Development of a Framework and Criticality Analysis Model for the Implementation of Reliability Centered Maintenance

THESIS

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....Dedicated

to

My Beloved Family

&

Parents....

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CERTIFICATE

This is to certify that the thesis entitled **“Development of a Framework and Criticality Analysis Model for the Implementation of Reliability Centered Maintenance**” submitted by **GAJANAND GUPTA,** ID. No. **2013PHXF0201P** for the award of Ph.D. Degree of the Institute embodies the original work done by him under my supervision.

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ABSTRACT

Reliability Centered Maintenance (RCM) originated to optimize the maintenance process of aircrafts in 1960s for the Boeing Company. RCM started with a comprehensive zero-based review of necessities of every component in its working context and rapidly it became the cornerstone of present maintenance scenario. Today RCM has become one of the best strategies for maintenance around the globe. RCM is an organized procedure for creating and enhancing the maintenance necessities of a physical asset in its working context to improve the intrinsic reliability by consistently consolidating the ideal use of reactive, preventive, condition-based and proactive maintenance.

The responsibilities of RCM have been expanded from the improvement of maintenance activities dependent on Failure Mode, Effects and Criticality Analysis (FMECA). Literature provides the different frameworks with different sets of elements of RCM. Most of the frameworks are dependent on qualitative analysis of the system and implementation of RCM is limited to criticality analysis using conventional FMECA only. Applications of conventional FMECA have raised some significant issues for the criticality analysis. Therefore, there is a need to develop a framework and criticality analysis model for the implementation of RCM. The objectives of the thesis are: (i) Development of a framework for the implementation of RCM, (ii) Development of a model for identification of criticality levels of subsystems/components of a system, and (iii) To propose an approach of FMECA for criticality analysis of different failure modes of a system. To achieve the objective of the proposed research, this thesis includes the seven chapters. Some of the salient features of these chapters are described as follows:

Chapter 1 introduces the research motivation, objectives and methodology of the research. The background and introduction of RCM also presented in this chapter.

In chapter 2, comprehensive literature review of RCM is presented to identify the evolution of RCM definitions and research. One hundred twenty research papers are reviewed based on the development, implementation, and application of RCM in different areas.

In chapter 3, Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of nineteen existing RCM frameworks presented. These frameworks categorized into three groups (Group A, B, and C) based on their emphasis on qualitative, quantitative, or

practical application aspects and strengths, weaknesses, opportunities, and threats for each group of frameworks were identified.

In chapter 4, ten most significant elements are identified from the SWOT analysis. The contextual interrelationship and their sequence of importance is established using Interpretive Structural Modeling (ISM) approach between the identified elements and an ISM model is developed. Thereafter, using the ISM model, a framework is developed that provides the structured implementation process of RCM. The significance of the proposed framework is that it will help the maintenance managers, engineers, practitioners, and consultants to implement RCM successfully in an organization. In addition, it presents the sequential and decision-making approach for systematic implementation of RCM in an organization in a phase wise manner.

In chapter 5, a model developed to identify the criticality levels of subsystems/components of a system using Analytic Network Process (ANP). The five major evaluation criteria, i.e. (i) Cost, (ii) Functional dependencies, (iii) Complexity, (iv) Maintainability, and (v) Safety impact and 15 sub-criteria are proposed based on the feedback from maintenance managers, engineers, practitioners and consultants. It has been concluded that the proposed methodology will provide a realistic solution to decision-makers for maintenance planning by prioritizing the critical subsystems/components for RCM implementation.

In chapter 6, Failure Modes and Effects Analysis (FMEA) is presented to find out the failure modes of each component of a conventional lathe machine and the criticality analysis of each failure mode using (i) Conventional FMECA, (ii) Mean and Range value of RPN, and (iii) Fuzzy FMECA approach. A comparative analysis of all these three approaches is also conducted and concluded that fuzzy FMECA can be considered as a better approach of FMECA for criticality analysis of different failure modes of a system.

Chapter 7 discussed the overall conclusion and future scope of the present research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/ Abbreviation	Description
AHP	Analytic Hierarchical Process
AI	Artificial Intelligence
ANP	Analytic Network Process
ARCM	Accelerated Reliability Centered Maintenance
BPA	Bonneville Power Administration
CBM	Conditional-Based Maintenance
CBR	Case-Based Reasoning
CCPP	Combined Cycle Power Plant
CDF	Core Damage Frequency
CF	Criticality Factor
CMMS	Computerized Maintenance Management System
CNC	Computer Numerical Control
DOD	Department of Defense
DEA	Data Envelopment Analysis
EDS	Electric Distribution Systems
EMU	Electric Motor Unit
EPDS	Electric Power Distribution System
EPRI	Electric Power Research Institute
FAA	Federal Aviation Administration
FFA	Functional Failure Analysis
FFMEA	Function, Failure Modes and Effects Analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FSI	Functionally Significant Items
FTA	Fault Tree Analysis
GRP	Generalized Renewal Process
IEEE	Institute of Electrical and Electronics Engineers
IOSR	International Organization of Scientific Research
IRCMAS	Intelligent Reliability Centered Maintenance Analysis System
ISM	Interpretive Structural Modeling
LCC	Life Cycle Costing
LRCM	Living Reliability Centered Maintenance
LTA	Logic Tree Analysis
MADM	Multiattribute Decision-Making
MCDM	Multi Criteria Decision Making
MIC-MAC	Matriced Impacts Croises Multiplication Appliquesaun Classement
MMS	Maintenance Management Software
MSI	Maintenance Significant Items
MSG	Maintenance Steering Group

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/ Abbreviation	**Description**
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
NASA	National Aeronautics And Space Administration
PHM	Prognostics & Health Management
PM	Preventive Maintenance
PSO	Particle Swarm Optimization
PT&I	Predictive Testing And Inspection
PWR	Pressurized Water Reactor
RBR	Rule-Based Reasoning
RCAM	Reliability-Centered Asset Maintenance
RCFA	Root Cause Failure Analysis
RCM	Reliability Centered Maintenance
RGA	Reliability Growth Analysis
RP	Renewal Process
RPN	Risk Priority Number
RRCM	Reliability and Risk Centered Maintenance
RtCM	Reliability & Technique Centered Maintenance
SAE	Society of Automotive Engineers
SEM	Structural Equation Modeling
SCM	Supply Chain Management
SSIM	Structural Self-Interaction Matrix
SWOT	Strengths, Weakness, Opportunities, and Threats
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TPM	Total Productive Maintenance
TQM	Total Quality Maintenance
UK	United Kingdom
USA	United State of America

CHAPTER 1

INTRODUCTION

This chapter presents an overview of Reliability Centered Maintenance (RCM) with introduction to RCM, research motivation, objectives, methodology, and outline of the thesis.

1.1 Overview of RCM

RCM is used by a large number of organizations around the world to deal with reliability problems. With each new RCM professional, new thoughts and applications for RCM were established, which enhanced the overall RCM. Esteemed organizations have been formed as the number of RCM specialists. According to National Aeronautics and Space Administration (NASA), the responsibilities of RCM have been expanded to improve the maintenance activities based on Failure Mode, Effects and Criticality Analysis (FMECA) (NASA, 1996).

RCM embodies the familiar proverb that "Necessity is the mother of invention". RCM was originated to optimize the maintenance process of aircraft in the 1960s for the Boeing company. In 1968, airline administrators together established an investigation group, i.e. Maintenance Steering Group-1 (MSG-1) to improve the maintenance strategies. The subsequent reports MSG1, MSG2, and MSG3, presented in 1968, 1970, and 1980, individually (MSG1, 1968; MSG2, 1970; MSG3, 1980). MSG-1 helped to build up a preventive maintenance program for the Boeing 747 airplane, historically the first maintenance program applying RCM concepts and afterward permitted by the Federal Aviation Agency (FAA), which was in charge of managing aircraft maintenance practices in the United State of America (USA). The standards of MSG-1 connected in

MSG – 2, and at the same time MSG-3 has developed the Preventive Maintenance (PM) program. These concepts were connected by the Department of Defense (DOD) of united airlines in 1972. MSG concepts were synchronized by DOD in 1974 and marked as "RCM". In 1974, as a title “Reliability Centered Maintenance” of a report was presented the first time. This report was prepared by united airlines (Nowlan and Heap, 1978) under the authorization of DOD. It has turned into a report developed based on all ensuing RCM approaches which have been utilized for aircrafts by then. Nowlan and Heap (1978), Rausand (1998) and Smith (1993) published the history of RCM in detail progressively.

As presented before, the first application of RCM was within the aircraft industry in the USA, and after some time it was utilized by DOD. So it can be inferred that RCM applied in those fields where any failure of a given component is catastrophic. Afterwards, application of RCM additionally discovered in the fields like a nuclear power plant, power distribution system, oil and gas industry, manufacturing industry, process industry, construction, railway and so forth.

1.2 Introduction of RCM

RCM has been one of the most recent and successful methodologies in maintenance around the world. With an end goal to accomplish aggregate lifecycle management, it is robustly preferred to understand the systematic planning method of maintenance tasks. RCM is such a systematic approach for the selection of relevant and suitable maintenance strategies.

RCM suggests that the maintenance function must be focused on assuring reliability of equipment and systems. According to Nowlan and Heap (1978), the RCM refers to a planned maintenance program intended to recognize the intrinsic reliability capabilities of a system. In 1983, the Electric Power Research Institute (EPRI) initiated RCM on nuclear power plants and defined RCM as “a systematic consideration of system functions, the way of functions that can fail, and a priority-based consideration of safety and economics that identifies applicable and effective PM tasks”. Society of Automotive Engineers (SAE) Standard defines RCM Process as “a specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operating context”(McKenna and Oliverson, 1997). RCM helps the manufacturer in maintenance suggestions and the reliability specialist for the selection of ideal methodology in playing out the exact maintenance on the right equipment at the correct time for the correct reasons. According to Crocker and Kumar (2000), RCM permits logisticians to decide the best maintenance strategy for every component of a system. NASA (1996) states that "RCM combines PM, Predictive Testing and Inspection (PT&I), reactive maintenance, and proactive maintenance to improve the probability that a machine or a component will work in the requisite behavior over its designed life-cycle with the least amount of maintenance and downtime". According to Rausand (1998) RCM mainly gives the answers to the following seven questions.

i. What are the functions and associated performance standards of the equipment in its present operating context?
ii. In what ways does it fail to fulfill its functions?
iii. What is the cause of each functional failure?
iv. What happens when each failure occurs?

v. In what way does each failure matter?
vi. What can be done to prevent each failure?
vii. What should be done if a suitable preventive task cannot be found?

1.2.1 Objectives of RCM

From literature, researchers have been identified various objectives of RCM.

- To improve network reliability and reduce maintenance expenses (Mansour and Noradin, 2015).
- To determine equipment and plant PM requirements (Chopra *et al.*, 2014; Ning and Yujun, 2015).
- To develop and optimize the PM programs (Kennedy, 2006; Matteson, 1985; Nowlan and Heap, 1978).
- To identify the maintenance tasks (Ahmadi *et al.*, 2009; Morais *et al.*, 2006).
- To decrease the maintenance cost by monitoring the most important functions of a system and avoid or remove maintenance actions that are not strictly necessary (Rausand, 1998).
- To obtain the most cost-effective PM program (Rausand, 1998).
- To identify the criticality of components for implementing a PM maintenance program (Dehghanian and Fotuhi-Firuzabad, 2012).
- To preserve system function (Smith, 1993).
- To identify the failure modes which are the causes of functional failure and prioritize the failure modes to reflect their importance for the system (Smith, 1993).

1.2.2 Benefits of RCM

The following benefits can be obtained by implementing RCM in an organization.

- Contributes high-quality maintenance plans at low cost and in less time.
- The feasibility of recorded maintenance history of each system and coordination with a particular component and its failure modes with criticality analysis.
- Maintenance requirements can be indicated optimally.
- Improved maintenance plans.
- The accessibility of upkeep history of each system.
- The premise of standard, online data trade among the staff and administration of an association.

1.3 Research Motivation

The expanding development of innovation and competition among industries, organizations utilize various strategies and policies to improve productivity and reduce cost. Maintenance is a policy which is utilized in production industries to reduce costs, improve productivity, and to advance with the worldwide competition. RCM focuses on preserving the system function to decrease the maintenance cost and avoiding or removing maintenance actions that are not strictly necessary (Rausand, 1998; Smith, 1993). RCM literature reveals that the criticality analysis of a system is the key element for the implementation of RCM. RCM provides a framework to the administration to resolve the complexity of the maintenance issues by supplementing all the conventional methodologies (Dehghanian *et al.*, 2012). The outcome of the RCM process is to select the appropriate maintenance actions to improve the reliability and availability of the system.

Researchers have been continuously working on various aspects of RCM in the last two decades. Some standalone research has been carried out in the area of ***Power distribution*** (Abbasghorbani *et al.*, 2014; Adoghe *et al.*, 2012; Aldhubaib, 2013; Barai *et al.*, 2012; Bertling *et al.*, 2005; Dehghanian and Fotuhi-Firuzabad, 2012; Fischer *et al.*, 2011; Heo *et al.*, 2014; Jie *et al.*, 2005; Mansour and Noradin, 2015; Morais *et al.*, 2006; Piasson *et al.*, 2016; Sabouhi *et al.*, 2016; Smith and Hinchcliffe, 2004; Souza and Álvares, 2008; Tirapong and Titti, 2014), ***Manufacturing*** (Altaf Tarar, 2014; Dogahe and Sadjadi, 2015; Fore and Mshipha, 2010; Fore and Mudavanhu, 2011; Fuentes-Huerta *et al.*, 2018; Jasiulewicz-Kaczmarek, 2015; Ramli and Arffin, 2012; Singh *et al.*, 2010; Supsomboon and Hongthanapach, 2014), ***Airline*** (Ahmadi *et al.*, 2009; Kennedy, 2006; Mokashi *et al.*, 2002; Ning and Yujun, 2015; Pourjavad *et al.*, 2011), ***Nuclear power*** (Chen and Zhang, 2012; Huang *et al.*, 2012), ***Process*** (Albarkoly and Park, 2015; Chopra *et al.*, 2014, 2016; Li and Gao, 2010; Liang *et al.*, 2012; Vishnu and Regikumar, 2016), ***Oil & Gas*** (Prabhakar and Raj, 2013; Selvik and Aven, 2011; Tang *et al.*, 2017; Wei *et al.*, 2012), ***Construction*** (El-Haram and Horner, 2002), ***Transportation*** (Bae *et al.*, 2009), ***Railway*** (Carretero *et al.*, 2003; García Márquez *et al.*, 2003) etc.

From the literature, it has been observed that there is a lack of structured and implementable procedure for RCM. The adoption of a framework that provides the required flow of various elements for structured implementation process is one of the success factors for RCM. Since the implementation of RCM is a strategic decision, it is necessary that maintenance engineers, practitioners, managers and consultants of different organizations tends to use a framework and they cannot afford to make a mistake in the selection of a proper framework. A greater hurdle in this selection process is the availability of a large number of frameworks with the different elements of RCM.

So it is necessary to study the existing RCM frameworks, and develop a framework which will provide the structured implementation process of RCM to the maintenance experts of the organizations. Additionally, criticality analysis has been observed as a key element in literature for the implementation of RCM. Hence, there is a need to develop a criticality analysis model to identify the criticality level of subsystems/components.

1.4 Objectives of the Research

The following objectives need to be fulfilled with the proposed research:

- Study of existing techniques and frameworks of RCM through a comprehensive literature review.
- Development of a framework for the implementation of RCM.
- Development of a model to identify the criticality levels of subsystems/components of a system for the implementation of RCM.
- To propose an approach of FMECA for the criticality analysis of different failure modes of a system.

1.5 Methodology

The following methodology has been used to achieve the objectives of the research:

- A thorough literature review is carried out to identify the existing tools, techniques, and frameworks of RCM and also, to identify the development, implementation and applications of RCM in different areas.
- Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is conducted to identify the most significant elements from the various elements of existing RCM frameworks based on strengths, weaknesses, opportunities, and threats of these frameworks.

- The contextual interrelationship and their sequence of importance is established using Interpretive Structural Modeling (ISM) approach between the identified elements of RCM. An ISM model is developed for the elements of RCM using the established interrelationship and their sequence of importance. Thereafter, using the ISM model, a framework is developed that provides the structured implementation process of RCM.
- A methodology is proposed to identify the criteria and sub-criteria associated with criticality and a model is proposed to identify the criticality levels of each subsystems/components of a system for the implementation of RCM. The fifteen sub-criteria and five major criteria i.e. (i) Cost, (ii) Functional dependencies, (iii) Complexity, (iv) Maintainability and (v) Safety impact are determined for the proposed criticality analysis model. The proposed model is applied to identify the criticality levels of subsystems/components of a Computer Numerical Control (CNC) lathe machine using Analytic Network Process (ANP) for validation.
- FMEA is developed to identify the different failure modes of a conventional lathe machine and the criticality analysis of each failure mode is performed using three approaches: (i) Conventional FMECA, (ii) Mean and Range value of RPN, and (iii) Fuzzy FMECA approach. A comparative analysis of all three approaches is also done to propose a better approach of FMECA for the criticality analysis of different failure modes of a system for the implementation of RCM.

1.6 Outline of the Thesis

Chapter 1 presents the introduction, objectives, and methodology of the thesis. Chapter 2 provides a thorough literature review of RCM. Chapter 3 presents a SWOT analysis of existing RCM frameworks. Chapter 4 presents the development of a framework for the implementation of RCM based on the SWOT analysis of existing RCM frameworks using ISM approach. Chapter 5 presents the proposed model for criticality analysis to identify the criticality levels of subsystems/components of a system using ANP. It also presents a case study on CNC lathe machine. Chapter 6 presents FMEA and comparison of criticality ranking of failure modes of a conventional lathe machine using three approaches: (i) Conventional FMECA, (ii) Mean and Range value of RPN and (iii) Fuzzy FMECA approach. Chapter 7 presents overall conclusion and future scope of this research.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a thorough literature review of RCM to identify the evolution of reliability centered maintenance definitions and research. One hundred twenty research papers are reviewed and categorized into three categories based on the focus (i) Development (ii) Implementation and (iii) Application of RCM.

2.1 Introduction

RCM has been one of the best strategies in maintenance around the globe. It helps to understand the intrinsic reliability by consistently consolidating the ideal blend of reactive, preventive, condition-based and proactive maintenance; RCM is an organized procedure for creating and enhancing the maintenance necessities of a physical asset in its working context. It is a sort of basic innovation needed in the organization around the globe. It is a deliberate strategy which utilizes the usefulness of the components and results of failure to figure out which adjusting errands are to be performed and when.

RCM started with a comprehensive zero-based review of the necessities of every component in its working context and rapidly it became the cornerstone of present maintenance scenario (Moubray, 1997). RCM in a plant depends on the assumption that the ease of use of a given plant relies upon its outline, development, quality and the manner by which it is worked. This ease of use can be guaranteed by setting up a compelling upkeep plan and increased through an upgrade, change or training (Pintelon *et al.*, 1999).

2.2 Definitions of RCM

This section presents an aggregation of the different definitions of RCM with undertone by different authors. Numerous maintenance supervisors have acknowledged RCM and connected effectively crosswise over numerous disciplines. A few authors and practitioners over the globe have studied and gave remarks on RCM definitions. The inspiration here is to accumulate the definitions of RCM demonstrating how the destinations and extent of RCM have changed with time. EPRI defined RCM as "a systematic consideration of system functions, the way of functions that can fail, and a priority-based consideration of safety and economics that identifies applicable and effective PM tasks" (Rausand, 1998). SAE Standard defines RCM Process as "a specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operating context" (McKenna and Oliverson, 1997). Table 2.1 presents various definitions of RCM.

Table 2.1: Definitions of RCM

S.No.	**Author**	**Definitions of RCM**
1.	Nowlan and Heap (1978)	"RCM is a logical discipline for the development of scheduled maintenance programs".
2.	Matteson (1985)	"RCM is a rational, coherent approach to the problem of PM program design based on a decision tree".
3	Brauer and Brauer (1987)	"The RCM is a unique tool used by reliability, safety, and maintenance engineers for developing optimum maintenance plans, which define requirements and tasks to be performed in achieving, restoring, or maintaining the operational capability of a system or equipment".
4	Moubray (1997)	"A process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context".

5	Rausand (1998)	"RCM is a technique for developing a PM program".
6	Reder and Flaten (2000)	"RCM is a systematic approach to define optimal strategies of routine maintenance where system functionality can be preserved in the most cost-effective manner".
7	Mokashi *et al.* (2002)	"RCM philosophy focuses the maintenance resources only on those items that affect the system reliability, thereby making the maintenance programme cost effective on the long run".
8	El-Haram and Horner (2002)	"RCM is a systematic approach for identifying the most applicable and cost-effective maintenance task for building elements, services and equipment and from a rigorous analysis of the consequences of failure".
9.	Deshpande and Modak (2002b)	"RCM is a unique tool used by reliability, safety and maintenance engineers for developing optimum maintenance plans that define requirements and tasks to performed in restoring or maintaining the operational capability of a system or equipment".
10	Backlund and Akersten (2003)	"RCM combines several well-known risk management techniques and tool, such as failure mode and effect analysis and decision trees, in a systematic approach, to support effective and efficient maintenance decisions".
11	Gabbar *et al.* (2003)	"RCM process is intended to determine the most realistic and optimized maintenance requirements of any physical asset to continue its stated operating condition".
12	Carretero *et al.* (2003)	"RCM is a systematic approach to systems functionality, failures of that functionality, causes and effects of failures, and infrastructure affected by failures".
13	García Márquez *et al.* (2003)	"RCM is a process used to decide what must be done to ensure that any physical asset, system or process continues to do whatever its users want it to do".
14	Bertling *et al.* (2005)	"RCM is a systematic qualitative approach to organizing maintenance".
15	Penrose (2005)	"The RCM approach assists the manufacturer or supplier in maintenance recommendations and the reliability specialist in selecting the optimum approach in performing the right maintenance on the right equipment at the right time for the right reasons".
16	Conachey (2005)	"RCM is a part of overall risk management so that the maintenance program can effectively manage the risk of undesirable end events associated with equipment failures".

17	Kennedy (2006)	“RCM is a structured, logical process for developing or optimizing the maintenance requirements of a physical resource in its operating context to realize its inherent reliability where inherent reliability is the level of reliability, which can be achieved with an effective maintenance program”.
18	Morais *et al.*(2006)	“RCM is a process to identify PM requirements for complex systems”.
19	Ahmadi *et al.* (2009)	“RCM is a systematic methodology used to identify the maintenance tasks that are necessary to realize the inherent reliability of items at the lowest possible cost”.
20.	Kianfar and Kianfar (2010)	“RCM is a systematic and disciplined approach for designing the PM for the plants”.
21	Li and Gao (2010)	“RCM analyzes the functions and failures of a system and identifies the consequences of these failures to implement preventive measures using a standardized logical resolution procedure”.
22	Fore and Mudavanhu (2011)	“RCM is a structured process, which develops or optimizes maintenance requirements of a physical resource in its operating context to realize its inherent reliability by logically incorporating an optimal combination of reactive, preventive condition-based and proactive maintenance practices”.
23	Pourjavad *et al.* (2011)	“RCM is one of the well-established systematic methods for selecting applicable and suitable maintenance operation types. In RCM, failure consequences and their preventive operations are systematically analysis, and possible maintenance planning is determined”.
24	Adoghe *et al.* (2012)	“RCM is a maintenance practice that focuses on failure analysis, root-cause analysis, and corrective actions”.
25	Barai *et al.* (2012)	“RCM is an industrial improvement approach focused on identifying and establishing the operational, maintenance, and capital improvement policies that will manage the risks of equipment failure most effectively”.
26	Dehghanian *et al.* (2013a)	“RCM is referred to as a well-organized method wherein the maintenance process of system components is linked to improvements in the system reliability”.
27	Igba *et al.* (2013)	“RCM is a method of capturing the potential causes of downtime and poor performance by preventing failures and having a proactive approach to operations and maintenance”.

28	Yssaad *et al.* (2014)	"RCM is a systematic process used to determine what has to be accomplished to ensure that any physical facility can meet continuously its designed functions in its current operating context".
29	Heo *et al.* (2014)	"The RCM technique is a structured framework for analyzing the functions and potential failures of a transmission component, with a focus on preserving reliability".
30	Chopra *et al.* (2014)	"RCM is a most systematic and efficient process to address an overall programmatic approach to the optimization of plant and equipment maintenance".
31	Ning and Yujun (2015)	"RCM is the process that adopting logic determination method to determine equipment PM requirements, according to the principles that the minimal resource consumption to keep equipment inherent reliability and safety".
32	Mansour and Noradin (2015)	"RCM strategy attempts to present an organized framework for the improvement of network reliability and the reduction of maintenance expenses by relying on cost/benefit studies and the reliability analysis of networks".

From the above definitions, it is clear that RCM is a ***logic*** (Nowlan and Heap, 1978), an ***approach*** (Barai *et al.*, 2012; Bertling *et al.*, 2005; Carretero *et al.*, 2003; El-Haram and Horner, 2002; Kianfar and Kianfar, 2010; Matteson, 1985; Penrose, 2005; Reder and Flaten, 2000), ***process*** (Fore and Mudavanhu, 2011; Gabbar *et al.*, 2003; García Márquez *et al.*, 2003; Kennedy, 2006; Morais *et al.*, 2006; Moubray, 1997; Ning and Yujun, 2015; Yssaad *et al.*, 2014), ***set of tools and techniques*** (Brauer and Brauer, 1987; Rausand, 1998; Backlund and Akersten, 2003; Deshpande and Modak, 2002a), ***structured/organized framework*** (Heo *et al.*, 2014; Mansour and Noradin, 2015), ***method*** (Ahmadi *et al.*, 2009; Dehghanian *et al.*, 2013a; Igba *et al.*, 2013; Pourjavad *et al.*, 2011), ***maintenance practice*** (Adoghe *et al.*, 2012), and ***philosophy*** (Mokashi *et al.*, 2002). From the literature review of RCM frameworks, it has been observed that the terminology "process" is most suitable for RCM. Hence, we have considered the RCM as a process in this research. The goals for which RCM has implemented, also discussed in literature are as to improve network reliability and reduce maintenance expenses (Mansour and Noradin, 2015), to determine equipment and plant preventive maintenance requirements (Chopra *et al.*, 2014; Ning and Yujun, 2015), to develop and optimize the PM programs (Kennedy, 2006; Matteson, 1985; Nowlan and Heap, 1978), and to identify the maintenance tasks (Ahmadi *et al.*, 2009; Morais *et al.*, 2006).

A review of one hundred twenty research papers is presented here which were obtained by searching the research publication databases with key-words 'Reliability centered maintenance' or 'RCM'. The reviewed articles were obtained from fifty-six international journals, seventeen Institute of Electrical and Electronics Engineers (IEEE) conferences proceedings, sixteen others National & International conferences, one book and one thesis as shown in Table 2.2. These articles include description, development, implementation, application and case studies of RCM.

Table 2.2: Distribution of the research papers in different journals and conferences

	Number of References	**Percentage (%)**
(A) Journals		
International Journal of Reliability Engineering And System Safety	14	11.68
Journal of Quality in Maintenance Engineering	7	5.84
International Journal of Engineering And Technology	4	3.34
International Journal of Electrical Power And Energy Systems	3	2.5
International Journal of Computers And Industrial Engineering	2	1.66
IEEE Transactions on Industry Applications	2	1.66
Journal of Mechanical Engineering And Technology	2	1.66
National Technical Information Service	2	1.66
South African Journal of Industrial Engineering	2	1.66
***Others (one reference of each journal)**	47	40
IEEE Proceedings	17	14.17

(B) National and International Conferences	16	14.16
(C) Misllaneous (books and thesis)**	2	1.66
Total	120	100

* American Journal of Applied Sciences, Journal of Engineering, Journal of Applied Mechanics and Materials, International Journal of Computers and Structures, International Journal of Control Engineering Practice, CSEE Journal of Power and Energy Systems, International Journal of Electric Power Systems Research, Journal of Electrical Generation and Distribution Systems and Power Quality Disturbances, International Journal of Energy, International Journal of Expert Systems with Applications, IEEE Systems Journal, IEEE Transactions on Energy Conversion, IEEE Transactions on Power Delivery, IEEE Transactions on Power Systems, IEEE Transactions on Reliability, International Atomic Energy Agency, Journal of IET Generation, Transmission & Distribution, International Journal of Control and Automation, International Journal of E-Business Development, Journal of International Business Research, International Journal of Physical Sciences, International Journal of Quality & Reliability Management, International Journal of Scientific & Technology Research, Journal of Engineering, Design and Technology, International Organization of Scientific Research (IOSR) Journal of Mechanical and Civil Engineering, Journal of Central South University, International Journal of Social, Behavioral, Educational, Economic, Business and Industrial Engineering, Journal of International Transactions on Electrical Energy Systems, Journal of Marine Policy, Journal of Mechanical Science and Technology, Journal of Loss Prevention in the Process Industries, Journal of Modelling and Simulation in Engineering, Journal of Mathematical Problems in Engineering, Journal of Nuclear Engineering and Design, Journal of Production Planning & Control, Procedia Computer Science, Procedia Techonolgy, Journal of Reliability Engineering, Journal of Risk and Reliability in Marine Technology, International Journal of Robotics and Computer Integrated Manufacturing, International scientific Journal of Transport Problems, International Journal of Reliability and Safety, International Journal of Advanced Manufacturing Technology.

2.3 Research Contribution in RCM

In this section, one hundred twenty research papers by various authors from different organizations from 1978 till Sepetmber, 2018 have been reviewed and classified into three categories based on the (i) Development, (ii) Implementation, and (iii) Application of RCM. The first research paper on RCM is published in 1978. Out of one hundred twenty (120) papers, twenty four (24) papers (20%) published in development, fourty two (42) papers (35%) in implementation, and fifty four (54) papers (45%) in the application category. Authors from thirty one (31) countries have published the research papers on RCM in which half of the papers were published from USA, Iran, China, Sweden and United Kingdom (UK). Distribution of all one hundred twenty (120) reviewed articles based on first author's country and year of publication are shown graphically in Figure 2.1 and Figure 2.2 respectively.

Based on the literature review, it has been observed that the research on RCM is being carried out in more than 13 sectors i.e. ***Power distribution*** (Abbasghorbani *et al.*, 2014; Adoghe *et al.*, 2012; Aldhubaib, 2013; Barai *et al.*, 2012; Bertling, 2005; Bertling *et al.*, 2005; Payman Dehghanian *et al.*, 2011, 2012, 2013a, 2013b, 2013c; Dehghanian and Fotuhi-Firuzabad, 2012; Fischer *et al.*, 2011; Goodfellow, 2000; Heo *et al.*, 2014; Jie *et al.*, 2005; Mansour and Noradin, 2015; Moradi *et al.*, 2018; Morais *et al.*, 2006; Penrose, 2005; Piasson *et al.*, 2016; Pourahmadi *et al.*, 2017; Purucker *et al.*, 1992; Reder and Flaten, 2000; Sarchiz et al., 2011; Siqueira, 2004; Smith and Hinchcliffe, 2004; Souza and Álvares, 2008; Tirapong and Titti, 2014; Yssaad *et al.*, 2014; Yssaad and Abene, 2015), ***Manufacturing*** (Abdul-Nour *et al.*, 1998; Ahmad and Karim, 2016; Altaf Tarar, 2014; Deshpande and Modak, 2002a; Dogahe and Sadjadi, 2015; Fore and Mshipha, 2010; Fore and Mudavanhu, 2011; Fuentes-Huerta *et al.*, 2018; Jasiulewicz-Kaczmarek, 2015; Kimura *et al.*, 2002; Pintelon et al., 1999; Pujadas and Frank Chen, 1996; Ramli and Arffin, 2012; Richet *et al.*, 1995; Singh *et al.*, 2010; Supsomboon and Hongthanapach, 2014; Zhou *et al.*, 2007), ***Airline*** (Ahmadi *et al.*, 2009; Crocker and Kumar, 2000; Hlinka, 1990; Kennedy, 2006; Leverette, 2006; Matteson, 1985; Mokashi *et al.*, 2002; Ning and Yujun, 2015; Nowlan and Heap, 1978; Pourjavad *et al.*, 2011), ***Nuclear power plant*** (Chen and Zhang, 2012; Huang *et al.*, 2012; Martorell *et al.*, 1996; NPES, 2007; Vasconcelos *et al.*, 2009), ***Steam & Hydro power plant*** (Afefy, 2010;

Backlund, 2005; Fischer *et al.*, 2012; Igba *et al.*, 2013; Narnaware *et al.*, 2014; Sabouhi *et al.*, 2016; Srikrishna *et al.*, 1996), ***Process*** (Albarkoly and Park, 2015; Chopra *et al.*, 2014, 2016; Fonseca and Knapp, 2000; Li and Gao, 2010; Liang *et al.*, 2012; Vishnu and Regikumar, 2016), ***Oil & Gas*** (Bevilacqua *et al.*, 2005; Prabhakar and Raj, 2013; Selvik and Aven, 2011; Tang *et al.*, 2017; Wei *et al.*, 2012), ***Construction*** (El-Haram and Horner, 2002; Neves *et al.*, 2004), ***Mining*** (Morad *et al.*, 2014), Transportation *(Bae et al.*, 2009), ***Railway*** (Carretero *et al.*, 2003; García Márquez *et al.*, 2003; Pedregal *et al.*, 2004), ***Marine*** (Jambulingam and Jardine, 1986; Mokashi *et al.*, 2002), ***Artificial intelligence*** (Cheng *et al.*, 2008; Cheng and Jia, 2005), and ***Ware house*** (Van Jaarsveld and Dekker, 2011). The distribution of reviewed papers in various industry sectors is presented graphically in Figure 2.3. From Figure 2.3, it is clear that half of the research papers published were from power distribution, manufacturing and airline industries. Table 2.3 presents the author's contribution in different industry sectors. The detailed literature review is presented in the following subsections.

2.3.1 Review based on the development of RCM

In this section, research papers based on the description and development of RCM are reviewed. A total of twenty four (24) papers are published from 1978 till September 2018. Nowlan F.S. (1978) first introduced the concept of RCM as a logical control for the improvement of a planned maintenance program for the airline industry. They discussed the development and implementation and provided the basic logic decision diagram for RCM. Matteson (1985) developed the RCM concept for the airline industry. He states that the first application of RCM was on Boeing - 747. The FAA and the DOD have in this way received it and connected to numerous new transport and military airplanes.

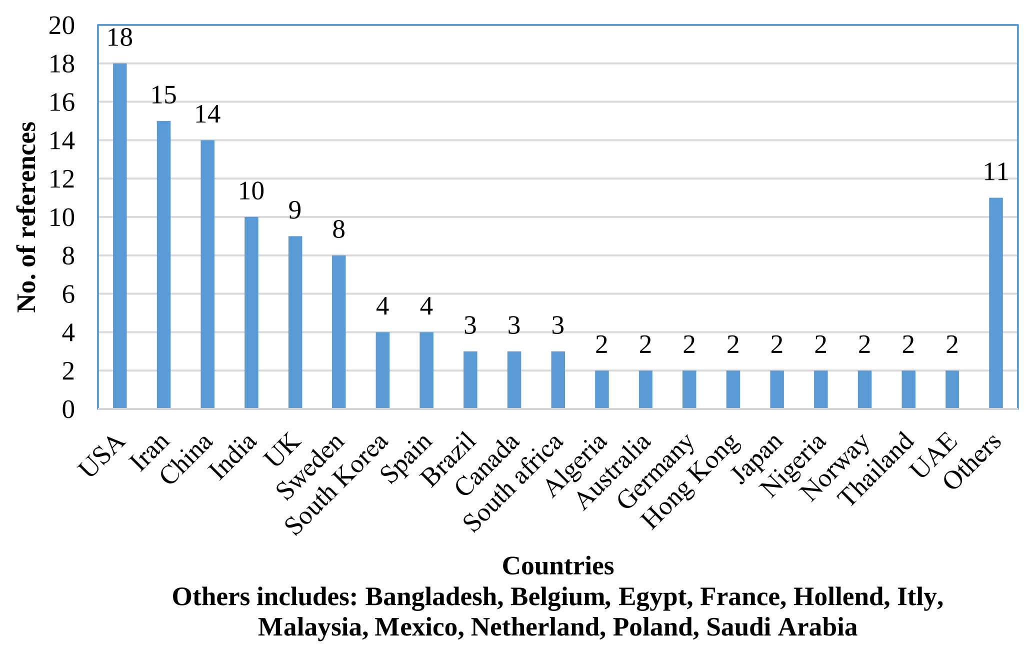

Figure 2.1: Distribution of reviewed papers by researchers from different countries (as per the first author)

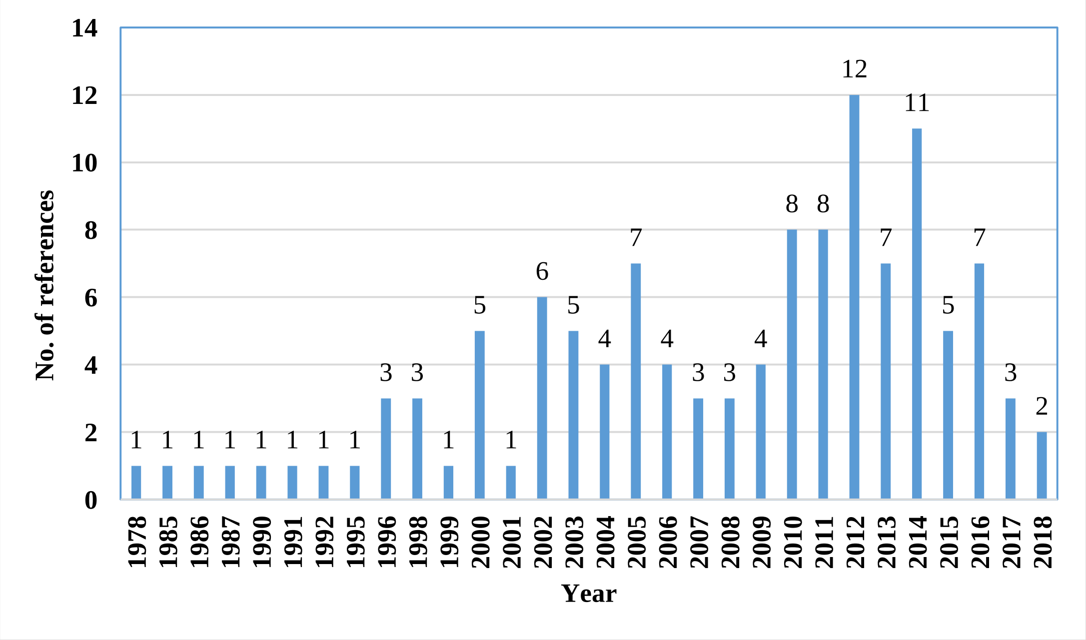

Figure 2.2: Year-wise distribution of reviewed papers

Kennedy (2006) and Leverette (2006) also introduced and developed the RCM for the airline industry. Many authors attempted to develop RCM in different sectors i.e. power distribution (Bertling, 2005; Morais *et al.*, 2006), oil & gas (Prabhakar and Raj, 2013; Selvik and Aven, 2011), manufacturing (Singh *et al.*, 2010), etc. after successful implementation in the airline industry. Year wise distribution of reviewed papers focused on the development of RCM is presented graphically in Figure 2.4. The detailed literature review of these is as follows.

Nowlan and Heap (1978) introduced the concept of RCM and discussed the development and implementation of an RCM program for Air-line industry. They provided the basic decision logic diagrams in RCM to evaluate proposed scheduled maintenance tasks, to distinguish noteworthy things and hidden functions based on failure outcomes and to evaluate the likely cost viability of a proposed assignment when planned maintenance isn't required to ensure working safety of the accessibility of concealed functions and so forth. As indicated by them, in a planned maintenance program, just three kinds of assignments should be performed i.e., assess a part to recognize a potential failure, to discover failures that have just happened however were not apparent to the component operating team, modify and dispose of a thing before a most extreme reasonable age is surpassed.

According to Matteson (1985), RCM has ended up being a profoundly powerful swap for the earlier natural procedures, for choosing PM tasks and to focus around keeping up innate safety and reliability at least expense. He presented the underlying knowledge in the development of RCM for the airline industry as the following characteristics: air transport design, operations, the role and kind of PM tasks, the definitions of functions and failure, and the effect of criticality, etc.

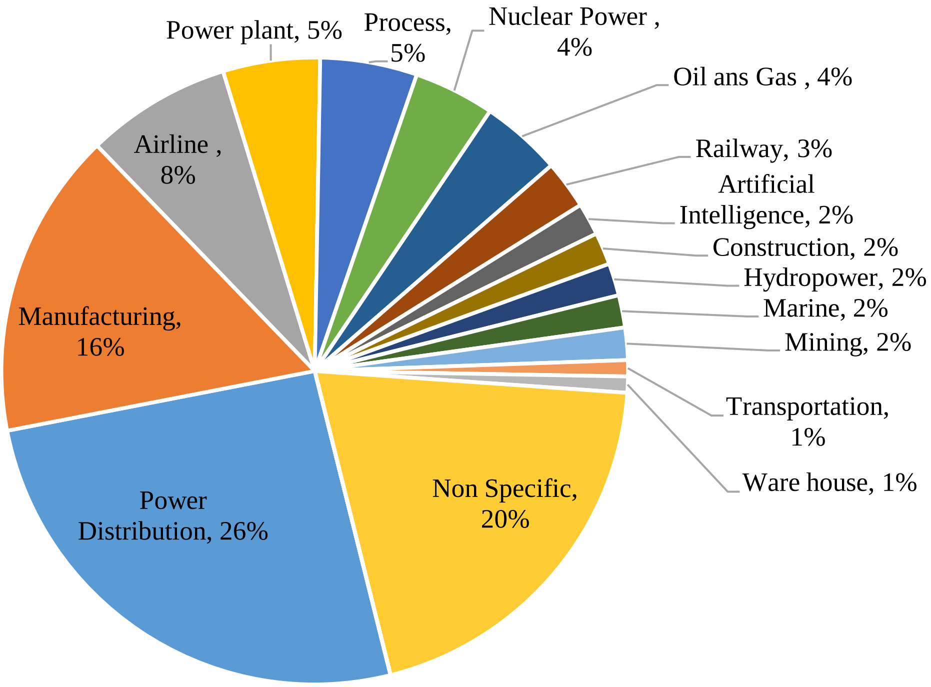

Figure 2.3: Distribution of reviewed papers in different industry sectors

Brauer and Brauer (1987) presented an overview of RCM concept and process to illustrate its practicability and flexibility as an effective engineering technique for developing a system maintenance program. They considered RCM as an extraordinary tool utilized by reliability and safety engineers. It was expressed that the utilization of decision logic empowers organized investigation of failure mode, rate, and criticality information to decide the best support prerequisites which are required for fruitful usage of RCM. They additionally discussed the advantages of RCM as (i) Improvement of high quality maintenance plans in a brief time and diminished cost, (ii) The accessibility of upkeep history of each system, (iii) Confirmation of thinking about the failure mode and criticality of each system in improving the upkeep program, and (iv) Premise of standard, online data trade among the staff and administration of an association.

Rausand (1998) and Rausand and Vatn (1998) presented a structured approach consisting of 12 steps for RCM. These steps are “(i) Study preparation (ii) System selection and definition (iii) Functional Failure Analysis (FFA) (iv) Critical item selection (v) Data collection and analysis (vi) FMECA (vii) Selection of maintenance actions (viii) Determination of maintenance intervals (ix) PM comparison analysis (x) Treatment of non-critical items (xi) Implementation and (xii) In-service data collection and updating".

It was expressed that the RCM technique gave a structure to use working background in a more orderly manner and concluded that the accomplishment of RCM depends partly on the accessibility of productive and user-friendly software i.e. Maintenance Management Software (MMS).

Table 2.3: Authors contribution in different industry sectors in RCM

Sector	References
Power distribution	Abbasghorbani *et al.* (2014); Adoghe *et al.* (2012); Aldhubaib (2013); Barai *et al.* (2012); Bertling (2005); Bertling *et al.* (2005); Dehghanian *et al.* (2011, 2012, 2013a, 2013b, 2013c); Dehghanian and Fotuhi-Firuzabad (2012); Fischer *et al.* (2011); Goodfellow (2000); Heo *et al.* (2014); Jie *et al.* (2005); Mansour and Noradin (2015); Moradi *et al.* (2018); Morais *et al.* (2006); Penrose (2005); Piasson *et al.* (2016); Pourahmadi *et al.* (2017); Purucker *et al.* (1992); Reder and Flaten (2000); Sarchiz *et al.* (2011); Siqueira (2004); Smith and Hinchcliffe (2004); Souza and Álvares (2008); Tirapong and Titti (2014); Yssaad *et al.* (2014); Yssaad and Abene (2015)
Manufacturing	Abdul-Nour *et al.* (1998); Ahmad and Karim (2016); Altaf Tarar (2014); Deshpande and Modak (2002b); Dogahe and Sadjadi (2015); Fore and Mshipha (2010); Fore and Mudavanhu (2011); Fuentes-Huerta *et al.* (2018); Jasiulewicz-Kaczmarek (2015); Kimura *et al.* (2002); Pintelon and Nagarur (1999); Pujadas and Frank Chen (1996); Ramli and Arffin (2012); Richet *et al.* (1995); Singh *et al.* (2010); Supsomboon and Hongthanapach (2014); Zhou *et al.* (2007)
Airline	Ahmadi *et al.* (2009); Crocker and Kumar (2000); Hlinka (1990); Kennedy (2006); Leverette (2006); Matteson (1985); Mokashi *et al.* (2002); Ning and Yujun (2015); Nowlan and Heap (1978); Pourjavad *et al.* (2011)
Nuclear power plant	Chen and Zhang (2012); Huang *et al.* (2012); Martorell *et al.* (1996); NPES (2007); Vasconcelos *et al.* (2009)
Steam &	Afefy (2010); Backlund (2005); Fischer *et al.* (2012); Igba *et al.* (2013); Narnaware

Hydropower plant	*et al.* (2014); Sabouhi *et al.* (2016); Srikrishna *et al.* (1996)
Process industries	Albarkoly and Park (2015); Chopra *et al.* (2014, 2016); Fonseca and Knapp (2000); Li and Gao (2010); Liang *et al.* (2012); Vishnu and Regikumar (2016)
Oil & Gas	Bevilacqua *et al.* (2005); Prabhakar and Raj (2013); Selvik and Aven (2011); Tang *et al.* (2017); Wei *et al.* (2012)
Construction	El-Haram and Horner (2002); Neves *et al.* (2004)
Mining	Morad *et al.* (2014)
Transportation	Bae *et al.* (2009)
Railway	Carretero *et al.* (2003); García Márquez *et al.* (2003); Pedregal *et al.* (2004)
Marine	Jambulingam and Jardine (1986); Mokashi *et al.* (2002)
Artificial Intelligence	Cheng *et al.* (2005, 2008)
Ware house	Van Jaarsveld and Dekker (2011)

They have also identified a few advantages i.e. cross-discipline use of knowledge, traceability of decisions, enrollment of skilled persons for maintenance preparation and implementation, cost aspects, and problems encountered as identification of maintenance significant items, lack of reliability data, trade-off analysis, assessing proper interval during the use of the RCM technique in few offshore case studies.

Backlund and Akersten (2003) proposed an RCM necessity administration approach dependent on process and prerequisite administration standards. They presented RCM in a Swedish hydropower organization and talked about the issues and inadequacies which moved towards becoming snags to advance of RCM introduction as "lack of Computerized Maintenance Management System (CMMS), RCM computer system, plant register, unavailability of documentation and information, communicating problems, lack of overcharging maintenance management strategy". It was expressed that introduction of RCM involves the no. of stages, i.e., "an initiation, a pilot study, planning and preparation, an analysis, an implementation, and a living program phase".

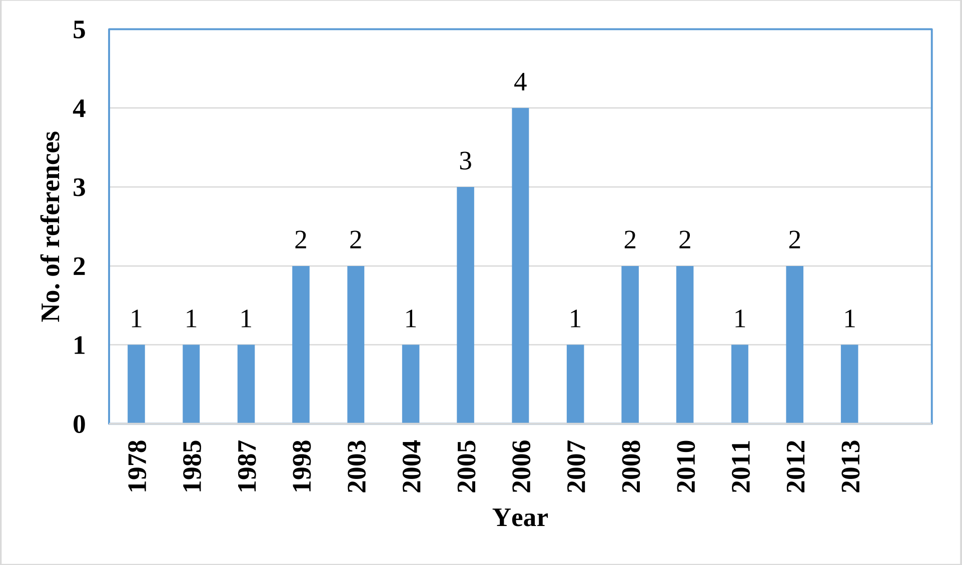

Figure 2.4: Year-wise distribution of reviewed papers focused on the development of RCM

Gabbar *et al.* (2003) presented the limitations of a classical RCM as: “time and effort consuming process, not enough information available to select the appropriate maintenance plan”. To overcome these drawbacks, they proposed an enhanced RCM process integrated with CMMS.

Smith and Hinchcliffe (2004) presented the four important features to describe and distinguish the RCM: “preserve system function, identify failure modes that can defeat the function, prioritize functional need, and select applicable and effective PM tasks for the high priority failure modes”. To implement these features, a RCM process was developed consisting of seven steps: “(i) System selection and information collection (ii) System boundary definition (iii) System description and functional block diagram (iv) System functions and functional failures (v) FMEA (vi) Logic Tree Analysis (LTA) (vii) Task selection” and two additional steps “(viii) Task packaging, and (ix) Living RCM (LRCM) program” were proposed to make a complete RCM program.

Bertling (2005) and Bertling *et al.* (2005) proposed a Reliability-Centered Asset Maintenance (RCAM) approach which was created based on RCM standards and incorporates building up a quantitative connection between system reliability and maintenance endeavors. The important steps of this methodology are "system reliability analysis, component reliability modeling, system reliability and cost/benefit analysis". A functional correlation between failure rate and maintenance measures has been created for a cable part. Results demonstrate that RCAM strategy can be utilized to thought about various maintenance techniques and PM methodologies dependent on the aggregate cost of maintenance, which incorporates the effect of the PM measure on the system reliability.

Cheng *et al.* (2005, 2008, 2010) presented strategies incorporating Artificial Intelligence (AI), such as, Case-Based Reasoning (CBR) and Rule-Based Reasoning (RBR) into RCM procedure to enhance the proficiency of RCM, and an Intelligent RCM Analysis System (IRCMAS) using CBR and RBR was developed. The use of the IRCMAS decreases the prerequisite ability needed of RCM experts, abbreviates the improvement time of the RCM program, and upgrades the cost adequacy of the RCM process.

Morais *et al.* (2006) demonstrated the RCM for capacitor voltage transformers, which has been developed based on the experience of maintenance teams of a critical Brazilian power transmission organization. Measurable evaluation of failures in that organization has been performed, with an end goal to contemplate a large number of failure potential outcomes.

Kennedy (2006) defined RCM as a structured and logical process with two key elements; Decision/logic diagram and FMECA, and seven steps. The key distinction between RCM and Total Productive Maintenance (TPM) was examined as RCM was developed as a maintenance enhancement technique though TPM perceives that the maintenance alone can't enhance reliability.

Leverette (2006) proposed the NAVAIR RCM process with four major steps: planning and preparation, analysis, implementation, and sustaining the program and implemented with the help of Integrated RCM system software.

Vasiu (2007) presented the RCM perspective on maintenance along with a brief introduction to the major principles. He described RCM with seven steps as "(i) Prepare for the analysis, (ii) Select the equipment to be analyzed, (iii) Identify functions, (iv) Identify functional failures, (v) Identify and evaluate (categorize) the effects of failure, (vi) Identify the causes of failure, and (vii) Select maintenance tasks". The RCM procedure was applied to the service brakes of motorcars.

Singh *et al.* (2010) presented a relationship between RCM and TPM and discussed the ten main stages of RCM and four main stages of TPM. It was concluded that it is troublesome for the plant administration to choose whether RCM is more gainful to TPM.

Selvik and Aven (2011) proposed that RCM is a precise investigation technique for scheduling the PM and proposed a Reliability and Risk Centered Maintenance (RRCM) framework by incorporating risk as the reference. A case from the oil and gas industry is displayed to show the relevance of RRCM. The RRCM framework was developed based on the existing RCM, with additional features of uncertainty analysis.

Chen and Zhang (2012) developed a framework for Reliability & Technique Centered Maintenance (RtCM) to remove the issues of traditional RCM. The issues of traditional-RCM was presented as “(i) Lack of analysis of the generic devices, (ii) Lack of effective technical criteria to determine the condition monitoring, (iii) Lack of effective quantitative analysis model for maintenance interval, and (iv) Large resources input, long life cycle analysis”. RtCM introduced identification of critical component, through the analysis of functional failures and concluded that analysis of the component inside the limits could be utilized to recognize and separate the critical and non-critical components. Furthermore, in the handy utilization of enhanced strategies, RtCM endeavored to acquaint a quantitative estimate to the selection of system and determination of the maintenance interval. However, it was not productive as it was time-consuming task.

Huang *et al.* (2012) discussed current issues of conventional RCM as “lacking quantificational facility on importance analysis, technical state estimate, and maintenance policy” and presented an enhanced RCM technique. A framework for armament component depot-level maintenance policy was built up, which offered logical establishment for the foundation of depot-level maintenance policy.

Prabhakar and Raj (2013) introduced RCM as a proven tool for continuous reliability improvement and elucidated the limitations of conventional RCM as a reasonable likelihood, FMECA, sub-optimality. To overcome these limitations, an accelerated RCM (A-RCM) was developed for an oil refinery. Prevalent failure modes of the plant or location from the equipment history or the output of the existing Root Cause Failure Analysis (RCFA) program were the key inputs of the developed model. A methodology for implementation of Accelerated RCM (ARCM) with four stages: (i) Reliability audits and analysis (ii) Identifying likely failure modes (iii) FMECA on critical equipment and (iv) Sustaining the program were proposed.

2.3.2 Review based on the implementation of RCM

In this section, research papers related to the new development of a method, a process, an approach or a framework to implement the RCM in various industry sectors are reviewed. A total of fourty two (42) papers are published on only implementation work for RCM from 1978 to September 2018. Many researchers attempted to develop, a ***qualitative and quantitative approach*** (Pintelon *et al.*, 1999; Crocker and Kumar, 2000; Reder and Flaten, 2000; Eisinger and Rakowsky, 2001; Mokashi *et al*., 2002; Awad and Afif Asad, 2016)***, mathematical models*** (Bae *et al.*, 2009; Heo *et al.*, 2014; Singh and Suhane, 2014; Piasson *et al.*, 2016, Moradi *et al.*, 2018), ***software*** (Sarchiz *et al.*, 2011; Barberá *et al.*, 2011, Vasconcelos *et al.*, 2009), ***framework*** (Fonseca and Knapp, 2000; Dehghanian *et al.*, 2013a, 2013b)***, establishment of the importance of training and data management*** **(**Chopra *et al.*, 2014), ***model for identification of critical components*** (Dehghanian and Fotuhi-Firuzabad, 2012; Dehghanian *et al.*, 2011, 2012; Martorell *et al.*, 1996; Sabouhi *et al.*, 2016; Pourahmadi *et al.*, 2017) ***to implement the RCM mainly for Airline*** (Ahmadi *et al.*, 2009; Crocker and Kumar, 2000; Pourjavad *et al.*, 2011), ***process*** (Chopra *et al.*, 2014; Fonseca and Knapp, 2000; Vishnu and Regikumar, 2016), ***manufacturing*** (Fuentes-Huerta *et al.*, 2018; Jasiulewicz-Kaczmarek, 2015; Kimura *et al.*, 2002; Pintelon *et al.*, 1999; Ramli and Arffin, 2012), ***nuclear power*** (Martorell *et al.*, 1996; Vasconcelos *et al.*, 2009), ***Oil and Gas*** (Tang *et al.*, 2017), and ***power distribution*** (Adoghe *et al.*, 2012; Dehghanian *et al.*, 2012, 2011, 2013a, 2013b; Fischer *et al.*, 2012;

Heo *et al.*, 2014; Moradi *et al.*, 2018; Piasson *et al.*, 2016; Pourahmadi *et al.*, 2017; Reder and Flaten, 2000; Sabouhi *et al.*, 2016; Sarchiz *et al.*, 2011) industry sector. Year wise distribution of reviewed papers based on the development of RCM is presented graphically in Figure 2.5. The detailed literature review of this section is as follows.

Martorell *et al.* (1996) proposed a methodology for prioritization to critical equipment to implement the RCM in the atomic power industry using Core Damage Frequency (CDF) approach. A simplified CDF model was embraced as a hazard measure, which augments the number of essential events related with equipment having a place within the system under study that becomes visible in the last rankings of fundamental events.

Pintelon *et al.* (1999) developed and customized the maintenance concepts with an end goal to more likely fit the particular needs regarding technical and managerial prerequisites of the organization to execute the RCM in an automobile company. The researchers concentrated fundamentally on the most proficient method to decide the ideal maintenance concept.

Crocker and Kumar (2000) proposed another way to implement RCM utilizing the ideas of soft and hard life to optimize the aggregate maintenance cost. Soft life was characterized as the age of the segment after which it will be rejected whenever the engine or one of its modules, containing it, is recuperated. Hard life was characterized as the age of the part, at or by which the segment must be supplanted. After accomplishing this age, the system containing the given segment will be rejected for ensuing recuperation. The proposed model was implemented to locate the ideal maintenance strategies on account of military aero-engines utilizing Monte Carlo reproduction.

Fonseca and Knapp (2000) developed another framework to implement RCM in the initial periods of the process design and actualized in the chemical industry. An estimated interpretation scheme which thinks about local, product, and adjacent machinery impacts was made to organize the component failure modes prone to encourage in the chemical process. A computer system was proposed which reads the process flowsheet dependent on the pertinent machine working information and produces the final RCM accessibility structure chart.

Reder and Flaten (2000) identified the technical steps like establish the scope, identify what is not in the scope, specify performance goals, identify the problem, identify resources available and create necessary procedures to implement RCM on an underground distribution cable.

Mokashi *et al.* (2002) discussed in particular issues prone to be experienced in implementation of RCM on ships such as “(i) Lack and portability of failure data, (ii) Basic equipment condition could not be taken for granted, (iii) Shipboard personnel are rarely trained in maintenance management or risk assessment techniques, especially those that require a statistical approach, (iv) Shipboard personnel are already overburdened, (v) Ships operate in isolation from repair and spares facilities, (vi) Lack of adequate redundancy, (vii) Rigid prescriptive requirements of various regulatory bodies, (viii) Recommendations from equipment suppliers have be to followed in the guarantee period, (ix) Equipment suppliers do not give an FMEA, (x) RCM analysis results are unique to each operating context,and (xi) Ships crew keeps changing”. It was concluded that instead of taking a gander at RCM as an approach and endeavoring to utilize it in that capacity, it helps well to consider it as a philosophy and utilize its controlling standards to help a more secure plan to maintenance technique.

Kimura *et al.,* (2002) proposed a computer-aided FMEA and its fundamental concepts for the implementation of RCM. FMEA is a great technique to broadly explore potential machine failure and to forecast reliability of a system. For approving the projected computer-aided FMEA approach, a few tests were performed on mechatronics items.

Bae *et al.* (2009) presented an advanced RCM process utilizing computational procedures, for example, Reliability Growth Analysis (RGA), and connected the technique on an urban transportation system, specifically, a standard Electric Motor Unit (EMU) subsystem. The fundamental idea of the proposed RCM was the enhancement of the RCM-based maintenance time.

Ahmadi *et al.* (2009) described similarities and contrasts among RCM and Prognostics & Health Management (PHM). Besides, the paper depicted a few parts supplementing RCM and PHM one another and sort of adjustments that must be done to accomplish fruitful incorporation for flying aircraft.

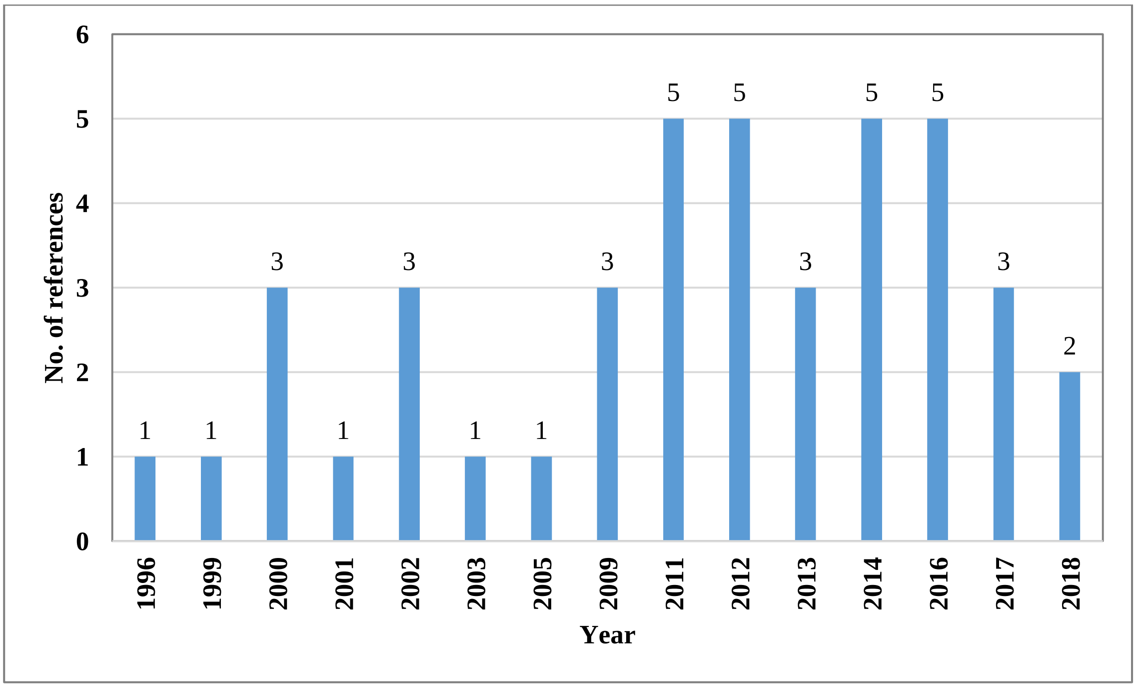

Figure 2.5: Year-wise distribution of reviewed papers related to the implementation of RCM

Dehghanian *et al.* (2011, 2012) and Dehghanian and Fotuhi-Firuzabad (2012) proposed a qualitative-quantitative approach using Analytic Hierarchical Process (AHP) and Fuzzy AHP to identify the critical components for the implementation of RCM. They proposed five criteria as “total number of components, the total number of component failures, component repair duration, component investment cost, component repair, and maintenance cost” to determine the most critical components. Dehghanian and Fotuhi-Firuzabad (2012) developed a method with reliability point of view to identify the most critical component in power distribution systems. The developed method was implemented on the “Stockholm city distribution test system, i.e. the BIRKA system”.

Sabouhi *et al.* (2016) developed a novel risk-based framework for a criticality estimation of plant components to perform more focused maintenance strategies for the implementation of RCM. Critical components were recognized by evaluating “their failure effect on system reliability, electric safety, cost, and the environment”. The developed method was implemented on a real Combined Cycle Power Plant (CCPP) in Iran.

Pourjavad *et al.* (2011) analyzed RCM indicators, i.e. Mean Time to Repair (MTTR) and Mean Time Between Failures (MTBF) in the mining industry and identified their dependency on production quantity and stated that while implementation of RCM, MTTR, and MTBF does not depend on the production quantity.

Barberá *et al.* (2011) proposed a method to evaluate RCM software that depends on a group of factors, i.e. “RCM methodology alignment, organizational needs fulfillment, software performance and software implementation at the operational and organizational levels”.

Sarchiz *et al.* (2011) proposed a model using optimization strategies to implement RCM for Electric Distribution Systems (EDS).

Ramli and Arffin (2012) demonstrated a study on RCM usage in the preventive maintenance strategies for an automobile organization. The RCM has been utilized to evaluate and execute a decision-making process based on RCM decision-making diagram tool in which maintenance policy should be selected based on the criticality of the component. An FMEA has been performed to evaluate the criticality of the component.

Bugaj (2012) discussed the RCM process analysis steps as “functional failures, failure modes, and failure analysis” and concluded that the failure analysis is the basic step to implement RCM in aviation.

Dehghanian *et al.* (2013a, 2013b) presented a practical framework for the implementation of RCM procedure for power distribution systems. The framework includes the three stages, i.e. “pre, main and post analysis” of RCM. In the first stage, the pre requirements of the study were outlined, a methodology was developed to determine the critical components from the reliability perspective in the second stage and in the third stage, the analysis was completed by accounting both technical and financial outcomes for a selection of the maintenance strategies. A case study of the proposed method has been done on a distribution system in Sweden.

Johnson (2013) presented that the conventional practices to perform the criticality analysis are deficient and proposed a strategy using Moubray’s P-F interval and hidden/evident criteria that is repeatable and instructive for criticality analysis. It was concluded that without FMECA of important components RCM couldn't be properly implemented.

Chopra *et al.* (2014) presented that role of training and data management is important for the implementation of RCM, and concluded that training and data management is key for successful implementation of RCM.

Pourahmadi *et al.* (2017) proposed an efficient method using game theory to evaluate the criticality of a component for the reliability of a system. Another optimization framework was also proposed to implement RCM in power systems with the involvement of identified critical components.

Vishnu and Regikumar (2016) proposed a model using optimal maintenance strategies for each component based on its criticality and FMEA to implement RCM in process plants. The proposed model was verified with the maintenance data of a titanium dioxide manufacturing process plant.

Piasson *et al.* (2016) proposed a multiobjective model to illuminate the mathematical problem of optimizing RCM scheduling of an Electric Power Distribution System (EPDS). The primary objective was to limit the PM costs while boosting the index of reliability of the entire system. The reliability indices of the EPDS segments were assessed and updated using a fuzzy inference system.

Emovon *et al.* (2017) presented a literature survey of three major elements of a maintenance system i.e "risk assessment, maintenance strategy selection, and maintenance task interval determination of a maintenance system" to provide appropriate information relating to the requirement for researchers. It was concluded that tools used within the framework of RCM for the advancement of the above three major elements have impediments and there is a need to develop another methodology that avoid such impediments.

Moradi *et al.* (2018) proposed a model for the implementation of RCM in microgrids. To identify the critical component of a system using a decision-making process was the main element of the developed framework to implement RCM. A Multi-Attribute Decision-Making (MADM) approach in conjunction with a reliability-driven Criticality Factor (CF) was used to establish the weights of RCM attributes and identification of the critical components.

2.3.3 Review based on the application of RCM

In this section, research papers related to ***optimization of maintenance strategies*** (Niu *et al.*, 2010; Rose *et al.*, 2010; Siqueira, 2004; Yssaad *et al.*, 2014; Yssaad and Abene, 2015), ***reliability improvement*** (Tirapong and Titti, 2014), ***productivity improvement*** (Morad *et al.*, 2014), ***machine efficiency improvement*** (Supsomboon and Hongthanapach, 2014), ***development of computerized facility maintenance management system*** (Lee *et al.*, 2013), ***FMEA and Fault Tree Analysis (FTA)*** (Souza and Álvares, 2008), ***spare parts stock control for redundant systems*** (Van Jaarsveld and Dekker, 2011), ***financial planning for the PM*** (Mansour and Noradin, 2015), ***analysis of repair level for missile*** (Ning and Yujun, 2015) using the application of existing RCM approach are reviewed. In addition to these, many authors contributed to research based on direct application of existing RCM in various sectors, i.e. Airline (Hlinka, 1990; Wang *et al.*, 2007), Construction (El-Haram and Horner, 2002; Neves *et al.*, 2004), Manufacturin***g*** (Abdul-Nour *et al.*, 1998; Ahmad and Karim, 2016; Altaf Tarar, 2014; Deshpande and Modak, 2002b; Dogahe and Sadjadi, 2015; Fore and Mshipha, 2010; Fore and Mudavanhu, 2011; Pujadas and Frank Chen, 1996; Richet *et al.*, 1995), Marine (Jambulingam and Jardine, 1986), Nuclear power (Huang *et al.*, 2012), Oil and Gas (Bevilacqua *et al.*, 2005; Wei *et al.*, 2012), Power distribution (Abbasghorbani *et al.*, 2014; Aldhubaib, 2013; Barai *et al.*, 2012; Goodfellow, 2000; Jie *et al.*, 2005; Penrose, 2005; Purucker *et al.*, 1992), Power plant (Afefy, 2010; Fischer *et al.*, 2012; Igba *et al.*, 2013; Srikrishna *et al.*, 1996), Process industry (Chopra *et al.* 2016; Albarkoly and Park, 2015; Li and Gao, 2010; Liang *et al.*, 2012), Railway *(Carretero et al., 2003; García Márquez et al.*, 2003; Pedregal *et al.*, 2004). A total of fifty four (54) research papers were published on the application of RCM from 1978 to September 2018. Year wise distribution of reviewed papers on the application of RCM is presented graphically in Figure 2.6. A detailed review presented as follows;

Jambulingam and Jardine (1986) demonstrated the combination of RCM and Life Cycle Costing (LCC) for a chiller unit. The failure and censor perceptions were used in Weibull analysis of the chiller unit. It was concluded that the RCM approach is an efficient tool to float from the conventional hard time maintenance to on-condition or health monitoring maintenance with the end goal to limit maintenance costs.

Hlinka (1990) emphasized the application of RCM in the small transport aircraft category and concluded that RCM slowly penetrates to commuter aircraft and its application can also reduce operating costs.

Smith *et al.* (1991) stated that RCM program support corporate Total Quality Maintenance (TQM) objectives for accomplishment of consumer loyalty through the generation and conveyance of value products and concluded that RCM focuses on the maintenance function' through the identification of particular component failure modes that tries to improve PM activities for boosting availability and reliability.

Purucker *et al.* (1992) proposed an RCM model for Bonneville Power Administration (BPA)'s substation maintenance constrained to transformers and breakers and exhibited the functional prerequisites for the proposed RCM framework in three territories, i.e. hardware, decision support, and software. They presented the seven RCM objectives for BPA system i.e. reduce maintenance costs, optimize maintenance resources, optimize maintenance tasks, optimize RCM instrumentation, enhance safety, improve cm/pm ratio, provide life extension.

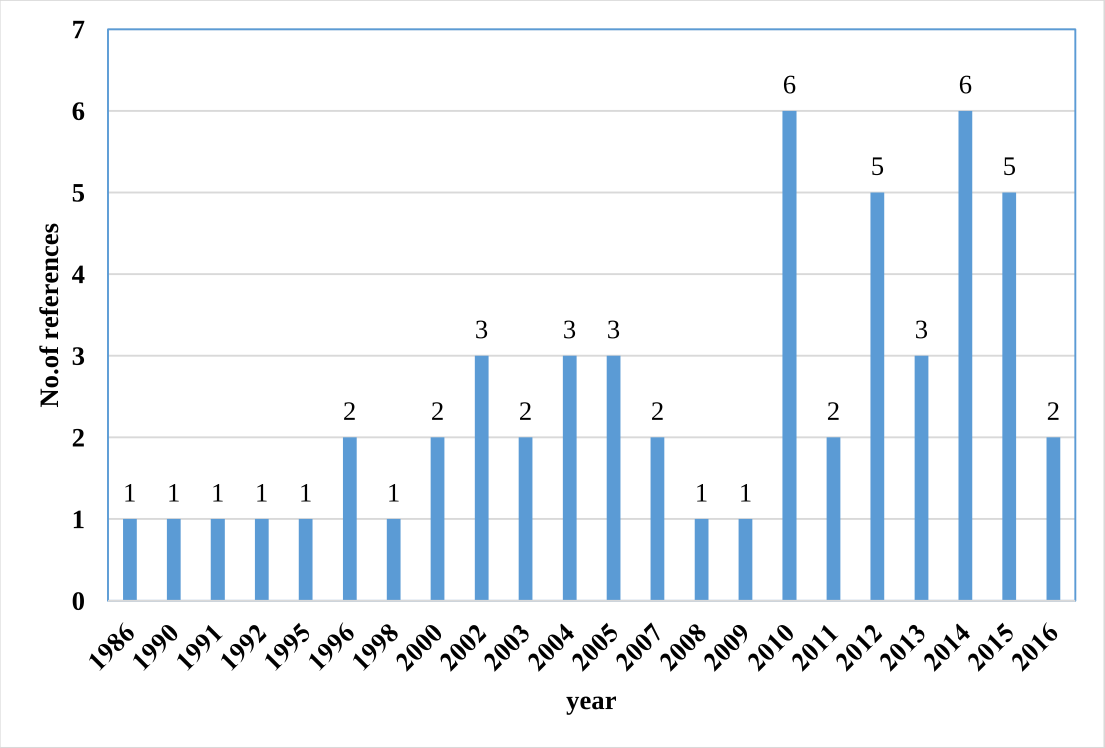

Figure 2.6: Year-wise distribution of reviewed papers based on the application of RCM

Richet *et al.* (1995) applied RCM approach in fifteen similar foundries and it turned out to be an especially an all around technique. The adjusted methodology for the association of maintenance in such associations where the absence of assets is a noteworthy imperative. Pujadas and Frank Chen (1996) developed a specific maintenance decision support system depending on RCM and the USA branch of Defense's FMECA. An LTA was used to help the decision procedure by performing the maintainability assessment,.

Srikrishna *et al.* (1996) presented a maintenance strategy for coal-based power plant situated in light of the RCM to deal with prominence the greatest accessibility of the component at an ideal maintenance cost.

Abdul-Nour *et al.* (1998) described a method for selection of critical components and development of an ideal maintenance strategy using reliability information of every component, lead time and repair time, safety consequences of system failure for an aluminum plant. Criticality of components was calculated using different factors, i.e. “effect of the machine downtime, safety and environmental incidence of machine failure, the utilization rate of the machine, the technical complexity of the machine and need of external maintenance resources”.

Ben-Daya (2000) presented the relationship between TPM and RCM and concluded that RCM has played an imperative role in TPM implementation successfully.

El-Haram and Horner (2002) conducted a comparative analysis of RCM and FMECA for construction projects, and a direct study was done on 18 houses drawn from Dundee city council housing stock. The advantages of applying RCM to existing building stock was assessed and concluded that RCM could prompt a decrease of 18.5 percent in maintenance costs.

Deshpande and Modak (2002a, 2002b) applied RCM in steel melting shop of a medium scale steel organization for the process of “vacuum degassing/vacuum oxygen decarburizing”. Safety consideration was the significant aspect for selection of the system. PM activities for example “inspection/checking, cleaning, lubrication, replacement, and adjustment were selected for different failure modes to protect the function of a system. Neves *et al.* (2004) proposed a model considering the connection between maintenance cost and its impact on the reliability index utilizing RCM. This model was utilized to look at the cost-viability of different maintenance policies for a disintegrating structure.

Siqueira (2004) used RCM for the power distribution system to optimize the maintenance intervals among various activities. Penrose (2005) used RCM philosophy to select the electrical motor investigation techniques for rotating machines.

Zhou *et al.* (2007) used a reliability-centered predictive maintenance method for a constantly observed system subject to degradation because of the flawed maintenance and assumed that the system is persistently observed and the failure rate function in present maintenance cycle can be determined specifically through condition-based predictive maintenance.

Souza and Álvares (2008) performed an analysis on FMEA and FTA for the study of failures and to assess the effect of the RCM on a power generating system.

Niu *et al.* (2010) and Niu and Pecht (2009) presented a Condition Based Maintenance (CBM) system for development of maintenance concept regarding “condition monitoring, health assessment, and prognostics” that includes RCM to optimize maintenance cost and employs data fusion strategy. The benefits were summarized as cost-effectiveness, accuracy, and generality.

Li and Gao (2010) used RCM considering redical maintenance and applied in the petrochemical industry. Fore and Mshipha (2010) used traditional RCM approach based on FMEA to manage PM for a ferrochrome processing plant. They selected electric arc furnace as critical equipment and applied RCM decision logic based on the FMEA analysis. It was proved that maintenance cost had been reduced by 20 % after implementing RCM.

Van Jaarsveld and Dekker (2011) proposed an approximate and analytical approach to identify the least amount of stock in case of redundant and multiple component systems using RCM. (Fore and Mudavanhu, 2011) used the RCM approach to improve the plant maintenance in a chipping and sawmill company.

Barai *et al.* (2012) applied RCM methodology for Goliath crane of transmission tower industry which is used to transfer raw material from raw material yard to different machines in the fabrication shop. It was concluded that RCM could utilized for Indian organization to reduce the no. of failures and optimize the PM cost.

Liang *et al.* (2012) evaluated a reciprocating compressor using RCM, "to decrease the ambiguity of maintenance, the number of system failures and its impacts and to encourage operational safety" using FMEA. After that, risk matrix and logic determination method were proposed to evaluate the importance of failure mode and to develop the maintenance plan for the high-risk faults respectively.

Igba *et al.* (2013) used RCM for the maintenance activities of wind turbine gearbox and optimize the importance of resources to minimize the total cost to the operator.

Lee *et al.* (2013) proposed a CMMS depended on a combination of RCM and automated data gathering using multi-agent technology and implemented in an automobile company in Korea.

Yssaad *et al.* (2014) utilized the RCM to optimize the maintenance management based on the FMECA analysis of Electric Feeder System. To make sure safety through PM actions economically preserve the functions were used as the two primary objectives of RCM.

Altaf Tarar (2014) presented the selection of predictive maintenance based on RCM rather than PM to recognize causes of forthcoming failures and concluded that an organization could accomplish improved production and quality leading to a competitive advantage with successful RCM implementation through selection of a suitable maintenance plan.

Tirapong and Titti (2014) introduced a method for the forecast, assessment, and enhancement of reliability for a distribution system. The method depended on power interruption analysis, maintenance costs and proper selection of maintenance strategies utilizing RCM.

Morad *et al.* (2014) researched on the utilization of ideal maintenance process for reducing the component failures for the trucks in “Sungun Copper Mine” using RCM. Generalized Renewal Process (GRP) and Renewal Process (RP) technique were used for repairable and non-repairable components to perform the probabilistic failure process.

Supsomboon and Hongthanapach (2014) applied RCM to increase machine reliability. The critical components of the test machine were examined in a case study, where the machine behavior and outcomes were obtained by using a Pro Model-based simulation model. The critical components were selected based on RPN from FMEA. It was concluded that to improve equipment reliability; the critical components required immediate attention based on essential historical data quantitatively.

Yssaad and Abene (2015) presented the application of the new rational RCM model to optimize the maintenance management for power distribution components and concluded that this approach improves the reliability and availability of the electrical systems and also increases the person’s safety.

Albarkoly and Park (2015) utilized RCM in cement factories of Libya for the improvement of maintenance policies and identified the issues which obstruct the accomplishment of the maintenance policies used in cement plants of Libya. It was concluded that RCM depends upon the identification of components whose failure can cause unwanted outcomes and specifically influence the stability of production in a factory.

Rezk *et al.* (2016) applied RCM methodology to the safety injection system. FMECA was applied to evaluate the failure modes and the effect on the component, system, and plant. LTA was used to determine the optimum maintenance tasks and concluded that implementing RCM will reduce component failure and improve reliability and availability of the system.

Chopra *et al.* (2016) developed the relationship between RCM implementation factors and productivity enhancement of process industries. They have highlited that proactive maintenance can be consider to improve the productivity and profitability of the enterprises.

2.4 Research Gaps

Following research gaps are identified from the literature review of RCM:

- From the literature review, it has been observed that there is a need to develop a framework for the implementation of RCM which can use both quantitative as well as qualitative analysis together at the same time of a system. Literature review reveals that none of the framework is available that can be implemented to take care of both quantitative and qualitative analysis of a system. Most of the frameworks were based on the qualitative analysis, and a few frameworks were based on quantitative analysis of a system.

- It has been observed that there is a need to develop a criticality analysis model for identification of criticality levels of components/subsystems of a system. Most of the articles in literature focus on the identification of the critical failure modes of the components using FMECA, but a little work has been done on how to identify the criticality levels of components/subsystems of a system. Performing FMECA for a number of components is a more complex and time-consuming activity. Rather, first find out the most critical component of a system and then perform the FMECA for that particular component will be most effective and less time-consuming in the RCM.
- It has been observed that there is a need to consider a better approach rather than the conventional approach of FMECA for the criticality analysis of a system or component to determine the appropriate maintenance actions for the implementation of RCM. Literature review reveals that the criticality analysis in RCM frameworks is limited to conventional FMECA approach only. However, criticality analysis using the conventional FMECA approach reported a number of shortcomings in the literature due to its determination of RPN.
- Review of RCM reveals that none of the researchers have included the comparison of system reliability after the implementation of the determined maintenance actions based on FMECA. Just to incorporate the determination of maintenance actions based on the FMECA in RCM framework is not enough, so there is a need to

incorporate the comparison of system reliability in RCM framework and to develop a model for determination and comparison of system reliability.

- It has been observed that there is a need to develop a decision logic model for the determination of appropriate maintenance actions based on the outcomes of criticality analysis. A few researchers have been focused on a particular method or model of decision logic to determine the appropriate maintenance actions in literature.

CHAPTER 3

SWOT ANALYSIS OF RCM FRAMEWORKS

This chapter presents SWOT analysis of nineteen existing RCM frameworks, which are selected from the preliminary literature review for a comparative study based on the different elements of these frameworks. These frameworks are categorized into three groups based on their emphasis on qualitative, quantitative, or practical application aspects. The SWOT analysis is performed to identify strengths, weaknesses, opportunities, and threats of each framework.

3.1 Introduction

A repeatable and consistent methodology is one of the most important requirement for the successful implementation of RCM. From the literature review, it has been observed that there is a lack of structured and implementable procedure for RCM and it is established that a structured implementation process is one of the success factor for the RCM in an organization. In this chapter, to overcome this issue, SWOT analysis is performed on the available RCM frameworks to recognize strengths, weaknesses, opportunities, and threats of these frameworks.

SWOT analysis initially developed for the business management literature. From the background of SWOT, it can be identified that it was originated from the need to realize why a business preparation failed and the researchers at Stanford Research Institute have developed it. It assesses an organization’s inside qualities and shortcomings and its external circumstances and intimidation. It is a significant tool since it focuses on the key elements of an organization’s situation inside a market. The objective of SWOT is to distinguish the degree to which the present methodology of an organization and what particular strengths and weaknesses are pertinent to, and fit for managing the progressions occurring with the business condition.

A SWOT analysis (Dalu and Deshmukh, 2001; Piercy and Giles, 1989; Weihrich, 1982) means to set up an organization for issues, which may emerge, taking into account the improvement of emergency courses of action. Strengths refer to innate capacities to contend. Weaknesses are the natural inadequacies that disabled growth and survival. Opportunities are the great shots and accessible for development. Threats are remotely employed difficulties, which might smother intrinsic strengths, quicken weaknesses. To prevail in any field, weaknesses must be defeated through strengths and threats must be changed into opportunities.

Ghazinoory *et al.* (2011) published a review paper on SWOT analysis. They have been found a significant work in more than five hundred fifty (550) research papers for making a strategic decision using SWOT analysis in many areas like manufacturing, transportation, IT, construction, electronics, oil & gas industries, etc..

Mishra *et al*. (2008) and Mishra and Chakraborty (2014) developed a SWOT analysis for the frameworks of total productive maintenance, world-class maintenance and lean implementation for making a strategic decision.

3.2 Existing Frameworks of RCM

The nineteen different RCM frameworks are identified from the literature review. Some of these frameworks were proposed by academicians, while most of them were proposed by practitioners who have developed these frameworks based on their practical experience with different organizations. The frameworks which are given by practitioners are qualitative, while only a few frameworks are available based on the quantitative analysis of reliability. In all these frameworks, the principal activities of RCM are organized as elements. The identified elements are presented in Table 3.1.

Table 3.1: Elements of RCM framework

Authors	Elements of Framework
Nowlan and Heap (1978)	1. Partitioning equipment into object categories. 2. Identifying significant items. 3. Evaluating maintenance requirement for each significant item. 4. Identifying items for which no applicable and effective task can be found. 5. Selecting maintenance intervals for each equipment. 6. Establishing an age exploration program
Srikrishna *et al*. (1996)	1. Selection of critical auxiliaries 2. Data collection 3. Selection of significant maintenance items 4. The maintenance decision process 5. Selection of maintenance periodicity
Rausand (1998)	1. Study preparation 2. System selection and definition 3. Functional Failure Analysis (FFA) 4. Critical item selection 5. Data collection and analysis 6. FMECA 7. Selection of maintenance actions 8. Determination of maintenance intervals 9. Preventive maintenance comparison analysis 10. Treatment of non-critical items 11. Implementation 12. In-service data collection and updating
Deshpande and Modak (2002)	1. System selection and information collection 2. System boundary definition 3. System description and function block diagram 4. System functions and functions failure 5. FMEA

	6. LTA 7. Task Selection
Gabbar *et al.* (2003)	1. Asset assessment 2. Assess failure 3. Decide maintenance strategy 4. Decide maintenance tasks 5. Optimize maintenance tasks 6. Check and validate 7. Task selection
Smith *and* Hinchcliffe (2004)	1. System selection and Information Collection 2. System boundary definition 3. System description and functional block diagram 4. System functions and functional failure 5. FMEA 6. LTA 7. Task selection
Penrose (2005)	1. Set boundaries and create a functional block diagram with partitioning of the system under review 2. Determine functional failures 3. Determine functionally significant items of the system 4. Perform an FMEA 5. Perform an LTA to determine the effectiveness of maintenance tasks for the FMEA 6. Determine servicing and lubrication tasks 7. Set maintenance requirements for the system 8. Draft and evaluate maintenance procedures 9. Determine tasks for inactive equipment and, Develop corrective maintenance processes, procedures and specifications
Cheng and Jia (2005)	1. Identification of functionally significant items 2. Retrieval of structure tree of FSI of the similar equipment from equipment case base. 3. FMEA 4. RCM logic decision analysis 5. Combining PM tasks to form an RCM program
Jie *et al*. (2005)	1. Preliminary classification of equipment 2. Historical maintenance database 3. Function, Failure Modes and Effects Analysis (FFMEA) 4. Identification of maintenance items and modes

	5. Formulation of maintenance program 6. Implementation of maintenance program 7. Evaluation of maintenance results
Bertling *et al.* (2005)	1. Define reliability model and required input data 2. Identify critical components by reliability analysis 3. Identify failure cause by failure mode analysis 4. Define a failure rate model 5. Model effect of PM methods on reliability for each failure cause 6. Deduce different plans for applying PM and evaluate the resulting effect on the component failure rate 7. Define and implement different strategies for PM 8. Estimate the resulting composite failure rate 9. Compare system reliability when applying different maintenance methods and PM strategies 10. Identify cost effective PM strategy
Niu and Pecht (2009)	1. Object identification 2. Determine ways of function failures 3. Determine failures models 4. Assessing the effects of failure 5. Identification of maintenance tasks 6. Identification of maintenance interval 7. Program evaluation & cost analysis
Singh *et al*. (2010)	1. Study preparation 2. System selection and definition 3. Functional failure analysis 4. Critical item selection 5. Data collection and analysis 6. FMECA 7. Selection of maintenance actions 8. Determination of maintenance intervals 9. PM comparison analysis 10. Implementation
Kianfar and Kianfar (2010)	1. System selection and information collection 2. System boundary definition 3. System descriptions and functional block diagram 4. System functions and functional failures 5. FMEA 6. Ranking of failure modes

	7. Task selection 8. Implementation
Selvik and Aven (2011)	1. Identification of Maintenance Significant Items (MSI) 2. PM task assessments 3. PM interval assessments 4. Packing of PM tasks 5. Uncertainty analysis 6. Uncertainty evaluation & presentation of results 7. Managerial review and judgment 8. PM program
Chen and Zhang (2012)	1. Boundary definition 2. Function analysis 3. Function failure & effect analysis 4. Identification of the critical equipment 5. Critical equipment failures and strategies application 6. PM evaluation of the non- critical equipment 7. Comparison analysis of maintenance tasks 8. Maintenance tasks list
Liang *et al*. (2012)	1. System division and identification of FSI 2. FMEA of FSI 3. Criticality analysis or risk analysis or identify the level of FSI 4. RCM logic, making maintenance strategy
Dehghanian *et al*. (2013)	1. System boundary identification 2. Critical component identification 3. Failure mode determination of critical components 4. Critical failure mode recognition 5. Failure cause specification of critical failure modes 6. Failure rate modeling of critical components 7. Load point/ system reliability evaluation 8. Outlining possible maintenance strategies
Prabhakar and Raj (2013)	1. Reliability audits and analysis 2. Identifying Likely failure modes 3. FMECA on critical equipment 4. Feedback and measurement
Yssaad *et al*. (2014)	1. Define the system-identify levels of indenture 2. Define ground rules and assumptions 3. Construction equipment tree 4. FMECA

	5. Assign maintenance focus levels based on criticality 6. Apply RCM decision logic 7. Identify maintenance tasks 8. Make recommendations and package final maintenance program 9. Feedback – continuous re-evaluation and improvement

3.3 Comparison of RCM Frameworks

The above frameworks are compared based on comprehensive analysis of literature, discussions with maintenance experts, practitioners, consultants, etc. The focus group method is used to conduct the comparison while visiting various industries and during attended international and national conferences. A focus group is a qualitative research as it asks participants for open-ended responses conveying opinions or feelings. Focus groups are used for generating information on collective views, and the meanings that lie behind those views.

It has been found that only a few frameworks are unique, while most of them are more or less similar. Only the naming and the sequence of elements are different. Based on the definition of each element, which is defined by their respective authors in the respective framework, similar elements are put together. A total of thirty-three different elements are presented in comparison Table 3.2, which presents a matrix of numbers in the order of each element (given row-wise), as mentioned in the corresponding frameworks (given column-wise). The order of each element presents the sequence of that element in the respective framework.

Table 3.2: Comparison of elements of RCM frameworks

S. No		**Authors/ consultants**	**Nowlan and Heap (1978)**	**Srikrishna *et al.* (1996)**	**Rausand (1998)**	**Deshpande and Modak (2002)**	**Gabbar *et al.* (2003)**	**Smith and Hinchcliffe (2004)**	**Penrose (2005)**	**Cheng and Jia (2005)**	**Jie *et al.* (2005)**	**Bertling *et al.* (2005)**	**Niu and Pecht (2009)**	**Singh *et al.* (2010)**	**Kianfar (2010)**	**Selvik and Aven (2011)**	**Chen and Zhang (2012)**	**Liang *et al.* (2012)**	**Dehghanian *et al.* (2013)**	**Prabhakar (2013)**	**Yssaad *et al.* (2014)**
		No. of elements	6	5	12	7	6	7	10	3	7	10	7	10	8	8	8	4	11	4	9
1	Name of elements	System boundary definition / Data collection and analysis / System boundary identification / Define system and subsystem boundaries		2	5	2		2			2		1	5	2		1		1		1
2		System functions and functions failures/ Assess failure / Determine functional failures / Functional failure analysis / Define			3	4	2	4	2				2	3	4		2			2	

	Name of elements	subsystem interface, functions and functional failure																			
3		FMECA / FMEA of FSI / Define failure modes for each functional failure / FFMEA / Identify failure cause by failure mode analysis / Failure cause specification of critical failure modes			6	5		5	4	2	3	3	3	6	5		3	2	5	3	4
4		Tasks selection / The maintenance decision process / Decide maintenance tasks / Develop corrective maintenance processes, procedures and specifications/ Selection of maintenance analysis / Outlining possible		4	7	7	4	7	10		5		5	7	7				8		7

		maintenance strategies / Categorize maintenance tasks																			
5	Name of elements	System selection and information collection / System selection and definition /Asset assessment			2	1	1	1			1			2	1						
6		LTA / RCM logic decision analysis				6	3	6	5	3								4			6
7		Implementation / Implement maintenance tasks / Define and implement different strategies for PM / Implementation of maintenance program			11						6	7		10	8		8				
8		System description and functional block diagram / Set boundaries and create a functional block	1			3		3	1						3						3

	Name of elements	diagram / System division / Construction equipment tree																			
9		Selection of critical auxiliaries / Critical item selection / Critical component identification / Identify critical components by reliability analysis		1	4							2		4			4		2		
10		Set maintenance requirements for the system / Determination of maintenance interval / PM interval assessments / Selection of maintenance periodicity	5	5	8				7				6	8		3					
11		Draft and evaluate maintenance procedures / PM analysis / PM task	3		9				8			6		9		2					

		assessments																			
12	Name of elements	Check and validate / Feedback and measurement / Evaluation of maintenance results / Feedback - continuous re-evaluation and improvement/ In-service data collection and updating/ Evaluation of the reliability outcomes			12		6				7								12	4	9
13		Selection of significant maintenance items / Identification of maintenance items and modes / Identification of MSI / Determine functionally significant items of the system / Identification of FSI	2	3					3	1	4					1		1			

14		Optimize maintenance tasks / Selection of optimal maintenance strategies					5										7		10		
15	Name of elements	Critical failure mode recognition											4						4		
16		Identifying Likely failure modes / Failure mode determination of critical components / Ranking of failure modes													6		5		3		
17		Load point / System reliability evaluation / Reliability audits and analysis / Define Reliability model and required input data										1							7	1	
18		Cost / Benefit analysis and ranking of strategies / Identify cost effective PM strategy										10	7						9		

19		Make recommendations and package final maintenance program / Preventive maintenance program														8					8
20	Name of elements	Determine tasks for inactive equipment / Treatment of non-critical items	4		10				9								6				
21		Determine servicing and lubrication tasks / Packing of PM tasks							6							4					
22		Criticality analysis / Risk analysis / Identify the level of FSI																3			5
23		Study Preparation			1									1							
24		Compare system reliability when applying different maintenance methods and PM strategies										9									

25		Failure rate modelling of critical components / Define a failure rate model										4							6		
26	Name of elements	Estimate the resulting composite failure rate										8									
27		Model effect of PM methods on reliability for each failure cause										5									
28		Reliability improvements via maintenance plans																	11		
29		Uncertainty analysis														5					
30		Uncertainty evaluation & presentation of results														6					
31		Managerial review and judgment														7					
32		Define ground rules and assumptions																			2
33		Age exploration program	6																		

3.4 SWOT Analysis

Since the implementation of the RCM program is a strategic decision, it is necessary that maintenance managers, practitioners, engineers, or consultants of different organizations should identify a proper framework as they cannot afford to make a mistake in the selection process. A greater hurdle in this selection process is the availability of a large number of frameworks with a different elements of RCM in the literature. To analyze these frameworks, a strategic tool, the SWOT was used to recognize them based on their strengths, weaknesses, opportunities and threats. The motive for the selection of SWOT was that it is an intense methodology to evaluate the existing frameworks. These frameworks are categorized together into three groups i.e. group A, B, and C based on their emphasis on qualitative, quantitative or practical application aspects respectively to perform the SWOT analysis and presented in Table 3.3.

SWOT analysis can be categorized as follows (Ghazinoory *et al*., 2011)

- ✓ The first category deals with problems in the implementation of new technologies within organizations that can be solved by organizing SWOT panel effectively.
- ✓ The second category deals with integrating SWOT with other decision-making techniques. In this study, the first category of SWOT analysis has been adapted as follows to analyze the RCM frameworks.
- **Strength:** If any RCM framework has a unique element/feature when compared to others, then it is considered as the strength for that framework.
- **Weakness:** If the common elements of RCM that were identified in the comparative analysis are missing in a framework, then it is considered as the weakness for that framework.

- **Opportunity:** In an RCM framework, if an element, which may not be an important element for RCM implementation or if it is not directly related to RCM, but if incorporated can provide a significant competitive advantage to the organization, then it is considered to be an opportunity for other frameworks.
- **Threat:** If an element in the framework, which may not be an important element for RCM implementation, but if it is not presented or implemented can spoil the entire implementation, then it is considered as a threat.

Based on these concepts of SWOT analysis, the strengths, weaknesses, opportunities, and threats for different frameworks of RCM are identified. Since the few frameworks having common elements, may have the same strengths, weaknesses, opportunities, and threats, it has been considered logically to perform a SWOT analysis on a group. The SWOT analyses for group A, B, and C frameworks are presented in Table 3.4, 3.5, and 3.6 respectively.

Table 3.3: Grouping of RCM Frameworks

Groups	Authors	Remarks
Group A	Cheng and Jia (2005); Kianfar and Kianfar (2010); Niu and Pecht (2009); Nowlan and Heap (1978); Prabhakar and Raj (2013); Rausand (1998); Selvik and Aven (2011); Singh *et al*. (2010); Smith and Hinchcliffe (2004)	Theoretical or Qualitative RCM approach
Group B	Bertling *et al*. (2005); Dehghanian *et al*. (2013); Jie *et al*. (2005); Yssaad *et al.* (2014)	Quantitative RCM approach
Group C	Chen and Zhang (2012); Deshpande and Modak, (2002); Gabbar *et al*. (2003); Liang *et al*. (2012); Penrose (2005); Srikrishna *et al*. (1996)	Practically applied frameworks in various industries

Table 3.4: SWOT analysis of group A frameworks

Strengths	**Weaknesses**
▪ Widely accepted framework ▪ Organized study for scheduling the PM ▪ Supports adaptive and dynamic maintenance strategy ▪ Provides a way to select the appropriate maintenance strategy ▪ Team-based improvement process ▪ Planned and controlled maintenance expenses ▪ Continuous improvement ▪ Established documented improvement methods ▪ Increases the reliability of the system by failure analysis ▪ Critical items dealt with a higher priority for maintenance action ▪ Maintenance tasks directed toward failure and functional degradation	▪ Restricted evaluation of risk and uncertainties ▪ Lack of quantitative reliability analysis ▪ Strategies are only rudimentary ▪ Strategies made on an ad-hoc basis ▪ A process where PMs are only widely carried out ▪ Lack of understanding of RCM concepts by top management ▪ Lack of in-house training facilities ▪ The contradiction of management activities ▪ The long time required for implementation ▪ Resistance to daily discipline ▪ Long-term process for data collection and failure analysis ▪ How to relate RCM process to cost reduction
Opportunities	**Threats**
▪ RCM process can be directly linked to the design phase of the equipment ▪ Needs to integrate RCM with other continuous improvement programmes ▪ Reduces maintenance tasks for the equipments or machines ▪ Improvement of inventive designs for maintenance ▪ Helps maintenance personnel to become multi-skilled ▪ Optimize the maintenance procedures of bottleneck operations ▪ Reduces item/equipment replacement ▪ Builds teamwork and cooperation among employees	▪ Resistance from employees ▪ Management may not be easily convinced ▪ Savings potential not easily seen by management ▪ Need of highly skilled maintenance personnel required for implementation ▪ Availability of system failure data

Table 3.5: SWOT analysis of group B frameworks

Strengths	**Weaknesses**
• The quantitative relationship between system reliability and maintenance effort • Straightforward algorithm for implementation of RCM • Consistent and planned reliability analysis • Reduces unexpected breakdowns • Financial planning for maintenance activities • Utilization of critical equipments for reliability analysis • Established for preventive maintenance tasks	▪ Substantial input data required to support the method ▪ The need of significant updates of relevant databases ▪ Limited to power distribution industry ▪ Implementation needs expertise ▪ The complex and time-consuming algorithm ▪ Lack of understanding of RCM concepts by top management ▪ Lack of in-house training facilities ▪ The contradiction of management activities
Opportunities	**Threats**
▪ Feedback system ▪ System Reliability Comparison ▪ Failure rate modeling ▪ Formulation of the maintenance program	▪ Reliability outcomes ▪ Highly skilled maintenance personnel required ▪ Estimation of composite failure rate

Table 3.6: SWOT analysis of group C frameworks

Strengths	**Weaknesses**
▪ Practically use of Qualitative failure analysis ▪ Use of Computer-aided RCM	▪ Lack of quantitative reliability analysis ▪ Focused on the practical use of the RCM approach to individual equipment rather than the entire system ▪ Practical use of the RCM approach limited to nuclear plant, power plant or power distribution industries
Opportunities	**Threats**
▪ PM evaluation of noncritical components ▪ Logic tree analysis ▪ Optimization of maintenance tasks	• Development of corrective actions for inactive components

3.5 Conclusion

A SWOT analysis was conducted on RCM frameworks which exist in literature and extensively used by industries around the globe. An extensive study of nineteen RCM frameworks has been done to identify the various elements involved in each of these frameworks. These frameworks were categorized into three different groups, i.e. group A, B, and C based on their emphasis on qualitative, quantitative, or practical application aspects. Group A frameworks involved qualitative RCM approaches, Group B frameworks were based on a quantitative approach, and Group C frameworks employed practical approaches which are implemented in different industries. The findings from each group frameworks based on SWOT analysis are as follows:

- **Group A**: These frameworks can be used for planning preventive maintenance based on continuous improvement. These frameworks provide a proper way to select the appropriate maintenance strategy to reduce maintenance costs. These frameworks can be used to plan & control the maintenance expenses; however, the lack of knowledge of quantitative reliability analysis is the major drawback in these frameworks.
- **Group B**: These frameworks provide a quantitative relationship between system reliability and maintenance effort based on logical and structured reliability analysis. However, the methodologies used in these frameworks are too complex, time-consuming and requires substantial input data.
- **Group C**: These frameworks are used in practice in various industries and based on qualitative failure analysis and computer-aided RCM. However, these frameworks also have the lacking of quantitative reliability analysis similar to group A frameworks.

In light of the analysis, it has been identified that each group of the framework has its own strengths and weaknesses. It was observed that some of the elements are the same for nearly all RCM frameworks and hence their threats and opportunities are almost similar. From the plethora of frameworks of RCM proposed by different authors and practitioners, it has been observed that the implementation of RCM was different from organization to organization, but the objectives are mostly similar. The SWOT recommends that execution of RCM is in no form a simple errand, as weaknesses and threats vigorously load it; however, it offers considerable strengths and opportunities to establish a competitive advantage. Also, this analysis has revealed a lot of shortcomings of RCM, which have kept the organizations on a back foot in implementing RCM. To overcome these shortcomings, I have been attempted an effort to develop a framework for the implementation of RCM based on the most significant elements identified from SWOT analysis, which described in details in the forthcoming chapter.

CHAPTER 4

DEVELOPMENT OF A FRAMEWORK FOR THE IMPLEMENTATION OF RCM

This chapter presents the development of a framework for the implementation of RCM. In this chapter, ten most significant elements are identified from the various elements of existing RCM frameworks based on SWOT analysis to help with development of a framework for the implementation of RCM. A model is developed to establish the contextual interrelationships between the identified elements and their sequence using ISM approach. Thereafter, a framework is developed for the implementation of RCM in an organization using ISM model.

4.1 Introduction

One of the important factors for the implementation of RCM in an organization is the adoption of a suitable framework that provides the required flow of various elements for structured implementation process. A framework focuses on how and why things should work, guiding a user through a task or experience. A framework saves from re-answering the same questions in every project.

In this chapter, ten most significant elements are selected out of the thirty-three elements from the various elements of existing RCM frameworks based on SWOT analysis. These elements not only affect the successful implementation of RCM but also influence one another. Thus, it is very essential to identify the mutual relationship between the RCM elements. Some of them are dependent, some are independents and some have interrelationship. The elements which have high driving power and dependency need more attention. The understanding of the hierarchy of RCM elements would be helpful for the maintenance practitioners, managers, consultants and engineers to implement the

RCM. This can be a guide for taking appropriate action for the successful implementation of RCM.

Lot of research has been carried out in the field of implementation of RCM. From the SWOT analysis, it has been observed that most of the frameworks are based on qualitative analysis and few frameworks on quantitative analysis. However, none of the framework can be implemented to take care of both qualitative and quantitative analysis together when needed. To overcome this shortcoming, we have attempted to develop a framework in two phases i.e. (i) Establishing the contextual interrelationship and their sequence of importance between the identified RCM elements, (ii) Developing a framework for the implementation of RCM. The main aim of this research is the development of roadmap for the implementation of RCM in an organization.

Hence, in this chapter, first we establish the interrelationship between the RCM elements and their sequence of importance using the ISM. Thereafter, based on the ISM, a framework for the implementation of RCM is developed.

4.2 Interpretive Structural Modeling

ISM was developed by Prof. John N. Warfield, Director of the "Institute for Advanced Study of George Mason University in Fairfax, Virginia. In ISM, an arrangement of divergent specifically and by implication, related elements are sorted out into an entire deliberated model (Warfield, 1974). Mandal and Deshmukh (1994) states that ISM provides the resources by which positioning can constrain empowering influences/factors. According to Ravi *et al.* (2005), ISM can be used to develop a consistent and efficient methodology.

According to Ravi and Shankar (2005), ISM includes an intuitive learning process where factors influencing issues under thought are set up into a thorough model. Thakkar *et al.* (2008) utilized ISM to scrutinize the matter of information technology (IT) implementation and accomplishment in indian manufacturing organizations to enhance the abilities in their supply chain. Jharkharia and Shankar (2004) utilized ISM to distinguish the shared effects of the IT enablers of the supply chain.

Agarwal *et al.* (2007) applied ISM and MICMAC to develop the framework in the supply chain of agile manufacturing. Faisal *et al.* (2007) used ISM MICMAC to explore the elements of empowering agents and to realize the imperative factor that decreases vulnerabilities in the supply chain. Phogat and Gupta (2018) developed a framework for the implementation of just-in-time in maintenance using ISM MICMAC. Mishra *et al.* (2015) developed a framework for implementation of world-class maintenance system using ISM MICMAC. Jadhav *et al.* (2014) developed a framework for sustainable lean implementation using ISM MICMAC. Table 4.1 presents the list of few researchers, who have been used the ISM to sort out the relations among empowering agents/obstructions of a system. Industry and academic expert’s estimation is an elementary concern to ISM. In this chapter, the ISM model of RCM elements has been developed utilizing the contribution of six maintenance experts of various industries and academia.

Table 4.1: Contributions of ISM

Authors	**Contributions in ISM**
Mandal and Deshmukh (1994)	Identified relationship for selection of Vendor.
Sharma *et al.* (1995)	Developed a hierarchical network for waste management in India.
Singh *et al.* (2003)	Development of interdependency between knowledge management variables.
Jharkharia and Shankar	Developed Mutual relationship between IT supported enablers of Supply

(2005)	Chain Management (SCM).
Ravi *et al.* (2005)	Developed a model for the variables of reverse logistics.
Ravi and Shankar (2005)	Developed a model for barriers of reverse logistics for automobile organization.
Faisal *et al.* (2007)	Proposed a model for Supply chain agility enablers.
Raj *et al.* (2008)	A relationship was developed for Indian FMS enablers.
Ramesh *et al.* (2010)	Used for the barriers of supply chain collaboration.
Khurana *et al.* (2010)	Developed a model for improving faith in Indian manufacturing industry
Jindal and Sangwan (2011)	Developed an ISM model to obtain proper hierarchy and interrelationship among the barriers of reverse logistics
Mittal and Sangwan (2011)	Used ISM to obtain a proper hierarchy and interrelationship among the obstacles of environmentally conscious technologies
Satpathy *et al.* (2012)	Used ISM for E-electricity utility services
Mishra *et al.* (2015)	Developed a framework for world-class maintenance systems
Soni and Kodali (2016)	Developed a framework of lean supply chain in indian manufacturing industry using ISM
Potdar *et al.* (2017)	Used ISM integrated fuzzy MICMAC for analysis of impediments of agile manufacturing

ISM methodology is demonstrated in the following stages and presented in Figure 4.1.

- Stage 1: List all the recognized RCM components.
- Stage 2: Ascertain appropriate relationship among RCM elements listed in step 1
- Stage 3: Develop a Structural Self-Interaction Matrix (SSIM) for RCM elements, which demonstrates the relations among RCM elements.
- Stage 4: Develop the reachability matrix from the SSIM and check the developed reachability matrix for transitivity. The transitivity of the suitable connection is a fundamental proposition made in ISM. It expresses that if an RCM element A is connected to B and B is connected to C; then A will be fundamentally connected to C.

- Stage 5: Separate the developed reachability matrix in Stage 4 into various levels by iteration method to identify the different levels of attributes.
- Stage 6: Transform the reachability matrix into its conical shape, i.e., most unitary (1) elements in the lower half and most zero (0) elements in the upper diagonal half of the matrix.
- Stage 7: Form a directed graph and detached the transitive connections dependent on the relations given over in the reachability matrix.
- Stage 8: Transform the resultant final digraph into an ISM model by expelling the nodes of elements.
- Stage 9: Re-examined the developed ISM model to check for hypothetical irregularity and make the obligatory alterations.
- Stage 10: Perform the MICMAC analyses to determine the dependence and driving power of each attribute.

4.3 Identification of RCM Elements

The nineteen existing RCM frameworks are found in literature and the elements of these frameworks presented in Table 3.1 in the previous chapter. In light of the meaning of

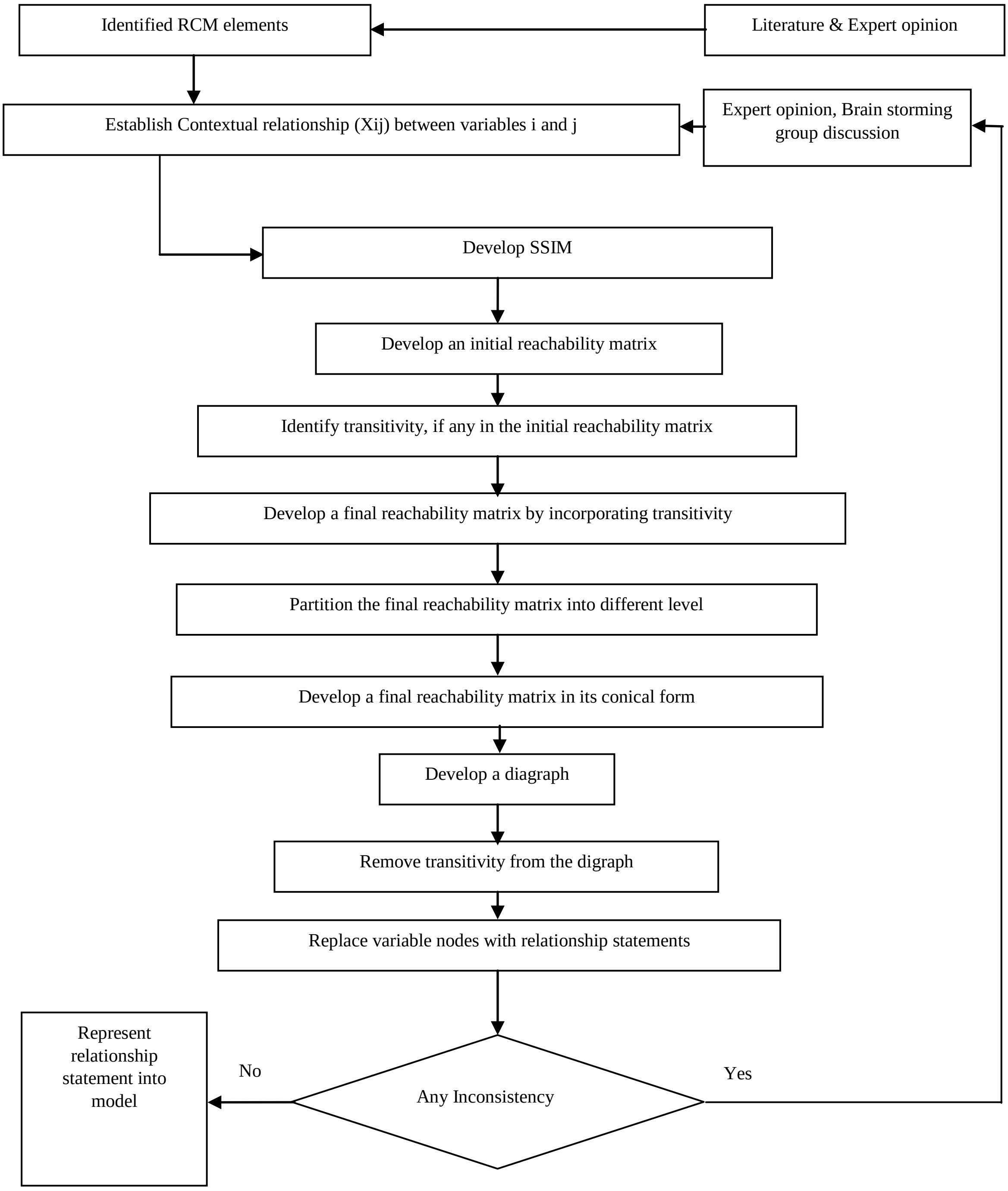

Figure 4.1: Flow chart of ISM methodology

each element, which is defined by different researchers in their respective framework, similar elements compared, clubbed, and presented in comparison Table 3.2. Thirty-three elements are analyzed from nineteen frameworks. Out of them, many researchers used around thirteen elements in their framework by changing the presentation or name of the element and remaining used in some unique frameworks. Even the sequence of elements was different in each framework. Based on the SWOT analysis, it has been observed that there is a need to develop a framework, that can be used for qualitative, as well as quantitative analysis while implementing the RCM. To overcome this shortcoming, with the help of hypothetical investigation and conceptualizing with maintenance experts from the industries who have actualized RCM, below ten most significant elements are identified from the thirty three elements of existing RCM frameworks based on SWOT analysis to develop a framework for the implementation of RCM.

- FMECA for critical subsystems/components
- Criticality analysis for subsystems/components
- Identification of subsystems/components
- Determination of maintenance actions
- System selection and information collection
- Implementation of maintenance actions
- Managerial review
- Make recommendation & package final maintenance program
- Reevaluation and improvement on continuous feedback
- Comparison of system reliability

4.4 Development of ISM Model

In this section, contextual interrelationship and their sequence between the identified RCM elements is established and an ISM model is developed. The distinctive stages specified above are being explained here for the development of the ISM Model.

4.4.1 Structural self-interaction matrix

The ISM methodology suggests the use of experts opinions based on brainstorming and group discussion technique for development of contextual relationship among the RCM elements. In this stage, for building up the logical interrelationship between the RCM elements based on SWOT analysis, all six maintenance experts were counseled. These experts from the industry and academia were very much familiar with RCM having an ordeal of more than ten years. Seeing at the top of the priority list the suitable relationship for each RCM element, the survival of a relation among every two rules (i and j) and the associated direction of the connection is addressed. To develop SSIM, underneath four symbols (V, A, X, and O) are used to give directional relationships between factors (i and j).

V - Depicts factor i will support to achieve factor j;

A - Depicts factor j will support to achieve factor i;

X - Depicts factor i and j will support to achieve each other;

O - Depicts both factors i and j are isolated

The consultations and discussions with the six maintenance experts, helped in identifying the relationship between the identified RCM elements. On the basis of contextual relationship between RCM elements, the SSIM has been developed. The final SSIM is presented in Table 4.2. The next step is to develop the initial and final reachability matrix for the SSIM.

Table 4.2: Structured self-intersection matrix

S. No.	Factors name	10	9	8	7	6	5	4	3	2	1
1	FMECA for critical subsystems/components	V	V	V	V	O	A	V	A	A	X
2	Criticality analysis for subsystems/ components	V	O	V	V	V	A	V	A	X	
3	Identification of subsystems/components	V	V	V	V	V	A	V	X		
4	Determination of maintenance actions	V	V	V	O	V	A	X			
5	System selection and information collection	V	V	V	V	V	X				
6	Implementation of maintenance actions	V	O	V	V	X					
7	Managerial review	X	V	V	X						
8	Make recommendation and package final maintenance program	A	V	X							
9	Reevaluation and improvement on continuous feedback	A	X								
10	Comparison of system reliability	X									

4.4.2 Initial reachability matrix

In this stage, the initial reachability has been obtained by transforming the information of each cell of SSIM into binary digits 1s or 0s. All V, A, X and O of Table 4.2 are replaced by the digit 1 (one) and 0 (zero) as per the following rules (Phogat and Gupta, 2018). Following these rules the initial reachability matrix is developed and presented in Table 4.3.

- If the (i, j) entry in the SSIM is V, the (i, j) entry in the reachability matrix becomes 1, and the (j, i) entry becomes 0.
- If the (i, j) entry in the SSIM is A, the (i, j) entry in the reachability matrix becomes 0, and the (j, i) entry becomes 1.
- If the (i, j) entry in the SSIM is X, the (i, j) entry in the reachability matrix becomes 1, and the (j, i) entry also becomes 1.
- If the (i, j) entry in the SSIM is O, the (i, j) entry in the reachability matrix becomes 0 and the (j, i) entry also becomes 0.

Table 4.3: Initial reachability matrix

S. No.	Factors name	1	2	3	4	5	6	7	8	9	10
1	FMECA for critical subsystems/components	1	0	0	1	0	0	1	1	1	1
2	Criticality analysis for subsystems/ components	1	1	0	1	0	1	1	1	0	1
3	Identification of subsystems/components	1	1	1	1	0	1	1	1	1	1
4	Determination of maintenance actions	0	0	0	1	0	1	0	1	1	1
5	System selection and information collection	1	1	1	1	1	1	1	1	1	1
6	Implementation of maintenance actions	0	0	0	0	0	1	1	1	0	1
7	Managerial review	0	0	0	0	0	0	1	1	1	1
8	Make recommendation and package final maintenance program	0	0	0	0	0	0	0	1	1	0
9	Reevaluation and improvement on continuous feedback	0	0	0	0	0	0	0	0	1	0
10	Comparison of system reliability	0	0	0	0	0	0	1	1	1	1

4.4.3 Final reachability matrix

To get the final reachability matrix transitivity needs to be determined. The transitivity of the contextual relation in ISM define as if variable A is related to B and B is related to C, then A is necessarily related to C. In this study, as per the experts opinion factor 1 is helping to achieve factor 4 and factor 4 is helping to achieve factor 6, then factor 1 will support to achieve 6 and this transitivity is presented by (*) in Table 4.4.

Table 4.4: Final reachability matrix

S. No.	Factors name	1	2	3	4	5	6	7	8	9	10	Driving Power
1	FMECA for critical subsystems/components	1	0	0	1	0	1*	1	1	1	1	7
2	Criticality analysis for subsystems/ components	1	1	0	1	0	1	1	1	1*	1	8
3	Identification of subsystems/components	1	1	1	1	0	1	1	1	1	1	9
4	Determination of maintenance actions	0	0	0	1	0	1	1*	1	1	1	6
5	System selection and information collection	1	1	1	1	1	1	1	1	1	1	10
6	Implementation of maintenance actions	0	0	0	0	0	1	1	1	1*	1	5
7	Managerial review	0	0	0	0	0	0	1	1	1	1	4
8	Make recommendation and package final	0	0	0	0	0	0	0	1	1	0	2

	maintenance program											
9	Reevaluation and improvement on continuous feedback	0	0	0	0	0	0	0	0	1	0	1
10	Comparison of system reliability	0	0	0	0	0	0	1	1	1	1	4
	Dependence	4	3	2	5	1	6	8	9	10	8	56

4.4.4 Level partition

The structural model in the form of diagraph needs to be develop after the final reachability matrix. Warfield (1974) has presented a series of partitions, which are induced by the reachability matrix. From these partitions, many properties of structural model can be identified easily (Farris and Sage, 1975). The reachability set and antecedent set are determined for each RCM element from the final reachability matrix to determine the level partition. The reachability set incorporates RCM element itself and other elements which it might encourage to accomplish; comparably, the antecedent set additionally comprises of RCM element itself and the other element which helps in accomplishing it. Thereafter, the intersection point of both the sets is identified for all RCM elements. The RCM element, for which the reachability set is same as the antecedent set, comes at the top level of the hierarchy. The top level RCM elements are, those will not lead the other element above their own level in the hierarchy. After the identification of the top level element, it is removed out from further analysis (i.e. RCM element from all different sets). After that, the same procedure is followed to find out the level of each RCM element. These levels turn out from the iteration process which helps in the development of the digraph and the final ISM model. Level 1 given to top element and level 9 given to bottom element of final ISM model. The level of each RCM element is presented in Table 4.5 to 4.13. Table 4.14 presents the level of all the elements after the 9th iteration. Level partitioning of each factor will lead to the formation of the ISM model.

Table 4.5: Level partition of reachability matrix (1^{st} Iteration)

S. No.	Element name	Reachability	Antecedent	Intersection	Level
1	FMECA for critical subsystems/components	1,4,6,7,8,9,10	1,2,3,5	1	
2	Criticality analysis for subsystems/ components	1,2,4,6,7,8,9, 10	2,3,5	2	
3	Identification of subsystems/components	1,2,3,4,6,7,8,9 ,10	3,5	3	
4	Determination of maintenance actions	4,6,7,8,9,10	1,2,3,4,5	4	
5	System selection and information collection	1,2,3,4,5,6,7,8 ,9,10	5	5	
6	Implementation of maintenance actions	6,7,8,9,10	1,2,3,4,5,6	6	
7	Managerial review	7,8,9,10	1,2,3,4,5,6 ,7, 10	7,10	
8	Make recommendation and package final maintenance program	8,9	1,2,3,4,5,6 ,7,8,10	8	
9	Reevaluation and improvement on continuous feedback	9	1,2,3,4,5,6 ,7,8,9,10	9	I
10	Comparison of system reliability	7,8,9,10	1,2,3,4,5,6 ,7, 10	7,10	

Table 4.6: Level partition of reachability matrix (2^{nd} Iteration)

S. No.	Element name	Reachability	Antecedent	Intersection	Level
1	FMECA for critical subsystems/components	1,4,6,7,8,10	1,2,3,5	1	
2	Criticality analysis for subsystems/ components	1,2,4,6,7,8,10	2,3,5	2	
3	Identification of subsystems/components	1,2,3,4,6,7,8, 10	3,5	3	
4	Determination of maintenance actions	4,6,7,8, 10	1,2,3,4,5	4	
5	System selection and information collection	1,2,3,4,5,6,7, 8,10	5	5	
6	Implementation of maintenance actions	6,7,8,10	1,2,3,4,5,6	6	
7	Managerial review	7,8,10	1,2,3,4,5,6,7 ,10	7,10	
8	Make recommendation and package final maintenance program	8	1,2,3,4,5,6,7 ,8,10	8	II
10	Comparison of system reliability	7,8,10	1,2,3,4,5,6,7, 10	7,10	

Table 4.7: Level partition of reachability matrix (3rd Iteration)

S. No.	Element name	Reachability	Antecedent	Intersection	Level
1	FMECA for critical subsystems/components	1,4,6,7,10	1,2,3,5	1	
2	Criticality analysis for subsystems/ components	1,2,4,6,7,10	2,3,5	2	
3	Identification of subsystems/components	1,2,3,4,6,7,10	3,5	3	
4	Determination of maintenance actions	4,6,7,10	1,2,3,4,5	4	
5	System selection and information collection	1,2,3,4,5,6,7, 10	5	5	
6	Implementation of maintenance actions	6,7,10	1,2,3,4,5,6	6	
7	Managerial review	7,10	1,2,3,4,5,6, 7, 10	7,10	III
10	Comparison of system reliability	7,10	1,2,3,4,5,6, 7, 10	7,10	III

Table 4.8: Level partition of reachability matrix (4th Iteration)

S. No.	Element name	Reachability	Antecedent	Intersection	Level
1	FMECA for critical subsystems/components	1,4,6	1,2,3,5	1	
2	Criticality analysis for subsystems/ components	1,2,4,6	2,3,5	2	
3	Identification of subsystems/components	1,2,3,4,6	3,5	3	
4	Determination of maintenance actions	4,6	1,2,3,4,5	4	
5	System selection and information collection	1,2,3,4,5,6	5	5	
6	Implementation of maintenance actions	6	1,2,3,4,5,6	6	IV

Table 4.9: Level partition of reachability matrix (5th Iteration)

S. No.	Element name	Reachability	Antecedent	Intersection	Level
1	FMECA for critical subsystems/components	1,4	1,2,3,5	1	
2	Criticality analysis for subsystems/ components	1,2,4	2,3,5	2	
3	Identification of subsystems/components	1,2,3,4	3,5	3	
4	Determination of maintenance actions	4	1,2,3,4,5	4	V
5	System selection and information collection	1,2,3,4,5	5	5	

Table 4.10: Level partition of reachability matrix (6th Iteration)

S. No.	Element name	Reachability	Antecedent	Intersection	Level
1	FMECA for critical subsystems/components	1	1, 2, 3, 5	1	VI
2	Criticality analysis for subsystems/ components	1, 2	2, 3, 5	2	
3	Identification of subsystems/components	1, 2, 3	3,5	3	
5	System selection and information collection	1, 2, 3, 5	5	5	

Table 4.11: Level partition of reachability matrix (7th Iteration)

S. No.	Element name	Reachability	Antecedent	Intersection	Level
2	Criticality analysis for subsystems/ components	2	2,3,5	2	VII
3	Identification of subsystems/components	2,3	3,5	3	
5	System selection and information collection	2,3,5	5	5	

Table 4.12: Level partition of reachability matrix (8th Iteration)

S. No.	Element name	Reachability	Antecedent	Intersection	Level
3	Identification of subsystems/components	3	3,5	3	VIII
5	System selection and information collection	3,5	5	5	

Table 4.13: Level partition of reachability matrix (9th Iteration)

S. No	Element name	Reachability	Antecedent	Intersection	Level
5	System selection and information collection	5	5	5	IX

Table 4.14: Final level of elements in the ISM model after the 9th iteration

Element No.	Name of element	Level
9	Reevaluation and improvement on continuous feedback	First
8	Make recommendation and package final maintenance program	Second
7	Managerial review	Third
10	Comparison of system reliability	Third
6	Implementation of maintenance actions	Fourth
4	Determination of maintenance actions	Fifth
1	FMECA for critical subsystems/components	Sixth
2	Criticality analysis for subsystems/components	Seventh
3	Identification of subsystems/components	Eighth
5	System selection and information collection	Ninth

4.4.5 Formation of ISM model

Initially, a digraph portrayed with the help of final reachability matrix. Digraph used to present the elements and their interdependencies in terms of nodes and edges, or it is the visual presentation of the elements and their interdependence. The ISM model is converted by removing the transitivity links from digraph and presented in Figure 4.2. The sequence of these elements in ISM model completes the RCM process and can be used to implement RCM in an organization in this sequence. From the model developed with the identified elements in this research, it is clear that the most important elements that enables the successful implementation of RCM are system selection and information collection, identification of subsystems/components of the system, criticality analysis for subsystems/components, which comes at the level eight to level ten whereas revaluation and improvement on continuous feedback dependent on other RCM elements has been appeared on the top of the hierarchy.

4.4.6 MICMAC Analysis

MICMAC analysis is to be carried out to determine the specialty of the group of attributes regarding dependency and driving power. The objective of MICMAC analysis is to evaluate the dependence and driver power of the elements (Mandal and Deshmukh, 1994; Faisal *et al*, 2006). The MICMAC principle is based on multiplication properties of matrices (Sharma *et al* 1995). The drive power of a demanding element is simply the entire number of factors (including self) which it might accomplish. The dependence power is the entire number of factors, which may help to accomplishing it. These dependence and driving powers are presented in Table 4.4. In this table, the driving and dependent power for each RCM element is calculated by adding the total number of 1's (including itself) row-wise and column-wise respectively. The driving and dependence

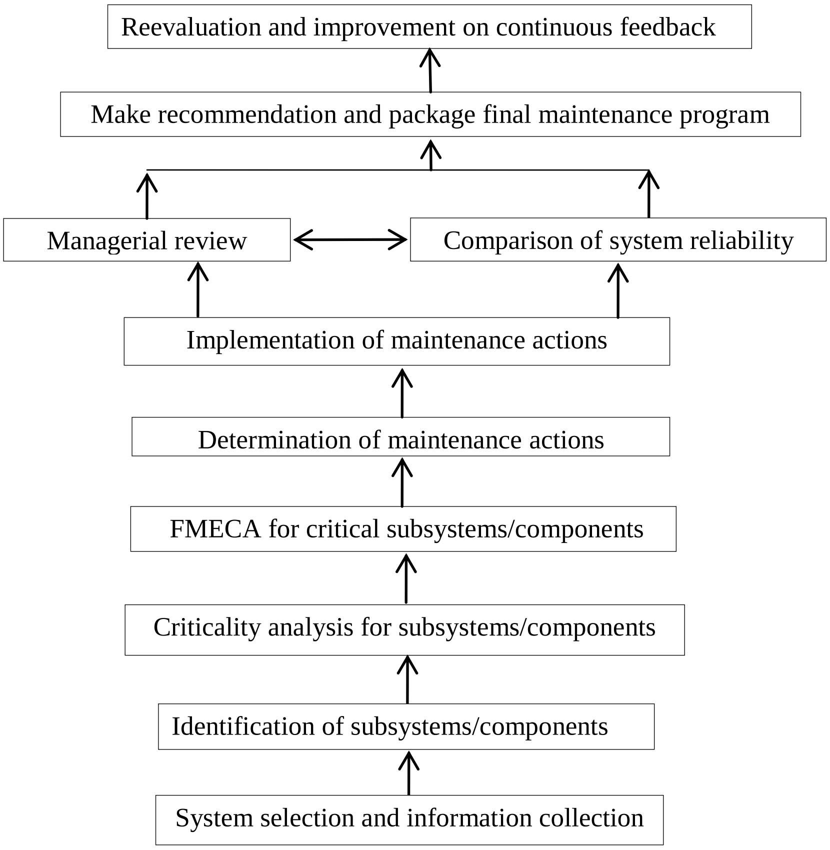

Figure 4.2: ISM Model for RCM

power diagram is presented in Figure 4.3. From Table 4.4, it is observed that RCM element number 1 (FMECA for critical subsystems/components) is having driving power of 7 and dependence of 4. Hence, in this figure, it is positioned at a place corresponding to driving power of 7 and dependence of 4. In MICMAC analysis, all the RCM elements are divided into following four groups.

- **Group-1:** Autonomous elements
- **Group-2:** Dependent elements
- **Group-3:** Linkage elements
- **Group-4:** Driving elements

Based on the above definition of each group, driving elements group consists of FMECA for critical subsystems/components, criticality analysis for subsystems/components, identification of subsystems/components, determination of maintenance actions based on criticality, and system selection and information collection. These RCM elements are the key drivers of RCM implementation in an organization. Maintenance personnel's of an organization has to focus more to these elements to successfully implement the RCM. No elements exists in autonomous and linkage group, which indicates all elements identified based on SWOT analysis are essential for RCM implementation framework and organizations should pay attention to all of them. Table 4.15 provides more details about the groups and its characteristics.

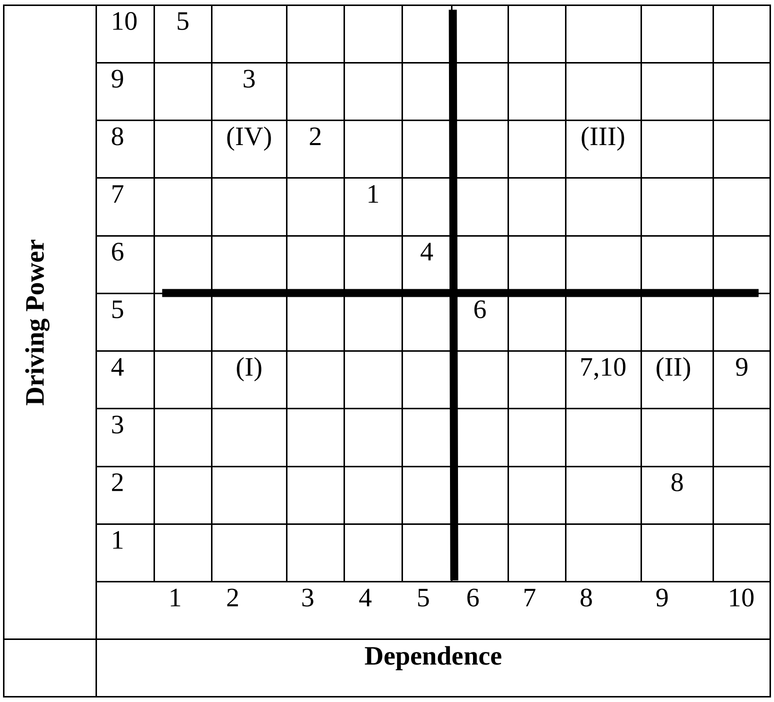

Figure 4.3: MICMAC analysis

Table 4.15: Groups of elements and its characteristics

Group No.	Group name	Characteristics	Driving Power	Dependence	RCM elements
I	Autonomous elements	These RCM elements relatively disconnetced from the system, with which they have hardly any link, which might not be extremely strong	Weak	Weak	-
II	Dependent elements	These RCM elements are automatic follows of other elements	Weak	Strong	• Implementation of maintenance actions • Managerial review • Make recommendation & package final maintenance program • Revaluation and improvement on continuous feedback • Comparison of System reliability
III	Linkage elements	These RCM elements are unstable, in the sense that any action on these elements will have an effect on others and also a feedback on themselves	Strong	Strong	
IV	Driving elements	These RCM elements are key drivers for implementation.	Strong	Weak	• FMECA for critical subsystems/components • Criticality analysis for subsystems/components • Identification of subsystems/components • Determination of maintenance actions • System selection and information collection

4.5 Proposed Framework for the Implementation of RCM

ISM model in Figure 4.2 suggests the priority order of RCM elements to develop a framework for the implementation of RCM. Framework for the implementation of RCM in phase-wise manner is presented in Figure 4.4, which is actually developed from ISM model. It presents the sequential and decision-making approach for systematic implementation of RCM in an organization in a phase-wise manner. This acts as a roadmap for the implementation of RCM in the organization. The framework is proposed into two phases i.e. (a) pre-implementation, and (b) post-implementation phase.

(a) Pre-implementation Phase

Pre-implementation phase considers the six elements i.e. (i) System selection and information collection, (ii) Identification of subsystems/components, (iii) Criticality analysis for subsystems/components, (iv) FMECA for critical subsystems/components, (v) Determination of maintenance actions, and (vi) Implementation of maintenance actions. The each element of pre-implementation phase is described as follows:

(i) System selection and information collection

According to Rausand (1998), before a decision is made to implement the RCM in an organization, two questions should be considered.

(a) For which systems, RCM implementation will be beneficial compare with existing maintenance program?

(b) At what level of assembly, RCM should be implemented?

All systems might be in principle benefit from the RCM implementation. We must make priorities depends on the available resources to implement RCM in an organization. Smith (1993) recommended system level as the starting point for RCM implementation. After the selection of system, the necessary information which will be required for subsequent steps should be collected in this step.

(ii) Identification of subsystems/components

A system is a set of subsystems that perform a main function in the organization. The systems may be broken down into subsystems/components for the purpose of RCM implementation. In this step, the major subsystems/components should be identify with primary physical boundaries of the system. For example, if a CNC machine is consider as a system then hydraulic, cooling, spindle assembly etc. can be consider as a subsystem for the implementation of RCM.

(iii) Criticality analysis for subsystems/components

Criticality analysis is a technique for prioritizing the subsystems/components based on their criticality rating. ISM model reveals that the criticality analysis is the key element for the implementation of RCM. In RCM literature, it has been performed based on the failure modes for all the subsystem/components. It might be more complex and time consuming tasks. In this research, we have been focused on prioritizing the subsystems/components based on their criticality levels. A model is developed and tested on CNC lathe machine in next chapter presenting that how to find the criticality levels of subsystems/components. Based on the criticality levels, the decision can be taken for further action in RCM. The term critical can be defined that how the failure of subsystem/component impact functioning of the entire system. In this framework, it has been suggested that if a subsystem/component is low critical, then no need to perform the further failure analysis, only corrective maintenance actions can be performed for such component. But, if the subsystem/component is high critical, then it needs to be further analyzed by performing FMECA.

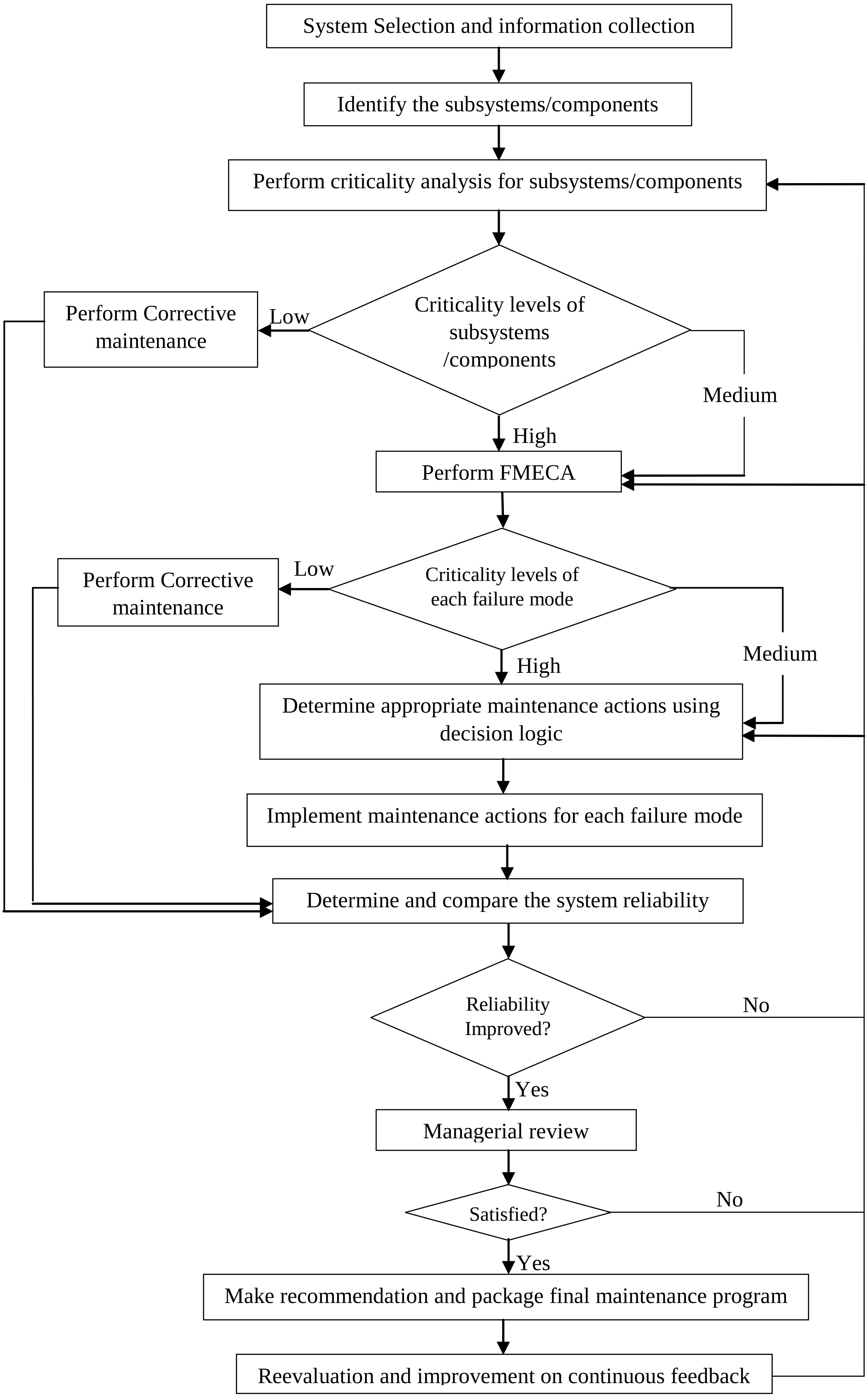

Figure 4.4: Proposed framework for the implementation of RCM

(iv) FMECA for critical subsystems/components

In this step, the highly critical subsystems/components need to be further classified into their subparts. The objective of this step is to identify the parts of the subsystem/component that are potentially critical with respect to the functional failure. After that, FMEA needs to be developed to identify the dominant failure modes of such parts. FMEA is a structured approach to access the effect of potential failure modes of each component or parts of a system. When the criticality analysis combines with FMEA, it becomes FMECA. In FMECA, the criticality level of each failure mode of each component/part needs to be identified based on the risk priority number. The implementation of RCM in literature is limited to conventional FMECA approach only. In this research, the Fuzzy FMECA approach is proposed for implementation of RCM to overcome the shortcomings of conventional FMECA reveals from literature. The fuzzy FMECA is described in detail in chapter 6. For further analysis of RCM, decision can be taken on the basis of criticality level of each failure mode. In this framework, it is proposed that, if the failure mode is low critical, then corrective maintenance action can be performed to improve the reliability of the system. But if it is high critical, then it needs to be determine the appropriate maintenance actions to improve the system reliability.

(v) Determination and implementation of maintenance actions

Selection of maintenance actions or task for each failure mode of each component based on the FMECA is the most important step to implement the RCM in an organization. Decision logic should be used to select the appropriate maintenance actions. The input to decision logic is the dominant failure modes from FMECA in previous step. The main idea is for each failure mode to decide whether a preventive maintenance task is applicable and effective, or it will be best to let the item deliberately run to failure and afterward carry out a corrective maintenance action. The reasons for performing the PM actions are: (i) to prevent a failure, (ii) to detect the onset of a failure, and (iii) to discover a hidden failure. Rausand (1998) suggests the five basic maintenance actions i.e. (i) scheduled on-condition task, (ii) scheduled overhaul, (iii) scheduled replacement, (iv) scheduled function test, and (v) run to failure using decision logic. According to Liang *et al.* (2012) maintenance actions can be classified into corrective maintenance, condition based maintenance, and preventive maintenance using decision logic presented in Figure 4.5. Nowlan and Heap (1978), Smith (1993), Coetzee and Claasen (2002) presented the different types of decision logics to select the maintenance actions for RCM. After the selection of appropriate maintenance actions using decision logic, these actions should be implemented for the further analysis of RCM.

(b) Post-implementation phase

Post- implementation phase considers the remaining four elements i.e. (i) Comparison of system reliability, (ii) Managerial review, (iii) Make recommendation and package final maintenance program, and (iv) Re-evaluation and improvement on continuous feedback.

After implementation of maintenance actions for each failure mode, perform the reliability analysis to find the impact of selected maintenance actions and compare the output of reliability analysis with the existing reliability data of that particular system. If the reliability of the system is not improved, then the selected maintenance actions need to be reviewed and repeat the procedure again. If the reliability of the system is improved, then the suggested maintenance program needs to be reviewed by the management of organization for the final recommendation to implement the RCM. After the successfully implementation of the RCM, continuous reevaluation should be performed based on the feedback received from the system.

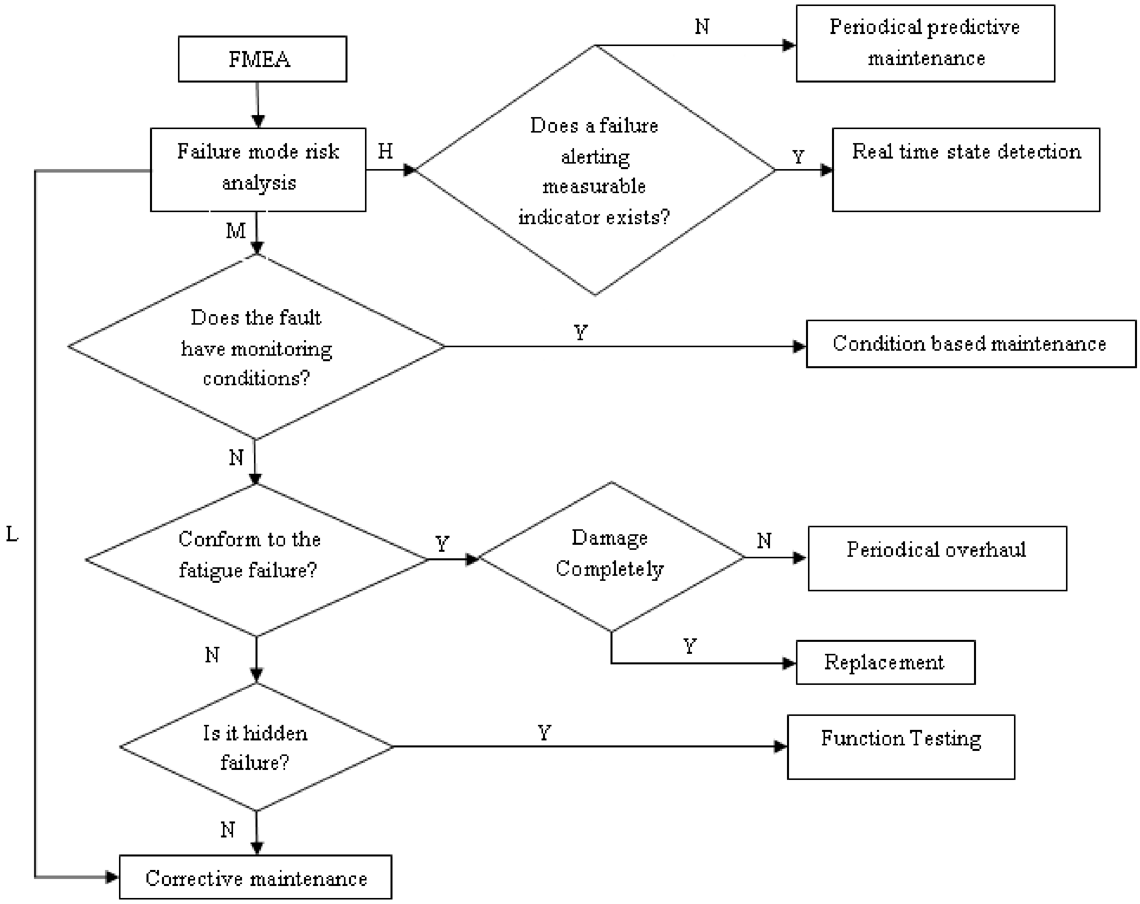

Figure 4.5: Decision logic for determination of maintenance actions (Liang *et al.*, 2012)

(* L = low, H = High, M = Medium, Y = Yes, N = No)

4.6 Conclusion

In this chapter, the ISM approach is used to establish the interrelationships among the identified elements. It has been used to prioritize and categorize these elements based on their importance, preference, and causality over and among each other. A multilevel hierarchy model has been developed from which, maintenance managers, engineers, practitioners who want to implement RCM, can easily visualize step by step procedure of RCM and can identify elements which require the highest attention and will pay attention accordingly. From MICMAC analysis, it has been found that none of the factors comes under the autonomous category, which indicates all elements identified from SWOT analysis are essential for the development of a framework for the implementation of RCM and organizations should pay attention to all of them. Based on the ISM model, a framework is developed for the implementation of RCM in an organization. The significance of the proposed framework for RCM implementation is that it can be used for qualitative and quantitative analysis together at the same time. However, the existing RCM frameworks, which are available in literature, can be utilized for either qualitative or quantitative analysis only. This framework will help the maintenance managers, engineers, practitioners, and consultants to implement RCM successfully in an organization. Also, it presents the sequential and decision-making approach for systematic implementation of RCM in an organization in a phase-wise manner. This acts as a roadmap for the implementation of RCM in an organization.

In this research, the developed ISM model of RCM framework elements is highly dependent on the judgement and experience of the experts team. The consequences of developed ISM model may fluctuate in a genuine situation. Validation of the developed ISM model can be done more robustly and quantitatively using Structural Equation Modeling (SEM).

CHAPTER 5

DEVELOPMENT OF A CRITICALITY ANALYSIS MODEL

Framework developed in previous chapter using ISM model and literature review reveals that criticality analysis of a system is the key element for the implementation of RCM. In this chapter, a methodology is proposed to identify the criteria and sub-criteria associated with criticality, and a model is proposed to identify the criticality levels of subsystems/components of a system for the implementation of RCM. The five major criteria i.e. (i) Cost, (ii) Functional dependencies, (iii) Complexity, (iv) Maintainability and (v) Safety impact and fifteen sub-criteria are determined for the proposed criticality analysis model. The proposed model is applied to identify the criticality levels of subsystems/components on a CNC lathe machine using Analytic Network Process (ANP) for validation.

5.1 Introduction

Criticality analysis is a technique for the assessment of criticality rating for every constitutive part. The criticality analysis mostly used in all the existing frameworks. It can be performed in two ways, first by identifying the critical failure modes for different components and second by identifying the criticality levels of subsystems/components of a system. According to Dehghanian *et al.* (2012), RCM provides a proper framework for management to resolve the complexity of the maintenance issues by complementing all the traditional strategies. Therefore, it would seems logical to have the maintenance managers, supervisors, and engineers focus their priorities on critical subsystems/components to avoid missing the possible opportunities for cost-effective decisions. Only then, it will be possible to focus and allocate resources effectively and efficiently to make preventive actions. To solve this problem, as the essential element of

RCM, it would be of great value to prioritize the components to apply the maintenance actions more efficiently.

Most of the research in literature focuses on the identification of the critical failure modes of the subsystems/components using FMECA, but a little work has done on how to identify the criticality of subsystems/components of a system. Performing FMECA for a number of subsystems/components will be more complex and time-consuming activity. Rather, first find out the most critical subsystem/component of a system and then perform the FMECA for that particular subsystem/component will be most effective for the implementation of RCM. Birnbaum (1969) was the first to measure the importance of a component structurally for a coherent system, which evaluates the "criticality" of a component. Barlow and Proschan (1975) and Boland and El-Neweih (1995), have studied the structural importance of the components of a system. The criticality analysis is extremely important for the system, as the failure of any critical component leads to failure of the entire system.

According to Jeyamala *et al.* (2013), a subsystem/component is said to be critical if the failure of that component has serious consequences. Carot and Sanz (2000) have studied the criticality analysis of each component for a non-repairable system. Dehghanian *et al.* (2011, 2012) and Dehghanian and Fotuhi-Firuzabad (2012) proposed a qualitative-quantitative approach based on AHP and Fuzzy AHP to determine the most critical subsystem/component to be prioritized in maintenance planning for implementation of RCM in power distribution sector. They proposed five criteria, i.e. (i) total number of components, (ii) total number of component failures, (iii) component repair duration, (iv) component investment cost, and (v) component repair and maintenance cost" to determine the most critical component. Pourahmadi *et al.* (2017) proposed an efficient method using game theory to evaluate the criticality of a subsystem/component. Sachdeva *et al*. (2008) performed the criticality analysis of various factors related to repair and failure of a subsystem/component using AHP. Khaira and Dwivedi (2017) performed the criticality analysis to enhance the availability of equipment in a graphite manufacturing industry. From the above literature, it has been observed that only a few researchers have attempted for identification of criticality of subsystems/components of a system based on the criteria related to the criticality of the system using AHP, fuzzy AHP, and game theory only in power distribution networks.

Therefore, in this chapter a methodology is proposed to find out the criteria and sub-criteria associated with criticality and a model is developed for criticality analysis. After that, ANP is used to identify the criticality level of each subsystems/components of a system for further analysis to implement the RCM in an organization. The developed model is applied to CNC lathe machine.

5.2 Model Development

In this section, development of the proposed model is described stepwise.

5.2.1 Determination of the criteria for criticality analysis

In this stage, a number of meetings and interviews were conducted with the maintenance engineers, managers, practitioners, experts and consultants of various industry organizations to determine the criteria and sub-criteria for defining the criticality of subsystems/components. Based on the feedback received from them and literature review, 15 sub-criteria are determined under the following five major criteria i.e. (1) Cost (2) Functional dependencies (3) Complexity (4) Maintainability and (5) Safety impact for the proposed criticality analysis model. All the criteria and sub-criteria are assigned a specific code number and presented in Table 5.1. The description of these criteria is being explained in the following subsections.

5.2.1.1 Cost

The consideration of economic aspects of a subsystem/component is a major factor in its criticality. The total cost of a subsystem/component concerning maintenance in the industrial organizations includes (i) Maintenance cost, (ii) Component investment cost, and (iii) Cost of production loss. In comparison to other subsystems/components, if a subsystem/component has a higher maintenance cost, then it needs to be assigned a higher criticality value. Maintenance cost directly affects by the availability of resources of repair and complexity of the subsystem/component. Cost of production directly depends on the total downtime of the system, which is controlled by the availability of resources to repair.

5.2.1.2 Functional dependencies

According to these criteria, the functional dependence of a component/subsystem in terms of process and their design is one of the main factors to find out the criticality. The design of subsystems/components has its significant contribution in the system reliability indices. If a subsystem/component is having the leading role in the system but if the design of the subsystem/component is not reliable, then that particular subsystem/component assigned more priority for criticality analysis.

5.2.1.3 Complexity

To ensure the smooth operation of a manufacturing system, the complexity of the subsystem/component is of great concern. This criterion divided into three sub-criteria:

(i) the probability of failure, (ii) total number of parts, and (iii) failure effect on the system. A component/subsystem which is having a large number of parts will have a significant contribution in the overall system reliability. In addition, at the same time, the frequency of failure and their effect on the system will impact the system availability.

5.2.1.4 Maintainability

Maintainability can be defined as an ability to repair of a system within the standard time duration. It is having a significant role in identifying the criticality of subsystems/components of a system. This criterion further divided into four sub-criteria: (i) the availability of technical specification, (ii) failure detection, (iii) total downtime, and (iv) facility required to repair. The repair process of few subsystems/components can take a long time, which results the system down for the large duration. When the failures are difficult to detect, downtime of the system will considerably increase. Hence, the subsystem/component having the longer downtime assigned more priority for criticality analysis.

5.2.1.5 Safety impact

While identifying the most critical subsystem/component of the system, safety impact is of great concern. This criterion divided into three sub-criteria: (i) human safety, (ii) resources safety, and (iii) environment safety. In case of a mechanical/electrical system, human and resource safety have significant role while environment safety has less impact but it also needs to be considered. The increasing requirements of maintenance in the unproductive use phase of the product lifecycle of systems produce a significant impact on the environment as the used oils, grease and cleaning agents are discarded into the environment.

Table 5.1: Criteria and sub-criteria for criticality analysis

S. No.	Major Criteria	Sub Criteria
C1	Cost	• C1S1 Maintenance Cost • C1S2 Component cost • C1S3 Cost of production loss
C2	Functional dependencies	• C2S1 Process dependencies • C2S2 Design dependencies
C3	Complexity	• C3S1 Probability of failure • C3S2 Total number of parts • C3S3 Failure effect
C4	Maintainability	• C4S1 Availability of technical specification • C4S2 Failure detection • C4S3 Total downtime • C4S4 Facility required to repair
C5	Safety Impact	• C5S1 Human safety • C5S2 Resources safety • C5S3 Environment safety

5.2.2 Description of the CNC lathe machine

To examine the applicability of the proposed methodology, CNC lathe machine is considered as a test system. Eleven subsystems/components of CNC lathe machine adopted from Wang *et al.* (2001) are used for criticality analysis. Each component/ subsystem considered as an alternative for the proposed model and each alternative assigned a particular code and presented in Table 5.2.

5.2.3 Development of the proposed model

In this step, the interactions between and within clusters and their elements are determined based on interdependencies among each other. Input-output analysis has done to determine the interdependencies. Based on the input-output analysis, the criticality analysis model is developed as shown in Figure 5.1.

Table 5.2: Alternatives of CNC lathe machine

Code of Alternative	Name of Alternative
A1	Turret
A2	Clamping Accessory
A3	Electric and Electronics system
A4	Main transmission
A5	X feed system
A6	Z feed system
A7	CNC system
A8	Hydraulic system
A9	Servo system
A10	Cooling system
A11	Spindle assembly

5.3 Methodology for Criticality Analysis

The identification of criticality levels is a Multi-Criteria Decision Making (MCDM) problem since it involves various criteria and sub-criteria. The ANP is applied to find out the criticality levels of subsystems/components for the defined alternatives. The ANP was proposed by Saaty (1996). ANP was used to solve the hierarchical problems, which are having inner/outer dependencies, influences between and within clusters (criteria, sub-criteria, and alternatives). ANP is widely used in literature for selection of best maintenance strategy (Dorri *et al.*, 2014; Sadeghi and Alborzi, 2012; Tajadod *et al.*, 2011; Zalim *et al., 2012)*, supplier selection (Gencer and Gurpinar, 2007; Sadeghi, 2012), SWOT analysis (Yuksel and Dagdeviren, 2007), R&D project selection (Lee and Kim, 2000; Meade and Presley, 2002). In the ANP technique, three types of matrices, i.e. unweighted supermatrix, weighted supermatrix, and the limit matrix are required for further analysis. In this process, all the three matrix are determined using super decision software. The detailed explanation is given in following sub-sections for further analysis.

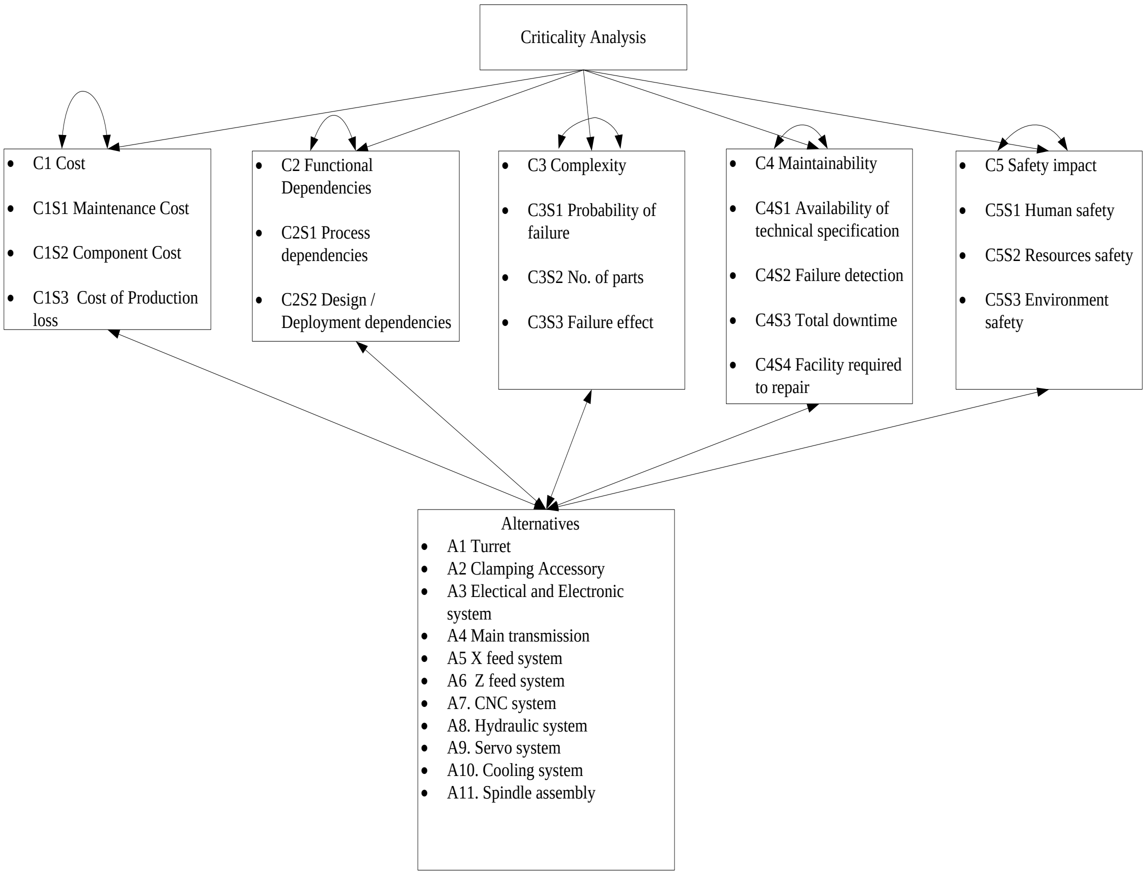

Figure 5.1: Proposed criticality analysis model

5.3.1 Determination of unweighted and weighted supermatrix

In this step, the input-output analysis is carried out using the super decision software with the help of maintenance engineers, managers, practitioners, experts, or consultants of various industrial organizations, to derive pairwise comparison judgments. The comparison or unweighted matrix among the elements is integrated after the input-output analysis. The matrix is composed of several sub-matrices in which each column of each block is a vector indicating the impact of the elements of the left side corresponding cluster on the elements at the top of the unweighted supermatrix. Clusters are compared with each other to obtain a stochastic supermatrix. The resulting priorities of the clusters used to determine the weight of the corresponding blocks. This led to the final comparison matrices to achieve the ratio scale vectors. The results of obtained final comparison matrices and the ratio scale vectors are shown in Table 5.3. After that, the final weighted supermatrix was determined by multiplication of Table 5.3 elements of their corresponding block in the unweighted supermatrix. The unweighted and weighted supermatrix is presented in Table 5.4 and Table 5.5 respectively.

Table 5.3: Weight of blocks of decision network

	Goal	C1	C2	C3	C4	C5
Goal	0	0	0	0	0	0
C1	0.1747	0.0001	0	0	0	0
C2	0.2912	0	0.0909	0	0	0
C3	0.1941	0	0	0.0909	0	0
C4	0.2427	0	0	0	0.0909	0
C5	0.0970	0	0	0	0	0.0001
Alternatives	0	0.9999	0.9090	0.9090	0.9090	0.9999

5.3.2 Determination of ratio scale priority of alternatives and criteria

In this step, the powers of weighted supermatrix were calculated to help in obtaining the limit supermatrix. After 15th iteration (15th power), the limit supermatrix is obtained and presented in Table 5.6. Each column of the limit supermatrix considered as the ratio scale priority of each element, i.e. (sub-criteria and alternatives) in the network. Table 5.7 presents the relative importance in term of ratio scale priority in the network, ratio scale priority of clusters, ratio scale priority of elements in their cluster of each criterion, sub-criteria and alternative. In this table, the cluster's (each criteria, i.e. cost, functional dependencies, complexity, maintainability, safety impact) ratio scale priority is calculated as equal to the sum of ratio scale priority of its elements (sub-criteria). The ratio scale priority of each element (sub-criteria and alternatives) within their clusters is calculated by normalizing their ratio scale priority in the related cluster.

5.3.3 Determination of criticality or priority ranking

The criticality ranking of each alternative is decided based on the values of ratio scale priority of elements in their cluster in Table 5.7. The highest value of ratio scale of alternative assigned the critical rank 1 and lowest value assigned as “11”. The criticality rank “1” is considered as most critical and “11” as least critical. The criticality ranking of all alternative or components/subsystems is presented in Table 5.8. Similarly, the priority ranking is decided for each criteria and sub-criteria in their cluster for criticality analysis and presented in Table 5.9 and 5.10 respectively. The priority of ratio scale of all alternatives, criteria and sub-criteria in its cluster is presented graphically in Figure 5.2, 5.3 and 5.4 respectively.

Table 5.4: Unweighted supermatrix

		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**C1S1**	**C1S2**	**C1S3**
Alternatives	A1	0	0	0	0	0	0	0	0	0	0	0	0.155771	0.217335	0.109609
	A2	0	0	0	0	0	0	0	0	0	0	0	0.065806	0.177215	0.061577
	A3	0	0	0	0	0	0	0	0	0	0	0	0.016751	0.040246	0.02624
	A4	0	0	0	0	0	0	0	0	0	0	0	0.129854	0.130247	0.028647
	A5	0	0	0	0	0	0	0	0	0	0	0	0.092708	0.088291	0.047271
	A6	0	0	0	0	0	0	0	0	0	0	0	0.06786	0.102728	0.096568
	A7	0	0	0	0	0	0	0	0	0	0	0	0.02495	0.020462	0.03064
	A8	0	0	0	0	0	0	0	0	0	0	0	0.043619	0.056432	0.020388
	A9	0	0	0	0	0	0	0	0	0	0	0	0.016789	0.026278	0.238661
	A10	0	0	0	0	0	0	0	0	0	0	0	0.228721	0.047913	0.302524
	A11	0	0	0	0	0	0	0	0	0	0	0	0.157171	0.092853	0.037875
C1	C1S1	0.262753	0.109452	0.271776	0.27635	0.323386	0.527854	0.262753	0.670795	0.591727	0.741845	0.078617	0	0.333333	0.75
	C1S2	0.078617	0.581552	0.067026	0.128271	0.088983	0.091498	0.078617	0.255956	0.333216	0.182955	0.262753	0.666667	0	0.25
	C1S3	0.65863	0.308996	0.661199	0.595379	0.587631	0.380648	0.65863	0.073249	0.075057	0.075201	0.65863	0.333333	0.666667	0
C2	C2S1	0.2	0.166667	0.875	0.875	0.833333	0.857143	0.857143	0.166667	0.125	0.125	0.875	0	0	0
	C2S2	0.8	0.833333	0.125	0.125	0.166667	0.142857	0.142857	0.833333	0.875	0.875	0.125	0	0	0
C3	C3S1	0.258285	0.249856	0.1365	0.1365	0.1365	0.104729	0.095338	0.121957	0.09739	0.088983	0.131112	0	0	0
	C3S2	0.104729	0.095338	0.625013	0.625013	0.625013	0.636986	0.654807	0.558425	0.569541	0.587631	0.660761	0	0	0
	C3S3	0.636986	0.654807	0.238487	0.238487	0.238487	0.258285	0.249856	0.319618	0.333069	0.323386	0.208127	0	0	0
C4	C4S1	0.052358	0.057613	0.055285	0.053938	0.052358	0.048866	0.059234	0.042921	0.065522	0.06479	0.067346	0	0	0
	C4S2	0.258636	0.322162	0.262201	0.499773	0.258636	0.257272	0.213451	0.245678	0.283324	0.256274	0.320069	0	0	0
	C4S3	0.57329	0.527138	0.565009	0.304152	0.57329	0.568441	0.588225	0.578598	0.517657	0.536783	0.442883	0	0	0
	C4S4	0.115716	0.093086	0.117504	0.142137	0.115716	0.12542	0.139089	0.132804	0.133497	0.142153	0.169702	0	0	0
C5	C5S1	0.262753	0.270557	0.648329	0.205091	0.217638	0.217638	0.270557	0.222728	0.1365	0.353132	0.217638	0	0	0
	C5S2	0.65863	0.644223	0.229651	0.716653	0.690959	0.690959	0.644223	0.707117	0.625013	0.060793	0.690959	0	0	0

	C5S3	0.078617	0.08522	0.12202	0.078257	0.091402	0.091402	0.08522	0.070155	0.238487	0.586076	0.091402	0	0	0
Goal	Criticality Analysis	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.4: Unweighted supermatrix (Continued…)

		C2S1	**C2S2**	**C3S1**	**C3S2**	**C3S3**	**C4S1**	**C4S2**	**C4S3**	**C4S4**	**C5S1**	**C5S2**	**C5S3**	**Criticality Analysis**
Alternatives	A1	0.23859	0.013792	0.293607	0.293731	0.178132	0.27766	0.339665	0.128903	0.332989	0.199454	0.241999	0.067007	0
	A2	0.212035	0.025024	0.114247	0.1555	0.133255	0.222128	0.174036	0.034274	0.218814	0.149786	0.165202	0.067007	0
	A3	0.031523	0.05662	0.111403	0.251508	0.129335	0.029324	0.024144	0.014727	0.025512	0.048562	0.040166	0.067007	0
	A4	0.060312	0.045617	0.097204	0.041307	0.128352	0.052969	0.106386	0.029404	0.091804	0.097523	0.12357	0.067007	0
	A5	0.098761	0.031251	0.086789	0.063049	0.086328	0.091335	0.06725	0.05362	0.074566	0.095281	0.086626	0.067007	0
	A6	0.09807	0.034361	0.075217	0.070698	0.075911	0.088431	0.06725	0.111147	0.074566	0.095281	0.086626	0.067007	0
	A7	0.015128	0.264084	0.072903	0.015771	0.085009	0.01406	0.014558	0.029225	0.014905	0.029881	0.024777	0.067007	0
	A8	0.093918	0.080885	0.047445	0.039438	0.042255	0.095826	0.05005	0.022536	0.04528	0.064889	0.059233	0.137831	0
	A9	0.022058	0.189077	0.043973	0.022049	0.059551	0.020182	0.01773	0.224638	0.018737	0.037172	0.030095	0.118237	0
	A10	0.043202	0.148055	0.040502	0.018686	0.060516	0.037956	0.038544	0.293405	0.034355	0.064889	0.049692	0.239051	0
	A11	0.086404	0.111235	0.016711	0.028262	0.021355	0.070129	0.100386	0.058122	0.068471	0.117283	0.092014	0.035831	0
C1	C1S1	0	0	0	0	0	0	0	0	0	0	0	0	0.318661
	C1S2	0	0	0	0	0	0	0	0	0	0	0	0	0.06601
	C1S3	0	0	0	0	0	0	0	0	0	0	0	0	0.615328
C2	C2S1	0	1	0	0	0	0	0	0	0	0	0	0	0.111111
	C2S2	1	0	0	0	0	0	0	0	0	0	0	0	0.888889
C3	C3S1	0	0	0	0.142857	0.75	0	0	0	0	0	0	0	0.177276
	C3S2	0	0	0.2	0	0.25	0	0	0	0	0	0	0	0.085225
	C3S3	0	0	0.8	0.857143	0	0	0	0	0	0	0	0	0.737498
C4	C4S1	0	0	0	0	0	0	0.236341	0.081935	0.081615	0	0	0	0.053548
	C4S2	0	0	0	0	0	0.19288	0	0.681725	0.157596	0	0	0	0.245838

	C4S3	0	0	0	0	0	0.700974	0.681725	0	0.760789	0	0	0	0.58411
	C4S4	0	0	0	0	0	0.106146	0.081935	0.236341	0	0	0	0	0.116504
C5	C5S1	0	0	0	0	0	0	0	0	0	0	0.888889	0.888889	0.778579
	C5S2	0	0	0	0	0	0	0	0	0	0.888889	0	0.111111	0.142823
	C5S3	0	0	0	0	0	0	0	0	0	0.111111	0.111111	0	0.078598
Goal	Criticality Analysis	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.5: Weighted supermatrix

		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**C1S1**	**C1S2**	**C1S3**
Alternatives	A1	0	0	0	0	0	0	0	0	0	0	0	0.155755	0.217314	0.109598
	A2	0	0	0	0	0	0	0	0	0	0	0	0.0658	0.177197	0.061571
	A3	0	0	0	0	0	0	0	0	0	0	0	0.01675	0.040242	0.026237
	A4	0	0	0	0	0	0	0	0	0	0	0	0.129841	0.130234	0.028644
	A5	0	0	0	0	0	0	0	0	0	0	0	0.092699	0.088283	0.047266
	A6	0	0	0	0	0	0	0	0	0	0	0	0.067853	0.102718	0.096558
	A7	0	0	0	0	0	0	0	0	0	0	0	0.024947	0.02046	0.030637
	A8	0	0	0	0	0	0	0	0	0	0	0	0.043614	0.056427	0.020386
	A9	0	0	0	0	0	0	0	0	0	0	0	0.016788	0.026275	0.238637
	A10	0	0	0	0	0	0	0	0	0	0	0	0.228699	0.047908	0.302494
	A11	0	0	0	0	0	0	0	0	0	0	0	0.157155	0.092843	0.037871
C1	C1S1	0.045302	0.018871	0.046858	0.047647	0.055756	0.091009	0.045302	0.115654	0.102022	0.127904	0.013555	0	0.000033	0.000075
	C1S2	0.013555	0.100268	0.011556	0.022116	0.015342	0.015776	0.013555	0.04413	0.057451	0.031544	0.045302	0.000067	0	0.000025
	C1S3	0.113557	0.053275	0.114	0.102652	0.101316	0.065629	0.113557	0.012629	0.012941	0.012966	0.113557	0.000033	0.000067	0
C2	C2S1	0.057471	0.047893	0.251437	0.251437	0.239464	0.246305	0.246305	0.047893	0.03592	0.03592	0.251437	0	0	0
	C2S2	0.229885	0.239464	0.03592	0.03592	0.047893	0.041051	0.041051	0.239464	0.251437	0.251437	0.03592	0	0	0
C3	C3S1	0.050469	0.048822	0.026672	0.026672	0.026672	0.020464	0.018629	0.023831	0.01903	0.017388	0.02562	0	0	0
	C3S2	0.020464	0.018629	0.122129	0.122129	0.122129	0.124468	0.127951	0.109117	0.11129	0.114824	0.129114	0	0	0

	C3S3	0.124468	0.127951	0.046601	0.046601	0.046601	0.050469	0.048822	0.062454	0.065083	0.06319	0.040668	0	0	0
C4	C4S1	0.012036	0.013244	0.012709	0.0124	0.012036	0.011234	0.013617	0.009867	0.015062	0.014894	0.015482	0	0	0
	C4S2	0.059456	0.07406	0.060276	0.11489	0.059456	0.059143	0.049069	0.056478	0.065132	0.058913	0.073579	0	0	0
	C4S3	0.131791	0.121181	0.129887	0.06992	0.131791	0.130676	0.135224	0.133011	0.119002	0.123398	0.101812	0	0	0
	C4S4	0.026601	0.021399	0.027012	0.032675	0.026601	0.028832	0.031975	0.03053	0.030689	0.032679	0.039012	0	0	0
C5	C5S1	0.030201	0.031098	0.074521	0.023574	0.025016	0.025016	0.031098	0.025601	0.01569	0.04059	0.025016	0	0	0
	C5S2	0.075705	0.074049	0.026397	0.082374	0.079421	0.079421	0.074049	0.081278	0.071841	0.006988	0.079421	0	0	0
	C5S3	0.009036	0.009795	0.014025	0.008995	0.010506	0.010506	0.009795	0.008064	0.027412	0.067365	0.010506	0	0	0
Goal	Criticality Analysis	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.5: Weighted supermatrix (Continued…)

		C2S1	**C2S2**	**C3S1**	**C3S2**	**C3S3**	**C4S1**	**C4S2**	**C4S3**	**C4S4**	**C5S1**	**C5S2**	**C5S3**	**Criticality Analysis**
Alternatives	A1	0.216898	0.012538	0.266913	0.267026	0.161936	0.252416	0.308783	0.117184	0.302715	0.199434	0.241974	0.067	0
	A2	0.192757	0.022749	0.10386	0.141363	0.12114	0.201932	0.158214	0.031158	0.19892	0.149771	0.165186	0.067	0
	A3	0.028657	0.051472	0.101275	0.228641	0.117576	0.026658	0.021949	0.013388	0.023193	0.048557	0.040162	0.067	0
	A4	0.054829	0.04147	0.088366	0.037551	0.116683	0.048153	0.096714	0.026731	0.083458	0.097514	0.123557	0.067	0
	A5	0.089782	0.02841	0.078898	0.057317	0.078479	0.083031	0.061136	0.048745	0.067786	0.095271	0.086617	0.067	0
	A6	0.089154	0.031237	0.068379	0.064271	0.06901	0.080391	0.061136	0.101041	0.067786	0.095271	0.086617	0.067	0
	A7	0.013752	0.240074	0.066275	0.014337	0.07728	0.012782	0.013235	0.026568	0.01355	0.029878	0.024774	0.067	0
	A8	0.085379	0.073531	0.043131	0.035853	0.038413	0.087113	0.045499	0.020487	0.041164	0.064882	0.059227	0.137817	0
	A9	0.020053	0.171887	0.039975	0.020045	0.054137	0.018347	0.016118	0.204214	0.017033	0.037168	0.030092	0.118226	0
	A10	0.039274	0.134594	0.036819	0.016988	0.055014	0.034505	0.035039	0.266729	0.031232	0.064882	0.049687	0.239027	0
	A11	0.078548	0.101121	0.015192	0.025693	0.019414	0.063753	0.09126	0.052838	0.062246	0.117271	0.092005	0.035828	0
C1	C1S1	0	0	0	0	0	0	0	0	0	0	0	0	0.055688
	C1S2	0	0	0	0	0	0	0	0	0	0	0	0	0.011536
	C1S3	0	0	0	0	0	0	0	0	0	0	0	0	0.107533

C2	C2S1	0	0.090917	0	0	0	0	0	0	0	0	0	0	0.032362
	C2S2	0.090917	0	0	0	0	0	0	0	0	0	0	0	0.2589
C3	C3S1	0	0	0	0.012988	0.068188	0	0	0	0	0	0	0	0.034423
	C3S2	0	0	0.018183	0	0.022729	0	0	0	0	0	0	0	0.016549
	C3S3	0	0	0.072734	0.077929	0	0	0	0	0	0	0	0	0.143204
C4	C4S1	0	0	0	0	0	0	0.021487	0.007449	0.00742	0	0	0	0.012997
	C4S2	0	0	0	0	0	0.017536	0	0.061981	0.014328	0	0	0	0.059669
	C4S3	0	0	0	0	0	0.063731	0.061981	0	0.069169	0	0	0	0.141774
	C4S4	0	0	0	0	0	0.009651	0.007449	0.021487	0	0	0	0	0.028278
C5	C5S1	0	0	0	0	0	0	0	0	0	0	0.000089	0.000089	0.07559
	C5S2	0	0	0	0	0	0	0	0	0	0.000089	0	0.000011	0.013866
	C5S3	0	0	0	0	0	0	0	0	0	0.000011	0.000011	0	0.007631
Goal	Criticality Analysis	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.6: Limit supermatrix

		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**C1S1**	**C1S2**	**C1S3**
Alternatives	A1	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643
	A2	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359
	A3	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017
	A4	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369
	A5	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667
	A6	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063
	A7	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003
	A8	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365
	A9	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023
	A10	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943
	A11	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848

C1	C1S1	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824
	C1S2	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874
	C1S3	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555
C2	C2S1	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276
	C2S2	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331
C3	C3S1	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106
	C3S2	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634
	C3S3	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032
C4	C4S1	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664
	C4S2	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067
	C4S3	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524
	C4S4	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583
C5	C5S1	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035
	C5S2	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458
	C5S3	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005
Goal	Criticality Analysis	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.6: Limit supermatrix (Continued…)

		C2S1	**C2S2**	**C3S1**	**C3S2**	**C3S3**	**C4S1**	**C4S2**	**C4S3**	**C4S4**	**C5S1**	**C5S2**	**C5S3**	**Criticality Analysis**
Alternatives	A1	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643	0.088643
	A2	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359	0.056359
	A3	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017	0.030017
	A4	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369	0.035369
	A5	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667	0.033667
	A6	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063	0.038063
	A7	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003	0.032003

	A8	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365	0.027365
	A9	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023	0.045023
	A10	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943	0.05943
	A11	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848	0.036848
C1	C1S1	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824	0.030824
	C1S2	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874	0.016874
	C1S3	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555	0.03555
C2	C2S1	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276	0.071276
	C2S2	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331	0.081331
C3	C3S1	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106	0.018106
	C3S2	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634	0.044634
	C3S3	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032	0.041032
C4	C4S1	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664	0.007664
	C4S2	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067	0.036067
	C4S3	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524	0.062524
	C4S4	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583
C5	C5S1	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035	0.015035
	C5S2	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458	0.031458
	C5S3	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005	0.009005
Goal	Criticality Analysis	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.7: Relative importance of clusters and elements

Clusters	Elements	Ratio scale priority in the network (1)	Ratio scale priority of clusters (2)	Ratio scale priority of elements in their cluster (3)= (1)/(2)
Cost	C1S1	0.030824	0.083248	0.370267
	C1S2	0.016874		0.202696
	C1S3	0.03555		0.427037
Functional dependencies	C2S1	0.071276	0.152607	0.467056
	C2S2	0.081331		0.532944
Complexity	C3S1	0.018106	0.103772	0.174479
	C3S2	0.044634		0.430116
	C3S3	0.041032		0.395405
Maintainability	C4S1	0.007664	0.122085	0.062776
	C4S2	0.036067		0.295425
	C4S3	0.062524		0.512135
	C4S4	0.01583		0.129664
Safety Impact	C5S1	0.015035	0.055498	0.270911
	C5S2	0.031458		0.566831
	C5S3	0.009005		0.162258
Alternatives	A1	0.088643	0.482787	0.183607
	A2	0.056359		0.116737
	A3	0.030017		0.062174
	A4	0.035369		0.07326
	A5	0.033667		0.069735
	A6	0.038063		0.07884
	A7	0.032003		0.066288
	A8	0.027365		0.056681
	A9	0.045023		0.093256
	A10	0.05943		0.123098
	A11	0.036848		0.076324

Table 5.8: Criticality ranking of alternatives

S. No.	Code of alternative	Name of alternative	Ration scale priority in the cluster	Criticality ranking
1	A1	Turret	0.183607	1
2	A2	Clamping Accessory	0.116737	3
3	A3	Electric and Electronics system	0.062174	10
4	A4	Main transmission	0.07326	7
5	A5	X feed system	0.069735	8
6	A6	Z feed system	0.07884	5
7	A7	CNC system	0.066288	9
8	A8	Hydraulic system	0.056681	11
9	A9	Servo system	0.093256	4
10	A10	Cooling system	0.123098	2
11	A11	Spindle assembly	0.076324	6

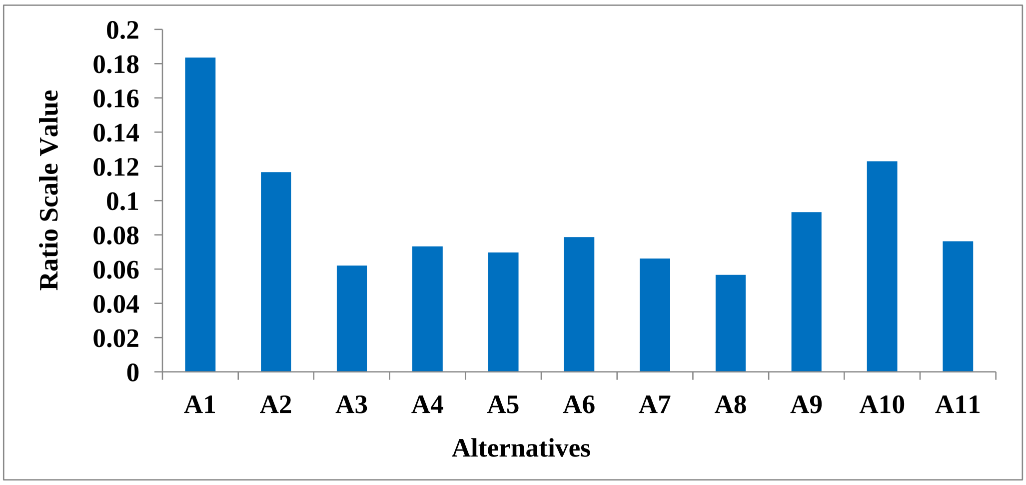

Figure 5.2: Priority of ratio scale in its cluster of alternatives

Table 5.9: Priority ranking of criteria for criticality analysis

S. No.	Code of Criteria	Name of Criteria	Ration scale priority of cluster	Priority ranking
1	C1	Cost	0.083248	4
2	C2	Functional dependencies	0.152607	1
3	C3	Complexity	0.103772	3
4	C4	Maintainability	0.122085	2
5	C5	Safety Impact	0.055498	5

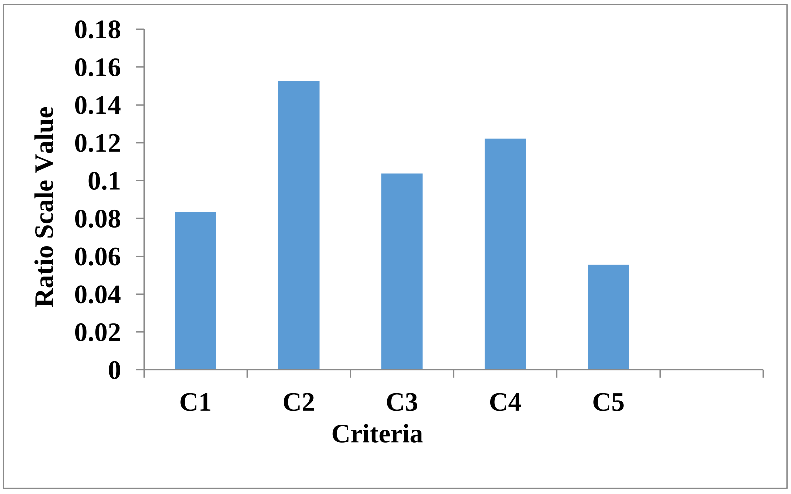

Figure 5.3: Priority of ratio scale in its cluster of criteria

Table 5.10: Priority ranking of sub-criteria for criticality analysis

S. No.	Code of Sub-Criteria	Name of Sub-Criteria	Ration scale priority of in their cluster	Priority ranking in the cluster
1	C1S1	Maintenance cost	0.370267	**2**
2	C1S2	Component cost	0.202696	**3**
3	C1S3	Cost of production loss	0.427037	**1**
4	C2S1	Process dependencies	0.467056	**2**
5	C2S2	Design dependencies	0.532944	**1**
6	C3S1	Probability of failure	0.174479	**3**
7	C3S2	Total number of parts	0.430116	**1**
8	C3S3	Failure effect	0.395405	**2**
9	C4S1	Availability of technical specification	0.062776	**4**
10	C4S2	Failure detection	0.295425	**2**
11	C4S3	Total downtime	0.512135	**1**
12	C4S4	Facility required to repair	0.129664	**3**
13	C5S1	Human safety	0.270911	**2**
14	C5S2	Resources safety	0.566831	**1**
15	C5S3	Environment safety	0.162258	**3**

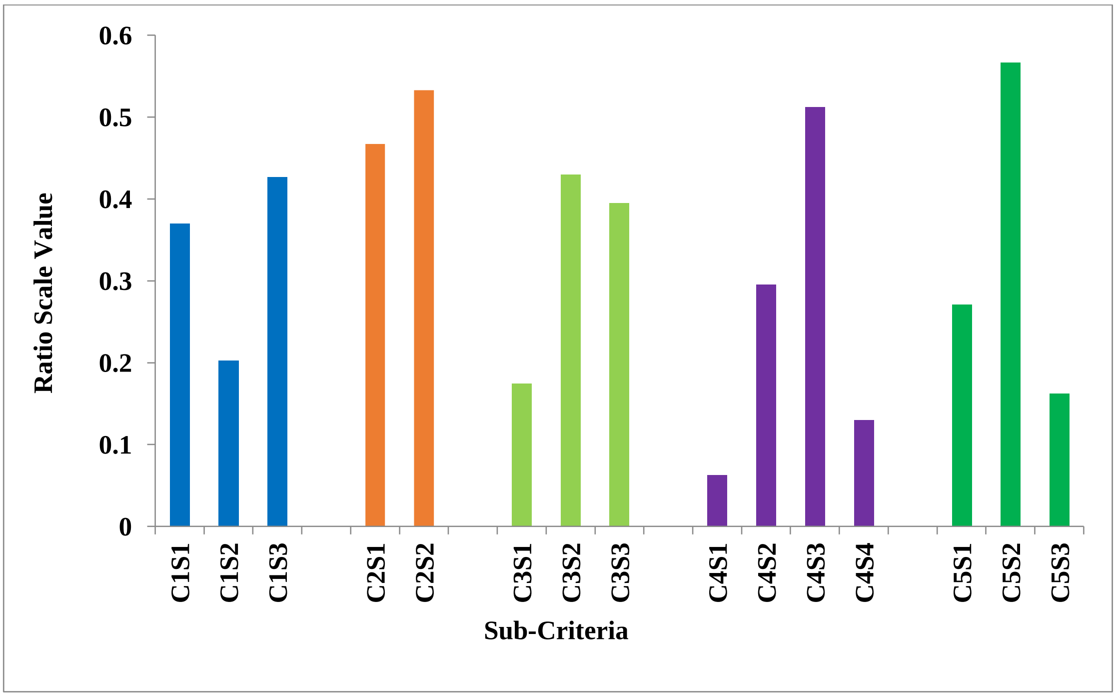

Figure 5.4: Priority of ratio scale in its cluster of sub-criteria

5.4 Results

This study indicates that the functional dependencies cluster has the most precedence among all criteria clusters in decision-making and within this cluster, the design dependency of each alternative has the most precedence in decision-making. The maintainability of each alternative has the second most precedence in decision-making within which the total downtime of each alternative has the most precedence in decision-making. It has been observed that turret is the most critical and hydraulic system is the least critical component of a CNC lathe machine. However, these results are validated based on the method used and interdependency of selected criteria only. There might be a possibility of variation in results if the criteria and their interdependency changes.

5.5 Conclusion

Identification of criticality levels of subsystems/components and their prioritization for maintenance activities is the essential step for the implementation of RCM. In this chapter, identification of the criticality levels of subsystems/components was considered as a multi-criteria decision problem and developed a hierarchical model in the form of a network for criticality analysis. After that, ANP is used to identify the criticality levels of subsystems/components for further analysis to implement the RCM. The ANP removes the ambiguity and uncertainty of pair-wise comparisons in AHP. The five major evaluation criteria i.e. (i) cost, (ii) functional dependencies, (iii) complexity, (iv) maintainability, and (v) safety impact and 15 sub-criteria (3 for each major criteria) were proposed based on feedback received from maintenance engineers, managers, practitioners, experts, and consultants of various industrial organizations and literature for the criticality analysis of components/subsystems. It is concluded that the proposed methodology will provide a realistic solution to decision-makers in prioritizing the critical subsystems/components for further analysis to implement the RCM. The proposed model was tested using a case study on a CNC lathe machine.

Based on the outcomes of the proposed model, the “turret” is the most critical component and the “hydraulic system” is the least critical component of a CNC lathe machine. Also, the functional dependencies are the most precedence among all criteria in decision-making and within this cluster, the design dependency of each alternative has the most precedence in decision-making. The maintainability of each alternative has the second most precedence in decision-making within which the total downtime of each alternative has the most precedence in decision-making.

CHAPTER 6

FMECA APPROACHES FOR CRITICALITY ANALYSIS

This chapter presents FMEA to find out the various failure modes of a conventional lathe machine and the criticality analysis of each failure mode using three approaches: (i) Conventional FMECA, (ii) Mean and Range value of RPN, and (iii) Fuzzy FMECA approach. A comparative analysis of all the above three approaches is also presented to propose a better approach of FMECA for the criticality analysis of a different failure modes of a system.

6.1 Introduction

Catic *et al.* (2011) defined the criticality as a relative proportion of components failure modes effects on which reliable and safe operation of the system implied. FMEA broadly utilized for characterizing, distinguishing and dispensing with potential failures from system, design, or process for the criticality analysis (Stamatis, 1995). In 1960, FMEA originated the first time in the aerospace and automotive industry (Bowles and Peldez, 1995). Juran (1989) defined FMEA as a methodology, to analysis a proposed design for possible ways in which failure can happen. Sharma *et al.* (2005) defined it as a bottom-up and structured approach to investigate the effect of potential failure modes. According to Popovic *et al.* (2010), It can be defined as a procedure to evaluate the system reliability that can be applied to its lifetime. FMEA process can be used to analyze failures and prevention of their occurrences (Devadasan *et al.,* 2003). FMEA can be applied for a product’s development and its design stages (Ben-daya and Raouf, 1996). Ahsen (2008) defines the objective of FMEA is to prevent failures and assist the administration in a more efficient allocation of assets. Furthermore, FMEA is an approach to assess the risks and therefore the standards of FMEA is to recognize potential hazards together with the focused system and prioritize the remedial actions (Catic *et al.*, 2011). When the criticality analysis combines with FMEA, Then FMEA becomes FMECA.

FMECA helps to direct the maintenance on the desired failure modes and prevent the failure causes. It follows with the selection of optimal maintenance actions using decision logic in the final stage of RCM. It is a comprehensive tool to assist in structuring maintenance management procedures, by systematically considering each failure mode of a system. According to Bertolini (2006) failure modes analysis provides some information about (i) the functional importance of the subsystem, (ii) description of all potential failure modes of the system, and (iii) criticality analysis which ranks all failure modes in a logical order.

To determine the criticality ranking of failure modes for the selection of maintenance actions is a vital issue in FMECA. The RPNs are used to determine the criticality ranking of failure modes in conventional FMECA. The RPN can be determined by just multiplying the evaluation criteria, i.e. Occurrence (O), Severity (S) and Detection (D) of each failure mode but it may not be realistic in some applications. It proved to be one of the most imperative early preventive actions for systems which can prevent the sudden failure. However practical applications reveal that the criticality analysis using conventional FMECA have been considerably criticized for a number of reasons (Ben-daya and Raouf, 1996; Bowles, 2003; Braglia *et al.*, 2003a; Chang *et al.*, 2001; Gargama and Chaturvedi, 2011; Gilchrist, 1996; Pillay and Wang, 2003; Sankar and Prabhu, 2001; Teng and Ho, 1996; Xu *et al.*, 2002). Specifically:

- The RPN is strongly dependents only on the small variation of three parameters, i.e. S, O and D. The same RPN could result starting from different values of S, O, and D.
- The consideration of the relative importance of S, O, and D is not taken into account. Also, the equal importance assumed of these three risk factors.
- Interdependencies between different failure modes and their effects of a system are not taken into account.
- The precise estimation of these three factors is difficult. The linguistic scale can be used to provide more information in FMEA.
- To determine RPN, the mathematical formula "RPN = S * O * D" has been debated, as it lacks a completely scientific basis.

Significant efforts have been made in FMEA literature to overcome these drawbacks of the conventional FMECA. As a result, Fuzzy logic is widely used in FMECA literatures. Bowles and Peldez (1995) presented two fuzzy-based approaches, first is based on numerical ranking and another is based on linguistic ranking for RPN calculation. They state that fuzzy resolves several problems in conventional method evaluation and has various advantage compared to numerical methods: (i) it allows to evaluate the criticality of failure mode directly using the linguistic fuzzy term, (ii) qualitative as well as quantitative data can be used for evaluation, and (iii) it gives a more flexible structure for combining these three parameters (S, O and D). Chang *et al.* (1999) used fuzzy linguistic terms to assess O, S and D, and grey relational analysis to determine the risk priorities of potential causes. Xu *et al.* (2002) proposed a fuzzy FMEA assessment for a gas turbocharger of a diesel engine. Pillay and Wang (2003) developed a fuzzy rule based approach to avoid the utilization of a conventional method for calculating RPN. Braglia *et al.* (2003a) proposed a fuzzy “Technique for Order of Preference by Similarity to Ideal Solution” (TOPSIS) FMECA, which is a fuzzy version of the technique for order preference by TOPSIS method and states that fuzzy allows to combine severity, detectability and probability of a failure in a more flexible structure. Braglia *et al.* (2003b) proposed a risk function using fuzzy if-then rule. Lertworasirikul *et al.* (2003) proposed a fuzzy Data Envelopment Analysis (DEA) approach for FMECA of Pressurized Water Reactor (PWR) auxiliary feed-water system. Sachdeva *et al.* (2009a, 2009b) presented the FMECA using TOPSIS approach for prioritizing the failure causes for the pulping system of a paper mill. Wang *et al.* (2009) proposed a fuzzy weighted geometric mean approach to evaluate the risk in FMECA. Bertolini (2006) presented a fuzzy VIKOR criticality analysis for FMECA technique and tested by means of an industrial case study, dealing with an Italian oil refinery. It was concluded that fuzzy logic appears to be a powerful tool for performing a complete criticality analysis because (i) it is possible to consider a potentially larger number of failure criteria, (ii) it is possible to give degree of importance to the criteria themselves, (iii) it makes the analysis simpler, because of use of precise data in the form of fuzzy numbers, and (iv) it is possible to manage the evaluation of tangible (quantitative) and intangible (qualitative) criteria. Yang *et al.* (2010) proposed a new FMECA model using fuzzy theory for a CNC machine tool. Zafiropoulos and Dialynas (2005) developed a methodology for the reliability prediction and FMECA of electronic devices using fuzzy logic. Zadeh (1965) proposed fuzzy FMECA and concluded that it is easy and admissible for fuzzy logic to deal with FMECA related information because it can build up the confidence of experts, allows imprecise data to be used so that it can easily treat many states of components and system and other fuzzy information included in FMECA.

Hence, in this chapter, FMEA to find out the various failure modes of each component of a conventional lathe machine is performed and after that Fuzzy FMECA, and Mean and Range value of RPN are used to perform the criticality analysis of each failure mode of a conventional lathe machine. A comparative analysis of all the above approaches is done to find out a better approach of FMECA for the criticality analysis of different failure modes of a system for the implementation of RCM. The fuzzy FMECA approach is also applied on a conventional milling machine and compared with conventional FMECA. The results for conventional milling machine are attached in Appendix – A.

6.2 Conventional FMECA

The conventional FMECA is a tool for evaluating potential failure modes and their causes. It helps in prioritizing the failure modes and recommends remedial measures for the prevention of catastrophic failures and the improvement of the quality of the product. There are two phases in FMECA. In the first phase, it deals with the identification of the potential failure modes and their effects, and in the second phase, it deals with performing criticality analysis to identify the criticality level of each failure mode by ranking the RPN (Sharma et al., 2006). The conventional FMECA described in the following eight steps. A flow chart adopted from Pillay and Wang (2003) for FMECA is presented in Figure 6.1.

- Identify the system and divide it into subsystems to focus the search for components.
- Identify all potential failure modes, their causes and the effects of failure modes of the entire system.
- Assess each failure mode in terms of S, O, and D.

- Determine the RPN using “RPN = S * O * D”.
- Determine the critical ranking of each failure mode.
- Determine whether remedial action is required or not.
- Develop recommendations to improve the system performance.
- Prepare a FMECA report by summarizing the analysis in tabular form.

6.3 FMEA of Conventional Lathe Machine

In this section, to perform the FMECA, a lathe machine is considered with three major subsystems i.e. (i) feed mechanism (including the feed motor, feed rod, lead screw etc.), (ii) carriage (including the tool post, cross slide, saddle etc.), and (iii) headstock assembly (including the gearbox, bearings, belt drive, motor, chuck etc.). Based on the working structure of conventional lathe machine, the six highly critical components in terms of Functionally Significant Items (FSI) i.e. (i) electrical motor, (ii) oil seals, (iii) gearbox, (iv) bearing, (v) lead screw, and (vi) belt drive are identified. FSI can be defined as a component which has a significant impact of its function on the system. The six functionally significant items and FMEA chart of lathe machine components are presented in Figure 6.2 and Table 6.1 respectively.

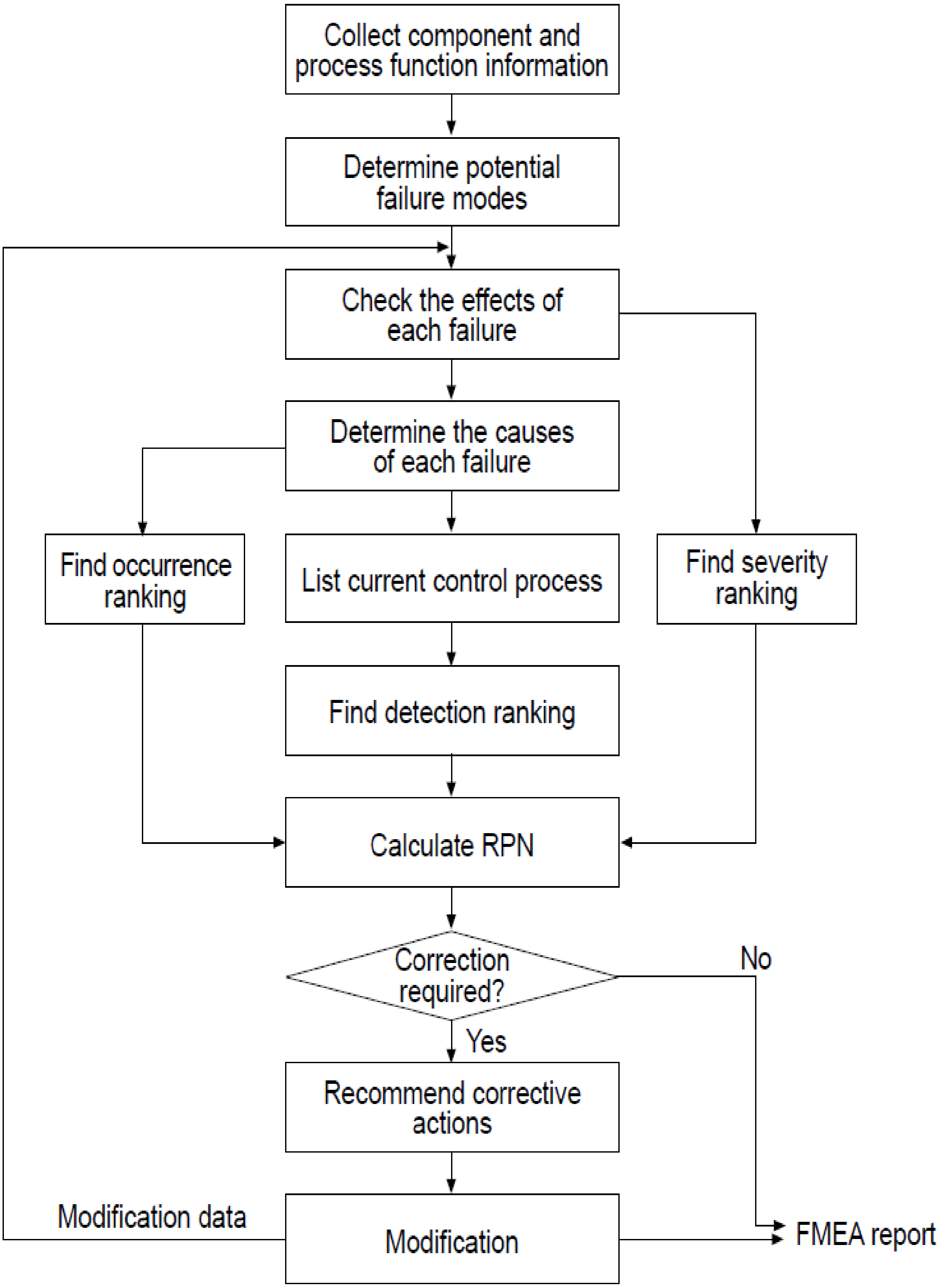

Figure 6.1: Conventional FMECA process flow chart (Pillay and Wang, 2003)

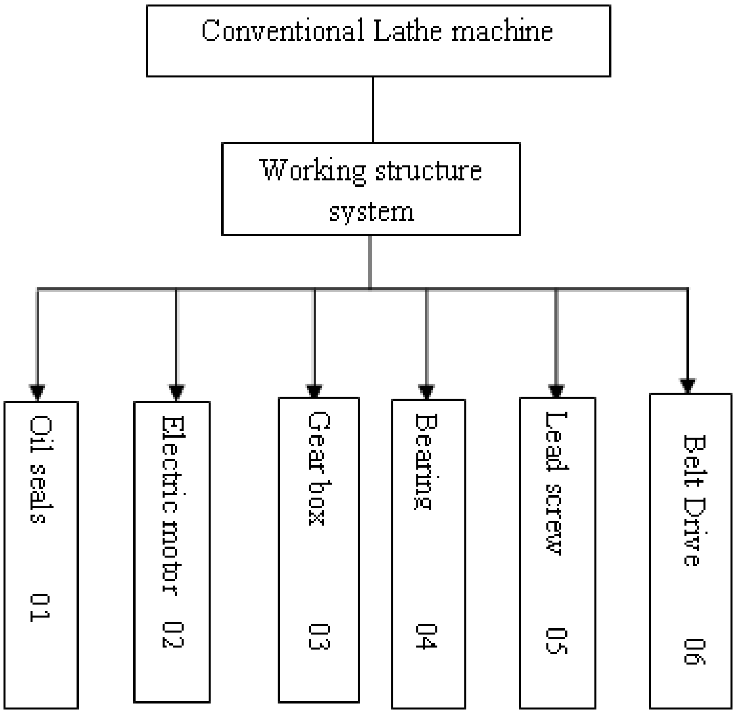

Figure 6.2: FSI of lathe machine

Table 6.1: FMEA of lathe machine components

Component	Component Function	Failure Mode	Failure Effect
1. Oil Seals	Provide a leak-proof seal between parts	1.1. Face Wear	Leakage in parts
		1. 2. Embrittlement	Seal components get damaged
2. Motor	Converts electrical energy to mechanical energy	2.1. Overheating failure	Cause separation of greases and breakdown of oils causing bearing failure.
		2.2. Power Supply Anomalies	Voltage unbalances lead to overheating and decreased efficiency.
3. Gear Box	Provides speed and torque conversions from a rotating power source	3.1. Wear	1. Gear teeth eroded by wear 2. Bearings seize
		3.2. Surface fatigue failure	1. Gear tooth may break 2. Formation of craters on gear teeth (Pitting)
		3.3. Breakage	Cracking of vital components in gears
4. Bearing	Supporting and aligning other parts of the lathe machine	4.1. Wear	Premature failure of contact surfaces
		4.2. Indentation	1. Denting on ball bearing 2. Bearing will not run properly
		4.3. Collapse	Bearing breakage due to deep-seated rust and uneven distribution of load.

5. Lead Screw	Converts rotary motion into linear motion	5.1. Failure	Wear and abrasion of the lead screw causes its failure
6. Belt drive	Power transmission between shafts	6.1. Pulley misalignment	Belt failure
		6.2. Belt Slip	Wear and heat generated with reduced belt life
		6.3. Belt fatigue	Broken belt

6.4. Criticality Analysis for Failure Modes of Conventional Lathe Machine

6.4.1 Conventional FMECA approach

Each failure mode is sequentially numbered as a failure mode pointer for the evaluation of risk priority of each component. The influence of three parameters: S, O, and D are considered to evaluate the criticality or risk priority of a component. The severity reflects the gravity of the failure consequences. Occurrence defined as an index of the frequency of component failure. Detection has defined an index to detect a failure assuming that it has occurred. These parameters are measured on a scale of 1 to 10, as the number 1 presents the weak importance of failure while number 10 presents the strong importance of failure. The classification criteria for each one of these parameters for failure mode evaluation is presented in Table 6.2. From these parameters, RPN is determined by multiplying S, O, and D. After that, the criticality ranking has been decided based on the value of RPN of various failure modes of each component. The highest value of RPN assigned the criticality ranking 1. The RPN’s of failure modes of each component are shown in Table 6.3 and Figure 6.3. It has been observed that failure mode number 6.3 and 3.1 is highest and lowest criticality ranking respectively. Also, criticality ranking for failure mode numbers (1.2, 4.2, and 4.3), (3.2, and 6.1), and (3.3, and 4.1) is same because of RPN value is equal as 18, 8 and 6 respectively.

Table 6.2: Evaluation Criteria of failure modes for conventional FMECA

Severity		Occurrence	
1	Insignificant effect. Minimal or no correction required.	**1**	Without failure registry in the last two years.
2	The very insignificant effect corrected immediately by the operation team.	**2**	1 or 2 failures in the past two years.
3	The insignificant effect corrected immediately by the maintenance.	**3**	3 or 4 failures in the past two years.
4	The minor effect, the component suffers to a gradual degradation case if not repaired.	**4**	5 or 6 failures in the past two years.
5	The moderate effect, the component does not execute its function, but the maintenance of failure does not demand the stop of the machine.	**5**	7 or 8 failures in the past two years.
6	The moderate effect, maintenance demands stop of the machine during one day or less.	**6**	9 or 10 failures in the past two years.
7	Critical effect, maintenance demands stop of the machine for more than one day.	**7**	10 or 11 failures in the past two years.
8	The very critical effect, the machine has to be stopped and takes longer repair time.	**8**	12 or 13 failures in the past two years.
9	The very critical effect, failure brusquely interrupts the system functions.	**9**	14 or 15 failures in the past two years.
10	The catastrophic effect that can cause damages to properties or people	**10**	More than 15 failures in the past two years.

Detection	
1	100% automatic inspection of the defect. Maintenance of the defect or the mechanical equipment is very obvious.
2	Almost 100% inspection of all parts of lathe machine is done automatically.
3	Failure identified automatically most of the times and sometimes by the manual inspection.
4	Failure in the lathe machine is indicated directly by the operator.
5	Failure identified by the maintenance team during daily inspections.
6	Lathe machine undergoes 100% manual inspection and observations.
7	Failure identified by abnormal noises.
8	Failure is identified by performing some tests and not just by direct inspection.
9	Failure identified by random or indirect tests only.
10	Occult failure, impossible to be identified by the operator or maintenance team.

Table 6.3: RPN and criticality ranking of failure modes for conventional FMECA

Failure Mode	Severity	Occurrence	Detection	RPN	Criticality Ranking	Failure Mode	Severity	Occurrence	Detection	RPN	Criticality Ranking
1.1	3	5	1	15	6	**4.1**	3	2	1	6	9
1.2	3	3	2	18	5	**4.2**	3	2	3	18	5
2.1	5	2	2	20	4	**4.3**	2	3	3	18	5
2.2	5	2	1	10	7	**5.1**	3	3	4	36	2
3.1	3	1	1	3	10	**6.1**	4	2	1	8	8
3.2	4	1	2	8	8	**6.2**	7	2	2	28	3
3.3	6	1	1	6	9	**6.3**	7	2	3	42	1

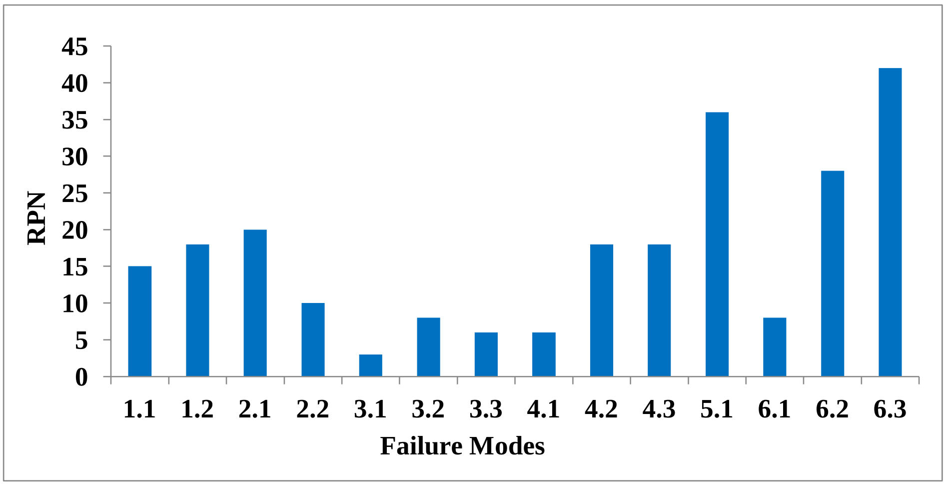

Figure 6.3: RPN values plot of failure modes using conventional FMECA

6.4.2 Mean and range value of RPN

RPN is one of the key factors in determining the criticality ranking of failure modes of a component, but there are drawbacks in determining the criticality ranking in conventional FMEA. In this approach, more than one failure mode is sharing the same RPN number, and therefore different criticality ranking cannot be assigned to those failure modes. Hence, a team of four members of various cross-functional expertise (2 academicians and two industrial experts) was constituted to reduce the subjectivity of the scores rating by different experts. The S, O, and D values from the criteria for failure mode evaluation presented in Table 6.2 is recorded individually from all four experts, and RPN is calculated by just multiplying S, O, and D for each of those experts assuming that the importance of all three parameters is same. The S, O, and D values are given by different experts for each failure mode is presented in Table 6.4. After that, mean and range value of RPN for each failure mode is determined. Mean value is the average mean of RPN and range value is difference of highest and lowest RPN for each failure mode. The mean and range value is presented in Table 6.5 and Figure 6.4. The following rule is proposed to decide the criticality ranking of each failure mode: “Higher the mean RPN value; higher will be the criticality ranking of that failure mode. If the mean RPN value is the same for two or more failure modes, Lesser the RPN range will be more critical of that failure mode”.

Table 6.4: S, O and D value of failure modes for mean and range value of RPN

S. No.	**Failure Mode**	**S**	**O**	**D**
1	1.1	(2, 3, 4, 5)	(7, 8, 9, 9)	(2, 3, 4,5)
2	1.2	(2, 3, 5, 6)	(6, 7, 8, 9)	(2, 3, 5, 6)
3	2.1	(4, 5, 7, 8)	(3, 4, 6, 7)	(2, 3, 5, 6)
4	2.2	(1, 2, 2, 3)	(2, 4, 4, 5)	(1, 1, 1, 2)
5	3.1	(9, 6, 9, 6)	(6, 7, 5, 5)	(4, 3, 2, 6)
6	3.2	(6, 8, 9, 8)	(6, 4, 5, 6)	(4, 3, 4, 4)
7	3.3	(9, 6, 6, 8)	(2, 6, 3, 3)	(9, 4, 9, 6)
8	4.1	(9, 5, 9, 6)	(2, 4, 4, 3)	(7, 9, 4, 9)
9	4.2	(4, 5, 6, 8)	(4, 5, 7, 8)	(1, 2, 3, 4)
10	4.3	(5, 4, 7, 8)	(4, 5, 7, 8)	(5, 7, 7, 8)
11	5.1.	(7, 8, 9, 9)	(3, 3, 5, 6)	(3, 4, 6, 7)
12	6.1	(2, 3, 5, 6)	(6, 5, 8, 9)	(4, 5, 6, 7)
13	6.2	(1, 2, 3, 4)	(2, 3, 4, 5)	(1, 1, 3, 3)
14	6.3	(5, 6, 8, 8)	(4, 5, 7, 8)	(3, 4, 6, 7)

Table 6.5: Criticality ranking of failure modes for mean and range value of RPN

Failure mode	S	O	D	RPN			Criticality ranking
				RPN	Mean	Range	
1.1	2	7	2	28	117.25	197.00	11
	3	8	3	72			
	4	9	4	144			
	5	9	5	225			
1.2	2	6	2	24	152.75	300.00	10
	3	7	3	63			
	5	8	5	200			
	6	9	6	324			
2.1	4	3	2	24	157.50	312.00	5
	5	4	3	60			
	7	6	5	210			
	8	7	6	336			
2.2	1	2	1	2	12.00	28.00	14
	2	4	1	8			
	2	4	1	8			
	3	5	2	30			
3.1	9	6	4	216	153.00	126.00	9
	6	7	3	126			
	9	5	2	90			
	6	5	6	180			
3.2	6	6	4	144	153.00	96.00	8
	8	4	3	96			
	9	5	4	180			
	8	6	4	192			
3.3	9	2	9	162	153.00	18.00	6
	6	6	4	144			
	6	3	9	162			
	8	3	6	144			
4.1	9	2	7	126	153.00	54.00	7
	5	4	9	180			
	9	4	4	144			
	6	3	9	162			
4.2	4	4	1	16	112.00	240.00	12
	5	5	2	50			
	6	7	3	126			
	8	8	4	256			
4.3	5	4	5	100	273.75	412.00	1
	4	5	7	140			
	7	7	7	343			
	8	8	8	512			
5.1	7	3	3	63	201.75	315.00	3
	8	3	4	96			
	9	5	6	270			
	9	6	7	378			
6.1	2	6	4	48	185.25	330.00	4

	3	5	5	75			
	5	8	6	240			
	6	9	7	378			
6.2	1	2	1	2	26.00	58.00	13
	2	3	1	6			
	3	4	3	36			
	4	5	3	60			
6.3	5	4	3	60	241.00	388.00	2
	6	5	4	120			
	8	7	6	336			
	8	8	7	448			

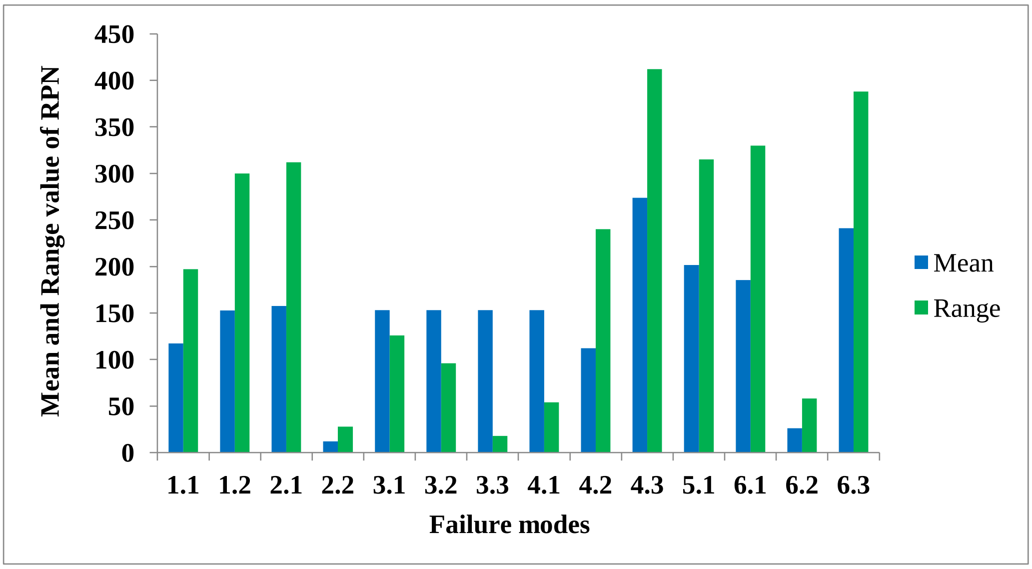

Figure 6.4: Mean and range values of RPN plot of failure modes

It has been observed that the mean RPN of the failure mode number 3.1, 3.2, 3.3 and 4.1 are same but the difference in their range value makes them appear in a particular critical order 3.3, 4.1, 3.2 and 3.1 which is justified when the seriousness of failure modes is observed. Among these four failure modes, 3.3 is the most critical failure mode having the least range value, as it presents the breakage in the gearbox which is a serious issue. While the other failure modes which are comparatively less serious are ordered in the way which automatically came out from the criticality order.

6.5 Criticality Analysis Using Fuzzy FMECA

A fuzzy approach of FMECA is used to evaluate the effect of functional failure and criticality analysis for each component of the lathe machine. The detailed explanation of this approach is presented here with a flowchart is shown in Figure 6.5.

6.5.1 Fuzzy membership function of S, O, and D

Each failure mode is sequentially numbered as a failure mode pointer for the evaluation of risk priority of each component. The influence of the parameters S, O and D is considered to evaluate the criticality or risk priority of a component. These parameters are measured on five-point linguistic scale V = {R= remote, L= low, M=moderate, H=high, VH= very high} and the evaluation criteria of each one of these parameter is presented in Table 6.6. To measure the average of linguistic scale values (V), trapezoidal fuzzy number is adopted from Yang *et al.* (2010) to defined the membership of these factors and presented in Figure 6.6. A team of four experts from maintenance areas was constituted to decide the rating of S, O, and D for each failure mode. The following equations are used to determine the deduced values of given rating of S_i, O_i, D_i for each failure mode.

$$S_i = (S_{iL}, S_{iM1}, S_{iM2}, S_{iR}) = \{\sum_{j=1}^{m}(S_{ijL}, S_{ijM1}, S_{ijM2}, S_{ijR})\}/m \qquad (6.1)$$

$$O_i = (O_{iL}, O_{iM1}, O_{iM2}, O_{iR}) = \{\sum_{j=1}^{m}(O_{ijL}, O_{ijM1}, O_{ijM2}, O_{ijR})\}/m \qquad (6.2)$$

$$D_i = (D_{iL}, D_{iM1}, D_{iM2}, D_{iR}) = \{\sum_{j=1}^{m}(D_{ijL}, D_{ijM1}, D_{ijM2}, D_{ijR})\}/m \qquad (6.3)$$

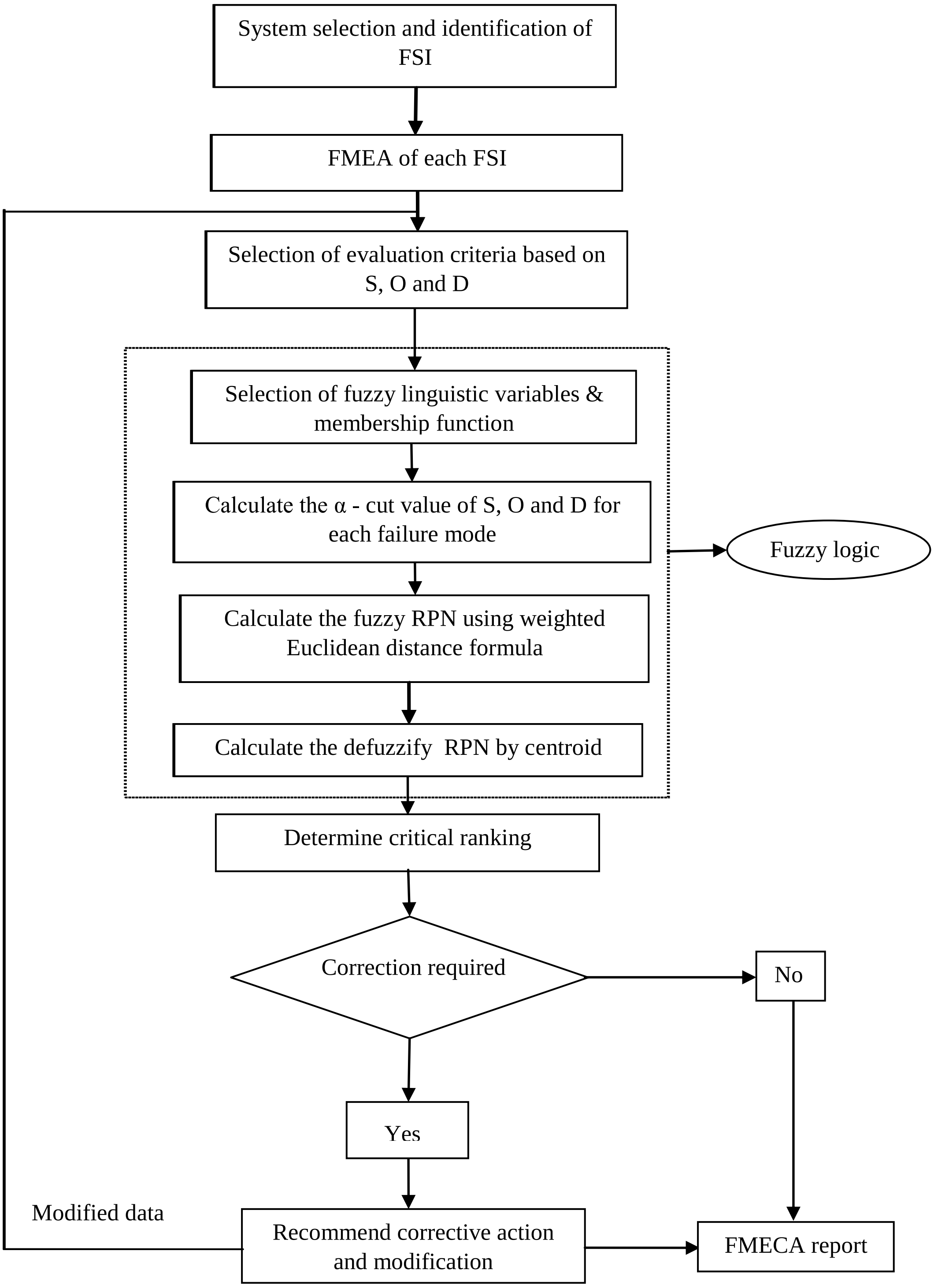

Figure 6.5: Flowchart of fuzzy FMECA

Where $i = 1,....,n$; $j = 1,.....,m$;

S_{ij} = Fuzzy scores of the i^{th} failure mode;

j = j^{th} expert;

m = Total no. of expert

The rating is given by experts for each failure mode and the deduced values determined by equation (6.1) to (6.3) of the membership function of these factors are shown in Table 6.7 and 6.8 respectively.

Table 6.6: Evaluation criteria of failure modes for fuzzy FMECA

	Severity		**Occurrence**
R	The insignificant effect corrected immediately by the maintenance.	**R**	The probability of failure is zero
L	The minor effect, the component suffers to a gradual degradation case if not repaired.	**L**	Failure is likely occurred once
M	The moderate effect, the component does not execute its function, but the maintenance of failure demands the stop of the machine.	**M**	The probability of failure is moderate (3 to 5 failures) in the past two years.
H	Critical effect, maintenance demands stop of the machine	**H**	The probability of failure is high (6 to 8 failures) in the past two years.
VH	The very critical effect, failure brusquely interrupts the system functions.	**VH**	The probability of failure is extremely high (9 or more failures) in the past two years.
	Detection		
R	Failure indicated directly by the operator.		
L	Failure identified by the maintenance team during daily inspections.		
M	Failure identified by abnormal noises		
H	Failure identified by thorough inspection and it is not feasible to be done		
VH	Occult failure, impossible to be identified by the operator or maintenance team		

Table 6.7: Rating of each failure mode for fuzzy FMECA

S. No.	**Failure Mode**	**Expert 1**			**Expert 2**			**Expert 3**			**Expert 4**		
		S	O	D	S	O	D	S	O	D	S	O	D
1	1.1	M	VH	L	L	VH	M	M	H	M	L	H	L
2	1.2	M	H	M	L	VH	M	M	H	M	M	M	L
3	2.1	M	M	M	H	M	M	M	M	M	H	M	L
4	2.2	L	L	R	L	M	R	R	L	R	L	M	R
5	3.1	H	M	M	H	M	L	M	L	H	VH	M	L
6	3.2	H	M	M	H	M	L	M	L	H	VH	M	L
7	3.3	VH	M	M	H	L	H	H	L	H	VH	M	M
8	4.1	M	H	M	M	H	L	M	M	M	H	H	M
9	4.2	M	H	M	M	M	L	M	M	L	H	H	L
10	4.3	H	H	H	H	M	H	M	H	H	M	M	M
11	5.1.	H	M	M	H	M	M	VH	L	M	VH	M	M
12	6.1	M	H	H	M	H	H	L	VH	L	M	H	M
13	6.2	L	M	R	L	L	R	L	L	M	L	M	R
14	6.3	H	M	M	H	H	M	M	M	M	H	H	M

Table 6.8: Membership function value of S, O and D of each failure mode

S. No.	**Failure Mode**	**S**	**O**	**D**
1	1.1	(2, 3, 4.5, 5.5)	(7, 8, 9, 9.5)	(2, 3, 4.5,5.5)
2	1.2	(2.5, 3.5, 5.25, 6.25)	(5.75, 6.75, 8, 8.75)	(2.5, 3.5, 5.25, 6.25)
3	2.1	(4.5, 5.5, 7, 8)	(3, 4, 6, 7)	(2.5, 3.5, 5.25, 6.25)
4	2.2	(0.75, 1.5, 2.5, 3.5)	(2, 3, 4.5, 5.5)	(0, 0, 1, 2)
5	3.1	(5.75, 6.75, 8, 8.75)	(2.5, 3.5, 5.25, 6.25)	(2.75, 3.75, 5, 6)
6	3.2	(5.75, 6.75, 8, 8.75)	(2.5, 3.5, 5.25, 6.25)	(2.75, 3.75, 5, 6)
7	3.3	(7, 8, 9, 9.5)	(2, 3, 4.5, 5.5)	(4.5, 5.5, 7, 8)
8	4.1	(3.75, 4.75, 6.5, 7.5)	(5.25, 6.25, 7.5, 8.5)	(2.5, 3.5, 5.25, 6.25)
9	4.2	(3.75, 4.75, 6.5, 7.5)	(4.5, 5.5, 7, 8)	(1.5, 2.5, 3.75, 4.75)
10	4.3	(4.5, 5.5, 7, 8)	(4.5, 5.5, 7, 8)	(5.25, 6.25, 7.5, 8.5)
11	5.1.	(7, 8, 9, 9.5)	(2.5, 3.5, 5.25, 6.25)	(3, 4, 6, 7)
12	6.1	(2.5, 3.5, 5.25, 6.25)	(6.5, 7.5, 8.5, 9.25)	(4, 5, 6.25, 7.25)
13	6.2	(1, 2, 3, 4)	(2, 3, 4.5, 5.5)	(0.75, 1, 2.25, 3.25)
14	6.3	(5.25, 6.25, 7.5, 8.5)	(4.5, 5.5, 7, 8)	(3, 4, 6, 7)

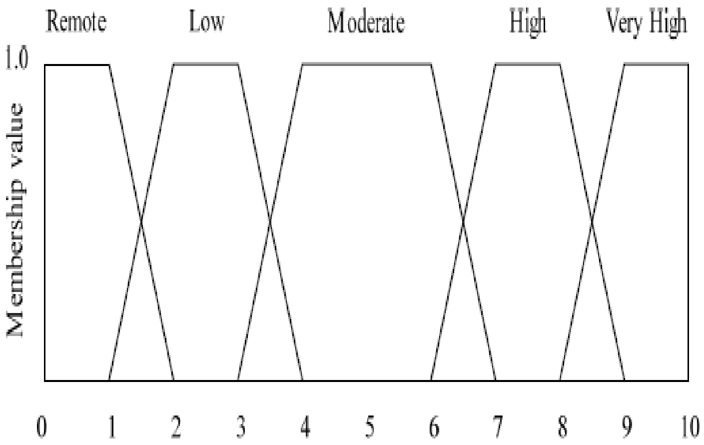

Figure 6.6: Membership function plot of S, O and D (Yang *et al.*, 2010)

6.5.2 Determination of fuzzy RPN values

The risk space diagram is adopted according to risk assessment on aviation safety management given by Yang *et al.* (2010) for calculating the α cut fuzzy value of S_i, O_i, and D_i and presented in Figure 6.7. The right-hand and left-hand values of S_i, O_i, and D_i are calculated by α- level using Zadehl's extension principle and are expressed by following equations.

$$S_{iL}^{\alpha} = S_{iL} + \alpha(S_{iM} - S_{iL}) \tag{6.4}$$

$$S_{iR}^{\alpha} = S_{iR} - \alpha(S_{iR} - S_{iM}) \tag{6.5}$$

$$O_{iL}^{\alpha} = O_{iL} + \alpha(O_{iM} - O_{iL}) \tag{6.6}$$

$$O_{iR}^{\alpha} = O_{iR} - \alpha(O_{iR} - O_{iM}) \tag{6.7}$$

$$D_{iL}^{\alpha} = D_{iL} + \alpha(D_{iM} - D_{iL}) \tag{6.8}$$

$$D_{iR}^{\alpha} = D_{iR} - \alpha(D_{iR} - D_{iM}) \tag{6.9}$$

Where $[S_{iL}^{\alpha}$ and $S_{iR}^{\alpha}]$ represents the left-hand and right-hand value of S interval of i^{th} failure mode by α-level. $[O_{iL}^{\alpha}, O_{iR}^{\alpha}]$ and $[D_{iL}^{\alpha}, D_{iR}^{\alpha}]$ represents O and D interval respectively. Subsequently left-hand and right-hand values of fuzzy RPN for each failure mode are calculated using weighted Euclidean distance formula using equations 6.10 and 6.11.

$$RPN_{iL}^{\alpha} = \sqrt{\sum_x w_x^2 (x_{iL}^{\alpha} - x_{i\min}^{\alpha})^2} \Big/ \sqrt{\sum_x w_x^2} \tag{6.10}$$

$$RPN_{iR}^{\alpha} = \sqrt{\sum_x w_x^2 (x_{iR}^{\alpha} - x_{i\min}^{\alpha})^2} \Big/ \sqrt{\sum_x w_x^2} \tag{6.11}$$

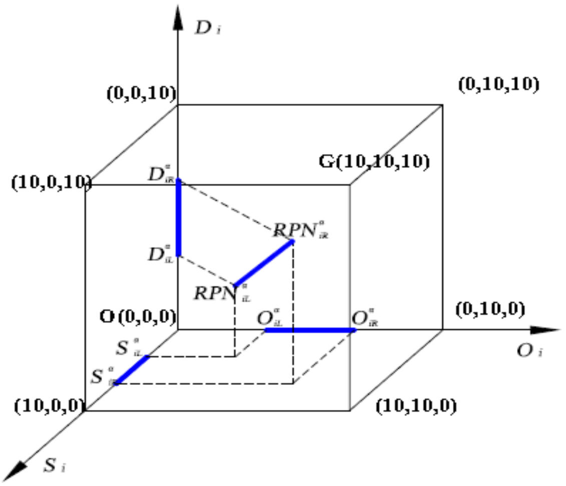

Figure 6.7: Risk space diagram of the ith failure mode (Yang et al., 2010)

Where W_x represents the weights of the risk factor $(x = S, O, D)$ which is adopted as [0.5396, 0.2970, 0.1634] respectively from Carmignani (2009). In the above equation $x_{i\min}$ represents the minimum value of x_i equals to zero according to Figure 6.6. After that centroid method is used to calculate the defuzzified RPN value. Then the criticality ranking of each failure mode is decided based on the defuzzified RPN value. The values of defuzzified RPN and criticality ranking of each failure mode using equations (6.4) to (6.11) are presented in Table 6.9 and Figure 6.8. It has been observed that the defuzzified RPN is different for each failure mode and none of the failure modes have the same criticality ranking.

Table 6.9: Defuzzified RPN and criticality ranking of failure modes for fuzzy FMECA

S. No.	**Failure Mode**	**α=0**		**α=0.5**		**α=1.0**		**Defuzzified RPN**	**Criticality Ranking**
		RPN_{iL}	RPN_{iR}	RPN_{iL}	RPN_{iR}	RPN_{iL}	RPN_{iR}		
1	1.1	3.72	6.58	4.14	6.18	4.58	5.79	5.17	12
2	1.2	3.48	6.88	3.95	6.42	4.42	5.96	5.19	11
3	2.1	4.11	7.69	4.61	7.19	5.1	6.7	5.9	7
4	2.2	1.13	3.96	1.51	3.47	1.89	3	2.5	14
5	3.1	5.06	8.11	5.54	7.72	6.03	7.32	6.63	4
6	3.2	5.06	8.11	5.54	7.72	6.03	7.32	6.60	5
7	3.3	6.12	8.69	6.59	8.4	7.06	8.11	7.5	1
8	4.1	4.06	7.66	4.56	7.16	5.05	6.66	5.86	8
9	4.2	3.83	7.47	4.32	6.97	4.82	6.48	5.65	9
10	4.3	4.56	8.04	5.06	7.54	5.56	7.04	6.3	6
11	5.1	6.08	8.62	6.56	8.44	7.04	8.15	7.49	2
12	6.1	3.84	7.08	4.3	6.62	4.76	6.17	5.47	10
13	6.2	1.28	4.33	1.74	3.84	2.22	3.35	2.8	13
14	6.3	4.98	8.31	5.48	7.81	5.97	7.31	6.65	3

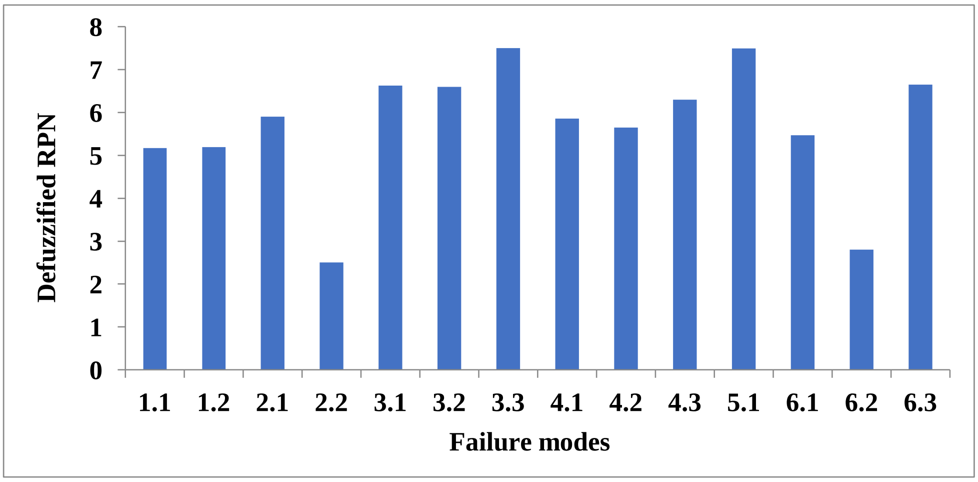

Figure 6.8: Defuzzified RPN values plot of failure modes

6.6 Comparative Analysis of Conventional FMECA, Mean and Range Value of RPN and Fuzzy FMECA

In this section, criticality ranking for each failure mode is compared using conventional FMECA, mean and range value of RPN, and fuzzy FMECA approach. The comparative analysis of criticality ranking of each failure mode is presented in Table 6.10 and Figure 6.9. It has been observed that none of the failure modes have the same criticality ranking using mean and range value of RPN and Fuzzy FMECA. Mean and range value of RPN considers the same importance of S, O, and D, which is not logical practically. The mean RPN value is the same for different failure modes. Therefore, the ranking is decided based on the range on the RPN value. Fuzzy FMECA considers the linguistic value and different weight of S, O, and D, which can be logically accepted and fuzzy RPN values are also different for each failure mode. Hence, Fuzzy FMECA can be considered as a better approach for criticality analysis of a system for the implementation of RCM.

Table 6.10: Comparison of criticality ranking of failure modes using all the three approaches

Component	Failure Mode	Mean and Range	Fuzzy FMECA	Conventional FMECA
1. Oil Seals	1.1. Face Wear	11	12	6
	1.2. Embrittlement	10	11	5
2. Motor	2.1. Overheating	5	7	4
	2.2. Power Supply anomalies	14	14	7
3. Gear Box	3.1. Wear	9	4	10
	3.2. Surface fatigue failure	8	5	8
	3.3. Breakage	6	1	9
4. Bearing	4.1. Wear	7	8	9
	4.2. Indentation	12	9	5
	4.3. Corrosion	1	6	5
5. Lead Screw	5.1. Wear	3	2	2
6. Belt Drive	6.1. Pulley misalignment	4	10	8
	6.2. Belt Slip	13	13	3
	6.3. Belt fatigue	2	3	1

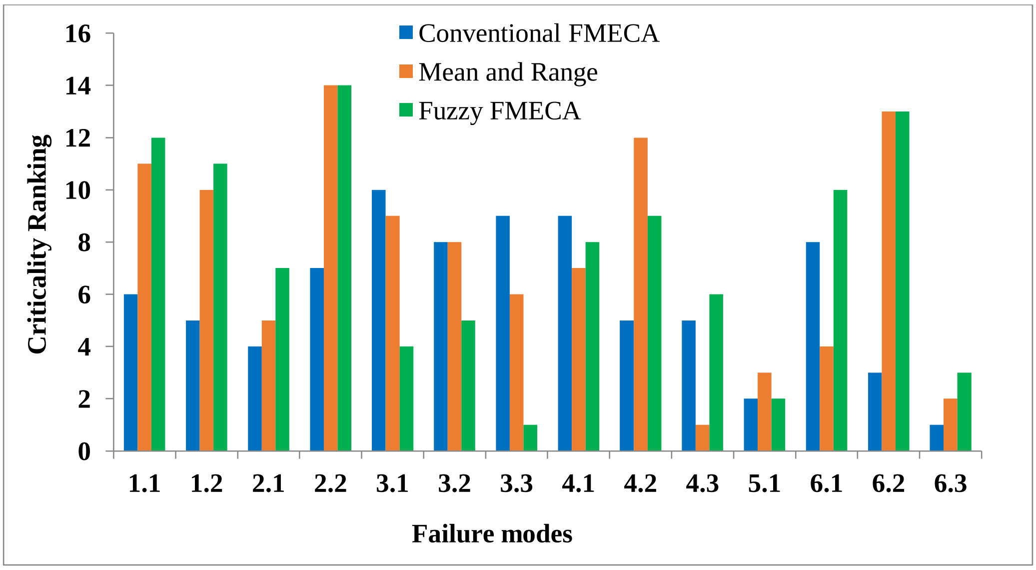

Figure 6.9: Comparative analysis plot of criticality ranking of failure modes

6.7 Conclusion

FMEA is conducted to find out the failure modes of each component of a conventional lathe machine and the criticality analysis of failure modes using three approaches: (i) conventional FMECA, (ii) mean and a range value of RPN, and (iii) fuzzy FMECA approach. A comparative analysis of all the above three approaches was done to find out a better approach of FMECA for criticality analysis of different failure modes of a system

Criticality analysis using conventional FMECA reveals that failure mode numbers (3.2 and 6.1), (3.3 and 4.1), and (1.2, 4.2 and 4.3) are having the same criticality ranking 8, 9 and 5 respectively. All these failure modes having the same RPN 8, 6 and 18, even the S, O and D value are different for these failure modes. All these failure modes will not have the same impact on the failure of lathe machine; therefore, defining the same criticality ranking for different failure modes is not logical. Also, as per the results, fatigue in the belt is the most critical and wear in the gearbox is the less critical failure mode.

Mean and a range value of RPN presents that all failure modes have different criticality ranking but the mean value of RPN for the failure mode 3.1, 3.2, 3.3 and 4.1 are same. Therefore, the criticality ranking is decided based on the range of the RPN value. Also, the importance of S, O, and D are considered as same. As per the results, corrosion in the bearing is most critical, and anomalies in power supply for the electric motor is least critical.

Criticality analysis using fuzzy presents that each failure mode is having different criticality ranking based on defuzzified RPN values determined by the fuzzy mathematics. Also, S, O, and D gave the different weight for calculating the defuzzified RPN values using the centroid method for various α–cut fuzzy values. According to the results, breakage in the gearbox is the most critical and anomalies in power supply for the electric motor is less critical, which are the most appropriate results compared to other two approaches.

Hence, it has been observed that fuzzy FMECA can be used to overcome the issues of conventional FMECA successfully. Fuzzy FMECA considers the linguistic value and different weights of S, O, and D, which can be logically accepted. This approach provides the more realistic results and flexible reflection in a real situation as FMEA is described in term of the fuzzy variable. Also, the interdependencies among the various failure modes can be explored easily using fuzzy. Finally, it is concluded that fuzzy approach can be considered as a better approach of FMECA for criticality analysis of different failure modes of a system for the implementation of RCM. Hence, we have used the fuzzy FMECA on conventional milling machine also and compared with conventional FMECA. The results are presented in Appendix–A.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

In this chapter, a summary of the research and major conclusions are presented. The objectives of this thesis are: (i) Development of a framework for the implementation of RCM, (ii) Development of a model to identify the criticality levels of subsystems/components of a system, and (iii) To propose an approach of FMECA for the criticality analysis of different failure modes of a system.

Chapter 2 presented a comprehensive literature review to identify the evolution of RCM definitions and related research. From the different definitions of RCM proposed by researchers, it has been observed that definitions and extent of RCM have been changed with time, started with a comprehensive zero-based review of necessities of every component in its working context and rapidly became the cornerstone of present maintenance scenario. It has also been observed that different authors have been using different terminology to refer to the same concepts of RCM in different areas. A total of one hundred twenty (120) research papers were reviewed with respect to the development, implementation, and application of RCM in different areas.

Further with the literature review of existing RCM frameworks, it was observed that most of the frameworks are either specific to a system or an industry type. Different frameworks proposed with different sets of elements of RCM in different sequences. In this chapter, the research gaps were identified and presented comprehensively. From the identified research gaps, it was recognized to develop a framework for the implementation of RCM, to develop a criticality analysis model for identification of criticality levels of each components/subsystems of a system and to propose an approach of FMECA for the criticality analysis of different failure modes of a system.

Chapter 3 presented a SWOT analysis of nineteen existing RCM frameworks, which were selected from the preliminary literature review for a comparative study based on the different elements of these frameworks. From the literature, it was observed that there is a lack of structured and implementable procedure for RCM and a structured implementation process is one of the success factors for the RCM in an organization. A SWOT analysis was conducted on existing RCM frameworks to overcome this issue. SWOT will encourage the administration to select the correct framework for an organization. These frameworks were categorized into three groups (Group A, B, and C) based on their emphasis on qualitative, quantitative, and practical application aspects. Group A frameworks involved qualitative RCM approaches; group B frameworks were based on a quantitative approach and group C frameworks employed practical approaches which were implemented in different industries. The findings from each group frameworks were as follows:

- **Group A**: These frameworks can be used for planning preventive maintenance based on continuous improvement. These frameworks provided a proper way to select the appropriate maintenance strategy to reduce maintenance costs and can be used to plan & control the maintenance expenses. However the lack of use of quantitative reliability analysis was the major drawback in these frameworks.
- **Group B**: These frameworks provided quantitative relationship between system reliability and maintenance effort based on logical and structured reliability analysis. However, the methodologies used in these frameworks were too complex, time-consuming and requires substantial input data.
- **Group C**: These frameworks were used in practice in various industries based on qualitative failure analysis and computer-aided RCM. However, these

frameworks also had the lack of quantitative reliability analysis similar to group A frameworks.

From the plethora of frameworks of RCM proposed by different authors and practitioners, it was observed that the usage of RCM was different from organization to organization, but the objectives were mostly similar. The SWOT analysis recommended that the execution of RCM was in no form a simple errand, as weaknesses and threats vigorously load of it. However, it offered considerable strengths and opportunities to establish a competitive advantage. Also, this analysis has revealed a lot of shortcomings of RCM, which have kept the organizations on a back foot in implementing RCM. It was recognized to develop a framework for the implementation of RCM based on the outcomes of SWOT analysis.

Chapter 4 presented a framework for the implementation of RCM. From the SWOT analysis, it was observed that most of the frameworks were based on the qualitative analysis and few frameworks on quantitative analysis. However, none of the framework can be utilized to take care of both qualitative and quantitative analysis together when needed. In this chapter, ten most significant elements were selected from the various elements of existing RCM frameworks based on the SWOT analysis. The ISM approach is used to establish the interrelationships of identified elements. It has been used to prioritize and categorize these elements based on their importance, preference, and causality over and among each other.

A multilevel hierarchy model has been developed from which, maintenance managers, engineers, practitioners who want to implement RCM, can easily visualize step by step procedure of RCM and can identify elements which require the highest attention. From

MICMAC analysis, it has been found that none of the factors comes under the autonomous category, which indicates all elements selected from SWOT analysis are essential for the RCM and organizations should pay attention to all of them.

Based on the ISM model, a framework was developed for the implementation of RCM in an organization. The significance of the proposed framework for RCM implementation is that it can be used for qualitative and quantitative analysis together at the same time. However, the existing RCM frameworks, which are available in literature, can be utilized for either qualitative or quantitative analysis only. This framework will help the maintenance managers, engineers, practitioners, and consultants to implement RCM successfully in an organization. Also, it presented the sequential and decision-making approach for systematic implementation of RCM in an organization in a phase-wise manner. This acted as a roadmap for the implementation of RCM in an organization.

Chapter 5 presented a methodology to identify the key factors associated with criticality and the development of a criticality analysis model for identification of criticality levels of subsystems/components of a system. The proposed model was applied on a CNC lathe machine for validation. It was observed that prioritization of critical subsystems/components in maintenance activities is the essential step for the implementation of RCM.

In this chapter, the identification of the criticality levels of subsystems/components was considered as a multi-criteria decision problem, and a hierarchical model was developed by using ANP. The ANP removes the ambiguity and uncertainty of pair-wise comparisons of AHP. The five major evaluation criteria i.e. (i) Cost, (ii) Functional dependencies, (iii) Complexity, (iv) Maintainability and (v) Safety impact and 15 sub-criteria were proposed based on feedback received from maintenance engineers, managers, practitioners, experts or consultants of various industrial organizations and literature for the criticality analysis of components/subsystems. It is concluded that the proposed methodology will provide a realistic solution to decision-makers in prioritizing the critical subsystems/components for further analysis to implement the RCM.

Based on the outcomes of the proposed model, the "turret" is the most critical component and the "hydraulic system" is the least critical component of a CNC lathe machine. In addition, the functional dependencies are the most precedence among all criteria in decision-making and within this cluster, the design dependency of each alternative has the most precedence in decision-making. The maintainability of each alternative has the second most precedence in decision-making within which the total downtime of each alternative has the most precedence in decision-making.

Chapter 6 presented FMEA to find out the failure modes of each component of a conventional lathe machine and the criticality analysis of failure modes using three approaches: conventional FMECA, mean and a range value of RPN, and fuzzy FMECA approach. The current issues of conventional FMECA for criticality analysis were presented in this chapter. A comparative analysis of all the above three approaches was also done to find out a better approach of FMECA for criticality analysis of different failure modes of a system.

Criticality analysis using conventional FMECA reveals that failure mode numbers (3.2 and 6.1), (3.3 and 4.1), and (1.2, 4.2 and 4.3) are having the same criticality ranking 8, 9 and 5 respectively. All these failure modes having the same RPN 8, 6 and 18, even the S, O and D value are different for these failure modes. All these failure modes will not have the same impact on the failure of lathe machine, therefore, defining the same criticality ranking for different failure modes is not logical.

Mean and a range value of RPN presented that all failure modes have different criticality ranking but the mean value of RPN for the failure mode 3.1, 3.2, 3.3 and 4.1 are same. Therefore, the criticality ranking was decided based on the range of the RPN value and the importance of S, O, and D were considered as same.

Criticality analysis using fuzzy approach presented that each failure mode have different criticality ranking based on defuzzified RPN values determined by the fuzzy mathematics. Also, S, O, and D gave the different weight for calculating the defuzzified RPN values using the centroid method.

It was observed that the fuzzy FMECA can be used to overcome the issues of conventional FMECA. Fuzzy FMECA considered the linguistic value and different weights of S, O, and D, which can be logically accepted. This approach provided more realistic results, and flexible reflection in a real situation, as FMECA was described in term of the fuzzy variables. Also, the interdependencies among the various failure modes were explored easily using fuzzy approach. Hence, it was concluded that the fuzzy approach can be considered as a better approach of FMECA for criticality analysis of different failure modes of a system for the implementation of RCM.

Specific Research Contributions of the Thesis

Specific research contributions of this thesis are:

- Review and classification of RCM literature based on the development, implementation, and application in different areas.
- SWOT analysis of the existing RCM frameworks.

- Identification of most significant elements of RCM.
- Development of a framework for the implementation of RCM.
- A criticality analysis model development and a case study based on the developed model on a CNC lathe machine.
- Proposing the Fuzzy FMECA as a better approach for criticality analysis of different failure modes of a system for the implementation of RCM.

Limitations and Future Scope of the Research

- The developed ISM model of RCM framework elements is highly dependent on the judgement and experience of the experts team. The consequences of developed ISM model may fluctuate in a genuine situation. Validation of the developed ISM model can be done more robustly and quantitatively using Structural Equation Modeling (SEM).
- The model development for the decision logic to determine the appropriate maintenance actions is not covered as the part of this thesis, that can be considered as a future scope of this study.
- The model development for the determination and comparison of system reliability is also not covered as the part of the thesis, that also can be considered as a future scope.
- In this dissertation, a fuzzy approach has been utilized for criticality analysis. However, results might be different or more useful, if the fuzzy approach can be combined with other decision making approaches like AHP, ANP, TOPSIS, DEMATEL, etc.

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APPENDIX -A

A.1 Criticality Analysis using Fuzzy FMECA for Conventional Milling Machine

A.1.1 FMEA of milling machine components

The FMEA chart of milling machine components shown in Table A.1

Table A.1: FMEA of the milling machine components

Component	Component Function	Failure Mode	Failure Effect
1. Seal Ring	Provide a leak-proof seal between parts	1.1. Face Wear	Leakage in parts
		1.2. Embrittlement	Seal components get damaged
2. Electric Motor	Converts electrical energy to mechanical energy	2.1. Overheating	Cause separation of greases and breakdown of oils causing bearing failure.
		2.2. Power Supply Anomalies	Voltage unbalances lead to overheating and decreased efficiency.
3. Gear Box	Provides speed and torque conversions from a rotating power source	3.1. Wear	1. Gear teeth eroded by wear 2. Bearing seize
		3.2. Surface fatigue failure	1. Gear tooth may break 2. Formation of craters on gear teeth
		3.3. Breakage	1. Cracking of vital components in gears
4. Bearing	Supporting and aligning other parts of the Milling machine	4.1. Wear	1. Premature failure of contact surfaces
		4.2. Indentation	1. The bearing will not run properly
		4.3. Corrosion	1. Uneven distribution of load due to material getting eroded 2. The bearing will not run
5. Belt drive	Power transmission	5.1. Pulley misalignment	1. Belt failure
		5.2. Belt Slip	1. Wear and heat generated with reduced belt life
		5.3. Belt fatigue	1. Breakage of belt

A.1.2 Criticality Analysis of Each Failure Mode Using Fuzzy Logic

Each failure mode is sequentially numbered as a failure mode pointer for the evaluation of risk priority of each component. The influence of three parameters severity, occurrence, and detection is considered to evaluate the criticality or risk priority of a component. These parameters are measured on a five-point linguistic scale V={R= remote, L= low, M=moderate, H=high, VH= very high} and same evaluation criteria of each one of the parameter are used according to Table 6.6. To measure the average of linguistic scale values (V), triangular fuzzy number is used to define the membership of these factors and presented in Figure A.1.

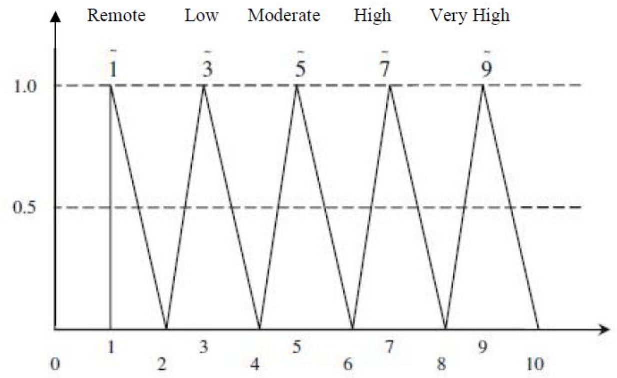

Figure A.1: Function plot of fuzzy linguistic scale for S, O, and D

A team of three experts from maintenance areas was constituted to decide the rating of severity, occurrence, and detection for each failure mode. The following equations are used to determine the deduced values of given rating of S_i, O_i, D_i for each failure mode.

$$S_i = (S_{iL}, S_{iM}, S_{iR}) = \{\sum_{j=1}^{m} (S_{ijL}, S_{ijM}, S_{ijR})\} / m \qquad \text{(A.1)}$$

$$O_i = (O_{iL}, O_{iM}, O_{iR}) = \{\sum_{j=1}^{m} (O_{ijL}, O_{ijM}, O_{ijR})\} / m \qquad \text{(A.2)}$$

$$D_i = (D_{iL}, D_{iM}, D_{iR}) = \{\sum_{j=1}^{m}(D_{ijL}, D_{ijM}, D_{ijR})\}/m \tag{A.3}$$

$i = 1,....,n$; $j = 1,.....,m$

Where

S_{ij} = The fuzzy scores of the ith failure mode;

j = jth expert; m = total no. of experts

The rating is given by each experts for each failure mode shown in Table A.2 and the deduced values determined by equation (A.1) to (A.3) of the membership function of these factors are shown in Table A.3. After that, defuzzified RPN values are calculated using equations 6.4 to 6.11 and presented in Table A.4.

Table A.2: Rating for each failure mode by FMEA experts

S.No.	Failure Mode No.	Expert 1			Expert 2			Expert 3		
		S	**O**	**D**	**S**	**O**	**D**	**S**	**O**	**D**
1	1.1	M	VH	L	M	H	M	L	VH	M
2	1.2	M	H	M	M	H	M	L	VH	M
3	2.1	M	M	M	M	M	M	H	M	M
4	2.2	L	L	R	R	L	R	L	M	R
5	3.1	H	M	M	M	L	H	H	M	M
6	3.2	H	M	M	M	L	H	H	M	M
7	3.3	VH	M	M	H	L	H	H	L	H
8	4.1	M	H	M	M	M	M	M	H	L
9	4.2	M	H	M	M	M	L	M	M	L
10	4.3	H	H	H	M	H	H	H	M	H
11	5.1	M	H	H	L	VH	M	M	H	H
12	5.2	L	M	R	L	L	L	L	L	R
13	5.3	H	M	M	M	M	M	H	H	M

Table A.3: Membership function of S, O, and D of each failure mode

S. No.	Failure Mode	Severity (S)	Occurrence (O)	Detection (D)
1	1.1	(3.33,4.33,5.33)	(7.33,8.33,9.33)	(3.33,4.33,5.33)
2	1.2	(3.33,4.33,5.33)	(6.67,7.67,8.67)	(4.00,5.00,6.00)
3	2.1	(4.67,5.67,6.67)	(4.00,5.00,6.00)	(4.00,5.00,6.00)
4	2.2	(1.67,2.33,3.33)	(2.67,3.67,4.67)	(1.00,1.00,2.00)
5	3.1	(5.33,6.33,7.33)	(3.33,4.33,5.33)	(4.67,5.67,6.67)
6	3.2	(5.33,6.33,7.33)	(3.33,4.33,5.33)	(4.67,5.67,6.67)
7	3.3	(6.67,7.67,8.67)	(2.67,3.67,4.67)	(5.33,6.33,7.33)
8	4.1	(4.00,5.00,6.00)	(5.33,6.33,7.33)	(3.33,4.33,5.33)
9	4.2	(4.00,5.00,6.00)	(4.67,5.67,6.67)	(2.67,3.67,4.67)
10	4.3	(5.33,6.33,7.33)	(5.33,6.33,7.33)	(6.00,7.00,8.00)
11	5.1	(3.33,4.33,5.33)	(6.67,7.67,8.67)	(5.33,6.33,7.33)
12	5.2	(2.00,3.00,4.00)	(2.67,3.67,4.67)	(1.33,1.67,2.67)
13	5.3	(5.33,6.33,7.33)	(4.67,5.67,6.67)	(4.00,5.00,6.00)

Table A.4: Defuzzified RPN and criticality ranking of each failure mode

S. No.	**Failure Mode No.**	**α=0**		**α=0.5**		**α=1.0**		**Defuzzified RPN**	**Criticality Ranking**
		RPN_{iL}	RPN_{iR}	RPN_{iL}	RPN_{iR}	RPN_{iL}	RPN_{iR}		
1	1.1	4.51	6.42	4.98	5.93	5.46	5.46	5.46	7
2	1.2	4.32	6.25	4.80	5.76	5.28	5.28	5.29	10
3	2.1	4.49	6.48	4.99	5.99	5.49	5.49	5.49	6
4	2.2	1.90	3.60	2.26	3.11	2.62	2.62	2.69	13
5	3.1	4.92	6.90	5.42	6.41	5.91	5.91	5.92	5
6	3.2	4.92	6.90	5.42	6.41	5.91	5.91	5.93	4
7	3.3	5.94	7.88	6.42	7.39	6.91	6.91	6.91	1
8	4.1	4.29	6.27	4.78	5.78	5.28	5.28	5.30	9
9	4.2	4.08	6.07	4.58	5.58	5.08	5.08	5.08	11
10	4.3	5.38	7.38	5.88	6.88	6.38	6.38	6.38	2
11	5.1.	4.41	6.34	4.89	5.86	5.37	5.37	5.38	8
12	5.2	2.13	4.08	2.61	3.59	3.09	3.09	3.10	12
13	5.3	5.12	7.11	5.62	6.61	6.11	6.11	6.12	3

A.2 Comparison of Criticality Analysis Using Fuzzy and Conventional FMECA

The criticality ranking using conventional FMECA is calculated using the method described in section 6.4.1 and presented in Table A.5. Thereafter, criticality ranking using fuzzy FMECA approach is compared with the traditional FMEA and presented in Table A.6.

Table A.5: Criticality ranking of each failure modes using traditional FMECA

Conventional Milling Machine

Failure Mode	Evaluation Factors						Evaluation Factors				
	Severity	**Occurrence**	**Detection**	**RPN**	**Criticality Ranking**	**Failure Mode**	**Severity**	**Occurrence**	**Detection**	**RPN**	**Criticality Ranking**
1.1	3	5	3	45	1	**4.1**	2	3	3	18	7
1.2	3	4	3	36	3	**4.2**	3	4	3	36	3
2.1	4	5	2	40	2	**4.3**	3	4	2	24	6
2.2	3	5	2	30	5	**5.1**	4	4	2	32	4
3.1	4	4	2	32	4	**5.2**	4	3	3	36	3
3.2	4	3	3	36	3	**5.3**	5	2	4	40	2
3.3	5	3	2	30	5						

Table A.6: Comparison of criticality ranking using Fuzzy and traditional FMECA

Component	Failure Mode	RPN value	Critical Ranking	Fuzzy RPN value	Criticality Ranking
1. Oil Seals	1.1.Face Wear	45	1	5.46	7
	1.2.Embrittlement	36	3	5.29	10
2. Motor	2.1.Overheating	40	2	5.49	6
	2.2.Power Supply Anomalies	30	5	2.69	13
3. Gear Box	3.1.Wear	32	4	5.92	5
	3.2.Surface fatigue failure	36	3	5.93	4
	3.3.Breakage	30	5	6.91	1
4. Bearing	4.1.Wear	18	7	5.30	9
	4.2.Indentation	36	3	5.08	11
	4.3.Corrosion	24	6	6.38	2
5. Belt drive	5.1.Pulley misalignment	32	4	5.38	8
	5.2.Belt Slip	36	3	3.10	12
	5.3.Belt fatigue	40	2	6.12	3

A.3 Conclusion

Criticality analysis using conventional FMECA reveals that failure modes number (1.2, 3.2, 4.2, and 5.2), and (2.1 and 5.3), and (3.1 and 5.1), and (2.2 and 3.3) are having the same criticality ranking 3, 2, 4 and 5 respectively. All these failure modes having the same RPN 36, 40 32, and 30 even the S, O and D value are different for these failure modes. All these failure modes will not have the same impact on the failure of milling machine. Therefore, defining the same criticality ranking for different failure modes is not logical.

Criticality analysis using fuzzy presents that each failure mode is having different criticality ranking and fuzzy RPN values determined by the fuzzy mathematics. Also, S, O, and D gave the different weight for calculating the defuzzified RPN values using the centroid method for various α – fuzzy cut values. According to the results, breakage in the gearbox is the most critical and anomalies in power supply for the electric motor is less critical, which are the most appropriate results compared to conventional approach.

Hence, it has been observed that fuzzy FMECA can be used successfully to overcome the issues of conventional FMECA. Fuzzy FMECA considers the linguistic value and different weights of S, O, and D, which is logically accepted. This provides the more realistic results and flexible reflection in a real situation as FMEA is described in term of the fuzzy variable. Also, the interdependencies among the various failure modes can be explored easily using fuzzy. Finally, it is concluded that fuzzy approach can be considered as a better approach of FMECA for criticality analysis of different failure modes of a system for the implementation of RCM.

LIST OF PUBLICATIONS

Peer- Reviewed International Journals Publications:

[1] **Gupta, G.,** Mishra, R.P. (2016) "A SWOT analysis of reliability centered maintenance framework", Journal of Quality in Maintenance Engineering, Vol. 22 No. 2, pp. 130 – 145.
Published by ***Emerald****,* ISSN: 1355-2511 *[ESCI & Scopus Indexed]*

[2] **Gupta, G.,** Mishra, R.P., Singhvi, P. (2016), "An application of reliability centered maintenance using RPN mean and range on conventional lathe machine", International Journal of Reliability, Quality, and Safety Engineering, Vol. 23, No. 6. Pp. 1640010-1-10.
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[3] **Gupta, G.,** Mishra, R.P. (2017), "A failure mode effect and criticality analysis of conventional milling machine using fuzzy logic: case study of RCM", Quality and Reliability Engineering International, Vol. 33, No. 2, pp. 347-356. *Published by* ***John Wiley & Sons,*** ISSN: 1099-1638 *[SCIE Indexed, Impact Factor 1.457]*

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[5] **Gupta, G.,** Mishra, R.P., "Comparative analysis of traditional and fuzzy FMECA approach for criticality analysis of a conventional lathe machine", International Journal of System Assurance Engineering and Management. (Submitted)

Peer-Reviewed International Conference Publications (Abroad):

[1] **Gupta, G.,** Mishra, R.P., Mundra, N., (2018), "Development of a framework for reliability centered maintenance", Proceeding of 8th International Conference in Industrial Engineering and Operations Management, Bandung, Indonesia, March 6-8, PP: 2383-2391, ISBN: 978-1-5323-5944-6; ISSN 2169-8767 [Scopus Indexed]

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[1] **Gupta, G.,** Mishra, R.P., (2015), "An application of the reliability centered maintenance: case study of conventional lathe machine", 8th ISDSI International Conference, Jan. 02 - 04, Hyatt Regency Pune, India, In: Metri, B., Singh, A.K. (2016) "Trends in Operations Management : Perspectives and Challenges, 1st edition, Excel India Publishers, pp. 161-169. ISBN: 978-93-86256-22-5

[2] **Gupta, G.,** Mishra, R.P., Singhvi P., (2015), "An application of reliability centered maintenance using RPN mean and range on conventional lathe machine", 7th International Conference on Quality, Reliability, Infocom Technology and Business Operations, Dec. 28-30, Delhi, India,

[3] **Gupta, G.,** Mishra, R.P., (2015), "An application of reliability centered maintenance using fuzzy logic on conventional lathe machine", International Conference on Evidence Based Management, March 20-21, BITS Pilani, Pilani Campus, India pp. 531-536. ISBN: 978-93-84935-18-4

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[5] **Gupta, G.,** Mishra, R.P., "Comparative analysis of traditional and fuzzy FMECA approach for criticality analysis of a conventional lathe machine", 9th International Conference on Quality, Reliability, Infocom Technology and Business Operations, 27-29 Dec. 2018, Delhi, India

Brief Biography of Candidate and Supervisor

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Gajanand Gupta is Assistant Professor, Gr.-II in the Department of Mechanical Engineering at Birla Institute of Technology and Science, Pilani, Rajasthan, India since December, 2012. He is a graduate in the discipline of Mechanical Engineering from University College of Engineering, Kota, India in 2009, post-graduate in mechanical engineering with specialization in production engineering from NIT Rourkela, Orissa, India in 2011 and pursuing his Ph.D. in the field of maintenance engineering and management from BITS Pilani, India. His teaching and research interests are primarily in the field of manufacturing engineering, industrial engineering, maintenance engineering and management, reliability engineering etc.

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Prof. Rajesh Prasad Mishra is Associate Professor in the Department of Mechanical Engineering at Birla Institute of Technology and Science, Pilani, Rajasthan. He did his B.E. from MGCGV Chitrakoot Satna MP, M.E., and Ph.D. from BITS Pilani. He is an active researcher in the field of maintenance engineering, lean manufacturing, optimization techniques, manufacturing systems, and simulation and analysis of RAMS. He is guiding 3 Ph.D.'s addition to a considerable number of research practices, dissertations, and thesis supervised. He is also an active person in research activities in collaboration with universities like LTU Sweden, UTK Knoxville, etc. He has published more than 50 research papers in international journals and conferences.