INVESTIGATIONS ON SELECTION OF MAINTENANCE STRATEGY USING ANALYTIC NETWORK PROCESS

Thesis submitted to

UNIVERSITY OF CALICUT

in fulfilment for the award of the degree of

DOCTOR OF PHILOSOPHY

By

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September 2020

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CERTIFICATE

This is to certify that the thesis entitled "**Investigations on Selection of Maintenance Strategy Using Analytic Network Process**" is the record of bonafide research work done by Ms. **Mary C Kurian** under my supervision and guidance at Department of Mechanical Engineering, Govt. Engineering College, Thrissur in fulfilment of the requirements for the Degree of Doctor of Philosophy under the Faculty of Engineering, University of Calicut.

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Certified that all corrections and suggestions by the thesis examiners in their report of evaluation as communicated in the letter No.156419/RESEARCH-C-ASST-1/2020/Admn dated 25.03.2021 are incorporated in the thesis.

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DECLARATION

I, **MARY C KURIAN,** hereby declare that the thesis entitled "**Investigations on Selection of Maintenance Strategy Using Analytic Network Process** " is based on the original work done by me under the guidance of **Dr. Shalij P. R**, Associate Professor, Department of Production Engineering, Govt. Engineering College, Thrissur for the award of Ph.D. under University of Calicut. I further declare that this work has not been included in any other thesis submitted previously for the award of any Degree, Diploma, Associateship or Fellowship or any other title for recognition.

Thrissur **MARY C KURIAN**

16.09.2020

ACKNOWLEDGEMENT

First and above all, I bow my head before the Almighty Lord, whose grace has been with me always throughout the research work.

I am thankful to **Dr. K.P. Indiradevi**, Director of Technical Education, Kerala and former Principal of Government Engineering College, Thrissur and **Dr.K.Vijayakumar**, former Director of Technical Education, Kerala for their wholehearted support during the conduct of this research. I am grateful to the Director and all the staff members of Directorate of Research, Calicut University for the timely support to complete the work and final submission of thesis.

I am also thankful to **Dr.Sheeba V S**, Principal, Government Engineering College, Thrissur and **Dr.Jayanand.B**, former Principal, Government Engineering College, Thrissur, and **Dr. Mohandas V P**, Head of Mechanical Engineering Department, Government Engineering College, Thrissur, for providing the facilities to successfully carry out this research work.

Creative guidance makes a scientific research qualitative, and this has been imparted to me by **Dr. Shalij P R**, Professor, Department of Production Engineering, Govt. Engineering College, Thrissur, as an inspiring guide. I would like to express my sincere thanks to him for the trust, the insightful discussion, offering valuable advice and for the support during the whole period of the research which made this work possible. I also acknowledge for his patience and guidance during the preparation of thesis report.

I am highly indebted to external doctoral committee member **Dr. Pramod V R**, Professor, Department of Mechanical Engineering, NSS College of Engineering, Palakkad, for the valuable suggestions and help extended for the fulfilment of this research work. I express my sincere gratitude to the faculty and supporting staff members of Mechanical Engineering for giving an opportunity to carry out my research work in the Department of Mechanical Engineering, Government Engineering College Thrissur.

I extend my thanks to **Dr. A. Ramesh**, **Prof. E.C.Ramakrishnan, Dr. C.P. Sunilkumar**, former heads, Department of Mechanical Engineering, **Dr.Bobby K.George**, Doctoral committee member, **Dr. K.R. Jayadevan**, Former Chairman of Doctoral Committee for the suggestions and encouragements extended to me during the course of the research work.

It was the guiding light and the heart's desire of my parents, (Late) Mr. C. V. Kurian and Mrs. Aleykutty Kurian that kept me moving throughout the research years. This endeavour would not have reached its completion without the support and motivation of my husband, Mr. Mathew K Abraham and my children, Dr. Varsha Mathews, Dr. Eby Mathew and Dr. Varna Mathew. The love and laughter of my grandchildren, Evan and Ian were instrumental in diminishing the stress of course completion and made the journey a fulfilling one.

I have been enormously benefited from the advice, support, co-operation and encouragement given by my colleagues, friends, students during the course of this research work. I would like to offer my sincere thanks to all of them.

Thrissur-9 **MARY C KURIAN**

16.09.2020

ABSTRACT

INVESTIGATIONS ON SELECTION OF MAINTENANCE STRATEGY USING ANALYTIC NETWORK PROCESS

Design and implementation of efficient maintenance program is essential for industries in enhancing the availability, reliability and safety of equipment. In this research work, the Analytic Network Process (ANP) method, an innovative and effective method for solving decision problems involving multiple criteria with interdependent relations is applied in industries for the selection of optimal maintenance strategy. The choice and application of a strategy is based on the distinct conditions and constraints of a particular company. Recognizing and incorporating these factors in the policy selection is cardinal in attaining maximum efficiency from the chosen method. Initially the determinants, criteria, sub criteria and possible maintenance alternatives of the strategy selection are determined by literature reviews and expert interviews.

Evaluations empower organisations to logically predict its future and achieve the targeted outcomes. The world-wide competitiveness in business creates stress on the manufacturing firms to perform strategically in a highly productive and competitive environment. In the current scenario, the catalyst for enhancing productivity and quality is machine, and not man and can be done only by adopting well formulated and tested maintenance scheme. The significance of maintenance in cost reduction, time management and safekeeping other assets by optimizing their manufacturing capacity and enhancing the Overall Equipment Effectiveness (OEE) is now well understood by worldwide business heads (Phogat and Gupta, 2017 Phogat and Gupta, 2019).,).

The basic principle of maintenance is to attenuate the risks by maximally retaining the operations of company assets. Maintenance is a major factor that helps in preserving the levels of availability, reliability, safety requisites and product quality (Mobley, 2002). Maintenance cost is also increasing critically with the growing competition between firms and this necessitates cost reduction techniques in maintenance and operations (Zaim et al., 2012). Hence, the manager has to propose the optimum strategy for each machine or system from a set of available maintenance options (Bevilacque and Braglia, 2000).

Maintenance policy decision is a Multiple Criteria Decision Making (MCDM) problem which includes specific determinants, dimensions (criteria), enablers (sub-criteria) and maintenance alternatives. The application of ANP is strongly favoured for intricate decision problems as it permits analysis of interconnected influences in a given model (Cheng and Li, 2004). The ANP model structures the decision problem hierarchically and connect the determinants, criteria, sub criteria, and maintenance alternatives. ANP method is applied for prioritizing the different factors involved and thereby determining the best strategy.

This research work analyses the maintenance strategies of various industries and compares the results. In order to explicate the difference between the maintenance strategies adopted by various industries, ANP method is applied in different industries for strategy selection and the results are compared. Comparison of these results proves that ANP is an effective technique in Multiple Criteria Decision Analysis (MCDA) for solving problems having interdependence relations with significant impact (Cheng et al., 2005). ANP method is useful as an assessment tool for maintenance alternatives which can be implemented in similar MCDA situations.

The evaluation of maintenance strategies is identified as a multiple criteria decision-making problem relating a number of qualitative and quantitative components. In decision problems, some factors are more important than the others. The priority weights of the determinants are calculated using pair-wise comparisons. Total desirability indices of maintenance are calculated on the basis of each of these determinants. These desirability indices and the priority weights of the determinants are used for the calculation of (OWSI) of the alternatives. From these values the most suited maintenance alternative is selected for a particular company.

This research work connects the various problems related to the decision of maintenance strategy in a unified structure and thereby helps the decision experts to prioritize the feasible alternatives. The suggested solution, evaluating the interdependence effects of the elements gives more useful and reasonable answer to the decision problems.

OWSI provides a quantified value that aids in objectively ascertaining priority of maintenance alternatives. In comparison to judgment based on rule of thumb estimate, this OWSI provides a better estimate of result. This research mainly focuses on providing valuable guidance to the practicing managers for developing an ideal decision-making model for maintenance strategy. Findings of this study may also be extrapolated to several other decision-making scenarios.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the current business scenario, financial environment of manufacturing industries is steered by the swift changes in business interests which necessitate them attaining highly competitive levels of performance (Hooi and Leong, 2017). Maintaining uninterrupted competitiveness worldwide in business creates stress on the manufacturing firms to perform strategically in a highly productive and competitive condition. On the other hand, industries have more clarity about the significant need for maintenance of their valuable facilities and equipment (Phogat and Gupta, 2019). These practices are currently utilized as a competing approach to raise profit (Sherwin, 2000).

Maintenance of the plant and machinery is one among the prime concerns in the present competitive manufacturing environment. The objective of maintenance is to reinstate the equipment or machinery and enabling it to perform its intended function. Maintenance is characterised as the merger of all technological and administrative practices along with care to safeguard the system in its prescribed functioning capacity (Swanson, 2001). In the past, organisations used to misinterpret maintenance cost as an unavoidable burden and execute maintenance procedures as a corrective function that is implemented in emergency situations only. Today, it is recognised that maintenance operations contribute to profit and are not considered merely as a “necessary evil” (Ighravwe and Oke, 2017; Waeyenberg and Pintelon, 2002).

The primary objective of the maintenance function is to make plant, equipment and machinery available for productive utilisation during the scheduled life, by operating under agreed conditions with minimum waste and minimum total cost. In order to achieve this, continuous development is needed in maintenance activities for developing new tools and techniques to cope up with the increased complexity, sophistication, and automation of equipment and systems. Over a period of time, many maintenance strategies have been developed based on different aspects like time for doing maintenance, frequency of maintenance, complexity and sophistication of equipment and safety requirements.

1.2 Research Gap

Problems related to manufacturing and production have received tremendous interest even in the past. Unfortunately, the same has not been true for maintenance problems. This has been one of the leading contributing factors to the low efficiency in this field (Mahfoud et.al.,2018). Mobley (2002) has rightly pointed out that unnecessary and improper activities lead to wastage of around one-third of maintenance spending. Today, the role of maintenance has ignited new research in the area. Moreover, the role of maintenance has changed from a 'necessary evil' to a 'profit contributor' and towards a 'partner of companies' to achieve world class competitiveness (Wang et al.,2007)

The challenge of maintenance personnel is the implementation of the appropriate maintenance strategy that enhances availability and productivity of the equipment. By virtue of its uniqueness and complexity, a collective maintenance strategy which is suitable for all cases is not available (Ahmad and Kamaruddin, 2017). It is necessary for organisations to spotlight on effective maintenance schemes to enhance the production flexibility (Gopalakrishnan and Skoogh, 2018; Singh and Sharma, 2014). Arbitrary selection of maintenance activities seems inadequate for manufacturing organisations (Rijsdijk and Tinga, 2016). Maintenance cost is enhancing critically with the growing competition between the firms and they need to concentrate more on cost reduction techniques in maintenance and operations (Zaim et al., 2012). The managers have to propose the optimum strategy for each machine or system from a set of available maintenance options (Bevilacque and Braglia, 2000).

1.3 Research Problem

The choice and application of a definite maintenance strategy is characterized by the distinct conditions and constraints of the individual organisations. Selection of maintenance strategy is a Multi-Criteria Decision Making (MCDM) problem which includes specific elements related to the organisation. Recognising and incorporating these factors in the maintenance policy is the primary step towards attaining maximum efficiency from the chosen method.

Most of the decision problems cannot be designed hierarchically as they include interconnection of higher stage elements over the lower level elements (Saaty, 1996). While designing decision problems entirely on a hierarchical model, issues may arise due to the dependency of high-level elements on low level elements (Saaty, 1996). Saaty has proposed the usage of Analytic Hierarchy Process (AHP) for solving the problems of independency between maintenance alternatives or criteria and Analytic Network Process (ANP) for solving the problems of dependency (Jin Woo Lee and Soung Hie Kim, 2000). AHP is not suitable for complex problems due to the vagueness, uncertainty and fuzziness related to the decision of experts (Agarwal and Singholi,2018).

A research work is conducted for modelling the process of selecting the best maintenance strategy of organisations. Identification of probable maintenance strategies, criteria for evaluating these strategies, interconnections between the criteria and formulating the problem as a MCDM problem using AHP is carried out in this doctoral research work.

1.4 Research Objectives

Identification of the factors that affect maintenance strategies of different industries and modelling of the selection of maintenance strategy with ANP as the multi-criteria decision making, would help industries in improving the maintenance programs. In order to achieve this, a doctoral research is carried out with the following objectives.

1. To identify the factors that affect the maintenance strategies in industries.
2. To develop a model for the maintenance strategy selection which can be used in different industries.
3. To model the maintenance strategy selection using ANP methods of solving multi-criteria decision-making problems
4. To identify the strategies that enhance maintenance performance and improve overall business productivity.

1.5 Steps followed in this Study

This research study was performed by following a definite order and the various steps are specified in figure 1.1. Numerous factors associated with maintenance activities were identified based on a comprehensive literature review and discussion with the experts in the relevant area. An appropriate framework for this study was developed incorporating these factors.

Industries were identified for the implementation of ANP method for maintenance strategy selection. For each industry, a focus group consisting of experts from the top management level and academic professionals was formed. Issues related to maintenance were evaluated to find their possible causes.

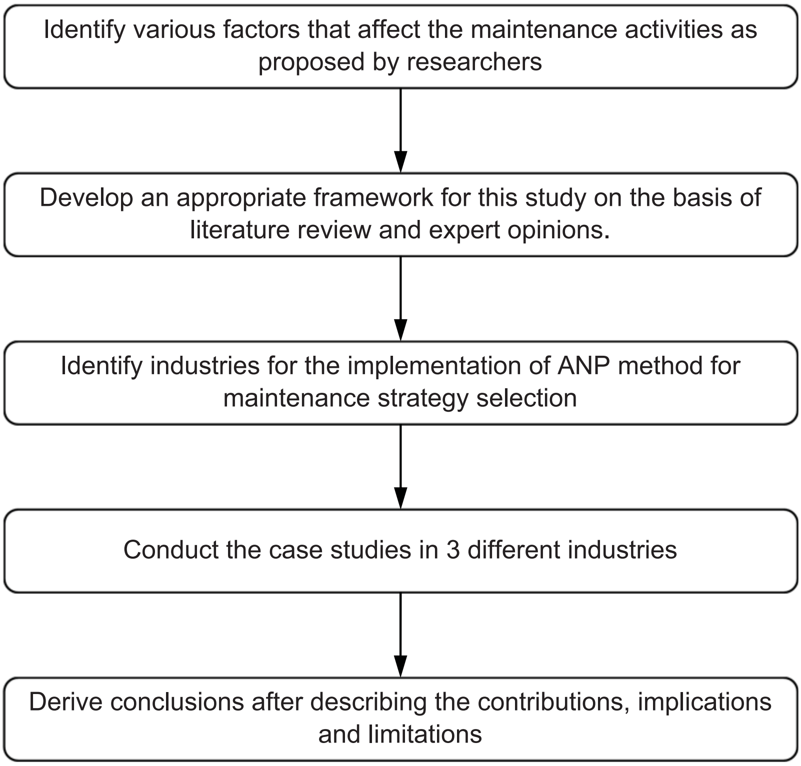

Figure 1.1 Research methodology

Determinants, dimensions / criteria, enablers / sub-criteria and possible maintenance strategies of the industry were identified. A questionnaire was developed based on these elements. Data collection was performed with the help of the focus group members. Case studies were conducted in three different industries and comparative analysis of the results was conducted. Conclusions were derived from these case studies. The research work is concluded describing the contributions, implications, limitations and future directions of this specific research work.

1.6. Structure of the Thesis

This research report consists of eight chapters, logically arranged to enable the reader to recognize the thoughts of the author in achieving the research objectives. The figure 1.2. depicts an overall picture of the structure of the thesis. The chapter contents are outlined as follows:

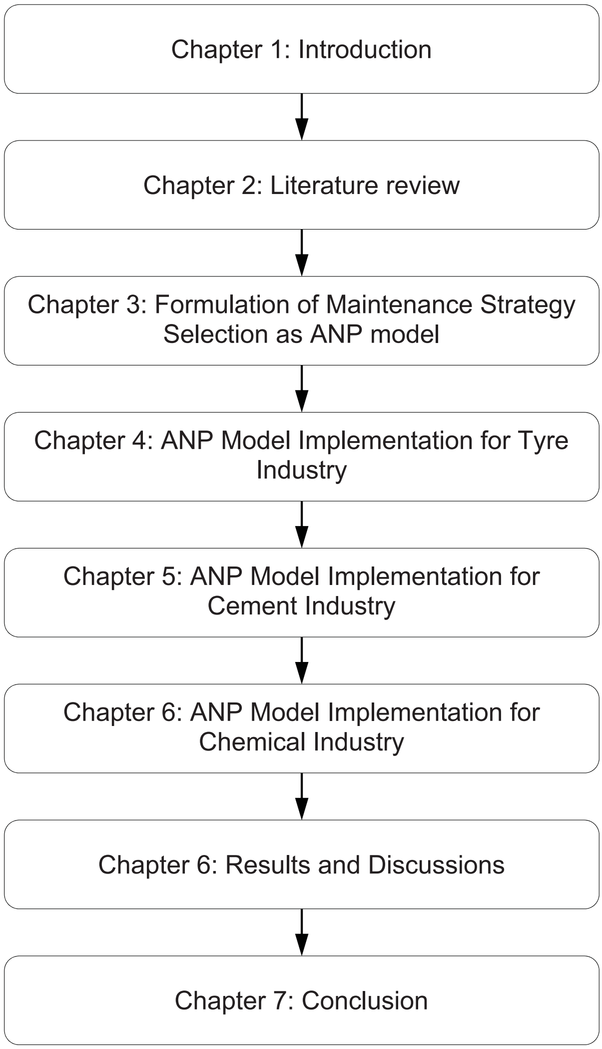

Fig.1.2 Structure of the Thesis

Chapter 1 describes the relevance of maintenance, research gap, research problem and the research objectives and the structure of the thesis. Steps followed in this specific effort is listed at the end of this chapter.

Chapter 2 narrates about the comprehensive literature review performed on the basis of this research study. Systematic literature survey was conducted in search of the relevance of maintenance, issues in maintenance, various maintenance strategies adaptable to industries, maintenance strategy decision problems, implementation of AHP/ ANP in decision problems and implementation of AHP/ ANP in maintenance strategy decision problems.

Chapter 3 illustrates the research methodology for maintenance strategy formulation. ANP model development, questionnaire preparation, data collection, priority vector/Eigen vector calculations, creation of super matrices, calculation of total desirability indices and computation of Overall Weighted Score Indices (OWSI) of the maintenance alternatives.

Chapter 4 describes the ANP model implementation for tyre industry. The OWSI of the four maintenance alternatives were calculated and autonomous maintenance was selected as the optimum maintenance strategy.

Chapter 5 describes the ANP model implementation for cement industry. The OWSI of the three maintenance alternatives were calculated and condition-based maintenance was selected as the optimum maintenance strategy.

Chapter 6 describes the ANP model implementation for chemical industry. The OWSI of the three maintenance alternatives were calculated and reactive maintenance was selected as the optimum maintenance strategy.

Chapter 7 includes the comparative analysis of the results obtained from these three industries.

Chapter 8 consists of the conclusion of this research study. The main contributions, implications, limitations and future recommendations of this specific work are illustrated in this chapter.

1.7 Conclusion

This chapter comprises of a brief introduction about the significance of maintenance activities. Research gap, research problem, research objectives and the structure of the thesis were also explained. The various phases followed in this research study was listed at the end of this chapter to obtain an overall picture of this specific work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Literature review is conducted to understand the present status of research on maintenance strategies and its selection and implementation. The details of the literature survey conducted and the major findings from the survey are presented in this chapter.

2.2 Methodology

A systematic literature survey was conducted in the areas of maintenance and strategy decision in search of the relevance of maintenance, specific issues of maintenance, various maintenance strategies, adoptable maintenance strategies in different industries, Multiple Criteria Decision Making (MCDM) problems, and methods of strategy selection.

Detailed search using keywords was conducted in well-known Journal publishers. The journal list includes Science direct, Emerald Insight, Inderscience, Springer, Elsevier, Taylor and Francis, and other academic journals. Hundreds of eligible papers were collected, abstracts and conclusions were initially examined, and the documents found to be relevant to the area of study were carefully studied

The keywords used for search were Maintenance, Maintenance Strategies, MCDM, AHP, ANP. The list of journals from which majority of the papers were collected are the following.

- **Emerald publishers**

  - Journal of Quality in Maintenance Engineering (JQME)
  - Manufacturing Technology &Management
  - Operations & Production Management
- **Inderscience publishers**
  - International Journal of Business Excellence
  - International Journal of Technology, Policy &Management
- **Elsevier publishers**
  - International Journal of Production Economics
  - International Journal of Forecasting

2.3 Relevance of maintenance

Organisations are finding it difficult to achieve the expected results after implementing advanced manufacturing techniques due to incompetent maintenance procedures which lead to poor machinery conditions and decline in overall production (Hooi and Leong, 2017). Efficiency and effectiveness of the machinery is crucial for attaining improved manufacture and organisational progress (Manu et al., 2011). Manufacturing systems need consistent care and maintenance to preserve them in the prescribed working conditions (Ahmed et al., 2005). Adequate maintenance can weaken the intensity of breakdowns and thereby prolong the period of activity of a system (Wikstan and Jonannson, 2006). Eliminating unusual breakdowns by removing root causes, achieving increased production through modernisations and enhancing machinery time by renovations are the goals of progresses in maintenance (Koussaimi et al., 2016).

Maintenance is defined as a group of actions completed in an asset to reinstate or maintain it in a specified condition. Maintenance of a system demands an efficient strategy which ensures the system's capability in performing the intended functions. The main task for maintenance personnel is the implementation of the preferred maintenance policy which enhances the effectiveness and availability of equipment.

Maintenance strategies consist of tasks involving various types of activities, resources, schemes and time (Dhillion,2006). Maintenance planning is followed by implementation of activities, supervision and guidance. The plan and actions are renewed on the basis of assessment of figures extracted from the performance of the elements. Effective procedures in maintenance can diminish the problems of breakdowns and prolong the external lifetime of a system (Wikston and Jonannson 2006).

Research papers describing the relevance of maintenance and the issues in the maintenance are conferred in this section. Details of the papers and the description of work are tabulated in table 2.1.

Table 2.1: Research studies on relevance of maintenance

Year	Author	Area	Description of work
2005	Ahmed, S., Hassan, M. and Taha, Z.	Relevance of maintenance	PM Can Go Beyond Maintenance – Excerpt from a case Implementation”,
2006	Dhillon, B.S.	Relevance of maintenance	Maintainability, maintenance and reliability for engineers
2006	Wikstan, J. and Jonannson, M.	Relevance of maintenance	Maintenance and reliability with focus on aircraft maintenance and spares provisioning
2011	Muchiri, P., Pintelon, L., and Gelders, L.	Relevance of maintenance	Development of maintenance function performance measurement framework indicators
2011	Manu, D., Vsihal, S., Anish, S., and Dureja, J.S.	Relevance of maintenance	TPM: a key strategy for productivity improvement in process industry

Year	Author	Area	Description of work
2012	Narayan, V.	Relevance of maintenance	Business performance and maintenance: How are safety, quality, reliability, productivity and maintenance related?
2013	Singh, R., Gohil A.M., Shah D.B. and Desai S.	Relevance of maintenance	Total Productive Maintenance (TPM) Implementation in a Machine Shop: A Case Study
2013	Somesh Kumar Sharma	Relevance of maintenance	Maintenance reengineering framework: a case study
2013	Kumar, U., Galar, D. Parida, A., Stenström C. and Berges, L.	Relevance of maintenance	Maintenance Performance metrics: a state-of-the-art review
2014	Ab-Samat, H., and Kamaruddin, S.	Relevance of maintenance	Opportunistic maintenance (OM) as a new advancement in maintenance approaches: A review
2015	Shafiee, M.	Relevance of maintenance	Maintenance strategy selection problem: an MCDM overview
2016	Koussaimi,M.A., Bouami,D. and, Elfezazi,S.	Relevance of maintenance	Improvement maintenance implementation based on downtime analysis approach
2017	Hooi, L.W. and Leong, T. Y	Relevance of maintenance	Total productive maintenance and manufacturing performance Improvement
2018	Gopalakrishnan,M and Skoogh,A	Relevance of maintenance	Machine criticality-based maintenance prioritisation: Identifying productivity improvement potential
2018	Arabzadeh, S.	Relevance of maintenance	Ranking of companies regarding the effective factors on technology transfer using FAHP and fuzzy TOPSIS techniques
2019	Naghiha, S., Maddahi, R. and Ebrahimnejad. A	Relevance of maintenance	An integrated AHP-DEA methodology for evaluation and ranking of production methods in industrial environments

Year	Author	Area	Description of work
2019	Phogat, S. and Gupta, A.K.	Relevance of maintenance	‘Expected maintenance waste reduction benefits after implementation of just in time (JIT) philosophy in maintenance (a statistical analysis) ‘
2019	Siponen, M., Haapasalo, H. and Harkonen, J.	Relevance of maintenance	Maintenance, repair, and operations inventory reduction and operational development

The availability and reliability of a system is essential to produce better quality products with minimum cost and thus attain a competitive advantage over competitors (Mucheri et al., 2011). Hence maintenance systems are considered as an unavoidable part in manufacturing and needs constant attention for attaining the expected operating conditions (Ahamed et al., 2005). Recent strategies of maintenance help enhancing process efficiency and decrease the frequency of failures (Somesh Kumar, 2013).

Production organisations are perennially thinking about cost reduction techniques and lies more emphasis on cost factors to attain maximum profit level (Naghiha et al., 2019). Arabzadeh (2018) describes how sustainable growth can be achieved by organisations through the implementation of technology transfer methods. Siponen et al. (2019) demonstrates the role of Maintenance, Repair, And Operations Inventory (MRO inventory) in the control of inventory leading to improvements in productivity and reduction in operational costs. Phogat and Gupta (2019) illustrate how Just-in-Time (JIT) management strategies can significantly reduce maintenance waste in organisations Productivity of manufacturing firms can be increased by applying maintenance prioritisation which involves identification of the critical machines (Gopalakrishnan and Skoogh, 2018).

Organisations begin to examine the maintenance costs when they start to optimize manufacturing costs (Kumar et al., 2013). Appropriate maintenance strategy is essential for these facilities to avoid the negative impacts of unexpected breakdowns which results in significant amount of repair costs, replacement costs and losses due to production interruptions, hazards etc. (Shafiee, 2015). During maintenance, all equipment in the organisation are corrected, reprocessed, altered and modified to meet the manufacturing requirements (Samat and Kamaruddin, 2014). Maintainability, the ease and swiftness in reinstating failed equipment to operational status after breakdown is an essential aspect to consider in the early stages of design (Narayan, 2012).

2.4 Various maintenance strategies adoptable to industries

It is very important to devise certain trigger points for initiation of a maintenance process. Programs and appraisals in a maintenance plan give awareness about what, when and how to do the maintenance activities (Ighravwe and Oke, 2017). Some policies undertake maintenance in a time-based protocol. Other plans may be condition-based or fault-based (Koenig et al.,2019; Rijsdijk and Tinga, 2016). Koenig et al. (2019) employed Condition-Based Maintenance (CBM) using vibration monitoring as a predictive method for identifying failures of baggage carts in airports.

Maintenance strategy is represented as corrective, predictive or preventive maintenance (Hemmati et al., 2018; Barsi et al., 2017; Kevin and Penlesky,1988; Cooke, 2003). The strategies of maintenance are aimed at enhancing process efficiency and decreasing the frequency of failures (Sharma, 2013). Research papers reporting the selection of maintenance strategy and their major contribution are discussed in this section. Details of the papers and the description of work carried out are tabulated in table 2.2.

Table 2.2 Research studies related to possible maintenance strategies to industries

Year	Author	Area	Description of work
1988	Kevin, F.G., Penlesky, R.J.	Maintenance strategy	A framework for developing maintenance strategies
1994	Paz, N. M. and Leigh, W.	Maintenance strategy	Maintenance Scheduling: Issues, Results and Research Needs.
1997	Kimura, Y.	Maintenance strategy	Maintenance Tribology: its significance and activity in Japan
1997	Triantaphyllou, E., Kovalerchuk, B., Mann, L, and Knapp, G.M.	Maintenance strategy	Determining the most important criteria in maintenance decision making
2001	Mechefske, C. K. and Wang, Z.	Maintenance strategy	Using fuzzy linguistics to select optimum maintenance and condition monitoring strategies.
2002	Waeyenbergh, G. and Pintelon, L.	Maintenance strategy	A framework for maintenance concept development
2002	Mobley R.K.	Maintenance strategy	An Introduction to Predictive Maintenance
2003	Cooke, F.L.	Maintenance strategy	Plant maintenance strategy: Evidence from four British manufacturing firms
2004	Bengtsson, M.	Maintenance strategy	Condition based maintenance system technology-where is development heading.
2005	Sharma, R.K., Kumar, D. and Kumar, P.	Maintenance strategy	FLM to select suitable maintenance strategy in Process industries using MISO model.
2007	Wang, L., Chu, J. and Wub, J.	Maintenance strategy	Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process.
2011	Khashayar, K., Jochen, D.	Maintenance strategy	A strategic standpoint on maintenance taxonomy
2012	Zaim, S., Turkyilmaz, A., Acar, M.F., Al-Turki, U. and Demirel, O.F.	Maintenance strategy	Maintenance strategy selection using AHP and ANP algorithms: a case study
2013	Sharma, S.K.	Maintenance strategy	Maintenance reengineering framework: a case study
2013	Elhdad, R., Chilamkurti, N., and Torabi, T.	Maintenance strategy	An ontology-based framework for process monitoring and maintenance in petroleum plant.

Year	Author	Area	Description of work
2013	Singh, R., Gohil A.M., Shah D.B. and Desai S.	Maintenance strategy	Total Productive Maintenance (TPM) Implementation in a Machine Shop: A Case Study
2014	Ab-Samat, H., and Kamaruddin, S.	Maintenance strategy	Opportunistic maintenance (OM) as a new advancement in maintenance approaches: A review
2015	Shafiee, M.	Maintenance strategy	Maintenance strategy selection problem: an MCDM overview
2016	Rijsdijk, C., and Tinga, T.	Maintenance strategy	Observing the effect of a policy: a maintenance case
2017	Basri E.I., Razak, I.H.A., AB-Samat, H. and Kamaruddin, S.	Maintenance strategy	Preventive maintenance (PM) planning: a review
2017	Ighravwe, D.E and Oke, S. A	Maintenance strategy	Ranking maintenance strategies for sustainable maintenance plan in manufacturing systems using fuzzy axiomatic design principle and fuzzy-TOPSIS.
2018	Hemmati, N., Galankashi, M. R., Imani, D. M., and Farughi, H.	Maintenance strategy	Maintenance policy selection: a fuzzy-ANP approach
2019	Koenig, F., Found, P. A., Kumar,M.	Maintenance strategy	Innovative airport 4.0 condition-based maintenance system for baggage handling DCV systems.
2019	Lai, C. T.A., Jiang, W. and Jackson, P. R.	Maintenance strategy	Internet of Things enabling condition-based maintenance in elevators service.

2.4.1 Preventive Maintenance

Preventive maintenance program applied on the basis of time, cost or breakdown is one of the initial proactive methods applied in maintenance activities (Basri et al., 2017). It is a planned strategy which is performed in prescribed intervals as per design data or service data when machine life is important than cost. While preventive maintenance was regarded as a non-value giving scheme in earlier years, it is now being admitted as a crucial demand in industry (Singh et al., 2013). Preventive maintenance policy which is prepared and executed after a stated span of operating time is beneficial in reducing the probability of breakdowns (Kimura, 1997). Preventive maintenance is implemented prior to system failure (Mechefske and Wang 2001) and the maintenance activities are performed regularly to eliminate sudden failures (Wang et al., 2007). In preventive maintenance, identification of the most efficient maintenance interval is crucial due to inadequate historical data (Triantaphyllou et al., 1997). Occasionally, Periodic maintenance (time-based maintenance) executed by organisations may lead to improper maintenance actions (Zaim et al., 2012).

2.4.2 Condition Based Maintenance (CBM)

One step ahead of preventive maintenance, condition-based maintenance is carried out while the machinery is in use, based on evaluation of repeated failures. Elhdad, et al. (2013) suggested a scheme for procedure monitoring and repairs to assure that maintenance experts have enough awareness about applying the correct choice at the correct time. Predictive maintenance is considered as the maintenance policy which depends on the condition of the equipment (Sharma et al., 2005; Mobley, 2002). It reduces spare inventory cost and avails more idea about spare part speculation. But it requires availability of data acquisition systems and a set of measurements to monitor real time machine performance. Continuous monitoring systems with data analysis systems and measurements are necessary to effectively carry out condition-based maintenance. Examples of monitoring systems used in various organisations are ultrasonic diagnostics, lubricating analysis and vibration monitoring. Bengtsson, M. (2004). Lai et al. (2019) demonstrated the advantages of Condition-Based Maintenance (CBM) over Corrective Maintenance (CM) and Time-Based Maintenance (TBM) by utilising remote monitoring through Internet of Things (IoT) technology methods for elevators. Koenig et al. (2019) used a novel condition-based maintenance (CBM) system based on Industry 4.0 to identify problems and meet the requirements of a high-speed baggage tunnel at Heathrow Airport Terminal 5.

2.4.3 Reactive Maintenance (RM)

Reactive maintenance (breakdown maintenance /corrective maintenance) is the oldest form of maintenance in which maintenance action is performed when system failure occurs (Khashayar and Jochen, 2011). In corrective maintenance, procedures such as restoration or overhaul are performed on a declined system to bring it back to its prescribed working status (Paz and Leigh, 1994). Yet, this strategy may cause great levels of system damage, huge restoration and repair costs and rapid failures (Lai et al., 2019; Basri et al., 2017). Breakdown maintenance which is considered most appropriate where revenue generation is high (Sharma et al., 2005) is the initial maintenance strategy in organisations (Wang et al., 2007; Waeyenberg and Pintelon, 2002). This maintenance strategy is executed subsequent to equipment damage or a major decrease in production and the related maintenance task is performed while the machinery stops functioning (Shafiee, 2015). Indutries adopt reactive maintenance strategy while the machines are not critical and parts are cheaper than machine downtime.

2.4.4 Autonomous Maintenance

In autonomous maintenance (AM), the operators in charge of the production activities are given more responsibilities. It follows a predetermined method to upgrade the skill levels of operators through managing and improving their machinery and processes by themselves. This is a modern approach to the maintenance activity where the operator of particular equipment is also responsible for its maintenance. This strategy is effectively implemented when the operators are motivated, trained and empowered to proactively maintain their own machines with proper knowledge. The implementation of autonomous maintenance reduces the production loss and increases the equipment availability and thus enhances OEE.

2.4.5 Opportunistic Maintenance (OM)

Opportunistic maintenance uses the “opportunity” of machine failure or stoppage to perform preventive maintenance of other critical parts. It is a combination of corrective maintenance and preventive maintenance (Samad & Kamarudin, 2014). One predominant form of this strategy is an opportunistic age replacement approach where during a single element failure, the other elements are also replaced along with the failed component by new ones. (Shafiee, 2015).

2.4.6 Risk-Based Maintenance (RBM)

Risk-based maintenance is an appropriate method to decrease the total hazard that can create as a result of unpredicted failures. The maintenance strategy is enhanced based on the calculated risks arising from equipment failure. High-risk properties are examined and preserved with larger regularity. On the other hand, the effort is minimized for low-risk properties to lessen the over-all effort and expenditure of the maintenance strategy. (Shafiee, 2015).

2.5 Maintenance strategy decision problems

Recent studies on maintenance strategy decision problems and the methods followed by the various industries are deliberated in this segment. The details of the papers and the description of work completed are displayed in Table 2.3.

The objective of maintenance strategy optimisation is to be capable of satisfying customer demand at nominal maintenance fee without losing reliability and utilisation time of the component (Samat and Kamaruddin, 2014). The performance of maintenance must be evaluated with the help of performance measures. Human factors must be incorporated in the selection, implementation and usage of these measures (Kumar et al.,2013).

Table 2.3 Recent studies on maintenance strategy decision problems

Year	Author	Area	Description of work
1998	Wireman, T.	Maintenance strategy decision	Developing Performance Indicators for Managing Maintenance
2003	Al-Najjar, B. and Alsyouf, I.	Maintenance strategy decision	Al-Najjar, B. and Alsyouf, I. (2003), “Selecting the most efficient maintenance approach using fuzzy multiple criteria decisions making.
2009	Karim, R., Söderholm, P., Candell,O.	Maintenance strategy decision	Development of ICT-based maintenance support services.
2013	Kumar, U., Galar, D. Parida, A., Stenström, C. and Berges, L.	Maintenance strategy decision	Maintenance Performance metrics: a state-of-the-art review
2014	Ab-Samat, H., and Kamaruddin, S.	Maintenance strategy decision	Opportunistic maintenance (OM) as a new advancement in maintenance approaches: A review
2014	Mendes, A.A., and Ribeiro, J.L.D.	Maintenance strategy decision	Establishment of a maintenance plan based on quantitative analysis in the context of RCM in a JIT production scenario.
2015	Parida, A., Kumar, U., Galar, D. and Stenström, C.	Maintenance strategy decision	Performance measurement and management for maintenance: a literature review
2017	FCao, W., Jia, X., Hu, Q., Song, W. and Ge, H.	Maintenance strategy decision	Selective maintenance for maximising system availability: a simulation approach.
2017, 2019	Phogat, S. and Gupta, A.K.	Maintenance strategy decision	Expected maintenance waste reduction benefits after implementation of Just in Time (JIT) philosophy in maintenance - a statistical analysis.

Proper usage of performance measures can highlight gaps for improvement by identifying core issues and finding solutions (Wireman,1998). Performance evaluation of maintenance schemes depends on distinct aspects (Parida et al., 2015). A quantitative method for the restoration of equipment was implemented by Mendes and Ribeiro (2014). Faccio et al. (2014) used several cost models to develop a quantitative technique to find the preferred maintenance strategy. Karim et al. (2009) proposed an e-maintenance management framework (eMMF) that helps in dealing with information and communication technology (ICT) based maintenance activities in organisations.

Al-Najjar and Alsyouf (2003) evaluated maintenance policies applying "fuzzy MCDM methodology". Phogat and Gupta (2019) implemented just in time (JIT) philosophy in an industry to apply waste reduction techniques in maintenance and thereby lowering the maintenance related costs. On the other hand, industries have more clarity about the substantial requirement for valued maintenance of their facilities and equipment (Phogat and Gupta, 2019). The fuzzy analytic network process (FANP) model developed by Hemmati, et al. (2018) is an innovative method to choose the maintenance strategy of an acid manufacturing company. Based on the assumption that the maintenance action is an undefined and activity oriented system, Ighravwe and Oke (2017) used an integrated fuzzy axiomatic design (FAD) principle and fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to select the perfect maintenance approach.

2.6 Implementation of AHP/ANP in decision problems

The Analytic hierarchy process, established by Thomas L. Saaty is a methodological technique based on mathematics for organising and analysing decision problems. The ANP method, an enhanced form of the AHP method is applied in complicated decision models. AHP is not suitable for solving problems having dependent elements in various stages of the hierarchy as it is based on the assumption that elements in a hierarchical model are independent. ANP is a generic form of AHP which permits complex interactions among elements of different levels (Saaty, 1996).

Decision problems having dependence and feedback associations between maintenance alternatives or criteria can be easily evaluated by ANP method (Zaim et. al, 2012). Recent research studies on the implementation of AHP/ANP in decision problems are deliberated in this section. The specifics of the papers and the description of work performed are arranged in Table in 2.4.

Table 2.4 Recent studies on Implementation of AHP/ANP in decision problems

Year	Author	Area	Description of work
1996	Saaty, T. L.	ANP	Decision Making with Dependence and Feedback: The Analytic Network Process
2000	Lee, J.W. and Kim, S.H.	ANP	Using analytic network process and goal programming for interdependent information system project selection
2004	Cheng, E.W. L. and Li, H.	ANP	Contractor selection using the analytic network Process.
2005	Cheng, E.W. L. and Li, H., Yu,L.	ANP	The analytic network process (ANP) approach to location selection: a shopping mall illustration.
2004	Niemira, M.P. and Saaty, T.L.	ANP	An Analytic network Process model for financial- crisis forecasting.
2006	Bayazit, O.	ANP	Use of analytic network process in vendor selection decisions.
2010	Sipahi, S. and Timor, M	ANP	The analytic hierarchy process and analytic network process: an overview of applications
2012	Aghaee, M. and Fazli, S.	MCDM	An improved MCDM method for maintenance approach selection: a case study of auto industry.
2012	Zaim, S., Turkyilmaz, A., Acar, M.F., Al-Turki, U. and Demirel, O.F.	AHP and ANP	Maintenance strategy selection using AHP and ANP algorithms: a case study

Year	Author	Area	Description of work
2017	Chand, M., Raj,T., Ravi Shankar.R.and Agarwal,A.	ANP	Select the best supply chain by risk analysis for Indian industries environment using MCDM approaches
2018	Agarwal D. and Singholi, A. K.S.	AHP	Performance analysis of a FLP problem using AHP-TOPSIS and FAHP-FTOPSIS.
2018	Ojha, R. and Vrat, P.	ANP	Prioritising factors for manufacturing growth in India: an analytic network process approach.

The Analytic Network Process (ANP) method structures the problem hierarchically and connects the determinants, criteria and sub-criteria with alternatives (Chand et al.,2017). The application of ANP is strongly favoured for intricate decision problems as it permits interconnected influences stated in the model (Cheng and Li, 2004). The ANP structure captures the feedback and dependence present between and within clusters of criteria and sub criteria (Niemira and Saaty, 2004). ANP method is applied for prioritising the determinants, criteria, sub criteria and determining the best strategy.

Most of the traditional MCDM schemes depend on the assumption of independence of individual criterion, which is not true (Aghaee and Fazli, 2012). AHP is not suitable for complex problems due to the vagueness, uncertainty and fuzziness related to the decision of experts (Agarwal and Singholi,2018). Sipahi and Timor (2010) conducted a detailed study about the current usage of AHP and ANP in group decision-making methods. Cheng et al. (2005) compared the findings of ANP and AHP in shopping mall selection and came to a conclusion that ANP was a more powerful tool in solving problems with substantial interdependent relationships. Ojha and Vrat (2018) applied ANP to determine the right priority structure for manufacturing growth in India which is influenced by eight key-drivers and five manufacturing industry-segments. Cheng and Li (2004) also successfully illustrated the use of ANP in contractor selection. Bayazit (2006) considered three suppliers and ten decision attributes to make pairwise comparisons for evaluating the alternatives for vendor selection. Aghaee and Fazli (2012) used ANP in solving MCDM problem in a vehicle industry. Niemira and Saaty (2004) implemented an ANP model in financial crisis forecasting which was back tested in the 1900s in the United States for a banking crisis.

2.7 Implementation of AHP/ANP in-maintenance strategy decision problems

Maintenance strategy decision comprises of distinct assessment criteria and sub criteria. This section illustrates the implementation of ANP as a decision analysis tool for maintenance strategy selection problems. Almeida and Bohoris, (1995) recommended the use of MCDM techniques for maintenance strategy selection. Recent research studies illustrating the implementation of AHP/ANP in maintenance strategy decision problems are discussed in this section. The particulars of papers and description of work carried out are tabulated in Table 2.5.

Table 2.5 Recent studies on implementation of AHP/ANP in maintenance strategy decision problems

Year	Author	Area	Description of work
1995	Almeida, A.T and Bohoris, G.A.	AHP and ANP in Maintenance strategy decision	Decision theory in maintenance decision making.
2000	Bevilacqua,M and Braglia,M	AHP and ANP in Maintenance strategy decision	The analytic hierarchy process applied to maintenance strategy selection
2012	Zaim, S., Turkyilmaz, A., Acar, M.F., Al-Turki, U. and Demirel, O.F.	Maintenance strategy	Maintenance strategy selection using AHP and ANP algorithms: a case study
2015	Shafiee, M.	maintenance	Maintenance strategy selection problem: an MCDM overview

Year	Author	Area	Description of work
2015	Baidya, R. and Ghosh,S.K.	AHP and ANP in Maintenance strategy decision	Model for a Predictive Maintenance System Effectiveness Using the Analytical Hierarchy Process as Analytical Tool.
2015	Adriaan, J.M. Goossens and Rob, J.I. Basten.	AHP and ANP in Maintenance strategy decision	Exploring maintenance policy selection using the Analytic Hierarchy Process; An application for naval ships.
2017	Ighravwe, D.E and Oke, S. A	Maintenance strategy	Ranking maintenance strategies for sustainable maintenance plan in manufacturing systems using fuzzy axiomatic design principle and fuzzy-TOPSIS.
2018	Hemmati, N., Galankashi, M. R., Imani, D. M., and Farughi, H.	Maintenance strategy	Maintenance policy selection: a fuzzy-ANP approach

The optimum maintenance approach is implemented by the decision maker from a predefined set of feasible alternatives after analysing and incorporating expenditure details, safety issues, environmental aspects, reliability of the maintenance strategy, labour force required for the facility etc. (Shaffle 2015). It is very crucial to measure some targets as it is difficult to express them in economic terms. Analytic Hierarchy Process is the only familiar technique that can quantify the consistency in the viewpoint of a decision maker (Almeida and Bohoris (1995). This work showed that appropriate maintenance actions can improve the productivity of the firm.

The fuzzy analytic network process (FANP) model developed by Hemmati, et al. (2018) is an innovative method considering risk, cost and added value to choose the maintenance strategy of an acid manufacturing company. Based on the assumption that the maintenance action is an indefinite and activity oriented system, Ighravwe and Oke (2017) uses an integrated fuzzy axiomatic design (FAD).

Bevilacqua and Braglia (2000) applied AHP to choose the most preferred maintenance strategy in a leading oil refinery in Italy. Baidya and Ghosh (2015) developed an AHP model for improving the effectiveness of a predictive maintenance system. Zaim et al. (2012) illustrated the use of AHP and ANP in picking the optimum maintenance strategy in the Turkish newspaper industry and Goossens and Basten (2015) implemented AHP for choosing the best maintenance strategy of naval ships.

2.8 Salient points of the literature survey

This comprehensive literature survey was performed in the areas of maintenance to search for its relevance and related issues. The focal points collected through the literature survey has been detailed in this chapter. This review highlights the significance of maintenance in enhancing the availability and reliability of machinery and thereby increasing the productivity of the firm and the quality of the product.

Secondly, the review focused on various maintenance strategies that are followed by the industries namely, preventive maintenance, condition-based maintenance, reactive maintenance, autonomous maintenance, opportunistic maintenance and risk-based maintenance. Recent research papers in this area were collected and analysed to acquire an extensive knowledge about the possible maintenance strategies in industries. Various maintenance strategies such as development of performance measurement, maintenance plan based on quantitative analysis, ICT based maintenance, fuzzy multiple criteria decisions making, just in time maintenance and selective maintenance are reviewed and analysed to arrive at the focal points that are reflected in this chapter. Research papers are collected in which AHP/ANP were used for strategy decisions like vendor analysis, shopping mall illustration, contractor selection, financial crisis forecasting etc. Finally, research papers in which maintenance strategy selection is performed according to AHP or ANP were reviewed and the main points are specified in this review. AHP/ANP were found to have been applied in newspaper industry, oil refinery, acid manufacturing company and in naval ships for optimum maintenance strategy selection.

CHAPTER 3

FORMULATION OF MAINTENANCE STRATEGY SELECTION AS THE ANP MODEL

3.1 Introduction

The ANP methodology of formulating the optimum maintenance strategy is illustrated in this chapter. The ANP method consists of both qualitative and quantitative parts. The qualitative component is used for identifying the decision criteria and formulating a network model of the decision problem. The quantitative component applies pair wise relations to allocate weights to the components and computes OWSI of the alternatives at the highest level. The various steps comprised in this methodology are explained in the subsequent sections.

3.2 ANP model development

The ANP tool models the problem by identifying the determinants, dimensions, enablers and alternatives of the MCDM problem. ANP is a powerful technique in sorting complex decision problems that involve variety of interactions and dependencies to arrive at a sophisticated final solution (Chand et al., 2018). In a system where different elements cannot be assumed to be independent; the recommended approach is ANP which is the general form of Analytic Hierarchy Process (AHP) (Chand et al.,2017). Maintenance strategy selection is a MCDM problem which includes specific determinants, dimensions, enablers and maintenance alternatives.

3.2.1 ANP model development methodology

The methodology adopted for applying ANP for the selection of maintenance strategy is described in figure 3.1.

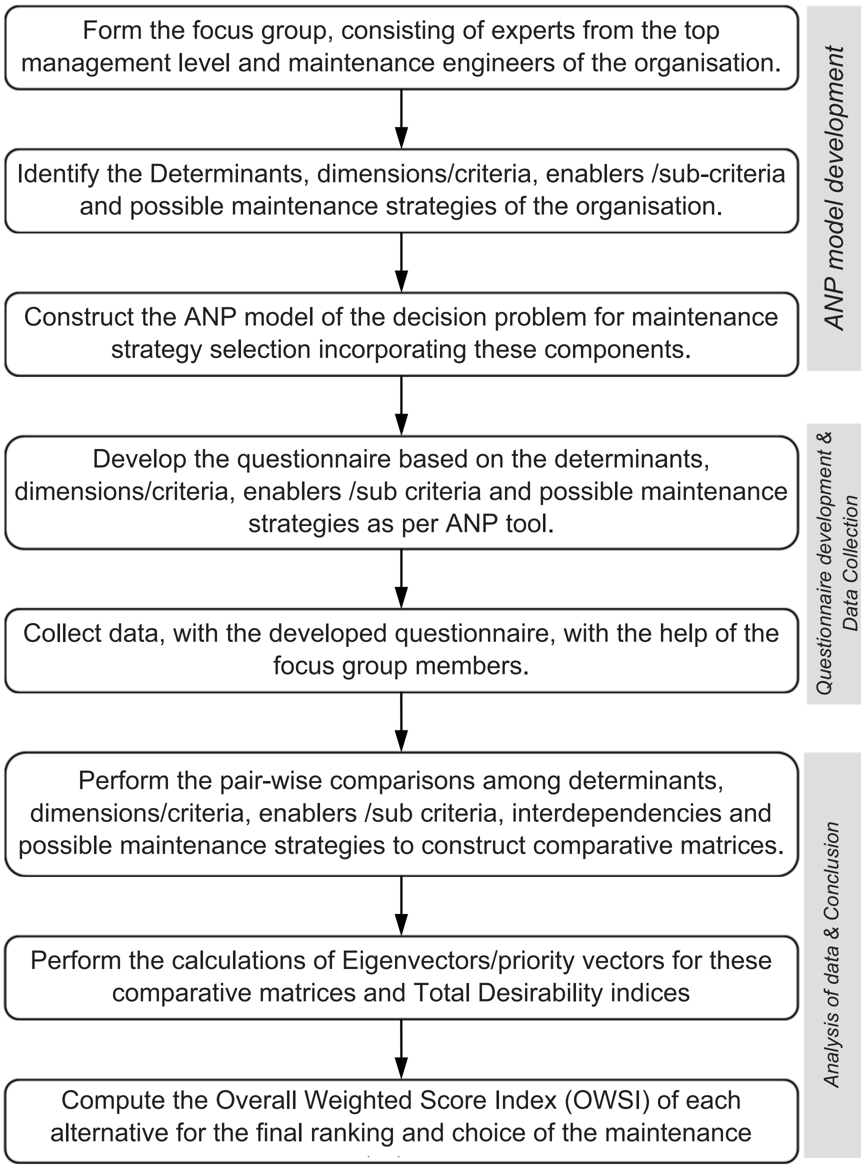

Figure 3.1 ANP model implementation methodology

As explained, a focus group consisting of the top management professionals and the maintenance professionals is required to be formed in the organisation. Ten respondents were chosen having more than ten years of experience. The value of comparison is finalized by the conglomeration of elicitation of these experts. Small sample size is admissible as experts in a company are few. Previous researchers including Saaty, the founder of ANP followed this method. The focus group identifies the Determinants, dimensions/criteria, enablers /sub-criteria and possible maintenance strategies of the organisation through discussions.

3.2.2 ANP model development Process

ANP is a powerful technique used for solving complex decision problems that involve variety of interactions and dependencies to arrive at a sophisticated final solution (Chand et al.,2018). In a system where different elements cannot be assumed to be independent; the recommended approach is ANP which is the general form of Analytic Hierarchy Process (AHP) (Chand et al.,2017).

This research encourages the application of ANP method as decision analysis tool which considers interdependent connections in the network structure that deals with maintenance strategy decision problems in industries.

The initial step is to structure the decision network of the problem. Fig.3.2. represents a typical structure of the hierarchical model using ANP methodology.

Determinants are the various factors that the industry aims to achieve by implementing an optimum maintenance strategy. The determinants could be, revenue growth, incorporation of forefront technology, elimination of dangers, competitiveness in the market etc. These features are directly affected by the outcomes of maintenance strategy selection. The choice of the determinants varies from industry to industry depending upon the type, location, and management structure (private, public, Govt. etc.) of the industry. As a typical example, government firms do not focus much on profit generation. The. determinants associated with a particular industry are finalised after literature analysis and deliberation with focus group members.

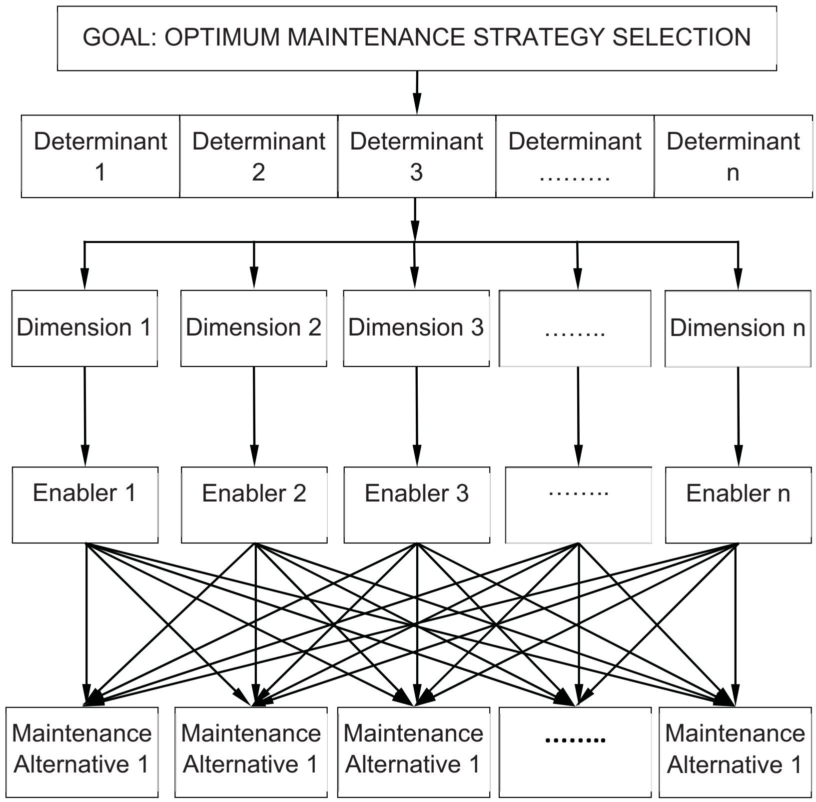

Figure 3.2 Typical structure of ANP model

Dimensions or Criteria are the characteristics of an industry that have to be optimised to achieve a determinant. Examples of criteria are professional concerns, payment aspects, safeness requisites, time requisites etc. The weightage of these dimensions differs between industries depending on the limiting aspect of that industry.

Enablers or sub-criteria are various factors that influence a certain criterion in a company. For example, appliance cost, operations cost, flaw detection cost, loss due to breakdowns, repair cost, consulting cost, inventory cost are the various sub-criteria that influence the criteria of payment aspects in an industry. The degree of importance of these sub-criteria differ between industries resulting in variations in the choice of the optimal maintenance strategy.

Maintenance strategy is the methodology adopted in relation to maintenance after careful consideration of the weightage or importance of determinants, dimensions and enablers in a particular industry. The description of various maintenance approaches is given in section 3.4.

ANP arranges the decision problem in a hierarchical model incorporating various components. The relevant dimensions, enablers and alternatives are arranged in the form of a hierarchy after positioning the decision problem, namely selection of maintenance strategy at the peak. The determinants are positioned in the second level and dimensions / criteria are placed in the third level. If enablers / sub-criteria are involved in the problem, they are placed in the fourth level. The final stage represents the alternative maintenance strategies of the company.

A decision network comprises of links, elements and clusters. Collection of related elements in a dimension or enabler is known as a cluster. The clusters and their elements are to be identified for each determinant of the maintenance strategy (Bayazit, 2006). Inter-dependencies are feedbacks and interactions within the clusters while outer-dependencies are feedbacks and interactions between the clusters (Saaty, 1999).

The model is developed to arrive at the optimum maintenance strategy among the alternative strategies. Initially, the decision problem is modelled using hierarchical model having determinants, dimensions, enablers and alternatives after identifying the relationships among them. The complex nature of maintenance problems necessitates ANP for evaluating the priority weights of all the determinants, dimensions, enablers and subsequently the Overall Weighted Score Index (OWSI) of the maintenance alternatives.

ANP method requires the collective opinion of the focus group members consisting of academic professionals and experts from various relevant departments. Initially the determinants, criteria, sub-criteria, alternatives maintenance strategies are determined by literature reviews and discussion with the experts in the focus group.

The determinants, dimensions, enablers and possible maintenance strategies associated with the maintenance strategy selection may be similar in industries. But the degree of importance varies from industry to industry. These elements are selected on the basis of their priority in a particular industry. The important elements related to the determinants, dimensions, enablers and possible maintenance strategies are found to be common by the focus groups in the case of cement and chemical industries. Hence, the ANP model and the questionnaire are the same for these two industries. However, marked difference is observable in the priority values of these elements and this has a major influence in the final grading of the maintenance alternatives.

However, in the case of tyre industry, the important elements connected with the determinants, dimensions, enablers and possible maintenance strategies are different from the other two industries. So, the questionnaire design and ANP model used for the tyre industry differ considerably from the others. After the development of ANP model and structuring the questionnaire, the methodology adopted is common for all industries. Elaborate explanation of the development and implementation of the models are described in the subsequent three chapters.

3.3 Questionnaire preparation

After constructing the hierarchical model, evaluation of the impact of individual components on the higher-level components is to be performed. For this purpose, in the ANP model, questions are formulated in terms of dominance or impact while creating pairwise comparisons. Determinants, Dimensions, enablers and possible maintenance strategies are recognised and a detailed questionnaire is constructed on the basis of these components.

The questionnaire helps in ascertaining relationship priority of different combinations of element with respect to a specific control criterion such as goal of the decision problem, dimensions, enablers and maintenance alternatives. Outer dependencies compare the impact of elements in a cluster on elements in another cluster with respect to a control criterion while Inner dependencies compare the influence of elements within the cluster (Saaty,1999).

The focus group members are also in authority of place ratings for the pairwise comparisons. These assessments were converted into numerical data that were processed and compared for the final evaluation of the maintenance alternative. The geometric mean (Saaty, 2007) of the assessments and the eigenvectors of the matrix were computed with the help of comparison tables. Normalisation of the components were achieved by dividing the factors by column total and the average row values in the normalized table gave the eigenvectors.

In ANP model, pair-wise questions are created enquiring dominance of influence of one element over the other with regards to a higher criterion. All questions are carefully constructed with similar perspective to avoid changes that would make the whole exercise futile. For example, the question can be either asked as which of the two elements has great influence over a given criterion or it could be which element is influenced more with respect to a higher criterion. In this work, the generic structure of questions was “Which element of the two exerts more influence on a specific control criterion?”.

The methodology of assigning priority vectors of pair wise comparisons is similar in ANP and AHP. The critical values that are obtained are specified on a fundamental scale table. A super matrix is created by assessing the pairwise priorities among inner elements and outer elements.

Table 3.1 Sample questionnaire for data collection in a typical industry

Comparison of determinants with respect to goal																		
Goal	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Forefront Technology																		Competitive market
Forefront Technology																		Privilege
Forefront Technology																		Hazard free
Competitive market																		Privilege
Competitive market																		Hazard free
Privilege																		Hazard free

Table 3.1 shows a part of the questionnaire used for collecting data in a typical industry. This part is used for comparing determinants with respect to the goal. The determinants in this example are Forefront Technology, Competitive market, Privilege and Hazard free. Each determinant is compared with the other three determinants. A table of comparison is formed using numbers 9 to 1 on left side and from 1 to 9 on the right side. If the left side element has greater preference than the right-side element for achieving the goal, then the numbers from 9 to 2 is marked on left side. Similarly, the right-side element possesses greater priority than the left side element the right-side numbers from 2 to 9 are marked. Larger numbers indicate

more preference and smaller numbers indicate lower preference. If they have equal priority ,1 is marked. Similarly, questionnaires are prepared to check all of the following:

1. Comparing priority of each determinant with respect to goal
2. Comparing priority of each dimension with respect to determinants
3. Comparing priority of each enabler with respect to dimensions
4. Checking for interdependencies among enablers
5. Comparing priority of each maintenance alternative with respect to enablers

3.4 Consistency

Consistency analysis is carried out to check the conformity of a finding with previously specified facts, form, or features. It is performed to ensure the reliability of the comparative scale and to establish the credibility of the research. Consistency analysis is carried out on all the matrices that contain responses to the questions developed. This analysis helps to enhance the quality of decisions by decreasing bias in responses and thus creating validity in the research results by logical and experimental methods (Pramod and Banwet, 2011). In this research study, consistency analysis ensures the reliability of the pairwise comparisons by calculating the consistency ratio of the comparative matrix and finding that they are within the acceptable limits

The parameters associated with the consistency analysis are Consistency index (CI), Random Index (RI) and Consistency Ratio (CR). The consistency index of a comparative matrix is computed by using the formula, $C.I. = (\lambda_{max} - n)/ (n-1)$ where, the λ_{max} is the principal Eigen value of the matrix and n is the size of the matrix. The consistency ratio (*CR*) is gained by the ratio of consistency index upon random index (Pramod and Banwet,2011). Consistency ratio less than or equal to 0.10 is mandatory (Pramod and Banwet,2011). Inputs are changed to adjust the consistency of the comparisons. Alterations are completed after confirming that they neither alter the judgment itself nor are they insignificant. Consistency check is accomplished for all matrices to assure the reliability of the results. Random index values for different order of matrices are given in Table 3.2.

Table 3.2 Saaty's table for Random Index vs order of the matrix

order	1	2	3	4	5	6	7	6	9	10
R.I.	0.00	0.00	0.58	0.90	1.11	1.25	1.35	1.40	1.45	1.49

3.5 Pairwise comparison matrix

Analytic network process requires the cooperation of managers from various departments that are inter-connected with the decision problem. Pairwise comparisons used to assign weights to the rank alternatives is the quantitative component of the ANP model. This pairwise comparison is carried out with the use of questionnaire. This problem incorporates the experience and knowledge of the maintenance professionals to structure it into a hierarchical model connecting the determinants, criteria and sub criteria to maintenance strategies. The assessment of ten experts in the focus group including members of top management of the relevant departments and academic professionals in this area can be used to create pair wise comparison matrices among determinants, dimensions, enablers and alternatives.

Elements are prioritized using the verbal assessment of degree of importance by decision makers as equal, moderate, strong, very strong and extreme priority. These are then interpreted to numerical values 1,3,5,7,9 correspondingly, along with 2,4,6,8, as intermediary numbers. Table 3.3. displays Saaty's fundamental scale table applied in ANP.

Tables for pair wise relations are constructed adopting 1–9 Saaty scale. Two options that have equal priority are assigned the value of 1 while a vast influence of the row element in comparison with the column element is recorded by the value 9. If the row element has weaker impact than the column element, the reciprocal is marked. The numerical values representing the findings of the pair-wise comparisons are arranged in the upper triangle of the square matrix.

Table 3.3 Saaty's fundamental scale table

Intensity of priority	Definition
1	Equal priority
3	Moderate priority
5	Strong priority
7	Very strong priority
9	Extreme priority
2,4,6,8	Intervening values

A sample pairwise comparison matrix of determinants is shown in Table 3. 4. In this matrix the relative priority of competitive market with respect to forefront technology is 7 while the relative priority of forefront technology with respect to competitive market is placed as 1/7, the reciprocal of 7. The diagonal values are marked as 1 which is the relative priority of a determinant with respect to the same determinant.

Table 3.4 Pairwise comparisons of determinants of a typical industry

Goal					
Determinants	Competitive Market	Forefront Technology	Privilege	Hazard free	Priority Vectors
Competitive Market	1	7	4	3	0.519
Forefront Technology	1/7	1	3	3	0.204
Privilege	1/4	1/3	1	1/7	0.067
Hazard free	1/3	1/3	7	1	0.210

Each of its elements, a_{ij} is the ratio of the absolute weight comparative to the importance of criterion i over the absolute weight comparative to the importance of criterion j. The elements in the main diagonal of matrix A will be equal to 1 and the elements of the down triangle are the inverse of the elements in the upper triangle i.e., $a_{ij} = 1/a_{ji}$.

The elements are normalized by dividing each value by the sum of that column. The average of each row of the normalized table is calculated to obtain priority vectors and consistency measure is computed. Principal eigen vector is calculated from the average of consistency measures.

3.6 Pairwise comparisons of determinants

Pair wise comparison method is used to calculate the relative priorities of the determinants for maintenance policy decision. Eigen vectors for the determinants are computed and ranked according to their priority weights. The eigenvectors of the determinants marked as Ca are employed for the estimation of OWSI for choosing the preferred maintenance strategy from the alternatives considered. The pairwise comparison of determinants results similar table, as presented in Table 3.4.

3.7 Pairwise comparisons of dimensions

Pair wise relation matrix of the dimensions is created to evaluate the relative priorities of the dimensions in the viewpoint of maintenance policy selection. Eigen vectors are computed and the dimensions are ranked according to their priority weights. The eigenvectors are depicted as Pj_a for the calculation of Total Desirability Indices. Table 3.5. displays a pairwise comparison matrix of the dimensions in a typical industry related to the competitive market determinant.

Table 3.5 Pairwise comparisons of dimensions in a typical industry

Competitive Market					
Dimensions	Professional Concerns	Payment Aspects	Safety Requisites	Critical Terms	Priority Vectors
Professional Concerns	1	3	8	7	0.567
Payment Aspects	1/3	1	7	5	0.295
Safety Requisites	1/8	1/7	1	1/3	0.046
Critical Terms	1/7	1/5	3	1	0.092

3.8 Pairwise comparisons of enablers

Two elements are compared with respect to a higher-level criterion. The number of determinants and dimensions considered in the model determines the number of pairwise relation matrices. The eigen vectors computed are imported as ADk_{ja} for the calculation of Total Desirability Indices. Table 3.6 shows a pair wise comparison matrix of the enablers connected to competitive market as determinant and payment aspects as dimension in a typical industry.

Table 3.6 Pairwise comparisons of enablers for a typical industry

Competitive Market, Payment Aspects					
Enablers	Appliance	Operating System	Flaw Detection	Back Up Inventory	Priority Vectors
Appliance	1	1	3	1/7	0.126
Operating System	1	1	3	1/7	0.126
Flaw Detection	1/3	1/3	1	1/9	0.053
Back Up Inventory	7	7	9	1	0.695

3. 9 Pair-wise comparisons of interdependencies

To estimate the interconnections among the enablers, pairwise comparisons are completed and the eigenvectors derived from the matrices are applied for the creation of Super matrices. Table 3.7 displays a pair wise comparison matrix of the interdependencies connected to competitive market as determinant, payment aspects as dimension and appliance as enabler in a typical industry.

Table 3.7 Pairwise comparison for interdependencies in a typical industry

Competitive Market, Payment Aspects, Appliance, Interdependencies				
Appliance	Operating System	Flaw Detection	Back Up Inventory	Priority Vectors
Operating System	1	3	1/7	0.161
Flaw Detection	1/3	1	1/8	0.074
Back Up Inventory	7	8	1	0.765

3.10 Pair-wise comparisons of alternatives

Pairwise relations are made to identify the relative influence of alternatives on the enablers with respect to the determinants. The number of enablers determine the number of pairwise relation matrices associated with the determinant. The eigen vectors computed are imported as S_{ikja} for the calculation of Total Desirability Indices (TDI). Table 3.8. shows a pairwise comparison matrix for alternatives in a typical industry connected to competitive market as determinant, payment aspects as dimension and appliance as enabler.

Table 3.8 Pairwise comparisons for alternatives for a typical industry

Competitive Market, Payment Aspects, Appliance, Alternatives				
Appliance	Condition Based Maintenance	Time Based Maintenance	Reactive Maintenance	Priority Vectors
Condition Based Maintenance	1	2	6	0.555
Time Based Maintenance	1/2	1	7	0.373
Reactive Maintenance	1/6	1/7	1	0.072

3.11 Formation of super matrices

The super matrix is a segregated matrix composed of sub matrices in which the inputs are gained from the pairwise relation matrices of interdependencies. The number of non-zero columns in the super matrix depends on the number of pairwise relation matrices of interdependencies. The non-zero values in the columns are the relative priority weights imported from the matrices of interdependencies. The super matrix will attain steady state by multiplying by itself till the raw values converge for each column of the matrix to equal values (Gencer and Gurupinar, 2007). By raising powers applying MATLAB, the convergence is performed to attain a long-term steady set of preferences. These values are imported as AI_{kja} for the calculation of Total Desirability Indices. Table 3.9 shows the super matrix before convergence related to competitive market determinant in a typical industry.

Table 3.9 Super matrix before convergence in a typical industry

COMPETITIVE MARKET													
	I	Q	E	A	OS	FD	BI	AS	MS	ES	TN	ER	TC
I	0	0.8	0.16	0	0	0	0	0	0	0	0	0	0
Q	0.9	0	0.84	0	0	0	0	0	0	0	0	0	0
E	0.1	0.2	0	0	0	0	0	0	0	0	0	0	0
A	0	0	0	0	0.16	0.11	0.43	0	0	0	0	0	0
OS	0	0	0	0.16	0	0.11	0.43	0	0	0	0	0	0
FD	0	0	0	0.07	0.07	0	0.14	0	0	0	0	0	0
BI	0	0	0	0.77	0.77	0.78	0	0	0	0	0	0	0
AS	0	0	0	0	0	0	0	0	0.67	0.5	0	0	0
MS	0	0	0	0	0	0	0	0.67	0	0.5	0	0	0
ES	0	0	0	0	0	0	0	0.33	0.33	0	0	0	0
TN	0	0	0	0	0	0	0	0	0	0	0	0.83	0.83
ER	0	0	0	0	0	0	0	0	0	0	0.5	0	0.17
TC	0	0	0	0	0	0	0	0	0	0	0.5	0.17	0

Table 3.10 shows the super matrix after convergence related to the competitive market determinant in a typical industry. The first column and first raw indicate short form of the determinants and enablers.

The super matrix values before convergence are imported from the matrix of interdependencies among the enablers connected to competitive market determinant. There are 13 pair wise comparison matrices related to each of the interdependent enablers and there will be 13 non zero columns in this super matrix. This super matrix attains a long-term stable set of values by raising powers using MATLAB. In this case, convergence is attained at ^49. The number of super matrices created depends upon the number of determinants in the decision model.

Table 3.10 Super matrix after convergence for a typical industry

	COMPETITIVE MARKET												
^49	I	Q	E	A	OS	FD	BI	AS	MS	ES	TN	ER	TC
I	0.3969	0.3969	0.3969	0	0	0	0	0	0	0	0	0	0
Q	0.4695	0.4695	0.4695	0	0	0	0	0	0	0	0	0	0
E	0.1336	0.1336	0.1336	0	0	0	0	0	0	0	0	0	0
A	0	0	0	0.2353	0.2353	0.2353	0.2353	0	0	0	0	0	0
OS	0	0	0	0.2353	0.2353	0.2353	0.2353	0	0	0	0	0	0
FD	0	0	0	0.0939	0.0939	0.0939	0.0939	0	0	0	0	0	0
BI	0	0	0	0.4356	0.4356	0.4356	0.4356	0	0	0	0	0	0
AS	0	0	0	0	0	0	0	0.3759	0.3759	0.3759	0	0	0
MS	0	0	0	0	0	0	0	0.3759	0.3759	0.3759	0	0	0
ES	0	0	0	0	0	0	0	0.2481	0.2481	0.2481	0	0	0
TN	0	0	0	0	0	0	0	0	0	0	0.4536	0.4536	0.4536
ER	0	0	0	0	0	0	0	0	0	0	0.2732	0.2732	0.2732
TC	0	0	0	0	0	0	0	0	0	0	0.2732	0.2732	0.2732

3.12 Computation of Total Desirability Indices (TDI)

The total desirability indices of the maintenance alternatives based on a specific determinant are calculated by using the priority weights obtained from the pair-wise comparisons of dimensions, enablers, alternatives and weights of enablers gained from the converged super matrix in the hierarchy of that determinant.

The priority values of the alternatives for the enablers based on a specific determinant are attained through the multiplication of the priority weights obtained from the pair-wise comparisons of dimensions, enablers, alternatives and weights of enablers gained from the converged super matrix in the hierarchy of that determinant The total desirability index of a maintenance alternative is the sum of the priority values of the alternatives for the enablers. The selection of the maintenance alternative is on the basis of Total Desirability Index. The desirability index, $\mathbf{D}_{ia}$, for the alternative ***'i'*** and the determinant ***'a'*** is defined as $\mathbf{D}_{ia} = \Sigma\, \Sigma\, \mathbf{P}_{ja}\, \mathbf{AD}_{kja}\, \mathbf{A}_{lkja}\, \mathbf{S}_{ikja}$

$\mathbf{P}_{ja}$ is the relative priority weight of dimension ***'j'*** on the determinant of ***'a'***

$\mathbf{AD}_{kja}$ is the relative priority weight for enabler ***'k'*** of dimension ***'j'*** in the determinant 'a' for the dependency(D) relationships between component levels.

Table 3.11 Total Desirability Indices (Competitive Market)

Dimensions	P_{ja}	Enablers	AD_{kja}	$A_{la}Ja$	Product	$S1_{kja}$	$S2_{kja}$	$S3_{kja}$	CBM	TBM	RM
PC	0.567	I	0.199	0.3969	0.045	0.669	0.267	0.064	0.0300	0.0120	0.0029
PC	0.567	Q	0.735	0.4695	0.196	0.723	0.206	0.070	0.1415	0.0403	0.0137
PC	0.567	E	0.065	0.1336	0.005	0.669	0.267	0.064	0.0033	0.0013	0.0003
CA	0.295	A	0.126	0.2353	0.009	0.555	0.373	0.072	0.0049	0.0033	0.0006
CA	0.295	OS	0.126	0.2353	0.009	0.748	0.180	0.071	0.0065	0.0016	0.0006
CA	0.295	FD	0.053	0.0939	0.001	0.748	0.180	0.071	0.0011	0.0003	0.0001
CA	0.295	BI	0.696	0.4356	0.089	0.753	0.172	0.075	0.0673	0.0154	0.0067
SR	0.046	AS	0.400	0.3759	0.007	0.780	0.137	0.083	0.0054	0.0009	0.0006
SR	0.046	MS	0.400	0.3759	0.007	0.790	0.133	0.077	0.0055	0.0009	0.0005
SR	0.046	ES	0.200	0.2481	0.002	0.580	0.355	0.065	0.0013	0.0008	0.0001
CT	0.092	TN	0.714	0.4536	0.030	0.767	0.148	0.085	0.0229	0.0044	0.0025
CT	0.092	ER	0.143	0.2372	0.003	0.767	0.148	0.085	0.0024	0.0005	0.0003
CT	0.092	TC	0.143	0.2732	0.004	0.737	0.186	0.077	0.0026	0.0007	0.0003
									0.2946	0.0823	0.0293

$\mathbf{A}_{lkja}$ is the stabilized relative priority weight (determined by the super matrix) for enabler ***'k'*** of dimension ***'j'*** in the determinant of **'a'** for interdependency (I) relationships within the enablers.

S_{ikja} implies the relative impact of the alternative ***i*** on enabler ***k*** of dimension ***j*** in the determinant *a*,

The last columns depict the priority values of the alternatives (P_{ja} AD_{kja} A_{Ikja} S_{ikja}) for the enablers. The total desirability index of a maintenance alternative is obtained from the sum of the priority values of the alternatives for the enablers.

Table.3.11 demonstrates the calculation of Total Desirability Indices for the maintenance alternatives related to the Competitive Market determinant.

3.13 Results

The Overall Weighted Score Indices (OWSI) for the alternatives are computed to give gesture to the maintenance policy selection for the organisation. The OWSI for an alternative is the addition of the products of the Total Desirability Indices (Día) and the relative priority weights of the determinants (Ca) and is represented as OWSIi = Σ Dia Ca. Table 3.11 illustrates the computation of Overall weighted Score indices for the maintenance alternatives. The maintenance alternatives namely, Condition Based Maintenance, Time Condition Based Maintenance and Reactive Maintenance are designated as CBM, TBM and RM respectively**.**

In this table the priority weights (Ca) of the determinants namely, Competitive Market, Forefront Technology, Privilege and Hazard free are 0.519, 0.204, 0.067 and 0.210 respectively. The Total Desirability Indices (Día) for the Condition Based Maintenance alternative are 0.295, 0.250,0.238 and 0.218. For example, the OWSI for CBM IS Calculated as; $OWSI_{CBM}$ = [(0.519×0.295) (0.204×0.250) + (0.067×0.238) + (0.210×0.218)] = 0. 704. Correspondingly $OWSI_{TBM}$ and $OWSI_{RM}$ are also calculated. The last column displays the normalized values of OWSI. Table 3.12 displays the Overall weighted Score indices of the maintenance alternatives.

Table 3.12 Overall weighted Score indices

Alternatives	Competitive Market	Forefront Technology	Privilege	Hazard free	OWSI	OWSI Normalized
Weights	0.519	0.204	0.067	0.210		
CBM	0.295	0.250	0.238	0.218	0.266	0.704
TBM	0.082	0.097	0.099	0.131	0.100	0.266
RM	0.029	0.026	0.025	0.028	0.011	0.030
					0.377	1.000

The $OWSI_{CBM}$ is observed to be high among these values and therefore Condition Based Maintenance (CBM) is selected as the optimum maintenance strategy for this industry.

CHAPTER 4

ANP MODEL IMPLEMENTATION FOR TYRE INDUSTRY

4.1 Introduction

This chapter demonstrates the ANP model application technique in a tyre industry. The determinants, dimensions, enablers and possible maintenance strategies are recognized with the aid of comprehensive literature survey and discussion with the authorities in the correct area. Pairwise comparison method is useful to estimate the relative preferences of the determinants, dimensions, enablers, interdependencies and maintenance alternatives and computing the priority vectors. Priority vectors are crucial in the ANP method for electing an ideal maintenance strategy for the organisation.

Maintenance was not generally regarded as a prime factor for attaining a competitive edge and enhancing productivity during the past years. The application of standards in maintenance activities help the organisations to achieve competitiveness (Carnero, 2014). Maintenance policy execution in a particular company is based on the specific circumstances of that company. Analysing these factors and choosing the preferred policy is the prime to achieve maximum effectiveness (Hong et al.,2012). The choice and application of a definite strategy is on the basis of distinct conditions and constraints of that particular company.

Recognising and incorporating these factors in the policy selection is the prime to attain maximum efficiency from the chosen method. Initially the determinants, criteria, sub criteria and possible maintenance alternatives of the strategy selection are determined by literature reviews and expert interviews. In the next stage,

ANP network model structures the decision problem hierarchically and connects the determinants, criteria, sub criteria, and maintenance alternatives. ANP method is applied for prioritising the determinants, criteria, sub criteria and determining the best strategy

4.2 Description of the Industry

The case study is carried out in Apollo Tyres Ltd., situated at Chalakudy in the Kerala State of India. Major products of the Ms. Apollo Tyres Ltd., are Tyres, Tubes and Flaps. The company was established in the year 1972. The turnover for the year 2019 is Rs.12350 Crores. Ms. Apollo Tyres Limited is an IS09001:2015 certified industry.

4.3. ANP model development for the tyre industry

A focus group comprising of ten key members of the organisation is formed for developing the model. The determinants, dimensions and enablers are derived from a consolidation of literature review, preparatory interviews and expert opinion in the tyre industry. The purpose of this illustrative ANP model is to choose the best maintenance strategy suiting a tyre industry acknowledging the primary concerns, viz. product quality and production enhancement. This choice becomes crucial for meeting manufacturing objectives of this industry.

The most significant and creative part for the perfect selection of maintenance strategy is the construction of a hierarchical model. Given below is the brief description of assortment criterion in the tree diagram.

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4.3.1 Determinants

Three determinants are identified by the focus group namely Revenue, Forefront Technology, and Hazard.

- **Revenue (R)**

  Revenue in the tyre industry stems from two major heads: original equipment sector and the replacement sector. The larger contribution is from the replacement sector. The demand and growth of the original equipment sector is tightly linked to the industrial movements in the automotive industry, whereas revenue from the replacement sector is expected to steadily rise. The tyre industry is also susceptible to setbacks with regards to the cost and supply of raw materials. Therefore, revenue generation is a key determinant in decision making in the tyre industry.

- **Forefront Technology (FT)**

  Progressively updating the technology of the tyre industry is essential for better production efficiency and systematic flow of data across supply chain and manufacturing operations. Digitalisation of data ensures that the manufacturing processes are more fact driven and enables predictions and planning for the future. Technological innovations in expediting and easing customer queries during the service tenure is also critical for tyre manufacturing units.

- **Hazard free (HF)**

  Tyre industry pose significant risks to its workers including hazard from machinery malfunction, slips, falls, rubber fumes and dust, increased noise levels and risk of fire during the manufacturing process. Accidents and ill health of workers certainly have an enormous human cost and can also lead to financial costs to the company in terms of loss of production and legal costs. Hence, it is essential to upkeep the machinery and maintenance activities to reduce the occupational exposure of toxic chemicals and to prevent threatening accidents in the plant.

4.3.2 Dimensions (Criteria)

In this program four dimensions are considered namely, Time Requisites, Expenditure Requirements, Security aspects and Critical Terms.

- **Time Requisites**

  In case of industries like the tyre industry where the demand of product is high, reducing production time and shutdown period is critical for excellent performance. This prevents loss of clientele due to shortcomings in not meeting with the requisite product load.

- **Expenditure Requirements**

  Expenditure analysis is critical in increasing profit of any industry. Expenditures are of various kinds like the inventory cost, consulting cost, loss from breakdown and cost of repairs

- **Security Aspects**

  Industries dealing with toxic fumes like that in tyre industry must analyse their security aspects before making a decision. It is important to ensure safety of the personnel, machines and that of the environment of the plant. Care should be taken to prevent errors and accident at all levels of manufacturing process.

- **Critical Terms**

  Other aspects to be analysed before choosing a particular strategy is the approval from top level management personnel, recognition of employee contribution, product quality improvement innovations, modern technology imbibition etc.

4.3.3 Enablers (Sub Criteria)

Enablers of the dimensions are also identified by the focus group. The enablers identified are shown in the Table 4.1. The Abbreviations used for indicating the same is also given in this table.

Table 4.1 Enablers of Dimensions

Time Requisites (TR)	**Expenditure Requirements (ER)**
Production Time (PT)	Breakdown Loss (BL)
Interim Upkeep (IU)	Inventory Cost (IC)
Design Changes (DC)	Consulting Cost (CC)
Shutdown Period (SP)	Repair Cost (RC)
Security Aspects (SA)	**Critical Terms (CT)**
Personal Safety (PS)	Product Quality (PQ)
Equipment Safety (ES)	Management Approval (MA)
Plant Guard (PG)	Employee Recognition (ER)
Ambiance Security (AS)	Modern Technology (MT)

4.3.3.1 Enablers of Time Requisites

Four enablers, namely Production Time, Interim Upkeep, Design Changes and Shutdown Period are identified by the focus group, for the dimension, Time Requisites.

- **Production Time**

  Production time can be optimized by production planning concerned with the overall operations of an organisation over a specified period of time.

- **Interim Upkeep**

  The failure of significant machineries in the production line results in larger cost due to idle time and loss of production. Considering profit aspects, implementation of a proper maintenance strategy can diminish the production loss for such machines.

- **Design Changes**

  The global competition characterised by technological advancements and increased market demand has been pushing industries across the world to enhance their goods and procedures. This transformation of manufacturing atmospheres has increased the manufacturing system competitiveness. These organizations are also financing considerably to update their maintenance by incorporating new designs and technology as an attempt to meet global standards,

- **Shutdown Period**

  Certain maintenance events needing added effort require dedicated additional time to implement these expansions. Primary concern in time constraints includes spare availability, manpower availability and proper tool availability.

4.3.3.2 Enablers of Expenditure Requirements

Focus group has identified four enables for the dimension ‘Expenditure Aspects’. They are Breakdown loss, Inventory Cost, Consulting Cost and Repair Cost.

- **Breakdown loss**

  Breakdowns and stoppages are maintenance problems that involve greatest losses and these amount to three times the cost of a well-organized preventive maintenance program.

- **Inventory Cost**

  In maintenance Programs spare parts inventory is crucial and inventory carrying cost enhances the total cost of maintenance

- **Consulting Cost**

  The consultation fee for different firms may be different and the frequent damages of the system requires frequent overhauling and it results in huge consultation fee. Maintenance strategy should be applied which reduces the rate and intensity of failure of the system.

- **Repair Cost**

  Rapid detection of failures requires training costs and professionals. The main object of fault diagnostic and prognostic practices associated with predictive and condition-based maintenance plans are to get quick information about the risk areas for failures and to enquire the reasons behind them. As a consequence, the time required for maintenance may be reduced and the availability of the production system can be improved.

4.3.3.3 Enablers of Security Aspects

Personal Safety, Equipment Safety, Plant Guard and Ambiance Security are the four enablers of the dimension, Security Aspects, as identified by the focus group.

- **Personal Safety**

  Interruptions in production and maintenance events may directly or indirectly affect workers. Therefore, it is crucial to gather their opinion about the probable maintenance procedures.

- **Equipment Safety**

  Make sure the machine is safe for any work that has to be done during normal use, when setting up, clearing blockages, carrying out repairs for breakdowns, and during planned maintenance

- **Plant Guard**

  Safety guidelines and safety promotional programmes are essential to preserve a healthy working atmosphere. Damages leading to intermissions in process procedures pose a source of threat to personnel and the general internal atmosphere of the plant.

- **Ambiance Safety**

  Safety policies and procedures maintains healthy working environment. Interruptions in operations due to failure may form a source of hazard to people and the whole environment

4.3.3.4 Enablers of Critical Terms

The enablers of Critical Terms as identified by the focus group are Product Quality, Management Approval, Employee Recognition and Modern Technology.

- **Product Quality**

  Some machine damages may cause diminution in product quality. Maintenance plays a vital role in upkeeping availability and reliability levels, product quality, and safety requirements

- **Management Approval**

  Some condition monitoring techniques are expensive and require specialist and experienced personnel for efficient data analysis. Top managers might be reluctant in implementing these maintenance procedures that involve high setup cost.

- **Employee Recognition**

  Some workers are against to predictive maintenance, since they have to do some extra duties in that program. Maintenance strategies can only be implemented according to acceptance by labours and trade unions.

- **Modern Technology**

  Some production requirements are relatively stable whereas there are others which are subject to major changes during development. To minimize unnecessary rework, it is sensible to implement strategic requirements first and hold the implementation of more volatile requirements.

4.3.4 Maintenance Strategies

Based on literature review and discussion with the experts in the relevant field, four maintenance strategies are considered as alternatives.

- **Corrective Maintenance (CM)**

  In corrective maintenance, procedures such as service or renovation are performed on a deteriorated system to bring it back to its prescribed working status (Paz and Leigh, 1994). This maintenance strategy is performed after the equipment failure or a major reduction in production and the associated maintenance job is completed while the machinery stops working (Shafiee, 2015). Industries implement this maintenance strategy while the machines are not critical and parts are cheaper than machine downtime.

- **Time Based Maintenance (TBM)**

  Time based preventive maintenance is used if life of the equipment is more significant than the expense related to the same procedure This technique is prepared on the basis of design or service figures and is implemented in regular periods.

- **Condition Based Maintenance (CBM)**

  The implementation of this maintenance program requires well awareness of the failure statistics and incorporates data acquisition systems and a set of measurements to monitor the machine performance in real time.

- **Autonomous Maintenance (AM)**

  This is a modern approach to the maintenance activity where the operator of particular equipment is also responsible for its maintenance. This strategy is effectively implemented when the operators are motivated, trained and empowered to proactively maintain their own machines with proper knowledge. The implementation of autonomous maintenance reduces the production loss and increases the equipment availability and thus enhances OEE.

Other maintenance approaches are not considered as they were not deemed suitable for this industry. For example, Opportunistic maintenance is not considered as lengthy periods of machinery shut down is impossible for this industry.

4.3.5 ANP Decision Model

The ANP decision model created for the selection of the best maintenance strategy is shown in Figure 4.1.

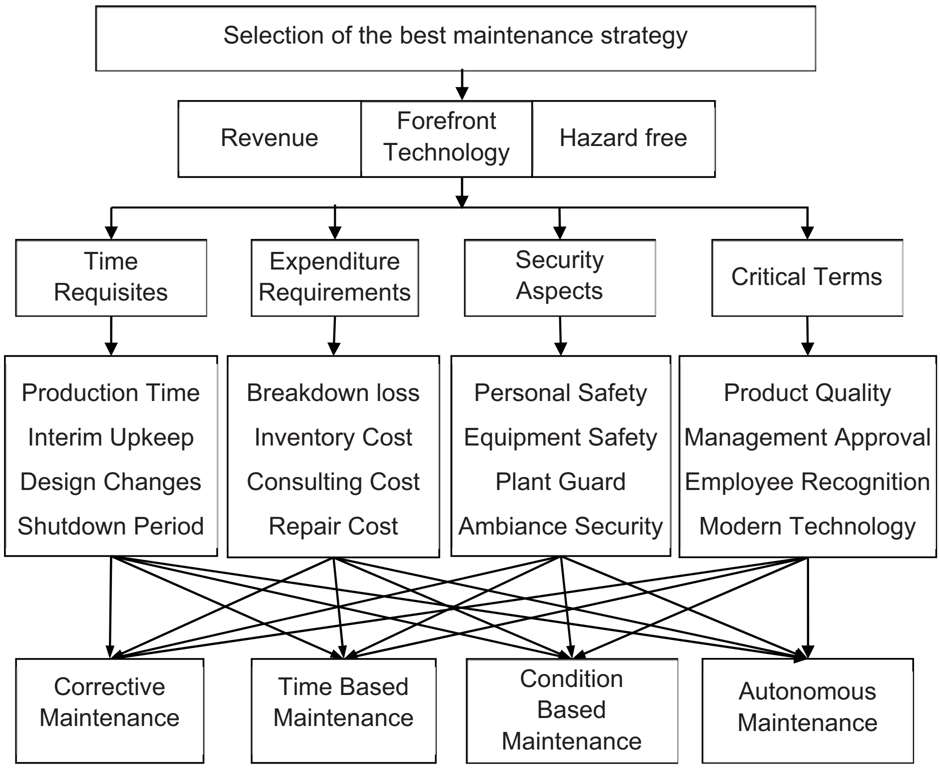

Figure 4.1 ANP model (Tyre Industry)

4.4 Data collection

Data collection is performed on the basis of the evaluations of the focus group members of the industry. A detailed questionnaire is constructed including the determinants, dimensions, enablers and possible maintenance strategies to identify the relative priority of the elements. These priority values are used for the computation of OWSI of the maintenance alternatives for determining the optimum maintenance strategy for the industry. The filling up of the questionnaire is carried out by the focus group members by collective discussion and reasoning. Table 4.2 shows a sample questionnaire for data collection in a tyre industry.

Table 4.2 Sample questionnaire for data collection in a tyre industry

COMPARISON OF DETERMINANTS WITH RESPECT TO GOAL																			
	GOAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
1	Revenue																		Forefront Technology
2	Revenue																		Hazard free
3	Forefront Technology																		Hazard free

The above table shows a questionnaire comparing various determinants with respect to the goal of the decision problem. Each determinant is compared with the other two dimensions. A table of comparison is formed using numbers 9 to 1 on left side and from 1 to 9 on the right side. If the left side element has greater influence than the right-side element, then the numbers from 9 to 2 is marked on left side. Similarly, if the right-side element possesses greater priority than the left side element the right-side numbers from 2 to 9 are marked. If they have equal priority ,1 is marked. Similarly, questionnaires are prepared to check all of the following.

1. Comparing priority of each determinant with respect to goal
2. Comparing priority of each dimension with respect to determinants
3. Comparing priority of each enabler with respect to dimensions
4. Checking for interdependencies among enablers
5. Comparing priority of each maintenance alternative with respect to enablers

4.5 Calculations

The stepwise calculations that are to be performed are described below:

1. Pairwise comparisons of determinants and the calculation of priority vectors of the determinants with respect to the goal of the decision problem are done.

2. Pairwise comparison of dimensions and the calculation of priority vectors of the dimensions with respect to the determinants are done.

3. Pairwise comparison of enablers and the calculation of priority vectors of the enablers with respect to the dimensions are done.

4. Pairwise comparison of interdependencies and the calculation of priority vectors of the interdependencies among the enablers are done.

5. Evaluation of alternatives and the calculation of priority vectors of the alternatives with respect to the enablers are done.

6. Super matrices are formed from the matrices of interdependencies

7. Super matrices of each of the determinant are converged to obtain a stable set of values.

8. Computation of Total Desirability Indices (TDI) of the alternatives related to each determinant are done.

9. Computation of Overall Weighted Score Indices (OWSI) for the maintenance alternatives, which is the prime factor in maintenance decision making is completed.

4.5.1 Pairwise comparisons of determinants

To determine the relative priorities of the determinants in choosing maintenance strategy alternative, pairwise comparison method is used. Using the data collected for pairwise comparison of the determinants, a pairwise comparison equal to 0.10 is essential for assuring the reliability of the results and is found by the ratio matrix is developed by assigning the priority values of the determinants in the matrix. Each element in the matrix is normalized by dividing by the sum of that column. The average of each row of the normalized table is the priority vector of the element in that row and using these values the consistency measure is computed. Principal eigen vector is calculated from the average of consistency measures. *C.I.* = $(\lambda_{max} - n)/(n-1)$ where, the λ_{max} is the principal eigen value of the matrix and n is the size of the matrix (Pramod and Banwet,2011). The consistency ratio (*CR*) less than or of consistency index upon random index (Pramod and Banwet,2011)

Table 4.3 shows a pairwise comparison matrix of the determinants with respect to the goal of the decision problem in a tyre industry. In this matrix the relative priority of forefront technology with respect to revenue is ¼ while the relative priority of revenue with respect to forefront technology is placed as 4, the reciprocal of 1/4. The diagonal values are marked as 1 which is the relative priority of a determinant with respect to the same determinant. The eigen vectors are the weighted priorities of the determinants which is an essential factor for the computation of OWSI of the maintenance alternatives and selection of optimum maintenance strategy. The priority vectors of the determinants namely, Forefront Technology, Revenue and Hazard free are0.120,0.608 and 0.272 respectively.

Table 4.3 Pairwise comparisons of determinants

Goal				
Determinants	Forefront Technology	Revenue	Hazard free	Priority Vectors
Forefront Technology	1	1/4	1/3	0.120
Revenue	4	1	3	0.608
Hazard free	3	1/3	1	0.272

4.5.2 Pairwise comparisons of dimensions

To compute the relative influence of the dimensions in view of maintenance policy perspective, a pair wise comparison matrix is created by means of the pairwise comparisons of the dimensions from the collected data. Eigen vectors are calculated and the dimensions were ranked according to their priority weights. Eigenvectors are posted as Pja in the Table for total Desirability Indices.

Table 4.4 Pairwise comparisons of dimensions

Hazard free					
Dimensions	Time Requisites	Expenditure Requirements	Security aspects	Critical Terms	Priority Vectors
Time Requisites	1	1	1/5	1/6	0.078
Expenditure Requirements	1	1	1/8	1/3	0.076
Security aspects	5	8	1	3	0.567
Critical Terms	6	3	1/3	1	0.279

Table 4.4 displays a pairwise comparison matrix of the dimensions in a tyre industry related to the hazard determinant. The dimensions Time Requisites, Expenditure Requirements, Security aspects and Critical Terms are compared and priority vectors are calculated. The eigen vectors/priority vectors are the weighted priority of the dimensions used for the computation of OWSI for determining the

optimum maintenance alternative for the industry. The priority vectors of the dimensions namely, Time Requisites, Expenditure Requirements, Security aspects and Critical Terms are 0.078, 0.076, 0.567 and 0.279 respectively.

4.5.3 Pairwise comparisons of enablers

Two enablers are related at a moment with respect to a high-level criterion and the number of such pairwise relation matrices depend on the number of determinants and criteria incorporated in the structural model. The eigenvectors calculated from the pair wise matrices are introduced as AD_{kja} in the Table for total Desirability Indices.

. Table 4.5 shows a pair wise comparison matrix of the enablers related to Hazard as determinant and Security aspects as dimension in a tyre industry. The eigen vectors are the weighted priority of the enablers namely, Personal Guard, Equipment Safety, Plant Security and Ambiance Security are calculated as 0.639, 0117, 0.122 and 0.122 respectively.

Table 4.5 Pairwise comparisons of enablers

Hazard free, Security Aspects					
Enablers	Personal Guard	Equipment Safety	Plant Security	Ambiance Security	Priority Vectors
Personal Safety	1	6	5	5	0.639
Equipment Safety	1/6	1	1	1	0.117
Plant Guard	1/5	1	1	1	0.122
Ambiance Security	1/5	1	1	1	0.122

4.5.4 Pairwise comparisons of interdependencies

Interdependencies between the enablers are obtained by creating priority vectors from the pair wise relations and are used in the formation of super matrices.

Table 4.6. displays a pair wise comparison matrix of the interdependencies connected to Hazard free determinant, Security aspects dimension and Personal Safety enabler in a tyre industry. The eigen vectors are calculated which are the priority weights of the enablers Equipment Safety, Plant Guard and Ambiance Security with respect to the enabler Employee Safety. The eigen vectors for Equipment Safety, Plant Guard and Ambiance Security are calculated as 0.333, 0.333and 0.3330.5 respectively. The super matrix is created by importing the values of the priority vectors from the matrix of interdependencies of the enablers

Table 4.6 Pair-wise comparisons of interdependencies

Hazard free, Security Aspects, Personal Safety				
Interdependencies	Equipment Safety	Plant Guard	Ambiance Safety	Priority Vectors
Equipment Safety	1	1	1	0.333
Plant Guard	1	1	1	0.333
Ambiance Security	1	1	1	0.333

4.5.5 Pairwise comparisons of alternatives

Comparisons in pair are formed to compute the relative weight of all maintenance policy strategies on the sub criteria with respect to the determinants and the number of sub criteria determines the number of such pair-wise matrices. This assessment enables in pointing the future into current position to decide what to do next to achieve the expected outcome (Eddie W. L. Cheng and Heng Li, 2004).

Table 4.7 shows a pairwise comparison matrix for alternatives in a tyre industry connected to Hazard free as determinant, Security Aspects as dimension and Personal Safety as enabler. The eigen vectors for Corrective Maintenance, Condition Based Maintenance, Time Based Maintenance and Autonomous

Maintenance are calculated as 0. 0.389, 0.180, 0.081and0.350 respectively. The Eigen vectors computed are imported as S_{ikja} for the calculation of Total Desirability Indices.

Table 4.7 Pair-wise comparisons of alternatives

Hazard free, Security Aspects, Personal Safety					
Alternatives	Corrective Maintenance	Condition based Maintenance	Time Based Maintenance	Autonomous Maintenance	Priority Vectors
Corrective Maintenance	1	3	4	1	0.389
Condition Based Maintenance	1/3	1	3	1/2	0.180
Time Based Maintenance	1/4	1/3	1	1/4	0.081
Autonomous Maintenance	1	2	4	1	0.350

4.5.6 Formation of super matrices

The super matrix is formed by the combination of various sub-matrices in which the values are imported from the priority vectors of interdependencies. This structural model comprises of four super matrices for the four determinants.

In this study, there are 16 sub-criteria, 16 pair-wise relation matrices and so 16 non-zero columns in the super matrix. Each of the non-zero values in the column is the relative influence weight associated with the interdependent pair-wise comparison matrices. The super matrix obtained by importing the values from the matrix of interdependencies for the determinant hazard is named as E and the super matrix before convergence is given below.

Table 4.8 shows the super matrix before convergence related to hazard determinant in a tyre industry.

Table 4.8 Super matrix for Hazard free before convergence

E	PT	IU	DC	SP	BL	IC	CC	RC	PS	ES	PG	AS	PQ	MA	ER	MT
PT	0	0.61	0.648	0.55												
IU	0.55	0	0.23	0.21												
DC	0.21	0.225	0	0.24												
SP	0.24	0.165	0.122	0												
BL					0	0.717	0.717	0.745								
IC					0.157	0	0.088	0.099								
CC					0.249	0.088	0	0.156								
RC					0.594	0.195	0.195	0								
PS									0	0.714	0.714	0.714				
ES									0.333	0	0.143	0.143				
PG									3333	0.143	0	0.143				
AS									0.333	0.143	0.143	0				
PQ													0	0.327	0.333	0.26
MA													0.327	0	0.333	0.327
ER													0.26	0.26	0	0.413
MT													0.413	0.413	0.334	0

4.5.7 Formation of converged super matrices

In the next level, the super matrix is made to converge to obtain a long-term stable set of weights. MATLAB enables the convergence of the interdependence relations by multiplying the matrix upon itself and is achieved at E46 for Hazard free. This is known as the converged super matrix and the stabilized values gained from this matrix named as AIkja is used for the computation of Total Desirability Indices for the determinant hazard. Similarly, three super matrices are also developed for forefront technology, competitive market and privilege**.**

Table 4.9 shows the super matrix after convergence related to hazard free determinant in a tyre industry**.** The stable values gained through this converged super matrix is imported as AIkja for the calculation of Total Desirability Indices (TDI).

Table 4.9 Super matrix for Hazard free after convergence

E^46	PT	IU	DC	SP	BL	IC	CC	RC	PS	ES	PG	AS	PQ	MA	ER	MT
PT	0.377	0.377	0.377	0.377												
IU	0.283	0.283	0.283	0.283												
DC	0.181	0.181	0.181	0.181												
SP	0.159	0.159	0.159	0.159												
BL					0.423	0.423	0.423	0.423								
IC					0.111	0.111	0.111	0.111								
CC					0.162	0.162	0.162	0.162								
RC					0.304	0.304	0.304	0.304								
PS									0.417	0.417	0.417	0.417				
ES									0.194	0.194	0.194	0.194				
PG									0.194	0.194	0.194	0.194				
AS									0.195	0.195	0.195	0.195				
PQ													0.233	0.233	0.233	0.233
MA													0.248	0.248	0.248	0.248
ER													0.240	0.240	0.240	0.240
MT													0.279	0.279	0.279	0.279

4.5.8 Computation of Total Desirability Indices (TDI)

The total desirability indices of hazard free determinant (D_i hazard) is created on the basis of hazard free hierarchy by applying the related influential priorities imported from the pair-wise ratio tables of dimensions, enablers, maintenance alternatives and the priority weights of enablers developed in the super matrix after convergence.

To determine the preferred maintenance alternative, it is essential to compute the index of total desirability, for the determinant 'a' and the maintenance alternative 'i' is defined as

$D_{ia} = \Sigma \Sigma P_{ja} A^D k_{ja} A^I k_{ja} S_i k_{ja}$ where P_{ja} is the related influential priority of criteria 'j' over determinant 'a', $A^D k_{ja}$ is the related influential priority of enabler 'k' of criteria 'j' in the determinant of 'a' for the dependence (D) connections in element levels.

$A^I k_{ja}$ is the balanced related influential priority resolved from the super matrix for enabler k of criteria 'j' in the determinant 'a' for interdependence (I) connections.

Sik_{ja} implies the related influence of the maintenance alternative 'i' on sub criterion 'k' of criterion 'j' of determinant 'a'.

The weighted priority values of the alternatives (P_{ja} $A^{D}k_{ja}$ $A^{I}k_{ja}$ Sik_{ja}) for the sub criteria that are applied to calculate the OWSI of the maintenance alternatives are displayed in the last three columns. The total desirability index of a maintenance alternative is obtained from the sum of the priority values of the alternatives for the enablers. Table.4.10 demonstrates the calculation of Total Desirability Indices for the maintenance alternatives related to the hazard determinant. Table 4.10 shows the desirability indices for the Hazard free determinant (Di Hazard free). It is based on the hazard free hierarchy using the priority weights obtained from the pair-wise comparisons of dimensions, enablers, alternatives, and weights of enablers from the converged super matrix

Table 4.10 Total Desirability Indices (Hazard free)

Dimensions	Pja	Enablers	AD*kja*	AIaJa	Product	S1kja	S2kja	S3kja	S4kja	TBM	CBM	CM	AM
TR	0.078	PT	0.377	0.522	0.015	0.088	0.213	0.233	0.467	0.001	0.003	0.004	0.007
TR	0.078	IU	0.283	0.246	0.005	0.136	0.193	0.255	0.416	0.001	0.001	0.001	0.002
TR	0.078	DC	0.181	0.121	0.002	0.130	0.227	0.084	0.560	0.000	0.000	0.000	0.001
TR	0.078	SP	0.159	0.112	0.001	0.497	0.251	0.103	0.150	0.001	0.000	0.000	0.000
ER	0.076	BL	0.423	0.631	0.020	0.087	0.087	0.087	0.087	0.002	0.002	0.002	0.002
ER	0.076	IC	0.111	0.067	0.001	0.094	0.215	0.180	0.511	0.000	0.000	0.000	0.000
ER	0.076	CC	0.162	0.102	0.001	0.288	0.162	0.060	0.489	0.000	0.000	0.000	0.001
ER	0.076	RC	0.304	0.200	0.005	0.080	0.176	0.476	0.268	0.000	0.001	0.002	0.001
SA	0.567	PS	0.417	0.639	0.151	0.292	0.136	0.063	0.508	0.044	0.021	0.010	0.077
SA	0.567	ES	0.194	0.117	0.013	0.328	0.136	0.075	0.461	0.004	0.002	0.001	0.006
SA	0.567	PG	0.194	0.122	0.013	0.388	0.159	0.083	0.370	0.005	0.002	0.001	0.005
SA	0.567	AS	0.195	0.122	0.013	0.280	0.280	0.128	0.312	0.004	0.004	0.002	0.004
CT	0.279	PQ	0.233	0.195	0.013	0.389	0.180	0.081	0.350	0.005	0.002	0.001	0.004
CT	0.279	MA	0.248	0.233	0.016	0.120	0.202	0.221	0.457	0.002	0.003	0.004	0.007
CT	0.279	ER	0.240	0.281	0.019	0.171	0.277	0.453	0.099	0.003	0.005	0.009	0.002
CT	0.279	MT	0.279	0.291	0.023	0.180	0.272	0.088	0.460	0.004	0.006	0.002	0.010
										0.077	0.053	0.038	0.130

4.6 Results

. The Overall weighted Score indices (OWSI) for the alternatives are computed to give gesture to the maintenance policy selection for the organisation. The aggregation of the products of the desirability indices (D_{ia}) and the relative importance weights of the determinants (C_a) is the Overall Weighted Score Index (OWSI) for a maintenance alternative which is the prime factor in maintenance decision making.

The OWSI for an alternative is the addition of the products of the Total Desirability Indices (Día) and the relative priority weights of the determinants (Ca) and is represented as OWSIi= Σ Dia Ca. Table 4.11 illustrates the computation of Overall weighted Score indices for the maintenance alternatives. The maintenance alternatives namely, Time Condition Based Maintenance. Condition Based Maintenance Corrective Maintenance and Autonomous Maintenance are designated as TBM CBM, CM and AM respectively**.**

Table 4.11 Overall Weighted Score Index

Alternatives	Hazard free	Forefront Technology	Revenue	OWSI	OWSI Normalized
Weights	0.2721	0.1199	0.6080		
TBM	0.0771	0.0522	0.0781	0.075	0.251
CBM	0.0531	0.0487	0.0558	0.054	0.182
CM	0.0378	0.0351	0.0349	0.036	0.120
AM	0.1304	0.1089	0.1397	0.133	0.448
				0.298	1.000

In this table the priority weights (Ca) of the determinants namely, Hazard, Forefront Technology, Revenue are 0.2721, 0.1199, and 0.6080 respectively. The Total Desirability Indices (Día) for the hazard free determinant are 0.0771, 0.0531, 0.0378and 0.1304 for TBM, CBM, CM and AM respectively. The Total Desirability Indices (Día)for the Time-Based Maintenance alternative are0.0771, 0.0522and0.0781 for the determinants namely, Hazard free, Forefront Technology and Revenue.

. For example, the OWSI for TBM IS Calculated as; $OWSI_i = \Sigma D_{ia}C_a$

$OWSI_{TBM}$= [(0.2721*0.0771 (0.1199*0.0522) + (0.6080*0.0781) =0.075. Correspondingly $OWSI_{CBM}$, $OWSI_{CM}$ and $OWSI_{AM}$ are also calculated. The last column displays the normalized values of OWSI.

It is observed from Table 4.11 that OWSI Normalized for Autonomous Maintenance (.4480) is found to be more as compared to Reactive Maintenance (0.120), Time Based Maintenance (0.251), Condition Based Maintenance (0.182) and Autonomous Maintenance is the most-suited alternative for the company.

CHAPTER 5

ANP MODEL IMPLEMENTATION FOR CEMENT INDUSTRY

5.1 Introduction

This chapter illustrates the ANP model implementation procedure in a cement industry. Involvement of executives from various departments is an essential for the formulation of ANP model in an effective manner. For this purpose, a panel of ten maintenance personal is formed

The formulation of the ANP model and pairwise comparison tables are carried out by the panel. Pairwise comparison method is used to determine the relative preferences of the determinants, dimensions, enablers, interdependencies and alternatives. These comparisons are used to establish the relative priorities of determinants, dimensions, enablers, interdependencies and alternatives. These priorities are applied in the ANP method for choosing a preferred maintenance strategy for the organisation.

5.2 Description of the Industry

The case study is carried out in Malabar Cements Limited situated at Walayar, Palakkad in the Kerala State of India. Major product of the Ms. Malabar Cements Limited is Portland Cement. The company was established in the year 1978 The turnover for the year 2018 is Rs. 230 Crores. Ms. in Malabar Cements Limited is an ISO 9001:2015 certified industry.

5.3. ANP model development for the cement industry

The determinants, dimensions and enablers are derived from a consolidation of literature review, preparatory interviews and expert opinion reviews in the cement industry. The purpose of this illustrative ANP model is to choose the preferred maintenance strategy in a cement industry which has large influence on product quality and loss of production. Hence the choice of the optimum maintenance policy is very essential for this industry to meet the manufacturing objectives. Structuring the problem as a hierarchy is the most significant and creative part for the perfect selection of maintenance strategy.

5.3.1 Determinants

Determinants of the maintenance strategy selection identified are Forefront Technology (FT), Competitive Market (CM), Privilege (PR) and Hazard free (HF). These are the factors that the industry aims to achieve through implementation of the proper maintenance strategy. Forefront Technology aims to possess technological advancement while Competitive Market determinant stands for attaining market competitiveness of the industry. Another determinant aims at having a privilege over other companies and the determinant hazard focusses on eliminating dangers.

- **Forefront Technology**

  The application of forefront technology intends to imbibe the most important and leading technology into practice. This is developed by incorporating add-ons and alterations in the old technologies. Updating the technology of the plant is essential to increase production, better control of carbon emissions and to improve quality of product.

- **Competitive Market**

India is the second largest producer of cement in the world and has many large players in the field. The increased focus of government on infrastructure development and the rapid growth in commercial and industrial constructions has raised the demand for good quality cement in the recent years. This increased demand is projected to escalate in the coming years. This has led to the high competitiveness of cement manufacturers and is hence, one of the key determinants in achieving the target goal.

- **Privilege**

  Among the 200 odd companies manufacturing cement in India, the top 20 companies own 70% of the production. In an industry with such varied choices, marketing strategies have to aim at boosting sales by being at the top of mind recall. Long term performance is essential for cement as a commodity and branding may be a differentiating factor between companies

- **Hazard free**

  Exposure to cement dust, poor ergonomics, falling objects unguarded equipment and improperly handled vehicles in the manufacturing site can pose significant risk to workers in the cement industry. Cement manufacturing units have to be vigilant in instituting preventive measures to reduce these incidents during the manufacturing process.

5.3.2 Dimensions (criteria)

Based on literature review and consultation with the focus group members, four dimensions and 13 sub criteria are identified. The four dimensions that were concluded after this exercise are Professional Concerns, Payment Aspects, Safeness Requisites and Critical Terms.

- **Professional Concerns**

  This criterion includes characteristics of the industry that constitute its professional standing in the market and comprises of the three sub criteria, namely the earnings of the plant, the quality of its produce and the professional image of the company. These are important to keep the company at a cutting edge with respect to accomplishing its goal

- **Payment Aspects**

  Payment aspects of running an industrial plant is an important decisive factor that guides the company towards achieving efficiency. This involves various heads like appliances cost, operating system cost, cost for setting up a backup inventory and expenses incurred for flaw detection.

- **Safety Requisites**

  Meeting safety requirements are cardinal to undeterred running of an industry as it involves the wellbeing of the plant employees, optimal state of machinery in the industry and the healthy status of the industrial ambiance. Flaws in meeting with these requisites can have huge expenses financially and in human terms for the company.

- **Critical Terms**

  The industry also requires timely training and updating its staff to excel in its performance. Changes in policies and administrative actions require consent from top level company professionals and employees of the unit have to give specified role and recognition for their contributions. These critical terms are also essential for the harmonised functioning of the industrial plant.

5.3.3 Enablers (Sub Criteria)

Sub criteria are identified based on literature review and consultation with the focus group members including experts from the relevant departments and academic professionals in this area. The sub criteria identified are shown in the Table 5.1.

The sub-criteria and their implications are explained in the subsequent sections

Table 5.1 Enablers (Sub Criteria)

Professional Concerns (PR)	**Payment Aspects (PA)**
Earnings (E) Quality (Q) Image(I)	Appliances (A) Operating System (OS) Back up Inventory (BI) Flaw Detection (FD)
Safety Requisites (SR)	**Critical Terms (CT)**
Employee Safety Machine Safety Ambiance Safety	Training Needs Top level Consent Employee Recognition

5.3.3.1 Enablers of Professional Concerns

- **Image**

  Manufacturing and maintenance performance have great influence in the image of the firm. Low quality products, delayed deliveries, deficit in order quantities, rude reply to complaints are the major reasons of image loss in organisations

- **Quality**

Equipment deterioration leads to the decrease in output quality. Maintenance plays a crucial role in safekeeping the product quality, reliability and availability levels of machines, and safety requisites

- **Earnings**

  Earnings of an industry is the net income or its profit achieved by deducting all costs such as cost of sales. taxes, operating costs etc. from the revenue i.e. the total income of the company gained by selling its goods or services. The failure of critical machines in the production line leads to idle time which causes wastage of time and production loss. Selection and usage of a well-suited upkeep approach can diminish production disruptions and thereby boost the company's earnings.

5.3.3.2 Enablers of Payment Aspects

- **Appliance:**

  Implementation of condition-based maintenance demands some new machines or equipment.

- **Operating System:**

  Various programs are needed to check the data retrieved from equipment used for condition-based maintenance.

- **Back up Inventory:**

  Organisations regularly strive to maintain optimum stock level to meet its specifications and to avoid over or under inventory that affect the monetary values. Reactive maintenance needs more additional parts than other maintenance strategies.

- **Flaw Detection:**

  Root causes of problems can be identified by automated fault diagnosis that is primarily dependent on input from sensors. In process industries, the most common failures are sensor failures. Recognition of sensor problems and process problems are the major focus in these industries.

5.3.3.3 Enablers of Safety Requisites

Certain industries, like chemical industries require very high safety levels. The factors that are considered to describe safety in an industry are:

- **Employee Safety:**

  Machine failures may lead to serious dangers to industry personnel from minor injury to death.

- **Machine safety:**

  Safety should be ensured for any work that has to be done for the optimal functioning of the equipment. Measures should be taken to address risks involved during initiation, use, repairs and maintenance of the equipment.

- **Ambience Safety:**

  Safety policies and procedures must ensure healthy working environment. Machine failures may compromise safety of the working environment.

5.3.3.4 Enablers of Critical Terms

- **Training needs:**

  Technicians or managers must be educated and trained for the efficient utilisation of operating systems used in predictive maintenance.

- **Employee Recognition:**

  Some workers are antagonistic about giving predictive maintenance as they have to assume extra responsibilities in that program. Maintenance strategies can only be implemented with the acceptance of labourers and trade unions.

- **Top level consent:**

  Effective data analysis using certain condition monitoring techniques may be expensive and sometimes require specialist personnel. Sometimes, top managers are disinterested in implementing these maintenance procedures due to high set up cost.

5.3.4 Maintenance Strategies

Three maintenance strategies that are currently adopted by the company are considered as alternatives.

- **Time Based Maintenance (TBM):**

  Preventive maintenance is a planned strategy which is performed in prescribed intervals as per design data or service data when machine life is more important than cost.

- **Condition Based Maintenance (CBM):**

  Condition based maintenance reduces spare inventory cost and avails more idea about spare part speculation. But it requires availability of data acquisition systems and a set of measurements to monitor real time machine performance.

- **Reactive Maintenance (RM):**

  Reactive maintenance is the oldest form of maintenance which is triggered after failure.

Other maintenance approaches are not suitable for this industry. For example, Opportunistic maintenance is not considered as lengthy periods of machinery shut down is impossible for this industry.

5.3.5 ANP decision model

The ANP model for selecting best maintenance strategy is formulated as shown in figure 5.1. The first level of the model shows the goal, which is the selection of the best maintenance strategy. Second level shows the Four Determinants identified by the focus group. Third level shows the four criteria identified by the focus group. The fourth level shows the sub-criteria of the respective area.

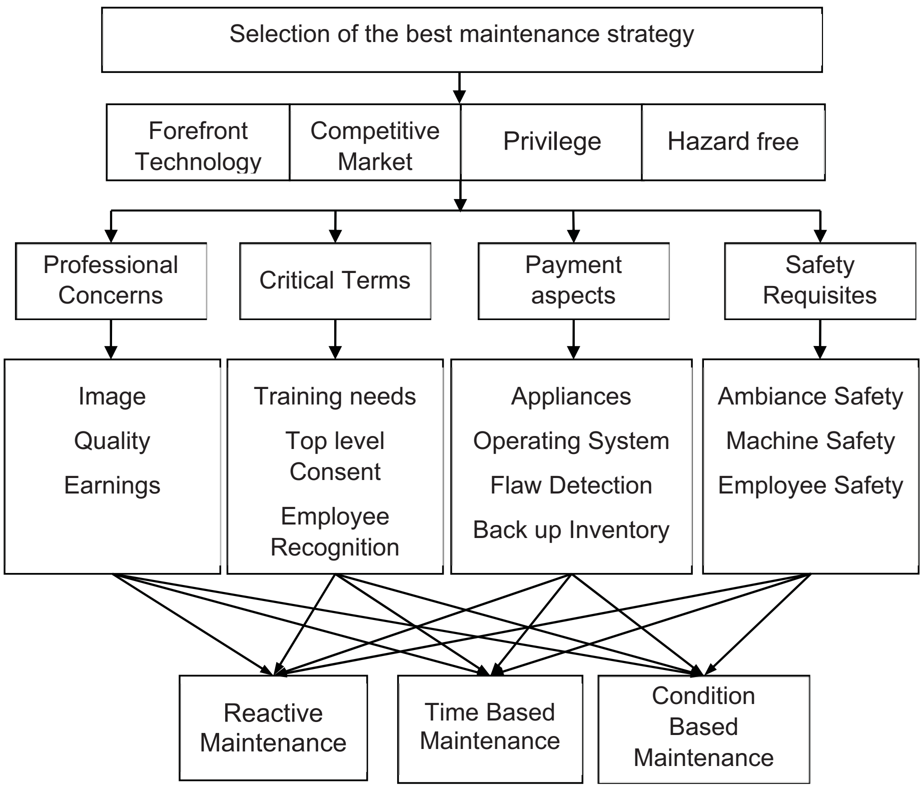

Figure 5.1 ANP model (Cement Industry)

5.4 Data collection

Data collection is performed on the basis of the evaluations of the focus group members of the industry. A detailed questionnaire is constructed based on the determinants, dimensions, enablers and possible maintenance strategies to identify the relative priority of the elements. These priority values are used for the computation of Overall Weighted Score Indices (OWSI) of the maintenance alternatives for determining the optimum maintenance strategy for the industry.

Table 5.2 Sample questionnaire for data collection in a cement industry

Comparison of dimensions with respect to determinant			
	FOREFRONT TECHNOLOGY	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	
1	Professional Concerns		Critical Terms
2	Professional Concerns		Payment Aspects
3	Professional Concerns		Safety Requisites
4	Critical Terms		Payment Aspects
5	Critical Terms		Safety Requisites
6	Payment Aspects		Safety Requisites

The above table shows a part of the questionnaire comparing various dimensions with respect to the forefront technology determinant. Each dimension is compared with the other three dimensions. A table of comparison is formed using numbers 9 to 1 on left side and from 1 to 9 on the right side. If the left side element has greater influence than the right-side element, then the numbers from 9 to 2 is marked on left side. Similarly, if the right-side element possesses greater priority than the left side element the right-side numbers from 2 to 9 are marked. If they have equal priority ,1 is marked. Similarly, questionnaires are prepared to check all of the following:

1. Comparing priority of each determinant with respect to goal
2. Comparing priority of each dimension with respect to determinants
3. Comparing priority of each enabler with respect to dimensions
4. Checking for interdependencies among enablers
5. Comparing priority of each maintenance alternative with respect to enablers

5.5 Calculations

The stepwise calculations that are to be performed are described below:

1. Pairwise comparisons of determinants and the calculation of priority vectors of the determinants with respect to the goal of the decision problem are done.

2. Pairwise comparison of dimensions and the calculation of priority vectors of the dimensions with respect to the determinants are done.

3. Pairwise comparison of enablers and the calculation of priority vectors of the enablers with respect to the dimensions are done.

4. Pairwise comparison of interdependencies and the calculation of priority vectors of the interdependencies among the enablers are done.

5. Evaluation of alternatives and the calculation of priority vectors of the alternatives with respect to the enablers are done.

6. Super matrices are formed from the matrices of interdependencies

7. Super matrices of each of the determinant are converged to obtain a stable set of values.

8. Computation of Total Desirability Indices (TDI) of the alternatives related to each determinant are done.

9. Computation of Overall Weighted Score Indices (OWSI) for the maintenance alternatives, which is the prime factor in maintenance decision making is completed.

5.5.1 Pairwise comparisons of determinants

To determine the relative priorities of the determinants in choosing maintenance strategy alternative, pairwise comparison method is used. Using the data collected for pairwise comparison of the determinants, a pairwise comparison matrix is developed by assigning the priority values of the determinants in the matrix. Each element in the matrix is normalized by dividing by the sum of that column. The average of each row of the normalized table is the priority vector of the element in that row and using these values the consistency measure is computed. Principal eigen vector is calculated from the average of consistency measures. $C.I. = (\lambda_{max} - n)/ (n-1)$ where, the λ_{max} is the principal eigen value of the matrix and n is the size of the matrix (Pramod and Banwet,2011). The consistency ratio (CR) less than or equal to 0.10 is essential for assuring the reliability of the results and is found by the ratio of consistency index upon random index (Pramod and Banwet,2011)

Table 5.3 shows a pairwise comparison matrix of the determinants with respect to the goal of the decision problem in a cement industry. In this matrix the relative priority of forefront technology with respect to privilege is 3 while the relative priority of privilege with respect to forefront technology is placed as 1/3, the reciprocal of 3. The diagonal values are marked as 1 which is the relative priority of a determinant with respect to the same determinant. The eigen vectors are the weighted priorities of the determinants which is an essential factor for the computation of OWSI of the maintenance alternatives and selection of optimum maintenance strategy. The priority vectors of the determinants namely, Competitive Market, Forefront Technology, Privilege and Hazard free are 0.519, 0.204, 0.067 and 0.210 respectively.

Table 5.3 Pairwise Comparisons of Determinants

Goal					
Determinants	Competitive Market	Forefront Technology	Privilege	Hazard free	Priority Vectors
Competitive Market	1	7	4	3	0.519
Forefront Technology	1/7	1	3	3	0.204
Privilege	1/4	1/3	1	1/7	0.067
Hazard free	1/3	1/3	7	1	0.210

5.5.2 Pairwise comparisons of dimensions

To compute the relative influence of the dimensions in view of maintenance policy perspective, a pair wise comparison matrix is created by means of pairwise comparisons of the dimensions from the collected data. Eigen vectors are calculated and the dimensions were ranked according to their priority weights. Eigenvectors are posted as Pja in the Table for total Desirability Indices.

Table 5.4 displays a pairwise comparison matrix of the dimensions in a cement industry related to the hazard free determinant. The dimensions Professional Concerns, Payment Aspects, Safeness Requisites and Critical Terms are compared and priority vectors are calculated. The eigen vectors/priority vectors are the weighted priority of the dimensions used for the computation of OWSI for determining the optimum maintenance alternative for the industry. The priority vectors of the dimensions namely, Professional Concerns, Payment Aspects, Safety Requisites and Critical Terms are 0.049, 0.141, 0.544 and 0.265 respectively.

Table 5.4 Pairwise comparisons of dimensions

Hazard					
Dimensions	Professional Concerns	Payment Aspects	Safety Requisites	Critical Terms	Priority Vectors
Professional Concerns	1	1/5	1/7	1/6	0.049
Payment Aspects	5	1	1/5	1/3	0.141
Safety Requisites	7	5	1	3	0.544
Critical Terms	6	3	1/3	1	0.265

5.5.3 Pairwise comparisons of enablers

Two enablers are related at a moment with respect to a high-level criterion and the number of such pairwise relation matrices depend on the number of determinants and criteria incorporated in the structural model. The eigenvectors calculated from the pair wise matrices are introduced as AD_{kja} in the Table for total Desirability Indices.

Table 5.5 Pairwise comparisons of enablers

Hazard, Safety Requisites				
Enablers	Ambiance Safety	Machine Safety	Employee Safety	Priority Vectors
Ambiance Safety	1	1	1/3	0.200
Machine Safety	1	1	1/3	0.200
Employee Safety	3	3	1	0.600

Table 5.5 shows a pair wise comparison matrix of the enablers related to Hazard as determinant and Safety Requisites as dimension in a cement industry. Eigen vectors are the weighted priority of the enablers namely, Ambiance Safety, M/c Safety and Employee Safety The eigen vectors for Ambiance Safety, Machine Safety and Employee Safety are calculated as 0.2, 0.2 and 0.6 respectively

5.5.4 Pairwise comparisons of interdependencies

Interdependencies between the enablers are obtained by creating priority vectors from the pair wise relations and are used in the formation of super matrices. Table 5.6 displays a pair wise comparison matrix of the interdependencies connected to Hazard free as determinant, Safety Requisites as dimension and Employee Safety as enabler in a cement industry. The Eigen vectors are calculated which are the priority weights of the enablers, Ambiance Safety and Machine Safety with respect to the enabler, Employee Safety. The Eigen vectors for Ambiance Safety and Machine Safety are calculated as 0.5 and 0.5 respectively. The super matrix is created by importing the values of the priority vectors from the matrix of interdependencies of the enablers

Table 5.6 Pair-wise comparisons of interdependencies

Hazard free, Safety Requisites, Employee Safety			
Inter Dependencies	Ambiance Safety	Machine Safety	Priority Vectors
Ambiance Safety	1	1	.5
Machine Safety	1	1	.5

5.5.5 Pairwise comparisons of alternatives

Comparisons in pair are formed to compute the relative weight of all maintenance policy strategies on the sub criteria with respect to the determinants and the number of sub criteria determines the number of such pair-wise matrices.

This assessment enables in pointing the future into current position to decide what to do next to achieve the expected outcome (Eddie W. L. Cheng and Heng Li, 2004).

Table 5.7 shows a pairwise comparison matrix for alternatives in a cement industry connected to Hazard determinant, Safeness Requirements dimension and Employee Safety enabler. The eigen vectors for Condition Based Maintenance, Time Based Maintenance and Reactive Maintenance are calculated as 0.56, 0.36 and 0.08 respectively. The Eigen vectors computed are imported as S_{ikja} for the calculation of Total Desirability Indices of the alternatives.

Table 5.7 Pair-wise comparisons of alternatives

Hazard free, Safety Requisites, Employee Safety				
alternatives	Condition based Maintenance	Time Based Maintenance	Reactive Maintenance	Priority Vectors
Condition Based Maintenance	1	2	6	.56
Time Based Maintenance	1/2	1	6	.36
Reactive Maintenance	1/6	1/6	1	.08

5.5.6 Formation of super matrices

The super matrix is formed by the combination of various sub-matrices in which the values are imported from the priority vectors of interdependencies. This structural model comprises of four super matrices for the four determinants.

In this study, there are 13 sub-criteria, 13 pair-wise relation matrices and so 13 non-zero columns in the super matrix. Each of the non-zero values in the column is the relative influence weight associated with the interdependent pair-wise comparison matrices. The super matrix obtained by importing the values from the matrix of interdependencies for the determinant hazard is named as A and the super matrix before convergence is given below. Table 5.8 shows the super matrix before convergence related to hazard determinant in a cement industry

Table 5.8 Super matrix (Hazard free)

A	I	Q	E	A	OS	FD	BI	AS	MS	ES	TN	ER	TC
I	0	0.25	0.5	0	0	0	0	0	0	0	0	0	0
Q	0.25	0	0.5	0	0	0	0	0	0	0	0	0	0
E	0.75	0.75	0	0	0	0	0	0	0	0	0	0	0
A	0	0	0	0	0.11	0.2	0.15	0	0	0	0	0	0
OS	0	0	0	0.11	0	0.2	0.15	0	0	0	0	0	0
FD	0	0	0	0.58	0.58	0	0.7	0	0	0	0	0	0
BI	0	0	0	0.31	0.31	0.6	0	0	0	0	0	0	0
AS	0	0	0	0	0	0	0	0	0.25	0.5	0	0	0
MS	0	0	0	0	0	0	0	0.25	0	0.5	0	0	0
ES	0	0	0	0	0	0	0	0.75	0.75	0	0	0	0
TN	0	0	0	0	0	0	0	0	0	0	0	0.83	0.83
ER	0	0	0	0	0	0	0	0	0	0	0.5	0	0.17
EC	0	0	0	0	0	0	0	0	0	0	0.5	0.17	0

5.5.7 Formation of converged super matrices

In the next level, the super matrix is made to converge to obtain a long-term stable set of weights. MATLAB enables the convergence of the interdependence relations by multiplying the matrix upon itself and is achieved at A57 for Hazard free. This is known as the converged super matrix and the stabilized values gained from this matrix named as AIkja is used for the computation of Total Desirability Indices for the determinant hazard free. Similarly, three super matrices are also developed for forefront technology, competitive market and privilege**.** Table 5.9 shows the super matrix after convergence related to hazard free determinant in a cement industry**.**

The stable values gained through this converged super matrix is imported as Alkja for the calculation of Total Desirability Indices (TDI).

Table 5.9 Super matrix (Hazard free) after convergence

A^57	I	Q	E	A	OS	FD	BI	AS	MS	ES	TN	ER	TC
I	0.2857	0.2857	0.2857	0	0	0	0	0	0	0	0	0	0
Q	0.2857	0.2857	0.2857	0	0	0	0	0	0	0	0	0	0
E	0.4286	0.4286	0.4286	0	0	0	0	0	0	0	0	0	0
A	0	0	0	0.1425	0.1425	0.1425	0.1425	0	0	0	0	0	0
OS	0	0	0	0.1425	0.1425	0.1425	0.1425	0	0	0	0	0	0
FD	0	0	0	0.3916	0.3916	0.3916	0.3916	0	0	0	0	0	0
BI	0	0	0	0.3233	0.3233	0.3233	0.3233	0	0	0	0	0	0
AS	0	0	0	0	0	0	0	0.3233	0.3233	0.3233	0	0	0
MS	0	0	0	0	0	0	0	0.2857	0.3233	0.3233	0	0	0
ES	0	0	0	0	0	0	0	0.4286	0.4286	0.4286	0	0	0
TN	0	0	0	0	0	0	0	0	0	0	0.4536	0.4536	0.4536
ER	0	0	0	0	0	0	0	0	0	0	0.2732	0.2732	0.2732
TC	0	0	0	0	0	0	0	0	0	0	0.2732	0.2732	0.2732

5.5.8 Computation of Total Desirability Indices (TDI).

After applying the associated influential priorities that have been imported from the pair-wise relation tables of dimensions, sub-criteria, maintenance alternatives and the priority weights of sub-criteria created by convergence in the super-matrix, the total desirability indices of the determinant hazard free (D_i hazard free) were calculated on the base of hazard free hierarchy.

To determine the preferred maintenance alternative, it is essential to compute the index of total desirability, for the determinant ‘a’ and the maintenance alternative ‘i’ is defined as

$D_{ia} = \Sigma\ \Sigma\ P_{ja}\ A^{D}k_{ja}\ A^{I}k_{ja}\ S_{i}k_{ja}$ where P_{ja} is the related influential priority of criteria 'j' over determinant 'a', $A^{D}k_{ja}$ is the related influential priority of enabler 'k' of criteria 'j' in the determinant of 'a' for the dependence (D) connections in element levels.

$A^{I}k_{ja}$ is the balanced related influential priority resolved from the super matrix for enabler k of criteria 'j' in the determinant 'a' for interdependence (I) connections.

Sik_{ja} implies the related influence of the maintenance alternative 'i' on sub criterion 'k' of criterion 'j' of determinant 'a'.

The weighted priority values of the alternatives ($P_{ja}\ A^{D}k_{ja}\ A^{I}k_{ja}\ Sik_{ja}$) for the sub criteria that are applied to calculate the OWSI of the maintenance alternatives are displayed in the last three columns. The total desirability index of a maintenance alternative is obtained from the sum of the priority values of the alternatives for the enablers. Table 5.10 demonstrates the calculation of Total Desirability Indices for the maintenance alternatives related to the hazard determinant.

Table 5.10 Total Desirability Indices (Hazard free)

Dimensions	Pja	Sub criteria	ADkja	AIaJa	Product	S1kja	S11kja	S111kja	CBM	TBM	RM
PC	0.049	I	0.200	0.2857	0.0028	0.753	0.172	0.075	0.0021	0.0005	0.0002
PC	0.049	Q	0.200	0.2857	0.0028	0.723	0.206	0.070	0.0020	0.0006	0.0002
PC	0.049	E	0.600	0.4286	0.0126	0.571	0.363	0.066	0.0072	0.0046	0.0008
PA	0.141	A	0.099	0.1425	0.0020	0.658	0.282	0.060	0.0013	0.0006	0.0001
PA	0.141	OS	0.099	0.1425	0.0020	0.595	0.347	0.058	0.0012	0.0007	0.0001
PA	0.141	FD	0.518	0.3916	0.0286	0.637	0.302	0.061	0.0182	0.0086	0.0017
CA	0.141	BI	0.284	0.3233	0.0129	0.575	0.366	0.059	0.0074	0.0047	0.0008
SR	0.544	AS	0.200	0.3233	0.0352	0.657	0.275	0.068	0.0231	0.0097	0.0024
SR	0.544	MS	0.200	0.2857	0.0311	0.571	0.363	0.066	0.0177	0.0113	0.0021
SR	0.544	ES	0.600	0.4286	0.1399	0.564	0.359	0.077	0.0789	0.0502	0.0108
CT	0.265	TN	0.714	0.4536	0.0858	0.545	0.370	0.085	0.0468	0.0318	0.0073
CT	0.265	ER	0.143	0.2732	0.0104	0.564	0.359	0.077	0.0058	0.0037	0.0008
CT	0.265	TC	0.143	0.2732	0.0104	0.580	0.350	0.070	0.0060	0.0036	0.0007
									0.2179	0.1305	0.0280

5. 6 Results

The Overall weighted Score indices (OWSI) for the alternatives are computed to give gesture to the maintenance policy selection for the organisation. The aggregation of the products of the desirability indices (D_{ia}) and the relative importance weights of the determinants (C_a) is the Overall Weighted Score Index (OWSI) for a maintenance alternative which is the prime factor in maintenance decision making.

The OWSI for an alternative is the addition of the products of the Total Desirability Indices (Día) and the relative priority weights of the determinants (Ca) and is represented as OWSIi= Σ Dia Ca. Table 5.11 illustrates the computation of Overall weighted Score indices for the maintenance alternatives. The maintenance alternatives namely, Condition Based Maintenance, Time Condition Based Maintenance and Reactive Maintenance are designated as CBM, TBM and RM respectively. The determinants namely, Competitive Market, Forefront Technology, Privilege and Hazard free are marked as CM, FT, PR and HZ.

In this table the priority weights (Ca) of the determinants namely, Competitive Market, Forefront Technology, Privilege and Hazard free are 0.519, 0.204, 0.067 and 0.210 respectively. The Total Desirability Indices (Día) for the hazard determinant is 0.218,0.131 and 0.028 for CBM, TBM and RM respectively. The Total Desirability Indices (Día)for the Time-Based Maintenance alternative are 0.082, 0.097,0.099 and 0.131 for the determinants namely, Competitive Market, Forefront Technology, Privilege and Hazard free. For example, the OWSI for TBM IS Calculated as; $OWSI_i = \Sigma D_{ia}C_a$

OWSI $_{TBM}$= [(0.519*0. 082) (0.204*0. 097) + (0.067*0. 099) + (0.210*0. 131)] =0.266. Correspondingly OWSI $_{CBM}$ and OWSI $_{RM}$ are also calculated. The last column displays the normalized values of OWSI.

Table 5.11 Overall Weighted Score Index

Alternatives	Determinants				OWSI	OWSI Normalized
	CM	FT	PR	HF		
Weights	0.519	0.204	0.067	0.210		
CBM	0.295	0.250	0.238	0.218	0.266	0.704
TBM	0.082	0.097	0.099	0.131	0.100	0.266
RM	0.029	0.026	0.025	0.028	0.011	0.030
					0.377	1.000

It is observed from Table 5.11 that OWSI normalized for Condition Based Maintenance (.704) is found to be more as compared to Reactive Maintenance (0.030) and Time-Based Maintenance (0.266) and CBM is the most-suited alternative for the company.

CHAPTER 6

ANP MODEL IMPLEMENTATION FOR CHEMICAL INDUSTRY

6.1 Introduction

This chapter describes the ANP model implementation technique in a chemical industry. This chapter includes a brief explanation about the determinants, dimensions, enablers and possible maintenance strategies connected to the maintenance strategy selection of the chemical industry. Pairwise comparison method is applied to evaluate the relative preferences of the determinants, dimensions, enablers, interdependencies and alternatives. These comparisons are to found the relative priorities of determinants, dimensions, enablers, interdependencies and alternatives which are applying in the ANP method for electing an ideal maintenance strategy for the organisation.

6.2 Description of the Industry

The case study is carried out in Fertilizers and Chemicals Travancore Limited (FACT) situated at Udyog Mandal, Kochi, - in the Kerala State of India. Major products of Fertilizers and Chemicals Travancore Limited (FACT) are Ammonium Sulphate and Ammonium Phosphate Sulphate (FACTAMFOS). The company was established in the year 1943. Ms. FACT is an ISO 9001:2014 certified industry.

6.3. ANP model development for the chemical industry

A focus group consisting of ten members in the senior managerial level with more than ten years of experience were formed for the development of ANP Model, pairwise comparison and implementing ANP based Maintenance Strategy formulation. The focus group examined the determinants, dimensions, enablers and the maintenance strategies of the cement manufacturing industry and decided to follow the same model for them also. However, selection of the determinants, dimensions, enablers and alternative strategies in the context of chemical industries are justified in the following sections.

6.3.1 Determinants

Determinants of the maintenance strategy selection are Forefront Technology (FT), Competitive Market (CM), Privilege (PR) and Hazard free (HF). These are the factors that the industry aims to achieve through maintenance strategy perspective. Forefront Technology aims to possess technological advancement while Competitive Market determinant stands for attaining market competitiveness of the industry. Another determinant aims at having a privilege over other companies and the determinant hazard focusses on eliminating dangers.

- **Competitive Market**

  The fertilizer market is fragmented with a mix of government, cooperative and private owned players. The straight fertilizer market is largely subsidised and dominated by government companies. However, chemical industry, namely complex fertilizers and innovative fertilizers receive high level of competition from private companies and international players.

- **Forefront Technology**

  It is important for chemical industries to use upfront technology to reduce their environmental footprint and to increase production without raising demand on non-renewable fuel sources. New and improved fertilizer products are also essential to boost the global crop yield and provide sustainable food security. Technological advancements are also essential to reduce toxic by-products of the manufacturing process and for viable and safe handling of these by-products.

- **Privilege**

  Due to increased number and type of players in the chemical industry market, gaining a credible labelling is critical to increase demand. The necessity of supreme quality encourages buyers to look for reputed branding of their products.

- **Hazard free**

  Chemical industry poses threats to the workers, manufacturing site, locality of the industry and ecosystem as a whole. Stringent safety protocols, adherence to manufacturing standards, protective equipment, serial screening for effects and upkeep of machinery is essential to prevent risks that arise from the manufacturing processes. Apart from manufacturing, handling of raw-materials, products and by-products also require careful vigilance, knowledge and planning.

6.3.2 Dimensions (Criteria)

Based on literature review and consultation with the focus group members, four dimensions and 11 sub criteria are identified. The four dimensions that were concluded after this exercise are Professional Concerns, Payment Aspects, Safeness Requisites and Critical Terms.

- **Professional Concerns**

  This criterion includes characteristics of the industry that constitute its professional standing in the market and comprises of the three sub criteria, namely the earnings of the plant, the quality of its produce and the professional image of the company. These are important to keep the company at a cutting edge with respect to accomplishing its goal

- **Payment Aspects**

  Payment aspects of running an industrial plant is an important decisive factor that guides the company towards achieving efficiency. This involves various heads like appliances cost, operating system cost, cost for setting up a backup inventory and expenses incurred for flaw detection.

- **Safety Requisites**

  Meeting safety requirements are cardinal to undeterred running of an industry as it involves the wellbeing of the plant employees, optimal state of machinery in the industry and the healthy status of the industrial ambiance. Flaws in meeting with these requisites can have huge expenses financially and in human terms for the company.

- **Critical Terms**

  The industry also requires timely training and updating its staff to excel in its performance. Changes in policies and administrative actions require consent from top level company professionals and employees of the unit have to give specified role and recognition for their contributions. These critical terms are also essential for the harmonised functioning of the industrial plant.

6.3.3 Enablers (Sub Criteria)

The enablers included in the four dimensions are listed in Table 6.1. The four dimensions that were concluded after this exercise are Professional Concerns, Payment Aspects, Safeness Requisites and Critical Terms.

Table 6.1 Enablers (Sub Criteria)

Professional Concerns (PR)	Payment Aspects (PA)
Earnings (E)	Appliances (A)
Quality (Q)	Operating System (OS)
Image(I)	Back up Inventory (BI)
	Flaw Detection (FD)
Safety Requisites (SR)	**Critical Terms (CT)**
Employee Safety	Training Needs
M/c Safety	Top level Consent
Ambiance Safety	Employee Recognition

6.3.3.1 Enablers of Professional Concerns

- **Image**

  The image of the organization is mainly influenced by its manufacturing and maintenance activities. Delayed distributions, shortage in quantities, low quality products, delay in response of complaints are some reasons for the image loss of firm.

- **Quality**

  Equipment deterioration can reduce the product quality. Maintenance plays a crucial role in safekeeping the availability and reliability levels, product quality, and safeness requirements.

- **Earnings**

  Excessive failures increase maintenance cost and decrease earnings. Selection of reasonable upkeep approach for such machines by considering yield aspects may diminish production disruptions which matters loss of production.

6.3.2.2 Enablers of Payment Aspects

- **Appliance:**

  Implementation of Condition Based Maintenance demands some new machines or equipment.

- **Operating System:**

  Various programs are recommended to check out the data retrieved from equipment used for Condition Based Maintenance.

- **Back up Inventory:**

  Every organisation constantly strives to maintain optimum inventory level to meet its requirements and avoid over or under inventory that can impact the financial figures. Reactive maintenance requires more additional parts compared to other maintenance methods.

- **Flaw Detection:**

  . Fault diagnosis shall be capable of locating one or few root causes of problems, so that corrective action can be taken to attend them. Automated fault detection and diagnosis relies heavily on inputs from sensors or derived measures of performance. However, in many situations, especially, in process industries, sensors themselves account for most common equipment failures. Hence, in such industries, major focus is needed in identifying sensor failures apart from process issues.

6.3.3.3 Enablers of Safety Requisites:

In manufacturing industries, the safety level requirements are often high specifically in chemical industry. The related issues describing the safety are:

- **Employee Safety:**

  The failure of many machines can lead to serious damage of personnel on site including minor injury and even death.

- **M/c safety:**

  Ensures that the machine is perfectly safe not only during normal use but also while carrying out all machine related activities such as setting up, clearing blockages, carrying out repairs for breakdowns as well as during planned maintenance.

- **Ambiance Safety:**

  Safety policies and procedures maintain healthy working environment, mitigating any source of hazard to personnel and plant environment, particularly during interruptions in operations arising due to failure.

6.3.3.4 Enablers of Critical Terms

- **Training needs:**

  In order to facilitate effective use of equipment as well as software used in predictive maintenance, technicians or managers may be required to go through special training.

- **Employee Recognition:**

  Some workers may resist predictive maintenance, since it may lead to additional works in the scheduled program. Hence, maintenance strategies can only be implemented subject to consent or acceptance by workers and trade unions

- **Top level consent:**

Many a times, condition monitoring techniques are costly and require experienced, specialist personnel for data analysis to guarantee its effectiveness. In such a situation, top management may not be interested in implementing such maintenance procedures as its setup cost is high.

6.3.4 Maintenance Strategies

Three maintenance strategies are generally adopted in industries.

- **Time Based Maintenance (TBM):**

  Time based preventive maintenance procedure is prepared on the basis of design or service figures and is implemented in regular periods. This technique is adapted where life of the equipment is more significant than the expense related to the same.

- **Condition Based Maintenance (CBM):**

  Condition based maintenance is most appropriate for equipment having huge capital cost and consisting of complex expendable items and also for constant parts which deteriorate due to extended usage or time. The implementation of this maintenance program requires well awareness of the failure statistics and incorporates data acquisition systems and a set of measurements to monitor the machine performance in real time.

- **Reactive Maintenance (RM):**

  Reactive maintenance is an oldest scheme of maintenance and is performed to restore a failed equipment to acceptable levels. Maintenance costs and machine downtime can be reduced through proper execution of this program

Other maintenance approaches are not suitable for this industry. For example, Opportunistic maintenance is not considered as lengthy periods of machinery shut down is impossible for this industry.

6.3.5 ANP Decision Model

The ANP model prepared is presented in Figure 6.1.

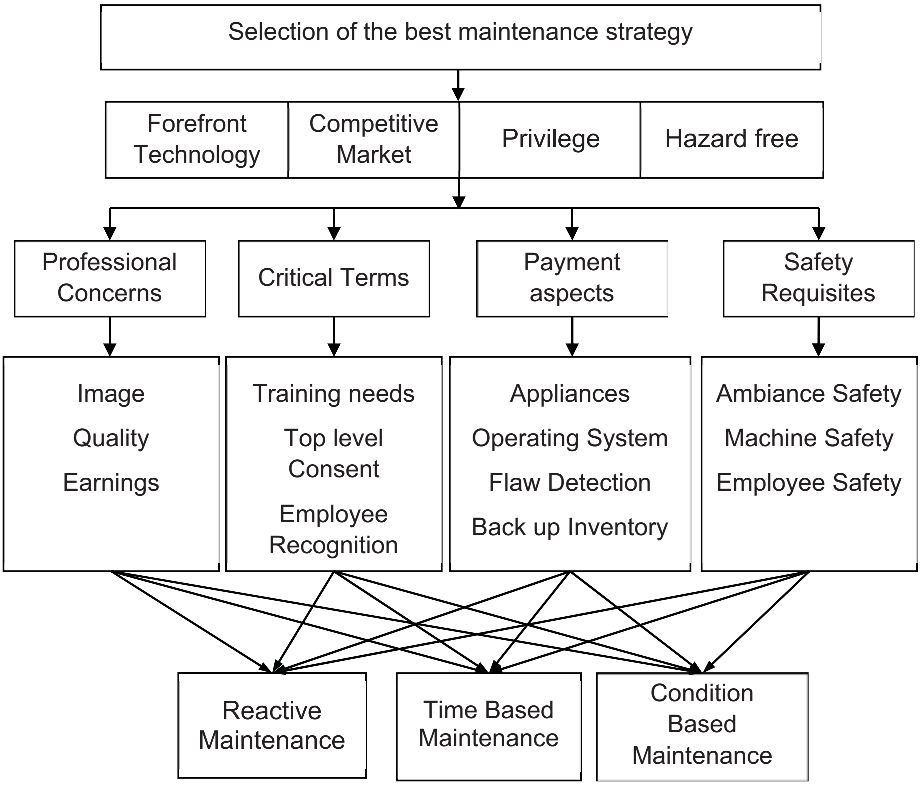

Figure 6.1 ANP model (Chemical Industry)

6.4 Data Collection

Data collection is performed on the basis of the evaluations of the focus group members of the industry. A detailed questionnaire is constructed based on the determinants, dimensions, enablers and possible maintenance strategies to identify the relative priority of the elements. Sample questionnaire for data collection in a chemical industry is shown in Table 6.2. These priority values are used for the computation of Overall Weighted Score Indices (OWSI) of the maintenance alternatives for determining the optimum maintenance strategy for the industry.

Table 6.2 Sample questionnaire for data collection in a chemical industry

Comparison of dimensions with respect to determinant																			
	FOREFRONT TECHNOLOGY	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
1	Professional Concerns																		Critical Terms
2	Professional Concerns																		Payment Aspects
3	Professional Concerns																		Safety Requisites
4	Critical Terms																		Payment Aspects
5	Critical Terms																		Safety Requisites
6	Payment Aspects																		Safety Requisites

The above table shows a questionnaire comparing various dimensions with respect to the forefront technology determinant. Each dimension is compared with the other three dimensions. A table of comparison is formed using numbers 9 to 1 on left side and from 1 to 9 on the right side. If the left side element has greater influence than the right-side element then the numbers from 9 to 2 is marked on left side. Similarly, if the right-side element possesses greater priority than the left side element the right-side numbers from 2 to 9 are marked. If they have equal priority ,1 is marked. Similarly, questionnaires are prepared to check all of the following:

1. Comparing priority of each determinant with respect to goal
2. Comparing priority of each dimension with respect to determinants
3. Comparing priority of each enabler with respect to dimensions

4. Checking for interdependencies among enablers
5. Comparing priority of each maintenance alternative with respect to enablers

6.5 Calculations

The stepwise calculations that are to be performed are described below:

1. Pairwise comparisons of determinants and the calculation of priority vectors of the determinants with respect to the goal of the decision problem are done.

2. Pairwise comparison of dimensions and the calculation of priority vectors of the dimensions with respect to the determinants are done.

3. Pairwise comparison of enablers and the calculation of priority vectors of the enablers with respect to the dimensions are done.

4. Pairwise comparison of interdependencies and the calculation of priority vectors of the interdependencies among the enablers are done.

5. Evaluation of alternatives and the calculation of priority vectors of the alternatives related to the enablers are done.

6. Super matrices are formed from the matrices of interdependencies

7. Super matrices of each of the determinant are converged to attain a stable set of values.

8. Computation of Total Desirability Indices (TDI) of the alternatives related to each determinant are done.

9. Computation of Overall Weighted Score Indices (OWSI) for the maintenance alternatives, which is the prime factor in maintenance decision making is completed.

6.5.1 Pairwise comparisons of determinants

To determine the relative priorities of the determinants in choosing maintenance strategy alternative, pairwise comparison method is used. Using the data collected for pairwise comparison of the determinants, a pairwise comparison matrix is developed by assigning the priority values of the determinants in the matrix. Each element in the matrix is normalized by dividing by the sum of that column. The average of each row of the normalized table is the priority vector of the element in that row and using these values the consistency measure is computed. Principal eigen vector is calculated from the average of consistency measures. $C.I. = (\lambda_{max} - n)/ (n-1)$ where, the λ_{max} is the principal eigen value of the matrix and n is the size of the matrix (Pramod and Banwet,2011). The consistency ratio (*CR*) less than or equal to 0.10 is essential for assuring the reliability of the results and is found by the ratio of consistency index upon random index (Pramod and Banwet,2011)

Table 6.3 Pairwise Comparisons of Determinants

Goal					
Determinants	Hazard free	Forefront Technology	Competitive Market	Privilege	Priority Vectors
Hazard free	1	4	3	4	0.489
Forefront Technology	1/4	1	3	3	0.224
Competitive Market	1/3	1/3	1	1/7	0.082
Privilege	1/4	1/3	7	1	0.204

Table 6.3 shows a pairwise comparison matrix of the determinants with respect to the goal of the decision problem in a chemical industry. In this matrix the relative priority of forefront technology with respect to Competitive Market is 3 while the relative priority of Competitive Market with respect to forefront technology is placed as 1/3, the reciprocal of 3. The diagonal values are marked as 1 which is the relative priority of a determinant with respect to the same determinant. The eigen

vectors are the weighted priorities of the determinants which is an essential factor for the computation of OWSI of the maintenance alternatives and selection of optimum maintenance strategy. The priority vectors of the determinants namely, Hazard free, Forefront Technology, Competitive Market and Privilege and are 0.489, 0.224, 0.082 and 0.204 respectively.

6.5.2 Pairwise comparisons of dimensions

To compute the relative influence of the dimensions in view of maintenance policy perspective, a pair wise comparison matrix is created by means of pairwise comparisons of the dimensions from the collected data. Eigen vectors are calculated and the dimensions were ranked according to their priority weights. Eigenvectors are posted as Pja in the Table for total Desirability Indices.

Table 6.4 Pairwise comparisons of dimensions

Competitive Market					
Dimensions	Professional Concerns	Payment Aspects	Safety Requisites	Critical Terms	Priority Vectors
Professional Concerns	1	1/5	1/7	1/6	0.349
Payment Aspects	5	1	1/5	1/3	0.269
Safety Requisites	7	5	1	3	0.290
Critical Terms	6	3	1/3	1	0.092

Table 6.4 displays a pairwise comparison matrix of the dimensions in a chemical industry related to the Competitive Market determinant. The dimensions Professional Concerns, Payment Aspects, Safeness Requisites and Critical Terms are compared and priority vectors are calculated. The eigen vectors/priority vectors are the weighted priority of the dimensions used for the computation of OWSI for determining the optimum maintenance alternative for the industry. The priority

vectors of the dimensions namely, Professional Concerns, Payment Aspects, Safety Requisites and Critical Terms are 0.349, 0.269, 0.290 and 0.092 respectively.

6.5.3 Pairwise comparison of enablers

Two enablers are related at a time with respect to a high-level criterion. The number of such pairwise relation matrices depend on the number of determinants and criteria incorporated in the structural model. The eigenvectors calculated from the pair wise matrices are introduced as AD_{kja} in the Table for total Desirability Indices.

Table 6.5 Pairwise comparison of enablers

Competitive Market, Safety Requisites				
Enablers	Employee Safety	Machine Safety	Ambiance Safety	Priority Vectors
Employee Safety	**1**	**3**	**4**	0.633
Machine Safety	1/3	1	1	0.192
Ambiance Safety	1/4	1	1	0.167

Table 6.5 shows a pair wise comparison matrix of the enablers related to Competitive Market determinant and Safety Requisites as dimension in a chemical industry. Eigen vectors are the weighted priority of the enablers namely, Ambiance Safety, M/c Safety and Employee Safety. The Eigen vectors for Ambiance Safety, Machine Safety and Employee Safety are calculated as 0.633, 0192 and 0.167 respectively.

6.5.4 Pairwise comparison of interdependencies

Interdependencies between the enablers are obtained by creating priority vectors from the pair wise relations and are used in the formation of super matrices.

Table 6.6 displays a pair wise comparison matrix of the interdependencies connected to Competitive Market determinant, Safety Requisites as dimension and Employee Safety as enabler in a chemical industry. The eigen vectors are calculated which are the priority weights of the enablers, Ambiance Safety and Machine Safety with respect to the enabler, Employee Safety. The eigen vectors for Ambiance Safety and Machine Safety are calculated as 0.5 and 0.5 respectively. The super matrix is created by importing the values of the priority vectors from the matrix of interdependencies of the enablers

Table 6.6 Pair-wise comparison of interdependencies

Hazard free, Safety Requisites, Employee Safety			
Interdependencies	Machine Safety	Ambiance Safety	Priority Vectors
Machine Safety	1	1	.5
Ambiance Safety	1	1	.5

6.5.5 Pairwise comparison of Alternatives

Comparisons in pair are formed to compute the relative weight of all maintenance policy strategies on the sub criteria with respect to the determinants and the number of sub criteria determines the number of such pair-wise matrices. This assessment enables in pointing the future into current position to decide what to do next to achieve the expected outcome (Eddie W. L. Cheng and Heng Li, 2004).

Table 6.7 Pair-wise comparison of alternatives

Competitive Market, Safety Requisites, Employee Safety				
Alternatives	Condition based Maintenance	Reactive Maintenance	Time Based Maintenance	Priority Vectors
Condition based Maintenance	1	1/8	1/3	.075
Reactive Maintenance	8	1	6	.753
Time Based Maintenance	3	1/6	1	.172

Table 6.7 shows a pairwise comparison matrix for alternatives in a chemical industry connected to Competitive Market determinant, Safeness Requirements dimension and Employee Safety enabler. The eigen vectors for Condition Based Maintenance, Reactive Maintenance and Time-Based Maintenance are calculated as 0.075, 0.753 and 0.172 respectively. The Eigen vectors computed are imported as S_{ikja} for the calculation of Total Desirability Indices of the alternatives.

6.5.6 Formation of super matrices

The super matrix is formed by the combination of various sub-matrices in which the values are imported from the priority vectors of interdependencies. This structural model comprises of four super matrices for the four determinants.

Table 6.8 Super matrix (Competitive Market)

Competitive Market													
	I	Q	E	A	OS	FD	BI	AS	MS	ES	TN	ER	TC
I		0.67	0.25										
Q	0.8	0	0.75										
E	0.2	0.33	0										
A				0	0.62	0.44	0.43						
OS				0.62	0	0.44	0.43						
FD				0.23	0.23	0	0.14						
BI				0.15	0.15	0.12	0						
AS								0	0.67	0.5			
MS								0.67	0	0.5			
ES								0.33	0.33	0			
TN											0	0.83	0.83
ER											0.5	0	0.17
TC											0.5	0.17	0

In this study, there are 13 sub-criteria, 13 pair-wise relation matrices and so 13 non-zero columns in the super matrix. Each of the non-zero values in the column is the relative influence weight associated with the interdependent pair-wise comparison matrices. The super matrix obtained by importing the values from the matrix of interdependencies for the determinant Competitive Market is named as A and the super matrix before convergence is given below.

Table 6.8 shows the super matrix before convergence related to Competitive Market determinant in the chemical industry

6.5.7 Formation of converged super matrices

In the next level, the super matrix is made to converge to obtain a long-term stable set of weights. MATLAB enables the convergence of the interdependence relations by multiplying the matrix upon itself and is achieved at A59 for competitive market. This is known as the converged super matrix and the stabilized values gained from this matrix named as Alkja is used for the computation of Total Desirability Indices for the determinant competitive market. Similarly, three super matrices are also developed for forefront technology, hazard free and privilege**.**

Table 6.9 shows the super matrix after convergence related to Competitive Market determinant in a chemical industry**.** The stable values gained through this converged super matrix is imported as Alkja for the calculation of Total Desirability Indices (TDI).

Table 6.9 Super matrix (Competitive Market) after convergence

	Competitive Market												
^59	I	Q	E	A	OS	FD	BI	AS	MS	ES	TN	ER	TC
I	0.347	0.347	0.347										
Q	0.439	0.439	0.439										
E	0.214	0.214	0.214										
A				0.348	0.348	0.348	0.348						
OS				0.348	0.348	0.348	0.348						
FD				0.178	0.178	0.178	0.178						
BI				0.126	0.126	0.126	0.126						
AS								0.376	0.376	0.376			
MS								0.376	0.376	0.376			
ES								0.248	0.248	0.248			
TN											0.454	0.454	0.454
ER											0.273	0.273	0.273
TC											0.273	0.273	0.273

6.5.8 Computation of Total Desirability Indices (TDI)

Pair-wise relation tables of dimensions, sub-criteria, maintenance strategies and the priority weights of sub-criteria were attained in the super matrix after convergence and by applying connected influential priorities on these, the total desirability indices of the determinant hazard free (D_i hazard free) is formed on the base of hazard free hierarchy.

To determine the preferred maintenance alternative, it is essential to compute the index of total desirability, for the determinant 'a' and the maintenance alternative 'i' is defined as

$D_{ia} = \Sigma \Sigma P_{ja} A^{D}k_{ja} A^{I}k_{ja} S_{i}k_{ja}$ where P_{ja} is the related influential priority of criteria 'j' over determinant 'a', $A^{D}k_{ja}$ is the related influential priority of enabler 'k' of criteria 'j' in the determinant of 'a' for the dependence (D) connections in element levels.

$A^{I}k_{ja}$ is the balanced related influential priority resolved from the super matrix for enabler k of criteria 'j' in the determinant 'a' for interdependence (I) connections.

Sik_{ja} implies the related influence of the maintenance alternative 'i' on sub criterion 'k' of criterion 'j' of determinant 'a'.

Table 6.10 Total Desirability Indices (Competitive Market)

Dimensions	Pja	Enablers	ADkja	AIaJa	Product	S1kja	S2kja	S3kja	CBM	RM	TBM
SR	0.349	ES	0.633	0.347	0.077	0.075	0.753	0.172	0.006	0.058	0.013
SR	0.349	MS	0.192	0.439	0.029	0.070	0.723	0.206	0.002	0.021	0.006
SR	0.349	AS	0.175	0.214	0.013	0.066	0.571	0.363	0.001	0.007	0.005
PA	0.269	A	0.312	0.348	0.029	0.060	0.658	0.282	0.002	0.019	0.008
PA	0.269	OS	0.280	0.348	0.026	0.058	0.595	0.347	0.002	0.016	0.009
PA	0.269	FD	0.280	0.178	0.013	0.061	0.637	0.302	0.001	0.009	0.004
PA	0.269	BI	0.128	0.126	0.004	0.059	0.575	0.366	0.000	0.002	0.002
PC	0.290	I	0.230	0.376	0.025	0.068	0.657	0.275	0.002	0.016	0.007
PC	0.290	Q	0.122	0.376	0.013	0.066	0.571	0.363	0.001	0.008	0.005
PC	0.290	E	0.648	0.298	0.056	0.077	0.564	0.359	0.004	0.032	0.020
CT	0.092	TN	0.400	0.454	0.017	0.085	0.545	0.370	0.001	0.009	0.006
CT	0.092	ER	0.400	0.273	0.010	0.077	0.564	0.359	0.001	0.006	0.004
CT	0.092	TC	0.200	0.273	0.005	0.070	0.580	0.350	0.000	0.003	0.002
									0.022	0.206	0.090

The weighted priority values of the alternatives ($P_{ja} A^{D}k_{ja} A^{I}k_{ja} Sik_{ja}$) for the sub criteria that are applied to calculate the OWSI of the maintenance alternatives are displayed in the last three columns. The total desirability index of a maintenance alternative is obtained from the sum of the priority values of the alternatives for the enablers. Table.6.10 demonstrates the calculation of Total Desirability Indices for the maintenance alternatives related to the competitive market determinant.

6. 6 Results

The Overall weighted Score indices (OWSI) for the alternatives are computed to give gesture to the maintenance policy selection for the organisation. The aggregation of the products of the desirability indices (D_{ia}) and the relative importance weights of the determinants (C_a) is the Overall Weighted Score Index (OWSI) for a maintenance alternative which is the prime factor in maintenance decision making.

The OWSI for an alternative is the addition of the products of the Total Desirability Indices (Día) and the relative priority weights of the determinants (Ca) and is represented as OWSIi = Σ Dia Ca. Table 6.11 illustrates the computation of Overall weighted Score indices for the maintenance alternatives. The maintenance alternatives namely, Condition Based Maintenance, Time Based Maintenance and Reactive Maintenance are designated as CBM, TBM and RM respectively. The determinants namely, Competitive Market, Forefront Technology, Privilege and Hazard free are marked as CM, FT, PR and HF respectively. In this table the priority weights (Ca) of the determinants namely, Competitive Market, Forefront Technology, Privilege and Hazard free are 0.0820, 0.2240, 0.2040 and 0.4890 respectively.

The Total Desirability Indices (Día) for the competitive market determinant are 0.0220, 0.2057 and 0.0904 for CBM, RM and TBM respectively. The Total Desirability Indices (Día) for the Time-Based Maintenance alternative are 0.0904, 0.0750, 0.0686 and 0.0757 for the determinants Competitive Market, Forefront Technology, Privilege and Hazard free in this order.

For example, the OWSI for TBM IS calculated as; $OWSI_i = \Sigma D_{ia}C_a$

$$OWSI_{TBM} = [(0.0820*0.0904)\ (0.2240*0.0750) + (0.2040*0.0686) + (0.4890*0.0757)]$$

$$= 0.0382.$$

Correspondingly OWSI $_{CBM}$ and OWSI $_{RM}$ are also calculated. The last column displays the normalized values of OWSI.

Table 6.11 Overall Weighted Score Index

Alternatives	CM	FT	PR	HF	OWSI	OWSI Normalized
Weights	0.0820	0.2240	0.2040	0.4890		
CBM	0.0220	0.0214	0.0233	0.0309	0.0114	0.0736
RM	0.2057	0.2020	0.2089	0.2050	0.1047	0.6788
TBM	0.0904	0.0750	0.0686	0.0757	0.0382	0.2476
					0.1543	1.0000

It is observed from Table 10 that OWSI normalized for Reactive Maintenance (0.6788) is found to be more as compared to Condition Based Maintenance (0.0736) and Time-Based Maintenance (0. 2476) and so Reactive Maintenance is the most-suited alternative for the company.

CHAPTER 7

RESULTS AND DISCUSSIONS

7.1 Introduction

Many organisations consider maintenance cost as inevitable and perform maintenance operations as a corrective function that is executed in emergency conditions only. The cost of maintenance is becoming increasingly critical with the increasing competition in the business environment. This necessitates the companies to focus more on cost reduction particularly in operations and maintenance (Zaim et al., 2012). The selection of maintenance strategy is a MCDM problem which consists of various determinants, dimensions, enablers and maintenance alternatives. The ANP model assemblies the MCDM problem in a hierarchical method and connects the determinants, criteria and sub criteria with alternatives.

7.2 Development of the ANP methodology for maintenance strategy formulation

This work utilizes data collected from expert committee including executives from various departments of the industry and professors from academic institutions through interviews and discussions and from detailed surveys of already published literature. Hence, it has been instrumental in identifying all tangible and intangible factors that affect maintenance decisions in the industry. This methodology enables maintenance personnel to compare different maintenance strategies and also to visualize the effect of strategy changes over time. This re-evaluation of company performance can also be used to make further improvements. This is also an excellent demonstration of how ANP can be used to arrive at decisions in difficult problems by understanding the problem characteristics.

The major objective of this research is to evolve the best maintenance strategy for the case organisations, which is a well proven MCDA tool, has been explored to materialize the objective. ANP necessitates the synergic output of the elicitations of experts in the relevant field. The synergic output was extracted by brainstorming with 10 senior executives from general manager to chief engineer of the case industries. At the outset, the priorities are made as per their opinion and the geometric mean of the response is finalized as the priority which is confirmed in a meeting and further validated by consistency analysis. In this regard it is possible to have a quantified output for the priority as OWSI. Instead of judgment based on rule of thumb estimate, a quantified value provides a good estimation of the result. This research acts as a valuable guide to the practicing managers to have an ideal model for future decisions. Such a result can be further used in many decision-making circumstances.

The various maintenance strategies commonly followed by the industries are preventive, condition based, reactive, corrective and autonomous maintenance. This paper describes a comparative study of maintenance strategy selection in cement industry, tyre industry and chemical industry

7.3 ANP model implementation for tyre industry

In the tyre industry the adaptable strategies are Time based preventive, Condition based, corrective and autonomous maintenance. In our study related to the tyre industry, the OWSI calculated for autonomous maintenance is found to be higher than the other three alternatives and hence chosen for implementation.

7.4 ANP model implementation for cement industry

In the cement industry the relevant methods are Condition Based Maintenance, Reactive and Time-Based Maintenance. The OWSI normalized for Condition Based Maintenance is found to be more when compared to Time-Based Maintenance and Reactive Maintenance and CBM is the most-suited alternative for the company

7.5 ANP model implementation for chemical industry

In the case of a chemical industry the possible strategies are Time based preventive, Condition based, and Reactive maintenance. The OWSI calculated for Reactive maintenance is higher than the other alternatives and is selected for implementation in the chemical industry.

7.6 CONCLUSION

From this comparative study, we conclude that the optimum maintenance strategy for one industry is different from other industries. Depending on the various determinants, dimensions, enablers and adaptable maintenance strategies, it varies from industry to industry.

The results stated in this research are based on the accumulation of replies of many officials in the industry. Therefore, the pairwise comparisons of the criteria, sub-criteria and alternatives reflect the knowledge and familiarity of the decision makers with the industry, processes, and its industrial environment. Meanwhile several issues in the pairwise comparisons are multifunctional in nature, a team of executives from several functional sections have accepted the questionnaires for comparison. The results obtained are valid only for the decision environment of the particular industry and hence these outcomes do not create everlasting dominion of one technique over another. Owing to the swift variations in the decision environments over time, this dominion may be subject to change. Furthermore, the decision atmosphere of the decision maker influences the preference of maintenance strategy.

CHAPTER 8

CONCLUSION

8.1 Introduction

The unique contribution of this paper is to have a comparative study on the best maintenance strategy. In this regard, the well proven MCDA tool named ANP has been explored. The evaluation of maintenance strategies is a multiple criteria decision-making problem having many qualitative and quantitative components. In decision problems, some factors are more important than the others. The objective of prioritising factors in the maintenance strategy selection model is to understand and analyse the role and impact of determinants, dimensions and enablers. The priority weights of the determinants are calculated using pair-wise comparisons. The major part of this study is to form a maintenance strategy selection model by considering main factors, sub factors and the relationship between these factors (Sadeghi & Manesh, 2012). The ANP method which is on the basis of these qualitative and quantitative factors is helpful to the policy makers dealing with strategy selection to define the priority of maintenance strategies (Ojha & Vrant,2018). Total desirability indices of maintenance are calculated on the basis of each of these determinants. These indices and the priority weights of the determinants are used for the calculation of OWSI of the alternatives. From these values the most suited maintenance alternative is selected for the company.

The ANP methodology speculates amazing results incorporating qualitative and quantitative aspects of the decision problem including the analysis of the decision maker in entering at the optimum feasible solution. This research work connects the various problems in the maintenance strategy decision in a unified structure and thereby helps the decision experts to prioritize the feasible alternatives. The suggested solution that includes the interdependence effects of the elements gives more useful and reasonable answer to the decision problems.

8.2 Contributions

The maintenance models and research methods followed in this study give certain valuable indications to the top management. Recognition and Analysis of the significant tangible and intangible parameters mentioned in the maintenance literature contribute a space to enhance level of maintenance in a certain situation. These models refined in this analysis depict a way to check periodically if the ongoing maintenance strategies are really giving the required outcome. ANP method is useful as an assessment tool for maintenance alternatives can be implemented in similar Multiple Criteria Decision Analysis (MCDA) situations.

OWSI provides a quantified value that aids in objectively ascertaining priority. When compared to judgment based on rule of thumb estimate, this value provides a better estimate of result. Our research aims at providing valuable guidance to the practicing managers for developing an ideal decision-making model. This finding may also be extrapolated to several other decision-making scenarios.

8.3 Implications

The ANP method is useful to the company to recognize the characteristics frequently stated in the maintenance literature. This will offer an occasion to increase the quality of maintenance in a particular environment. The approach described in this research begins by recognizing and analysing the important tangible and intangible parameters. Managers can practice these important parameters to attain a better understanding of the present maintenance approach. It also helps in identifying any shortcomings of the present maintenance strategy, if any. One can assign new responsibilities to maintenance staff in the company to achieve company-wide improvements in maintenance. Finally, the procedure stated in this study can be used by executives to re- estimate the company's situation and to suggest further improvements if required. Managers will also obtain a better idea regarding real time maintenance strategies in industries similar to the cement industry. The major contribution of this research is the successful application of the extensive ANP model for a particular industry. ANP model integrates wide-ranging variables of the plant supply chain and includes their inter dependences. The proposed ANP model in this article, not only guides the decision makers in the choice of the finest services, but also enables them to visualize the influence of numerous dimensions in arriving at the decisive solution.

8.4 Limitations

Inability to obtain large sample size due to low response rate is a limitation of this research. Data acquisition and creation of pair-wise comparison matrices are tasks that require huge effort and time. This study fails to address the strength of interdependencies between factors. Since the results are on the basis of responses from experts, it has significant dependence on the respondent's information and awareness of the firm and its processes. Since the studied issues are cross-functional, managers from various departments should have been interviewed to arrive at a conclusion. The response rate is also an important issue related to this research study as bigger sample size is essential for reliable conclusions.

8.5 Future Directions

Future research should include larger numbers and must have representation from small and medium sized firms to increase the generalist ability of the solution. The work should also include suggestions for executives higher up in the management hierarchy regarding the relevance of choosing the best maintenance strategy. Future studies should also help in identification of maintenance tasks in different strategies. Study should also help in structuring an industry database of maintenance and reliability information. One should prioritize routine outage preventive tasks to enhance reliability of the firm. This model can also be extrapolated to other industries as a part of research.

The constructive applications of ANP which is an excellent method to handle the issues related to multi-faceted factors are prolonged to the area of maintenance management. This model can be extended to other firms for research in maintenance issues expecting a fair concept about maintenance strategies. These researches help to recognize fruitful administrative factors and favourable maintenance practices that point to outstanding performance in industries.

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APPENDIX – I

FILLED IN QUESTIONNAIRE – TYRE INDUSTRY

PRIMARY LEVEL QUESTIONNAIRE																		
COMPARISON OF DETERMINANTS WITH RESPECT TO GOAL																		
	GOAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
1	Revenue						✓												Forefront Technology
2	Revenue							✓											Hazard free
3	Forefront Technology											✓							Hazard free
	REVENUE	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
4	Time Requisites											✓							Expenditure Requirements
5	Time Requisites											✓							Security Aspects
6	Time Requisites											✓							Critical Terms
7	Expenditure Requirements								✓										Security Aspects
8	Expenditure Requirements							✓											Critical Terms
9	Security Aspects									✓									Critical Terms
	Forefront Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
10	Time Requisites									✓									Expenditure Requirements
11	Time Requisites							✓											Security Aspects
12	Time Requisites														✓				Critical Terms
13	Expenditure Requirements								✓										Security Aspects
14	Expenditure Requirements							✓											Critical Terms
15	Security Aspects													✓					Critical Terms
	HAZARD	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
16	Time Requisites									✓									Expenditure Requirements
17	Time Requisites													✓					Security Aspects
18	Time Requisites												✓						Critical Terms
19	Expenditure Requirements																✓		Security Aspects
20	Expenditure Requirements							✓											Critical Terms
21	Security Aspects							✓											Critical Terms
SECONDARY LEVEL QUESTIONNAIRE																		
CHECK FOR THE INTERDEPENDENCIES AMONG ENABLERS WITH RESPECT TO DIMENSIONS																		
REVENUE																		
	TIME REQUISITES	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	

22	Production Time							✓											Interim Upkeep
23	Production Time				✓														Design Changes
24	Production Time					✓													Shutdown Period
25	Interim Upkeep							✓											Design Changes
26	Interim Upkeep							✓											Shutdown Period
27	Design Changes									✓									Shutdown Period
	Expenditure Requirements	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
28	Breakdown Loss				✓														Inventory Cost
29	Breakdown Loss								✓										Consulting Cost
30	Breakdown Loss						✓												Repair Cost
31	Inventory Cost											✓							Consulting Cost
32	Inventory Cost									✓									Repair Cost
33	Consulting Cost							✓											Repair Cost
	SECURITY ASPECTS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
34	Personal Safety						✓												Equipment Safety
35	Personal Safety								✓										Plant Guard
36	Personal Safety					✓													Ambiance Security
37	Equipment Safety									✓									Plant Guard
38	Equipment Safety						✓												Ambiance Security
39	Plant Guard							✓											Ambiance Security
	CRITICAL TERMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
40	Product Quality								✓										Management Approval
41	Product Quality						✓												Employee Recognition
42	Product Quality								✓										Modern Technology
43	Management Approval							✓											Employee Recognition
44	Management Approval									✓									Modern Technology
45	Employee Recognition									✓									Modern Technology
FOREFRONT TECHNOLOGY																			
	TIME REQUISITES	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
46	Production Time							✓											Interim Upkeep
47	Production Time							✓											Design Changes
48	Production Time							✓											Shutdown Period
49	Interim Upkeep												✓						Design Changes
50	Interim Upkeep													✓					Shutdown Period
51	Design Changes								✓										Shutdown Period
	EXPENDITURE REQUIREMENTS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
52	Breakdown Loss								✓										Inventory Cost
53	Breakdown Loss								✓										Consulting Cost
54	Breakdown Loss								✓										Repair Cost
55	Inventory Cost											✓							Consulting Cost
56	Inventory Cost												✓						Repair Cost
57	Consulting Cost										✓								Repair Cost
	SECURITY ASPECTS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	

58	Personal Safety							✓											Equipment Safety
59	Personal Safety							✓											Plant Guard
60	Personal Safety									✓									Ambiance Security
61	Equipment Safety								✓										Plant Security
62	Equipment Safety										✓								Ambiance Security
63	Plant Guard										✓								Ambiance Security
	CRITICAL TERMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
64	Product Quality											✓							Management Approval
65	Product Quality											✓							Employee Recognition
66	Product Quality											✓							Modern Technology
67	Management Approval										✓								Employee Recognition
68	Management Approval									✓									Modern Technology
69	Employee Recognition								✓										Modern Technology
										HAZARD									
	TIME REQUISITES	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
70	Production Time							✓											Interim Upkeep
71	Production Time							✓											Design Changes
72	Production Time					✓													Shutdown Period
73	Interim Upkeep							✓											Design Changes
74	Interim Upkeep								✓										Shutdown Period
75	Design Changes									✓									Shutdown Period
	EXPENDITURE REQUIREMENTS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
76	Breakdown Loss			✓															Inventory Cost
77	Breakdown Loss				✓														Consulting Cost
78	Breakdown Loss					✓													Repair Cost
79	Inventory Cost										✓								Consulting Cost
80	Inventory Cost										✓								Repair Cost
81	Consulting Cost											✓							Repair Cost
	SECURITY ASPECTS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
82	Personal Safety				✓														Equipment Safety
83	Personal Safety					✓													Plant Guard
84	Personal Safety					✓													Ambiance Security
85	Equipment Safety									✓									Plant Guard
86	Equipment Safety									✓									Ambiance Security
87	Plant Guard									✓									Ambiance Security
	CRITICAL TERMS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
88	Product Quality									✓									Management Approval
89	Product Quality											✓							Employee Recognition
90	Product Quality									✓									Modern Technology
91	Management Approval									✓									Employee Recognition
92	Management Approval									✓									Modern Technology

93	Employee Recognition										✓								Modern Technology
	CHECK FOR THE INTERDEPENDENCIES AMONG ENABLERS																		
	REVENUE																		
	TIME REQUISITES																		
	Production Time	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
94	Interim Upkeep								✓										Design Changes
95	Interim Upkeep							✓											Shutdown Period
96	Design Changes									✓									Shutdown Period
	Interim Upkeep	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
97	Production Time				✓														Design Changes
98	Production Time					✓													Shutdown Period
99	Design Changes									✓									Shutdown Period
	Design Changes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
100	Production Time						✓												Interim Upkeep
101	Production Time					✓													Shutdown Period
102	Interim Upkeep									✓									Shutdown Period
	Shutdown Period	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
103	Production Time									✓									Interim Upkeep
104	Production Time							✓											Design Changes
105	Interim Upkeep									✓									Design Changes
	EXPENDITURE REQUIREMENTS																		
	Breakdown Loss	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
106	Inventory Cost												✓						Consulting Cost
107	Inventory Cost							✓											Repair Cost
108	Consulting Cost									✓									Consulting Cost
	Inventory Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
109	Breakdown Loss						✓												Consulting Cost
110	Breakdown Loss							✓											Repair Cost
111	Consulting Cost									✓									Repair Cost
	Consulting Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
112	Breakdown Loss				✓														Inventory Cost
113	Breakdown Loss						✓												Repair Cost
114	Inventory Cost									✓									Repair Cost
	Repair Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
115	Breakdown Loss				✓														Inventory Cost
116	Breakdown Loss								✓										Consulting Cost
117	Inventory Cost											✓							Consulting Cost
	SECURITY ASPECTS																		
	Personal Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
118	Equipment Safety									✓									Plant Guard
119	Equipment Safety					✓													Ambiance Security
120	Plant Guard							✓											Ambiance Security
	Equipment Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
121	Personal Safety								✓										Plant Guard
122	Personal Safety				✓														Ambiance Security
123	Plant Guard							✓											Ambiance Security

	Plant Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
124	Personal Safety						✓												Equipment Safety
125	Personal Safety					✓													Ambiance Security
126	Equipment Safety						✓												Ambiance Security
	Ambiance Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
127	Personal Safety						✓												Equipment Safety
128	Personal Safety								✓										Plant Guard
129	Equipment Safety									✓									Plant Guard
CRITICAL TERMS																			
	Product Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
130	Management Approval							✓											Employee Recognition
131	Management Approval									✓									Modern Technology
132	Employee Recognition									✓									Modern Technology
	Management Approval	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
133	Product Quality						✓												Employee Recognition
134	Product Quality								✓										Modern Technology
135	Employee Recognition									✓									Modern Technology
	Employee Recognition	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
136	Product Quality							✓											Management Approval
137	Product Quality								✓										Modern Technology
138	Management Approval									✓									Modern Technology
	Modern Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
139	Product Quality							✓											Management Approval
140	Product Quality							✓											Employee Recognition
141	Management Approval							✓											Employee Recognition
CHECK FOR THE INTERDEPENDENCIES AMONG ENABLERS																			
FOREFRONT TECHNOLOGY																			
TIME REQUISITES																			
	Production Time	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
142	Interim Upkeep													✓					Design Changes
143	Interim Upkeep											✓							Shutdown Period
144	Design Changes								✓										Shutdown Period
	Interim Upkeep	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
145	Production Time							✓											Design Changes
146	Production Time							✓											Shutdown Period
147	Design Changes								✓										Shutdown Period
	Design Changes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
148	Production Time						✓												Interim Upkeep
149	Production Time							✓											Shutdown Period
150	Interim Upkeep										✓								Shutdown Period
	Shutdown Period	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
151	Production Time						✓												Interim Upkeep

152	Production Time								✓										Design Changes
153	Interim Upkeep											✓							Design Changes
	EXPENDITURE ASPECTS																		
	Breakdown Loss	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
154	Inventory Cost												✓						Consulting Cost
155	Inventory Cost												✓						Repair Cost
156	Consulting Cost											✓							Consulting Cost
	Inventory Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
157	Breakdown Loss							✓											Consulting Cost
158	Breakdown Loss								✓										Repair Cost
159	Consulting Cost										✓								Repair Cost
	Consulting Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
160	Breakdown Loss						✓												Inventory Cost
161	Breakdown Loss								✓										Repair Cost
162	Inventory Cost											✓							Repair Cost
	Repair Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
163	Breakdown Loss						✓												Inventory Cost
164	Breakdown Loss								✓										Consulting Cost
165	Inventory Cost											✓							Consulting Cost
	SECURITY ASPECTS																		
	Personal Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
166	Equipment Safety							✓											Plant Guard
167	Equipment Safety										✓								Ambiance Security
168	Plant Guard										✓								Ambiance Security
	Equipment Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
169	Personal Safety							✓											Plant Guard
170	Personal Safety									✓									Ambiance Security
171	Plant Guard										✓								Ambiance Security
	Plant Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
172	Personal Safety						✓												Equipment Safety
173	Personal Safety									✓									Ambiance Security
174	Equipment Safety										✓								Ambiance Security
	Ambiance Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
175	Personal Safety						✓												Equipment Safety
176	Personal Safety								✓										Plant Guard
177	Equipment Safety									✓									Plant Guard
	CRITICAL TERMS																		
	Product Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
178	Management Approval											✓							Employee Recognition
179	Management Approval									✓									Modern Technology
180	Employee Recognition								✓										Modern Technology
	Management Approval	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
181	Product Quality												✓						Employee Recognition
182	Product Quality											✓							Modern Technology

183	Employee Recognition								✓										Modern Technology
	Employee Recognition	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
184	Product Quality												✓						Management Approval
185	Product Quality											✓							Modern Technology
186	Management Approval									✓									Modern Technology
	Modern Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
187	Product Quality												✓						Management Approval
188	Product Quality										✓								Employee Recognition
189	Management Approval									✓									Employee Recognition
TERTIARY LEVEL COMPARISON																			
HAZARD FREE																			
TIME REQUISITES																			
	Production Time	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
190	Interim Upkeep							✓											Design Changes
191	Interim Upkeep							✓											Shutdown Period
192	Design Changes									✓									Shutdown Period
	Interim Upkeep	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
193	Production Time								✓										Design Changes
194	Production Time																		Shutdown Period
195	Design Changes				✓					✓									Shutdown Period
	Design Changes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
196	Production Time							✓											Interim Upkeep
197	Production Time				✓														Shutdown Period
198	Interim Upkeep								✓										Shutdown Period
	Shutdown Period	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
199	Production Time							✓											Interim Upkeep
200	Production Time							✓											Design Changes
201	Interim Upkeep									✓									Design Changes
EXPENDITURE ASPECTS																			
	Breakdown Loss	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
202	Inventory Cost											✓							Consulting Cost
203	Inventory Cost											✓							Repair Cost
204	Consulting Cost											✓							Consulting Cost
	Inventory Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
205	Breakdown Loss					✓													Consulting Cost
206	Breakdown Loss					✓													Repair Cost
207	Consulting Cost											✓							Repair Cost
	Consulting Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
208	Breakdown Loss				✓														Inventory Cost
209	Breakdown Loss					✓													Repair Cost
210	Inventory Cost											✓							Repair Cost
	Repair Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
211	Breakdown Loss					✓													Inventory Cost
212	Breakdown Loss				✓														Consulting Cost

213	Inventory Cost										✓								Consulting Cost
	SECURITY ASPECTS																		
	Personal Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
214	Equipment Safety									✓									Plant Guard
215	Equipment Safety									✓									Ambiance Security
216	Plant Guard									✓									Ambiance Security
	Equipment Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
217	Personal Safety				✓														Plant Guard
218	Personal Safety					✓													Ambiance Security
219	Plant Guard									✓									Ambiance Security
	Plant Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
220	Personal Safety				✓														Equipment Safety
221	Personal Safety					✓													Ambiance Security
222	Equipment Safety									✓									Ambiance Security
	Ambiance Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
223	Personal Safety					✓													Equipment Safety
224	Personal Safety					✓													Plant Guard
225	Equipment Safety									✓									Plant Guard
	CRITICAL TERMS																		
	Product Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
226	Management Approval									✓									Employee Recognition
227	Management Approval									✓									Modern Technology
228	Employee Recognition											✓							Modern Technology
	Management Approval	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
229	Product Quality									✓									Employee Recognition
230	Product Quality									✓									Modern Technology
231	Employee Recognition											✓							Modern Technology
	Employee Recognition	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
232	Product Quality									✓									Management Approval
233	Product Quality									✓									Modern Technology
234	Management Approval									✓									Modern Technology
	Modern Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
235	Product Quality									✓									Management Approval
236	Product Quality											✓							Employee Recognition
237	Management Approval									✓									Employee Recognition
	COMPARING ALTERNATIVES WITH RESPECT TO EACH STRATEGIES																		
	REVENUE																		
	Production Time	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
238	Time Based Maintenance											✓							Condition Based Maintenance
239	Time Based Maintenance											✓							Corrective Maintenance

240	Time Based Maintenance													✓					Autonomous Maintenance
241	Condition Based Maintenance										✓								Corrective Maintenance
242	Condition Based Maintenance												✓						Autonomous Maintenance
243	Corrective Maintenance											✓							Autonomous Maintenance
	Interim Upkeep	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
244	Time Based Maintenance											✓							Condition Based Maintenance
245	Time Based Maintenance											✓							Corrective Maintenance
246	Time Based Maintenance												✓						Autonomous Maintenance
247	Condition Based Maintenance									✓									Corrective Maintenance
248	Condition Based Maintenance											✓							Autonomous Maintenance
249	Corrective Maintenance											✓							Autonomous Maintenance
	Design Changes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
250	Time Based Maintenance									✓									Condition Based Maintenance
251	Time Based Maintenance											✓							Corrective Maintenance
252	Time Based Maintenance											✓							Autonomous Maintenance
253	Condition Based Maintenance										✓								Corrective Maintenance
254	Condition Based Maintenance										✓								Autonomous Maintenance
255	Corrective Maintenance										✓								Autonomous Maintenance
	Shutdown Period	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
256	Time Based Maintenance									✓									Condition Based Maintenance
257	Time Based Maintenance							✓											Corrective Maintenance
258	Time Based Maintenance											✓							Autonomous Maintenance
259	Condition Based Maintenance								✓										Corrective Maintenance
260	Condition Based Maintenance										✓								Autonomous Maintenance
261	Corrective Maintenance												✓						Autonomous Maintenance
	Breakdown Loss	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
262	Time Based Maintenance								✓										Condition Based Maintenance
263	Time Based Maintenance						✓												Corrective Maintenance

264	Time Based Maintenance											✓							Autonomous Maintenance
265	Condition Based Maintenance						✓												Corrective Maintenance
266	Condition Based Maintenance												✓						Autonomous Maintenance
267	Corrective Maintenance															✓			Autonomous Maintenance
	Inventory Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
268	Time Based Maintenance										✓								Condition Based Maintenance
269	Time Based Maintenance											✓							Corrective Maintenance
270	Time Based Maintenance														✓				Autonomous Maintenance
271	Condition Based Maintenance								✓										Corrective Maintenance
272	Condition Based Maintenance											✓							Autonomous Maintenance
273	Corrective Maintenance														✓				Autonomous Maintenance
	Consulting Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
274	Time Based Maintenance							✓											Condition Based Maintenance
275	Time Based Maintenance					✓													Corrective Maintenance
276	Time Based Maintenance									✓									Autonomous Maintenance
277	Condition Based Maintenance						✓												Corrective Maintenance
278	Condition Based Maintenance										✓								Autonomous Maintenance
279	Corrective Maintenance														✓				Autonomous Maintenance
	Repair Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
280	Time Based Maintenance											✓							Condition Based Maintenance
281	Time Based Maintenance											✓							Corrective Maintenance
282	Time Based Maintenance											✓							Autonomous Maintenance
283	Condition Based Maintenance									✓									Corrective Maintenance
284	Condition Based Maintenance										✓								Autonomous Maintenance
285	Corrective Maintenance											✓							Autonomous Maintenance
	Personal Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
286	Time Based Maintenance							✓											Condition Based Maintenance
287	Time Based Maintenance					✓													Corrective Maintenance

288	Time Based Maintenance									✓									Autonomous Maintenance
289	Condition Based Maintenance							✓											Corrective Maintenance
290	Condition Based Maintenance										✓								Autonomous Maintenance
291	Corrective Maintenance													✓					Autonomous Maintenance
	Equipment Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
292	Time Based Maintenance									✓									Condition Based Maintenance
293	Time Based Maintenance					✓													Corrective Maintenance
294	Time Based Maintenance										✓								Autonomous Maintenance
295	Condition Based Maintenance							✓											Corrective Maintenance
296	Condition Based Maintenance											✓							Autonomous Maintenance
297	Corrective Maintenance													✓					Autonomous Maintenance
	Plant Guard	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
298	Time Based Maintenance									✓									Condition Based Maintenance
299	Time Based Maintenance						✓												Corrective Maintenance
300	Time Based Maintenance									✓									Autonomous Maintenance
301	Condition Based Maintenance							✓											Corrective Maintenance
302	Condition Based Maintenance										✓								Autonomous Maintenance
303	Corrective Maintenance												✓						Autonomous Maintenance
	Ambiance Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
304	Time Based Maintenance							✓											Condition Based Maintenance
305	Time Based Maintenance							✓											Corrective Maintenance
306	Time Based Maintenance									✓									Autonomous Maintenance
307	Condition Based Maintenance								✓										Corrective Maintenance
308	Condition Based Maintenance											✓							Autonomous Maintenance
309	Corrective Maintenance													✓					Autonomous Maintenance
	Product Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
310	Time Based Maintenance									✓									Condition Based Maintenance
311	Time Based Maintenance						✓												Corrective Maintenance

312	Time Based Maintenance											✓							Autonomous Maintenance
313	Condition Based Maintenance								✓										Corrective Maintenance
314	Condition Based Maintenance												✓						Autonomous Maintenance
315	Corrective Maintenance													✓					Autonomous Maintenance
	Management Approval	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
316	Time Based Maintenance											✓							Condition Based Maintenance
317	Time Based Maintenance												✓						Corrective Maintenance
318	Time Based Maintenance									✓									Autonomous Maintenance
319	Condition Based Maintenance										✓								Corrective Maintenance
320	Condition Based Maintenance								✓										Autonomous Maintenance
321	Corrective Maintenance						✓												Autonomous Maintenance
	Employee Recognition	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
322	Time Based Maintenance											✓							Condition Based Maintenance
323	Time Based Maintenance											✓							Corrective Maintenance
324	Time Based Maintenance									✓									Autonomous Maintenance
325	Condition Based Maintenance										✓								Corrective Maintenance
326	Condition Based Maintenance								✓										Autonomous Maintenance
327	Corrective Maintenance					✓													Autonomous Maintenance
	Modern Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
328	Time Based Maintenance									✓									Condition Based Maintenance
329	Time Based Maintenance						✓												Corrective Maintenance
330	Time Based Maintenance										✓								Autonomous Maintenance
331	Condition Based Maintenance								✓										Corrective Maintenance
332	Condition Based Maintenance												✓						Autonomous Maintenance
333	Corrective Maintenance													✓					Autonomous Maintenance
TERTIARY LEVEL COMPARISON																			
COMPARING ALTERNATIVES WITH RESPECT TO EACH STRATEGIES																			
FOREFRONT TECHNOLOGY																			
	Production Time	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
334	Time Based Maintenance											✓							Condition Based Maintenance

335	Time Based Maintenance											✓							Corrective Maintenance
336	Time Based Maintenance												✓						Autonomous Maintenance
337	Condition Based Maintenance										✓								Corrective Maintenance
338	Condition Based Maintenance											✓							Autonomous Maintenance
339	Corrective Maintenance													✓					Autonomous Maintenance
	Interim Upkeep	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
340	Time Based Maintenance									✓									Condition Based Maintenance
341	Time Based Maintenance											✓							Corrective Maintenance
342	Time Based Maintenance										✓								Autonomous Maintenance
343	Condition Based Maintenance									✓									Corrective Maintenance
344	Condition Based Maintenance										✓								Autonomous Maintenance
345	Corrective Maintenance											✓							Autonomous Maintenance
	Design Changes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
346	Time Based Maintenance							✓											Condition Based Maintenance
347	Time Based Maintenance							✓											Corrective Maintenance
348	Time Based Maintenance									✓									Autonomous Maintenance
349	Condition Based Maintenance								✓										Corrective Maintenance
350	Condition Based Maintenance										✓								Autonomous Maintenance
351	Corrective Maintenance												✓						Autonomous Maintenance
	Shutdown Period	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
352	Time Based Maintenance							✓											Condition Based Maintenance
353	Time Based Maintenance						✓												Corrective Maintenance
354	Time Based Maintenance										✓								Autonomous Maintenance
355	Condition Based Maintenance							✓											Corrective Maintenance
356	Condition Based Maintenance											✓							Autonomous Maintenance
357	Corrective Maintenance													✓					Autonomous Maintenance
	Breakdown Loss	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
358	Time Based Maintenance									✓									Condition Based Maintenance

359	Time Based Maintenance					✓													Corrective Maintenance
360	Time Based Maintenance										✓								Autonomous Maintenance
361	Condition Based Maintenance								✓										Corrective Maintenance
362	Condition Based Maintenance										✓								Autonomous Maintenance
363	Corrective Maintenance														✓				Autonomous Maintenance
	Inventory Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
364	Time Based Maintenance										✓								Condition Based Maintenance
365	Time Based Maintenance												✓						Corrective Maintenance
366	Time Based Maintenance												✓						Autonomous Maintenance
367	Condition Based Maintenance										✓								Corrective Maintenance
368	Condition Based Maintenance											✓							Autonomous Maintenance
369	Corrective Maintenance											✓							Autonomous Maintenance
	Consulting Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
370	Time Based Maintenance							✓											Condition Based Maintenance
371	Time Based Maintenance						✓												Corrective Maintenance
372	Time Based Maintenance									✓									Autonomous Maintenance
373	Condition Based Maintenance							✓											Corrective Maintenance
374	Condition Based Maintenance										✓								Autonomous Maintenance
375	Corrective Maintenance													✓					Autonomous Maintenance
	Repair Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
376	Time Based Maintenance											✓							Condition Based Maintenance
377	Time Based Maintenance												✓						Corrective Maintenance
378	Time Based Maintenance										✓								Autonomous Maintenance
379	Condition Based Maintenance											✓							Corrective Maintenance
380	Condition Based Maintenance										✓								Autonomous Maintenance
381	Corrective Maintenance										✓								Autonomous Maintenance
	Personal Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
382	Time Based Maintenance							✓											Condition Based Maintenance

383	Time Based Maintenance						✓												Corrective Maintenance
384	Time Based Maintenance									✓									Autonomous Maintenance
385	Condition Based Maintenance							✓											Corrective Maintenance
386	Condition Based Maintenance										✓								Autonomous Maintenance
387	Corrective Maintenance												✓						Autonomous Maintenance
	Equipment Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
388	Time Based Maintenance									✓									Condition Based Maintenance
389	Time Based Maintenance								✓										Corrective Maintenance
390	Time Based Maintenance									✓									Autonomous Maintenance
391	Condition Based Maintenance								✓										Corrective Maintenance
392	Condition Based Maintenance										✓								Autonomous Maintenance
393	Corrective Maintenance												✓						Autonomous Maintenance
	Plant Guard	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
394	Time Based Maintenance							✓											Condition Based Maintenance
395	Time Based Maintenance							✓											Corrective Maintenance
396	Time Based Maintenance										✓								Autonomous Maintenance
397	Condition Based Maintenance								✓										Corrective Maintenance
398	Condition Based Maintenance											✓							Autonomous Maintenance
399	Corrective Maintenance													✓					Autonomous Maintenance
	Ambiance Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
400	Time Based Maintenance									✓									Condition Based Maintenance
401	Time Based Maintenance							✓											Corrective Maintenance
402	Time Based Maintenance									✓									Autonomous Maintenance
403	Condition Based Maintenance									✓									Corrective Maintenance
404	Condition Based Maintenance										✓								Autonomous Maintenance
405	Corrective Maintenance											✓							Autonomous Maintenance
	Product Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
406	Time Based Maintenance								✓										Condition Based Maintenance

407	Time Based Maintenance							✓											Corrective Maintenance
408	Time Based Maintenance											✓							Autonomous Maintenance
409	Condition Based Maintenance								✓										Corrective Maintenance
410	Condition Based Maintenance											✓							Autonomous Maintenance
411	Corrective Maintenance													✓					Autonomous Maintenance
	Management Approval	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
412	Time Based Maintenance										✓								Condition Based Maintenance
413	Time Based Maintenance						✓												Corrective Maintenance
414	Time Based Maintenance											✓							Autonomous Maintenance
415	Condition Based Maintenance						✓												Corrective Maintenance
416	Condition Based Maintenance												✓						Autonomous Maintenance
417	Corrective Maintenance													✓					Autonomous Maintenance
	Employee Recognition	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
418	Time Based Maintenance											✓							Condition Based Maintenance
419	Time Based Maintenance											✓							Corrective Maintenance
420	Time Based Maintenance						✓												Autonomous Maintenance
421	Condition Based Maintenance										✓								Corrective Maintenance
422	Condition Based Maintenance					✓													Autonomous Maintenance
423	Corrective Maintenance				✓														Autonomous Maintenance
	Modern Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
424	Time Based Maintenance									✓									Condition Based Maintenance
425	Time Based Maintenance						✓												Corrective Maintenance
426	Time Based Maintenance												✓						Autonomous Maintenance
427	Condition Based Maintenance								✓										Corrective Maintenance
428	Condition Based Maintenance											✓							Autonomous Maintenance
429	Corrective Maintenance														✓				Autonomous Maintenance
COMPARING ALTERNATIVES WITH RESPECT TO EACH STRATEGIES																			
HAZARD FREE																			
	Production Time	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	

430	Time Based Maintenance											✓							Condition Based Maintenance
431	Time Based Maintenance											✓							Corrective Maintenance
432	Time Based Maintenance												✓						Autonomous Maintenance
433	Condition Based Maintenance									✓									Corrective Maintenance
434	Condition Based Maintenance											✓							Autonomous Maintenance
435	Corrective Maintenance										✓								Autonomous Maintenance
	Interim Upkeep	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
436	Time Based Maintenance									✓									Condition Based Maintenance
437	Time Based Maintenance											✓							Corrective Maintenance
438	Time Based Maintenance											✓							Autonomous Maintenance
439	Condition Based Maintenance									✓									Corrective Maintenance
440	Condition Based Maintenance										✓								Autonomous Maintenance
441	Corrective Maintenance										✓								Autonomous Maintenance
	Design Changes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
442	Time Based Maintenance										✓								Condition Based Maintenance
443	Time Based Maintenance								✓										Corrective Maintenance
444	Time Based Maintenance													✓					Autonomous Maintenance
445	Condition Based Maintenance							✓											Corrective Maintenance
446	Condition Based Maintenance											✓							Autonomous Maintenance
447	Corrective Maintenance													✓					Autonomous Maintenance
	Shutdown Period	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
448	Time Based Maintenance							✓											Condition Based Maintenance
449	Time Based Maintenance						✓												Corrective Maintenance
450	Time Based Maintenance							✓											Autonomous Maintenance
451	Condition Based Maintenance								✓										Corrective Maintenance
452	Condition Based Maintenance							✓											Autonomous Maintenance
453	Corrective Maintenance										✓								Autonomous Maintenance
	Breakdown Loss	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	

454	Time Based Maintenance											✓							Condition Based Maintenance
455	Time Based Maintenance											✓							Corrective Maintenance
456	Time Based Maintenance												✓						Autonomous Maintenance
457	Condition Based Maintenance										✓								Corrective Maintenance
458	Condition Based Maintenance											✓							Autonomous Maintenance
459	Corrective Maintenance												✓						Autonomous Maintenance
	Inventory Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
460	Time Based Maintenance										✓								Condition Based Maintenance
461	Time Based Maintenance										✓								Corrective Maintenance
462	Time Based Maintenance													✓					Autonomous Maintenance
463	Condition Based Maintenance								✓										Corrective Maintenance
464	Condition Based Maintenance												✓						Autonomous Maintenance
465	Corrective Maintenance										✓								Autonomous Maintenance
	Consulting Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
466	Time Based Maintenance								✓										Condition Based Maintenance
467	Time Based Maintenance					✓													Corrective Maintenance
468	Time Based Maintenance										✓								Autonomous Maintenance
469	Condition Based Maintenance							✓											Corrective Maintenance
470	Condition Based Maintenance											✓							Autonomous Maintenance
471	Corrective Maintenance															✓			Autonomous Maintenance
	Repair Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
472	Time Based Maintenance										✓								Condition Based Maintenance
473	Time Based Maintenance												✓						Corrective Maintenance
474	Time Based Maintenance										✓								Autonomous Maintenance
475	Condition Based Maintenance										✓								Corrective Maintenance
476	Condition Based Maintenance									✓									Autonomous Maintenance
477	Corrective Maintenance							✓											Autonomous Maintenance
	Personal Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	

478	Time Based Maintenance							✓											Condition Based Maintenance
479	Time Based Maintenance						✓												Corrective Maintenance
480	Time Based Maintenance								✓										Autonomous Maintenance
481	Condition Based Maintenance							✓											Corrective Maintenance
482	Condition Based Maintenance												✓						Autonomous Maintenance
483	Corrective Maintenance										✓								Autonomous Maintenance
	Equipment Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
484	Time Based Maintenance							✓											Condition Based Maintenance
485	Time Based Maintenance					✓													Corrective Maintenance
486	Time Based Maintenance										✓								Autonomous Maintenance
487	Condition Based Maintenance								✓										Corrective Maintenance
488	Condition Based Maintenance											✓							Autonomous Maintenance
489	Corrective Maintenance													✓					Autonomous Maintenance
	Plant Guard	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
490	Time Based Maintenance							✓											Condition Based Maintenance
491	Time Based Maintenance						✓												Corrective Maintenance
492	Time Based Maintenance									✓									Autonomous Maintenance
493	Condition Based Maintenance								✓										Corrective Maintenance
494	Condition Based Maintenance										✓								Autonomous Maintenance
495	Corrective Maintenance													✓					Autonomous Maintenance
	Ambiance Security	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
496	Time Based Maintenance									✓									Condition Based Maintenance
497	Time Based Maintenance								✓										Corrective Maintenance
498	Time Based Maintenance									✓									Autonomous Maintenance
499	Condition Based Maintenance								✓										Corrective Maintenance
500	Condition Based Maintenance									✓									Autonomous Maintenance
501	Corrective Maintenance											✓							Autonomous Maintenance
	Product Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	

502	Time Based Maintenance							✓											Condition Based Maintenance
503	Time Based Maintenance						✓												Corrective Maintenance
504	Time Based Maintenance									✓									Autonomous Maintenance
505	Condition Based Maintenance							✓											Corrective Maintenance
506	Condition Based Maintenance										✓								Autonomous Maintenance
507	Corrective Maintenance												✓						Autonomous Maintenance
	Management Approval	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
508	Time Based Maintenance										✓								
509	Time Based Maintenance										✓								Corrective Maintenance
510	Time Based Maintenance											✓							Autonomous Maintenance
511	Condition Based Maintenance									✓									Corrective Maintenance
512	Condition Based Maintenance											✓							Autonomous Maintenance
513	Corrective Maintenance										✓								Autonomous Maintenance
	Employee Recognition	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
514	Time Based Maintenance											✓							Condition Based Maintenance
515	Time Based Maintenance											✓							Corrective Maintenance
516	Time Based Maintenance							✓											Autonomous Maintenance
517	Condition Based Maintenance										✓								Corrective Maintenance
518	Condition Based Maintenance								✓										Autonomous Maintenance
519	Corrective Maintenance						✓												Autonomous Maintenance
	Modern Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
520	Time Based Maintenance										✓								Condition Based Maintenance
521	Time Based Maintenance							✓											Corrective Maintenance
522	Time Based Maintenance											✓							Autonomous Maintenance
523	Condition Based Maintenance							✓											Corrective Maintenance
524	Condition Based Maintenance										✓								Autonomous Maintenance
525	Corrective Maintenance													✓					Autonomous Maintenance

LIST OF PUBLICATIONS

1. Mary C. Kurian, Shalij P. R., Pramod V. R., (2019), Maintenance strategy selection in a cement industry using analytic network process, Journal of quality in maintenance engineering, ISSN:1355-2511, Publication date - 13 November 2019, *Emerald insight, SCOPUS Indexed, ESCI Indexed*

2. Mary C. Kurian, Shalij P. R., Pramod V. R., C.P. Sunilkumar (2020) Maintenance strategy decision applying Analytic Network Process in industries: a comparative study, International Journal of Industrial and systems Engineering, *Inderscience publishers, Submission ID-IJISE-24170, Submission date-12/4/2019. Status-Accepted, Author to type setter - Proof approved. SCOPUS Indexed.*