallity Analysis Method in FMECA, In Proceedings of International Conference of Apperceiving and Intelligence Analysis, 166-167.

[87] Ngai, E.T.W., Xiu, L., and Chan, D.C.K., (2009), Application of Data Mining Technique in Customer Relationship Management: a Literature Review and Classifications, *Expert Systems and Applications*, Vol. 36, pp.2592-2602.

[88] Oordobadi, S., (2011), Inclusion of Risk in Evaluation of Advanced Technologies, *International Journal of Advanced Manufacturing Technology*, Vol.54, No.1-4, pp.413-420.

[89] Oolkalkar, A.D., Joshi, A. G. and Oolkalkar, D. S., (2009), Quality Improvement In Haemodialysis Process using FMEA, *International Journal of Quality and Reliability*

Management, Vol.26, Iss.8, pp. 817-830.
[90] Okumus, F., (2003), A Framework to Implement Strategies in Organizations, *Management Decision,* Vol.41, Iss.9, pp. 871-882.
[91] Patel, S. and Zaveri, J., (2010), A Risk-Assessment Model for Cyber Attacks on Information Systems, *Journal of Computers,* Vol.5, pp.352-359.
[92] Pons, D.J., (2010), Strategic Risk Management: Application to Manufacturing, *The Open Industrial and Manufacturing Engineering Journal,* Vol.3, pp. 13-29.
[93] Pilay, A., and Wang, J., (2003), Modified FMEA Using Approximate Reasoning, *Reliability Engineering and System Safety*, Vol.79, No.1, pp. 69-85.
[94] Puente, J., Pino, R., Prioire, P., and Fuente, D.L., (2002) A Decision Support System for Applying FMEA, *International Journal of Quality and Reliability Management*, Vol.19, No.2, pp.137-150.
[95] Quezada, L.E., Cordova F.M., Palominos, P., Godoy, K., and Ross, J., (2009), Method for Identifying Strategic Objectives in Strategy Maps, *International Journal of Production Economics*, Vol.122, pp.492-500.
[96] Rhee, S.J., and Ishii, K., (2003), Using Cost based FMEA to Enhance Reliability and Serviceability, *Advanced Engineering Informatics*, Vol.17, No.3-4, pp.179-188.
[97] Rausand, M., and Øein, K., (1996), The Basic Concepts of Failure Analysis, *Reliability Engineering and Systems Safety*, Vol.53, No.1, pp. 73-83.
[98] Rahman, S., (1998), Theory of Constraints : A Review of The Philosophy and Its Applications, *International Journal of Operations and Productions Management*, Vol.18, No.4, pp.336-355.
[99] Song, B., Lee, C., and Park, Y.C., (2012), Assessing the Risk of Service Failures based on the Ripple Effects: A Bayesian Network Approach, *International Journal of Production Economic*, 2012 , In press.
[100] Soderholm, P., and Karim, R., " An Enterprise Risk Management Framework for Evaluation of E-Maintenance," *International Journal of System Assurance and*

Engineering Management, 3, pp:219-228

[101] Shahin, A., (2004), Integration of FMEA and the Kano Model: An Exploratory Examination, *International Journal of Quality and Reliability Management*, Vol.21, No.7, pp. 731-746.

[102] Sharma, R.K., and Sharma, P., (2010), System Behaviour Modelling and Maintenance Decision Making Using RCA, FMEA, and FM, *Journal of Quality in Maintenance Engineering*, Vol.16, No. 1, pp. 64-88.

[103] Shankar, N. R. and Prabhu, B. S., (2001), Modified Approach for Prioritization of Failures in a System FMEA, *International Journal of Quality and Reliability Management*, Vol.18, Iss. 3, pp. 324-336.

[103] Sutrisno, A., and Kwon, H.M., (2010) An Expected Loss Model for Risk Prioritization in Service FMEA, *Journal of Supply Chain and Operations Management*, Vol.8, No.2, pp.27-38.

[104] Sutrisno, A., and Kwon, H.M., (2012) Corrective Action Strategy based on SWOT Analysis in Service FMEA, *Journal of Korean Society for Quality Management,* Vol.40, Iss.1, 25-38.

[105] Sawhney, R., Subburaman, K., Sonntag, C., Rao, P.R.V., and Capitzi, P., (2010), A Modified FMEA Approach to Enhance Reliability of Lean Systems, *International Journal of Quality and Reliability Management*, Vol.27, No.7, pp. 832-855.

[106] Seyedhoseini, S.M., and Hatefi, M.A., (2009), Two – Pillar Risk Management (TPRM): a Generic Project Risk Management Process, *Scientia Iranica Transaction E: Industrial Engineering*, Vol.16, No.2, pp.138-148.

[107] Seyedhoseini, S.M., Noori, S., and Hatefi, M.A., (2009), An Integrated Methodology for Assessment and Selection of the Project Risk Response Actions, *Risk Analysis,* Vol.29, Iss.5, pp. 752-763.

[108] Simons, J.V. Jr., (2004), Reliability-based Analysis of Service Recovery, *International Journal of Quality and Reliability Management*, Vol.21, Iss.1, pp.11-31.

[109] Shahin, A.,(2004) Integration of FMEA and The Kano Model : An Exploratory Examination, International Journal of Quality and Reliability Management, Vol.21, No.7, pp. 731-746.

[110] Stamatis, D.H., (1995), *Failure mode and effect analysis*, ASQ Quality Press. Milwaukee.

[111] Sharma, R.K., and Sharma, P., (2010), System Failure Behavior and Maintenance Decision Making Using RCA, FMEA, and FM, *Journal of Quality in Maintenance Engineering*, Vol.16, Iss.1, pp.64-88.

[112] Sachdeva, A., Kumar, D., Kumar, P., (2009), Multi-Factor Failure Mode Criticality Analysis Using TOPSIS, *International Journal of Industrial Engineering Azad Islamic University,* Vol.5, No.8, pp.1-9.

[113] Senol, S., (2007). Poisson Approach to Determine the Occurrence Degree in Failure Mode and Effect Reliability Analysis, *The Quality Management Journal*, Vol.14, No.2, pp. 29-40.

[114] Sharma, R.K., Kumar, D., and Kumar, P., (2005), Systematic FMEA Using Fuzzy Linguistic Modelling, *Reliability Engineering and System Safety*, Vol.22,Iss.9, 986-1004.

[115] Sharma, R.K., Kumar, D., and Kumar, P., (2007), Modelling and Analysing System Failure Behavior Using RCA, FMEA, and NHPPP Models, *International Journal of Quality and Reliability Management*, Vol.24, No.5, pp.525-546.

[116] Seyedhosseini, S.M., Safaei, N., and Asgharpour, M.J., (2006), Reprioritization of Failures in a System FMEA by Decision Making Trial and Evaluation Laboratory Technique, *Reliability Engineering and System Safety*, Vol.91, Iss.8, pp.872-881.

[117] Stamatis, D.H., 1995. Failure Mode and Effect Analysis, ASQ Quality Press, USA.,

[118] Shtub, A., Bard, J.F., and Globerson, S., Project management. Processes, Methodologies, and economics. Prentice Hall, New Jersey, 2005.

[119] Simons, J.V.Jr., (2004), Reliability-based Analysis of Service Recovery,

International Journal of Quality and Reliability Management, Vol.21, no.1, pp:11-31.
[120] Trzcieliňski, S. and Trzcieliňska, J., (2011), Some Elements of the Theory of Opportunities, *Human Factors and Ergonomics in Manufacturing & Service Industries*, Vol. 21, Iss.2, pp. 124-131.
[121] Torney, M., Kunizky, K., and Hermann, C., (2009), Service Development and Implementation: A Review of the State of The Art. *Proceedings of the 1st CRIP Industrial Product and Service System*, Cranfield University, United Kingdom, p.224.
[122] Thawesaengskulthai, N. and Tannock, J.D.T., (2008), A Decision Aid for Selecting Improvement Methodologies, *International Journal of Production Research,* Vol.46, No. 23, pp. 6271-6237.
[123] Tay, K.M., and Lim, P.C., (2005), Fuzzy FMEA with a Guided Rules Reduction System for Prioritization of Failures, *International Journal of Quality and Reliability Management*, Vol.23, No.8, pp. 1047-1066.
[124] Teng, G.S., Ho, M.H., Shumar, D., Liu, P.C., (2006), Implementing FMEA in a Collaborative Supply Chain Environment, *International Journal of Quality and Reliability Management*, Vol.23, No.2, 179-196.
[125] Tavana, M., and Banerjee, S., (1995), Strategic Assessment Model (SAM): A Multiple Criteria Decision Support System for Evaluation of Strategic Alternatives, *Decision Sciences*, Vol.1, pp: 120-143.
[126] Uzkurt, C., (2010), Customer Participation in the Service Process: a Model and Research Proposition, *International Journal of Service and Operations Management*, Vol.6, No.1, 17-37.
[127] Wielle, T.V., Iwaarden, J.V., Williams, and Elridge, S., (2011), A New Foundation for Quality Management in the Business Environment for the Twenty First Century, *Total Quality Management and Business Excellence*, Vol.22, No.5, 587-598.

[128] Wu,S., Neale, K., Williamson, M., and Hornby, M., (2010), Research Opportunities in Maintenance of Office Building Service Systems, *Journal of Quality in Maintenance Engineering*, Vol.16, Iss.1, pp.22-33.

[129] Wheelen, T.L. and Hunger, J. D., (2008), *Concepts in Strategic Management and Business Policy: 11th edition.* Pearson Prentice Hall, New Jersey.

[130] Wang, Y.M., Chin K.S., Poon G.K. W., and Yang, J.B., (2009), Risk Evaluation in FMEA Using Fuzzy Weighted Geometric Mean, *Expert System with Applications*, Vol.36, No.2, pp.1195-1207.

[131] Xing, K. and Xian, J., (2010), Empirical Research on Enterprise Organizational Capability Evaluation System Based on AHP, *Proceedings of International Conference Future Information Technology and Management Engineering* (FITME), pp.256-260.

[132] Xu, K., Tang, L.C., Xie, M., Ho, S.L., and Zhu, M.L., (2002), Fuzzy Assessment of FMEA for Engine Systems, *Reliability Engineering and System Safety*, Vol.75, No.1, pp.17-29.

[133] Yadav, O.P., and Singh, N., (2008), Perspectives and Challenges for Product Reliability Assurance in the Product Development Process, *International. Journal of Product Development,* Vol.5, No.1-2, pp. 4-16.

[134] Yang, Z., Peterson, R.T., and Cai, S., (2003), Service Quality Dimension of Internet Retailing: An Exploratory Analysis, *Journal of Service Marketing*, Vol. 17, No.7, pp.685-700.

[135] Yin, R.K., (1994), *Case Study Research: Design and Methods- 2nd edition.* Sage Publisher, London.

[136] Yadav, O.P., Singh, N., Chinnam, R.B., and Goel, P.S., (2003), A Fuzzy Logic Based Approach to Reliability Improvement Estimation During Product Development, *Reliability Engineering & System Safety,* Vol. 80, pp. 63-74.

[137] Yang, H. H and Chen, K.S., (2000), A performance Index Approach to Managing Service Quality , *Managing Service Quality*, Vol.10, Iss. 5, pp. 273-278.

[138] Zio, E., (2009) Reliability Engineering: Old Problems and New Challenges, Reliability *Engineering and Systems Safety*, Vol.92, No.2, pp. 125-141.

[139] Zaman, A.S.M., and Anjalin, U., (2011), Evolution of Service: Importance, Competitiveness, and Sustainability in the New Circumstances, *Journal of Service Science and Management*, Vol.4, No.3, pp.253-260.

[140] Zhang, J., and Zhu, Q., (2006), FMEA based Potential Risk Analysis of Lower Cost Region Sourcing, Proceedings of IEEE International Conference on Service Operation, Logistics, and Informatics, pp. 158-163.

[141] Zafiropoulos, E.P., and Dialynas, E.N., (2000), Reliability Prediction and FMECA of Electronic Devices Using Fuzzy Logic, *International Journal of Quality and Reliability Management,* Vol.22, No.2, pp. 183-200.

[142] Zammori, F., and Gabbrielli, R., (2012), ANP/RPN: A Multi Criteria Evaluation of the Risk Priority Number, *Quality and Reliability Engineering International*, Vo.28, No.1,85-104.

Appendix 1

Suppose that the B_i are mutually disjoint events whose union is Ω. In attempt for finding the probability of event A, summation the conditional probabilities of A given B_i must be done. Now observed that

$P(A) = P(A \cap \Omega)$

$= P(A \cap (\cup_{i=1}^{n} B_i))$

$= P(\cup_{i=1}^{n} (A \cap B_i))$

Since the events $A \cap B_i$ are disjoints,

$P(\cup_{i=1}^{n} (A \cap B_i)) = \sum_{i=1}^{n} P(A \cap B_i)$

$= \sum_{i=1}^{n} P(A|B_i)\, P(B_i)$

Appendix 2

Since X_{ki} and Y_{ki} are mutually independent, their joint probability density function is given by

$$f_{X_{ki},Y_{ki}} = \lambda_{ki}\mu_{ki}e^{-\lambda_{ki}x-\mu_{ki}y},\ 0< x, 0 < y \qquad \text{(A1)}$$

If the variable W_{ki} is changed as $W_{ki} = X_{ki} + Y_{ki}$ and $X_{ki} = Y_{ki}$, the joint probability density function of X_{ki} and Y_{ki} will be

$$f_{X_{ki}}, W_{ki}(x, w) = \lambda_{ki}\mu_{ki}e^{-(\lambda_{ki}-\mu_{ki})x-\mu_{ki}w},\ 0 < x < w \qquad \text{(A2)}$$

The probability density function of W_{ki} is obtained by integrating (A2) with x over its range, that is,

$$f_{w_{ki}}(w) = \int_0^w \lambda_{ki}\mu_{ki}e^{-(\lambda_{ki}-\mu_{ki})x-\mu_{ki}w}dx$$

$$= \frac{\lambda_{ki}\,\mu_{ki}}{\lambda_{ki}-\mu_{ki}}\{e^{-\mu_{ki}w} - e^{-\lambda_{ki}w}\},\ 0 < w$$

Thus, the equation (7) will be obtained.

An Improvement Strategy Based on the Failure Risk and Corrective Action Prioritization in Service FMEA

Agung Sutrisno

Department of Systems Management and Engineering
Pukyong National University

Abstract

As the contribution of service sectors to global economy grows, the importance of delivering error free service operation is undeniable. This thesis is concerned with endeavor to improve some limitations of the conventional FMEA in risk estimation and improvement strategy selection in service FMEA. In attempt to searching for new FMEA research opportunities in service sector, initial literature survey is performed. The results of the survey indicated the determination of failure occurrence rate is still based on subjective judgment, ignoring failure time occurrence and impact of business environment in proposing failure rectification effort. In this thesis, several ideas are suggested for improving the previous FMEA methodologies as below:

i) **The expected loss model**. Although many methodologies have been proposed to overcome limitations of the RPN estimation in conventional FMEA, the determination of the probability component in RPN estimation is still based on 1-10 ordinal scale with no scientific basis. Instead of using the RPN (Risk Priority Number) as metric to rank criticality of service failure in conventional FMEA, an expected loss model based on the conditional probability theory is proposed. By using the expected loss model, determination of failure probability component can be accomplished into more scientifically basis and can lead to an improved failure alleviation effort.

ii) **Time-dependent expected loss model**. Attribution of failure time occurrence is important in quality loss quantification; however, such aspect is not covered by conventional FMEA. Considering this discrepancy, a time-dependent expected loss model which based on assumption

of constant failure occurrence rate is formulated. The result of numerical estimation based on time-dependent expected loss model indicated that failure time occurrence cannot be neglected in quantifying quality loss during time span of service system's mission. Inclusion of failure time occurrence will provide decision makers with more realistic quality loss quantification.

iii) **SWOT based corrective action strategy selection model**. In spite of having equal important in risk management platform, reprioritization of FMEA-based competing corrective actions selection is still based on internal failure evaluation. The reality that business system is interacting with both of its inner and outer of environments is not considered. Considering impact of business environment, SWOT Analysis is integrated in estimating preference score of decision makers in appraising competing corrective actions. A model to estimate the benefit of considering impact of business environments based on impact factor of SWOT variables and their correlations with competing corrective actions are proposed.

All models presented in this thesis are intended to contribute to the body of knowledge. By using the models, if compared to conventional FMEA, the probability components of the RPN can be determined more scientifically. In addition, inclusion of failure time and utilization of the three models of loss function, the possibility of business loss escalation during system operational mission can be accommodated. Considering impact factor of SWOT variables in risk-based strategy selection enables decision makers to estimate consider impact of business environments prior determining strategic business decisions.

결함 위험성을 위한 개선 전략 및 FMEA 서비스의 우선적인 시정저치 방안

Agung Sutrisno

부경대학교 시스템 경영공학과

개요

서비스 부문의 공헌이 글로벌 경제에 크게 기여할수록 배달 실수가 없는 응용의 중요성도 높아지고 있다. 이 논문은 FMEA 서비스에게 있어 위험 측정에서 종래 FMEA가 가진 몇몇의 한계를 개선하기 위한 시도와 개선 전략 선정에 대해 초점을 맞춰서 다루고 있다. 서비스 부문에서 새로운 FMEA 연구 기회를 탐구하려는 첫 시도로 문헌 조사로부터 시작했다. 그 결과 고장 발생비율의 결정은 여전히 주관적인 판단을 바탕으로 되어있는 것을 밝혔으며, 고장 수정효과의 제안 중 고장 발생시기와 비즈니스 환경의 영향에 대해 눈을 감고 고려되지 않고 있다. 그러므로 이 논문에서 기존의 FMEA 방법론을 개선하기 위한 여러 방안들을 다음과 같이 제시한다.

i) **기대 손실 모형**. 기존의 FMEA의 RPN추정 한계를 극복하기 위해 많은 방법들이 제의되어 있는데도 불구하고 RPN추정에서 확률요소의 결정은 과학적 근거 없이 아직 1에서 10의 순서척도를 토대로 하고 있는 상황이다. 원래의 FMEA의 서비스 불능 임계를 매기는 미터법으로 RPN (위험 우선 수)을 사용하는 대신, 조건적 확률 이론을 근거로 한 기대 손실 모형이 제기된다. 기대 손실 모형을 사용함으로써 고장 확률

요소의 추정은 보다 과학적인 기반으로 또한 향상된 고장 완화 효과로 도달하여 달성될 것이다.

ii) **시간 의존적 기대 손실 모형**. 고장 시간 발생의 속성은 품질 손실 정량화에서는 중요하다; 그러나 이런 측면은 기존의 FMEA에서는 다루지 않는다. 이 차이를 고려해보면, 일정한 고장 발생률의 추정의 근거한 시간 의존적인 손실함수가 만들어지고 표현된다. 시간적인 기대 손실 모형을 토대로 한 수치적인 추정의 결과로부터 고장 수명시간 발생에 대해 품질 손실을 정량화하는 데에서는 서비스 시스템의 업무를 도외시하면 안 될 것을 보여준다. 고장 시간 발생을 내포하는 것은 의사결정자들에게 더 현실적으로 품질 손실 정량화가 된 것을 제공할 것이다.

iii) **시정조치 전략 선택 모형을 기초로 한 SWOT**. 위험 관리하에서 같은 중요성을 가지고 있음에도 불구하고, 시정조치 선택을 바탕으로 한 FMEA의 재정립은 여전히 내부의 고장 평가를 토대로 하고 있다. 비즈니스 시스템이 내부와 외부 환경에서의 상호작용되는 현실은 고려되지 않는 것이다. 비즈니스 환경의 영향에 관해서 고려했을 때, SWOT 분석은 경쟁적인 시정조치를 평가함으로써 의사결정자의 선호점수의 추정으로 통합된다. SWOT분석 변수의 영향 요소, 그리고 경쟁되는 시정정치과의 상관관계들을 근거로 한 비즈니스 환경의 영향을 고려하는 유익성을 추정하는 모형이 제시된다.이 논문에 나온 모든 모형은 지식체계에 기여하기 위한 의도로 소개된다. 그 모형들을 사용함으로써, 기존의 FMEA와 비교가 된다면, RPN가 가진 확률 요소들은 보다 과학적으로 추정될 수 있을 것이다. 게다가 고장수명과 손실함수의 3가지 모형의 사용을 포함하여, 시스템을 운영하는 업무 중의 비즈니스 손실의 확대 확률은 수용될 것으로 기대된다. 위험도 기반 전략 선정에 있어서 SWOT 변수들의 영향요소를

바라보면 결정을 내리는 의사결정자들에게 전략적 비즈니스 결정을 모색하는 바에 앞서 비즈니스 환경에 대한 영향을 고려하는 것이 가능하다.

Acknowledgement

Alhamdulillahirrobim alamin. Due to Allah Ta'alla the Almighty's guidance, help and blessing, all endeavors to undertake the study which reflected in this thesis can be accomplished in timely manner.

First above all, the author would convey gratitude and sincerely thanks to Prof. Hyuck Moo Kwon PhD for giving the opportunity to join Quality System Laboratory of PKNU to accomplish the studies. His expertise, patience, guidance in undertaking research and unflagging support in difficult moments during study time in Korea is invaluable. It is my pride becoming student from one of the Great Korean Quality scholar like You, Gyosunim.

Second, the author thanks to all professors who becomes members of my dissertation examination. Those great professors are Prof. Hyuck Moo Kwon, Prof Pyung -Hoi Koo, Prof. Young Seok Ock, Prof Young Jin Kim, and Prof. Seung Hoon Lee. All of inputs from you are invaluable in shaping quality of this thesis. The author is also indebted to all professors at Department of Systems Management and Engineering PKNU for all courses given during author's moment in studying in Korea.

Next, I have to present my thanks for brilliant minds from various lands in this globe. Their contributions both in tangible and intangible inputs during research completion are truly easing completion of author's study. Among them are Dr. Elizabeth Cudney of Missouri University of Science and Technology for all discussions pertaining Quality management issues, Dr. Tzong Ru (Jiun Shen) Lee for becoming a mentor and collaborator in part of this study, Dr. Sunil Bhamare for his inspiring study in contemporary reliability issues in product design and manufacturing. Not to forget, author's "virtual" guru, Prof. Ebrahim Shayan which teaches anything about researches years ago prior landing in this beautiful land. It is my pleasure and honor to meet great minds like all of you. The author is also indebted to Dr. Henky S. Nugroho and Dr-Ing. Budi Ibrahim, former master supervisors which introduced initially on FMEA during author's master thesis study in University of Indonesia and let the author enjoying unforgettable moment in setting up quality management system ISO 9000 in real world applications.

This thesis is also will not be realizable without the help from Indo- Korean friends in PKNU. Special thanks to Marcella Cornellis, Engelina Dengah, Karunia Mahardini, Stenly Tangkuman, Trytya Arungpadang, and Pandu Sandi Pratama. Their assistances in difficult moments in studying in Korea are unforgettable. The role of Miss Jang Hyeon Ae M.Eng, Miss Hyun Jin Jeong, Sun Heng Lee, my sonbe nim Dr. Kim Jung Taek will always blue in my mind. The author also thanks to Yangojangers, Dr. Lilik Pambudi, Don Nisnoni, M.Sc, and Yanuariska Putra, M.Sc as friend, good and patient listeners during hardships moment is unforgettable. Not to forget, author's friends within *Diktiers Network*, Khairul Annam in Sydney, Annastasia Ediati in Netherland, Iryanti Fatayat in Taiwan and others which always providing help when finding references is becoming dizzying problem during thesis research. May God will bless all of you.

Realization of this thesis is impossible without financial assistantship from Indonesian Ministry of National Education through the 2009 Overseas Scholarship Program for Young Lecturer. Thus, special thanks are given to the President of Sam Ratulangi University, Manado, Prof Donald Rumokoy, Ph.D and Dean College of Engineering, Prof. DR. Ellen Kumaat, DEA which gives recommendation and permission to undertake study in Korea.

Next, uninterrupted moral and material supports from both my parents from undergraduate level up until now are shaping author's confidence in undertaking overseas studies. Without their praying, care and love, studying in Korea is just a dream as beautiful as seen in Korean Drama.

At last, uncountable thanks are delivered to my superwoman and half of my

soul, Fatmarita Sutrisno, for her true love, praying and incredible patience for becoming both as father and mom for my pearls, Rahman and Rahma Sutrisno during my study leave. Their absence in author’s daily moment in Korea teaches on the meaning of a family.