# Selection of Suitable Maintenance Strategy for Agri-chemical / Fertilizer Production Plant using Analytic Hierarchy Process (AHP)


**By**

**Taha Razzaq**

Registration No: 00320175

Thesis Supervisor: Dr. Yasir Ahmad

Department of Engineering Management

College of Electrical and Mechanical Engineering (CEME)

National University of Sciences and Technology (NUST)

Islamabad, Pakistan


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# THESIS ACCEPTANCE CERTIFICATE

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Signature: ______________________

Name of Supervisor: Dr. Yasir Ahmad

Dated: 29 Aug 2023

Signature: ______________________

Name of HOD: Dr. Yasir Ahmad

Dated: 29 Aug 2023

Signature: ______________________

Name of Dean: Dr. Nasir Rashid

Dated: 29 AUG 2023

# Dedication

To my family, friends, and cousin with whom I share my joys and sorrows.

# Acknowledgements

I humbly offer my profound gratitude to the Almighty Allah, for it is to Him that all praises and thanks are due.

I am genuinely and deeply appreciative of my family, and I wish to extend my heartfelt gratitude to all those who played a pivotal role in aiding me to achieve this significant milestone. My special appreciation goes to my esteemed supervisor, the esteemed members of the research committee, and the invaluable staff of my institution, whose unwavering support and guidance have been instrumental in my success.

***Engr. Taha Razzaq***

# Abstract

Fertilizer Industry is one of the major contributing factors to the growth of sustainable agriculture in Pakistan. Fertilizer Production plants in Pakistan make up 3.9 % of the Large-Scale Manufacturing (LSMs) firms. Maintenance excellence and strategy in the production plants lowers the production cost, minimize equipment downtime, improve quality, increase productivity and result in achieving organizational goals and objectives. The study aims to identify the most important maintenance criteria and the most suitable maintenance strategy for the fertilizer production plan located in Pakistan. The research initiative/endeavor adopts a case study approach in a production plant located in Pakistan to obtain the opinions of the expert on maintenance strategy selection in Agri-Chemical / Fertilizer production plants. Analytic Hierarchy Process (AHP) used in the study is the most studied Multi-Criteria Decision Making (MCDM) technique for maintenance strategy selection in a variety of industries. Criteria for AHP hierarchy were identified through literature and expert consultation. The study concluded that the maintenance strategy developed from literature and expert consultation that consists a mix of Preventive Maintenance, Corrective Maintenance, Reliability Centered Maintenance (RCM) and other types may be the most suitable maintenance strategy for the fertilizer production plant with its own unique inherent factors. The study may be evaluated using Analytic Network Process (ANP) and other hybrid MCDM techniques, furthermore maintenance performance indicators can be developed and analyzed.

***Keywords:*** Maintenance Management; Fertilizers; Production Plants; Reliability Centered Maintenance (RCM); Maintenance Strategy Selection; Analytic Hierarchy Process (AHP); SuperDecisions®.

# Table of Contents

# List of Tables

# List of Figures

# List of Abbreviations

MS

Maintenance Strategy

MSs

Maintenance Strategies

MCDM

Multi-Criteria Decision Making

AHP

Analytic Hierarchy Process

ANP

Analytic Network Process

PM

Preventive Maintenance

CBM

Condition Based Maintenance

ECM

Energy Centered Maintenance

SD

SuperDecisions® (SD)

RTF

Run-To-Failure

RCM

Reliability Centered Maintenance

DCM

Design Centered Maintenance

CI

Consistency Index

LSM

Large Scale Manufacturing

CM

Corrective Maintenance

# CHAPTER 1. INTRODUCTION

## 1.1 Background

In today's fast-paced industrial world, maintenance strategies play a crucial role in maintaining the efficiency and reliability of machinery and equipment (Bashiri et al., 2011). Maintenance strategies are a critical aspect of ensuring the smooth operation of global industries. The development of effective maintenance strategies is essential to the success of any global industry, regardless of its size or sector. Implementing a robust maintenance strategy is essential for minimizing downtime, reducing costs, and ensuring that equipment and machinery function at peak performance (Karsak & Tolga, 2001). Global industries continue to grow and evolve, maintenance strategies must also adapt to meet changing needs and technological advancements. Effective maintenance strategies are crucial for ensuring the safety of workers and the general public in global industries (Azizi & Fathi, 2014). By implementing a proactive maintenance strategy, global industries can reduce the likelihood of unexpected equipment failures and minimize the impact of maintenance downtime. Maintenance strategies in global industries can range from reactive and preventative maintenance to predictive and condition-based maintenance, each with its own unique benefits and drawbacks (Gackowiec, 2019). As global industries become increasingly reliant on technology, maintenance strategies must also incorporate digital solutions such as machine learning, artificial intelligence, and the Internet of Things (IoT). Ultimately, the development and implementation of effective maintenance strategies are critical to the long-term success and sustainability of global industries in today's competitive marketplace (Werbińska-Wojciechowska & Winiarska, 2023).

### 1.1.1 World Fertilizer Industry

World fertilizer production has increased by over 60 times in the course of the 20th century. In the last 35 years alone, it has increased by 4 times to reach 136 million tons of nutrients. This corresponds to about 325 million tons of finished products. Such expansion would have been impossible without a stream of technological progress (Park, 2001). Large modern fertilizer complexes require sophisticated management and a fundamental understanding of the unit processes involved. Process efficiency is a function of the operational stability of the plant (Campbell et al., 2015). With increasing capital intensity, the cost of downtime becomes critically important. Most new investment will continue to be in Africa, Asia, and Latin America where the capital investment per ton of product is often higher than in Europe and North America. It is therefore all the more important for these regions to develop an adequate body of highly knowledgeable, experienced engineers and skilled labor (*IFA*, 1998). Similarly, maintenance management practices must be upgraded to ensure long term stability in the maintenance function which in turn increases the uptime of the machinery for the manufacturing units in small, medium, and large-scale manufacturing.

### 1.1.2 Fertilizer Industry in Pakistan

Fertilizers have been on the rise since the Green Revolution in Pakistan (1960s), along with modern crop varieties and irrigation water, they make up the major inputs towards the productivity growth of the agricultural sector (PACRA, 2023). Fertilizer sector has a substantial impact on economy of the country as it affects the national food security. Similarly, there is opportunity to strengthen the fertilizer industry in Pakistan and, in turn, strengthen the prospects for sustainable agricultural production with continued productivity growth (Ali et al., 2015). In the past decades, majority studies on fertilizers have focused on operations and management on farm level with an agronomic perspective (Ayub et al., 2002; Ayub, 1975; Shafi et al., 2007), thus neglecting fertilizer production, technology adaptation and manufacturing related maintenance management practices altogether. Fertilizer production is part of the Large-Scale Manufacturing (LSM) sector and it contributes 3.9% to LSM and 0.5% to the overall Gross Domestic Product (GDP) of the country. Statistics by PACRA (2023) claim that in the year 2022, the fertilizers' production was recorded at 9.1 million metric tons. Disparity in annual fertilizer production and consumption for Pakistan has historically averaged at 30 % more consumption than production (OECD, 2022). The disparity in consumption versus production, coupled with neglect in the manufacturing management of the fertilizers indicates a lack of interest in productivity enhancement.

### 1.1.3 Maintenance Strategies in Fertilizer Industry

In the current competitive environment, managers of manufacturing and service organizations try to make their organizations competitive by providing timely delivery of high-quality products (Park, 2001). Maintenance, as a system, plays a key role in reducing cost, minimizing equipment downtime, improving quality, increasing productivity, and providing reliable equipment and as a result achieving organizational goals and objectives (Bashiri et al., 2011). Similarly, Fertilizer production plants have an increased activity in maintenance functions, as they are fast paced and timelines are pre-defined. This increases the necessity to increase uptime of machinery and equipment (Kumar & Maiti, 2012). For effective maintenance system, a potent strategy is to be formulated, implemented, and executed as planned while at the same time incorporating the changes in the equipment and processes, also, facilitating the feedback process to improve the uptime in the machinery and equipment (Seiti et al., 2019). Selection of an appropriate maintenance strategy for each piece of equipment or system is a very complex task due to the difficulties concerning data collection, diversity of components and their functions, and large number of criteria that need to be taken into account and their subjectivity (Seiti et al., 2017). The decision-maker (i.e., system owner or service agent) must decide on the most appropriate maintenance strategy for equipment among a set of possible alternatives such as failure-based, time-based, risk-based, condition-based, total productive maintenance (Jawwad & Saleem, 2019). Moreover, many different goals or comparing criteria must be taken into consideration in making decision, including the investment required for implementation, safety aspects, environmental issues, failure costs, reliability of the strategy, and manpower utilization of the facility (Kumar & Maiti, 2012). Some of these goals taken as criteria cannot be expressed in monetary terms and thus, it is rather difficult to quantify them (Triantaphyllou et al., 1995). Therefore, the maintenance strategy selection (MSS) is considered as a complex multiple criteria decision making (MCDM) problem. The Multi-Criteria Decision Making (MCDM) approach consists of a finite set of alternatives (e.g., maintenance strategies) among which a decision-maker has to select or rank, and a finite set of criteria (economic, social, environmental, etc.) weighted according to their importance (Dorri et al., 2014). Each alternative is evaluated with respect to each criterion using a suitable measure. Then, the evaluation ratings are aggregated to obtain a global evaluation for each alternative. Finally, the alternatives are prioritized from the best (optimal) to the worst (Shafiee, 2015a). Kumar & Pandey (1993) reported that the important one of the major causes of lower availability rates is the lack of robust MSs, and that as much as 10% improvement in machine availability may be realized by adopting efficient MSs. Therefore improving the quality of maintenance strategy, the machine availability for important manufacturing functions can be improved. Machinery uptime will affect the overall manufacturing process and the facility would be able to improve its subsequent manufacturing functions. With an increase in the complexities of real industrial systems, maintenance decision making has become a challenge for maintenance managers. Authors proposed a novel integrated MCDM framework for the selection of an optimal maintenance strategy for the urea fertilizer industry. The selected maintenance strategy would be useful in increasing system availability and reducing the maintenance budget of the considered unit (Panchal et al., 2017a). Similarly, in many process industries the MCDM techniques have found their employability to select maintenance strategies for the diversely complex equipment systems. The systems can vary in their respective builds and the level of technology used to attain results for different tasks. Methodologies for the selection of maintenance strategies for fertilizer plants rely on historical data for machine failure, downtime, and experts' comments. By using the historically available and much reliable data, the MCDM techniques such as AHP can develop the best possible maintenance strategy but whence the system is newly established or is in the design process the much important and needed data is not available.

### 1.1.4 Maintenance Strategies for Fertilizer Industry in Pakistan

The scope for the maintenance strategy application in Pakistan is broad. Progress in the development of organized maintenance activity is required as the maintenance function, whence applied effectively, helps reduce the cost and machinery downtime and successfully increases the manufacturing efficiency which in turn can reduce the energy and efforts spent on the machinery maintenance. Similarly, the fertilizer industry in Pakistan is in much need of the development of maintenance strategies as the LSMs and SMEs in Pakistan have to bear the pressure of increasing demands with the increase in the mechanization of the farms and the increase in the nutrient decline in the soil. Furthermore, the fertilizer industry in Pakistan benefit from the maintenance strategies, that are effective and practical, in terms of reduced cost of equipment upkeep, spare parts and inventory, improved percentage efficiency of the equipment. Ultimately, these factors aligned with other contributors enhance the overall facility's productivity and if applied and extended towards national initiatives can render dramatically impressive results.

## 1.2 Purpose of the Study

Fertilizer industry in Pakistan is in its development state and since the country is just 75 years old, with much economic and political toil fertilizer industry is still in one of the stable industries as can be effectively seen on the yearly reports and daily analysis (Pakistan Stock Exchange (PSX), 2022). Pakistan is an agrarian country and fertilizers are an essential input to obtain substantial yields of crops. From the research perspective, fertilizer production plants have been neglected in the literature in regards to their maintenance management practices. Limited research on newly established fertilizer production facilities has been conducted in the world and no work has ever been done in Pakistan. This presents a gap in the literature for Pakistan and this requires a much deeper look into the maintenance practices of the fertilizer production facilities in Pakistan. This leaves an avenue to explore the possibilities in this area with academia, research, and industry.

## 1.3 Research Rationale

For newly established fertilizer production plants, lack of historical data renders the maintenance managers, unable to make informed decisions about the maintenance of the machinery. This may increase the equipment downtime, incur repair costs, results in maintenance rework and reduce production capacity of the whole fertilizer production plant. To overcome this challenge an appropriate multi-criteria decision-making technique may be used which may rely on the experience of the experts and builds on their prior knowledge of machinery and maintenance activities. This would result in a selection of a suitable maintenance strategy for the fertilizer plant that could depend on the inherent factors of the facility and would increase the uptime of the machinery, reduce repair costs, deter accidental breakdowns and improve the productivity of the fertilizer plant. According to Mardani et al. (2015) literature on MCDM techniques during the years 2000 to 2014, emphasizing on AHP as the dominant methodology can be empirically justified by the literature review conducted.

It can be safely concurred from the number of studies carried out by the researchers that an overwhelming majority of the researchers have successfully demonstrated the use of AHP among the popular MCDM techniques in a wide scope and numerous and diverse industrial settings for the selection of suitable maintenance strategy with industry specific expert judgements and data retrieval.

## 1.4 Problem Statement

The agricultural sector in Pakistan predominantly focuses on the cultivation of major crops such as maize, wheat, rice, cotton, and sugarcane. However, the successful cultivation of these crops necessitates the use of synthetic fertilizers due to Pakistan's unfavorable conditions, characterized by low soil organic matter and arid climate (Wakeel et al., 2022). The fertilizer industry depends upon the uptime of the machinery that it uses in the production of agrochemicals which are to be delivered to the consumers. Since the market in Pakistan for the agrochemicals is a seasonal one, so there lies a short window for the supply to meet the demand which in turn puts much pressure on the manufacturing plants. The fertilizer production plants are in dire need to maximize their machinery uptime in order to meet the demands and they need to have a suitable maintenance strategy in place to maximize their outputs. The maintenance strategy should be vibrant and flexible enough to incorporate the inherent factors of the organization. Similarly, fertilizer production plants are an integral part of the manufacturing sector in Pakistan. The ability of the production plants relies on the uptime of its machinery which in turn is important to maximize production. Maintenance strategies adopted for the production plant depend upon the historical machine failure data and can have a huge impact on the performance of the machinery. So, putting forward and adopting efficient and effective maintenance policies and strategies is the cornerstone for improved plant reliability and performance levels.

"For a new fertilizer production plant, there is an absence of historical data and the maintenance personnel lack the insights to develop an effective maintenance strategy". This challenge may be adequately addressed by adopting a decision-making technique which can incorporate the inherent factors present at the production facility by relying on experts and their experience to develop an effective maintenance strategy. This study aims to suggest a mechanism to select a suitable maintenance strategy for a new fertilizer production plant by using a suitable decision-making technique and to validate the practicality of the approach through a decision-making software.

## 1.5 Thesis Structure

The thesis is structured in the manner that each chapter coherently presents the existing knowledge and body of literature in an organized manner to elaborate the obvious gap in the literature. The thesis has six (6) chapters. The first chapter is the abstract chapter consisting of limited number of words to elaborate the whole study and work done in the research with results and analysis and future considerations. The next chapter is the introduction chapter elaborating the fertilizer industry of the world and then the condition of the fertilizer industry in Pakistan. Further, the chapter describes the importance of maintenance function and strategy for the improvement in fertilizer plant operations and machinery uptime for enhanced productivity.

Moreover, the introduction chapter explains the purpose of the study and the industrial setting in which the study was conducted to show the perspective from the researcher's point of view. Next, is the problem statement and research rationale of the study undertaken by the researcher. After the introduction chapter, there comes the literature review. Literature Review consists of the existing body of knowledge in extensive detail thus making the case for the execution of the study for the present gap in literature. The methodology chapter discusses, in relative detail, the Analytic Hierarchy Process (AHP) and its practicality for the use in this study to select the best and suitable maintenance strategy for the new fertilizer plant established in Pakistan with no historical data on machine failure. Results and Analysis chapter shows the outcomes of the research and the questionnaires that brought forward those outcomes.

Also, the chapter discusses in detail the analysis made by the researcher after the results to point out the novelty achieved by the result in the form of consideration of Energy-Centered Maintenance type. Finally, the chapter compares the calculations and results obtained by the use of numerical analysis in MS Excel spreadsheets with results obtained by the decision-making software SuperDecisions (SD). Finally, the last chapter of thesis forming the body, is conclusions and future research. The chapter provides a conclusion derived from the whole research and the following thesis report. At the end, the future avenues especially concerning Pakistan for research are highlighted regarding fertilizer industry, employing Analytic Hierarchy Process (AHP) and maintenance systems, decision making processes and Sustainable Development Goals (SDGs) set by the United Nations (UN).

# CHAPTER 2. LITERATURE REVIEW

## 2.1 Maintenance Management

Maintenance Management present an integrated and dynamic perspective, building on multiple activities, involving a number of domains and sub-domains resulting in a comprehensive system (Kelly, 2006).

Mobley et al. (2002) present a rather fantastic and multi-dimensional definition for maintenance. They present Maintenance as science, art, and philosophy at the same time rather than any singular form. Maintenance is a science as it employs physical laws of nature and physics allied with other contemporary sciences for its execution. It is governed by the same laws that are applicable to all other physical activities around and simultaneously affected by the immediate environment. Maintenance is an art because every scenario is different and the approach to these events by the humans involved are also different in respect to each other. Irrespective of the training and the existential factors some are better at it other than others (Harker, 1989). These qualities make maintenance an art form and provide a canvas for every artist. Maintenance is a philosophy because there is an element of decision making to it that offers a level of activeness and effectiveness spanning a wide range of physical and meta-physical variables with a changing level of fitness towards the organizational culture and values.

## 2.2 Integrated Maintenance System

"Maintenance is a dynamic activity comprised of a great number of variables interacting with one another, often in a random pattern. Industries and businesses that best manage the maintenance effort are cognizant of this dynamic randomness and develop structured maintenance systems to cope with it" (Niebel, 2014).

Different authors present different definitions based on literature and personal beliefs as well as personal experiences but all of them seem to point toward a single direction of a set of activities organized to manage man, material, and resources (both tangible and non-tangible) for the equipment/system to perform well.

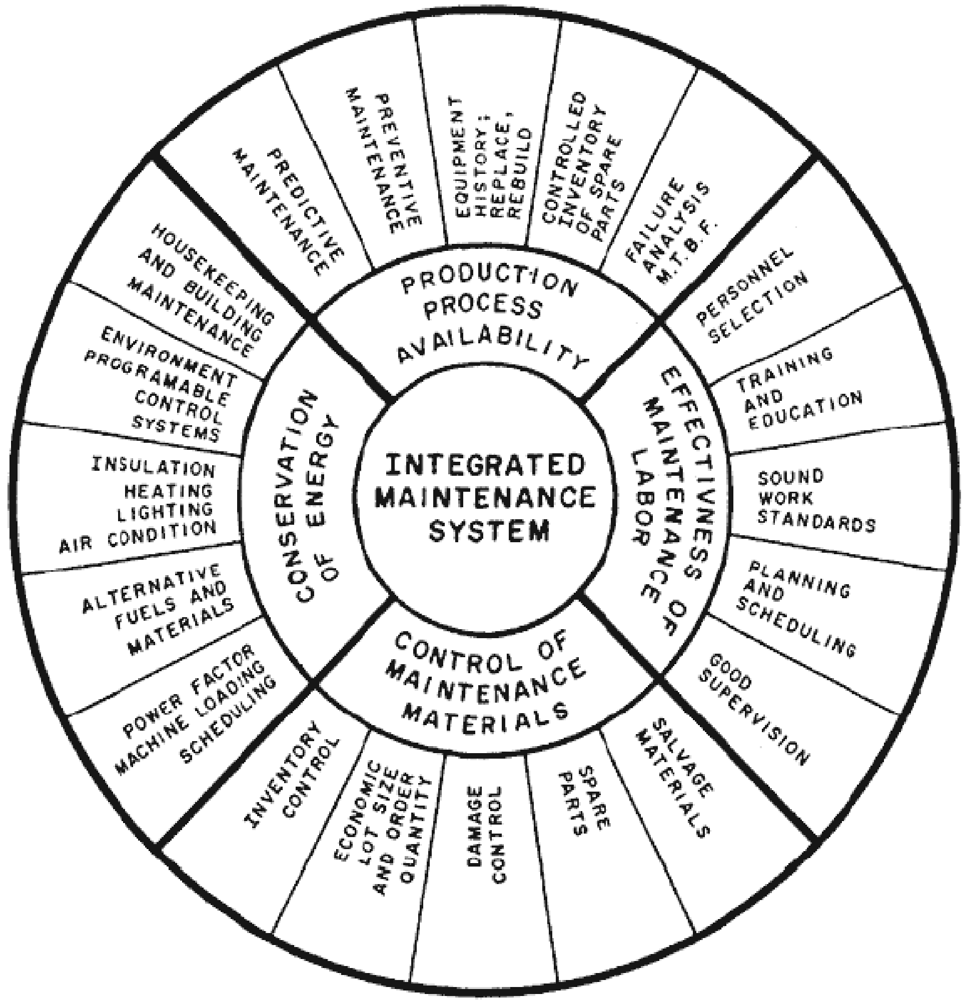



**Figure 2.1 Integrated Maintenance System (Niebel, 2014)**

## 2.3 Functions in Maintenance Management

Maintenance Management generally has a set of functions that enables the organization to help establish a firm basis for the overall upkeep of the equipment and help the production process in parallel. These functions have linked effects and work in consistent co-ordination to one and another to achieve desired results for the Maintenance system to perform well under the seen and unforeseen circumstances.

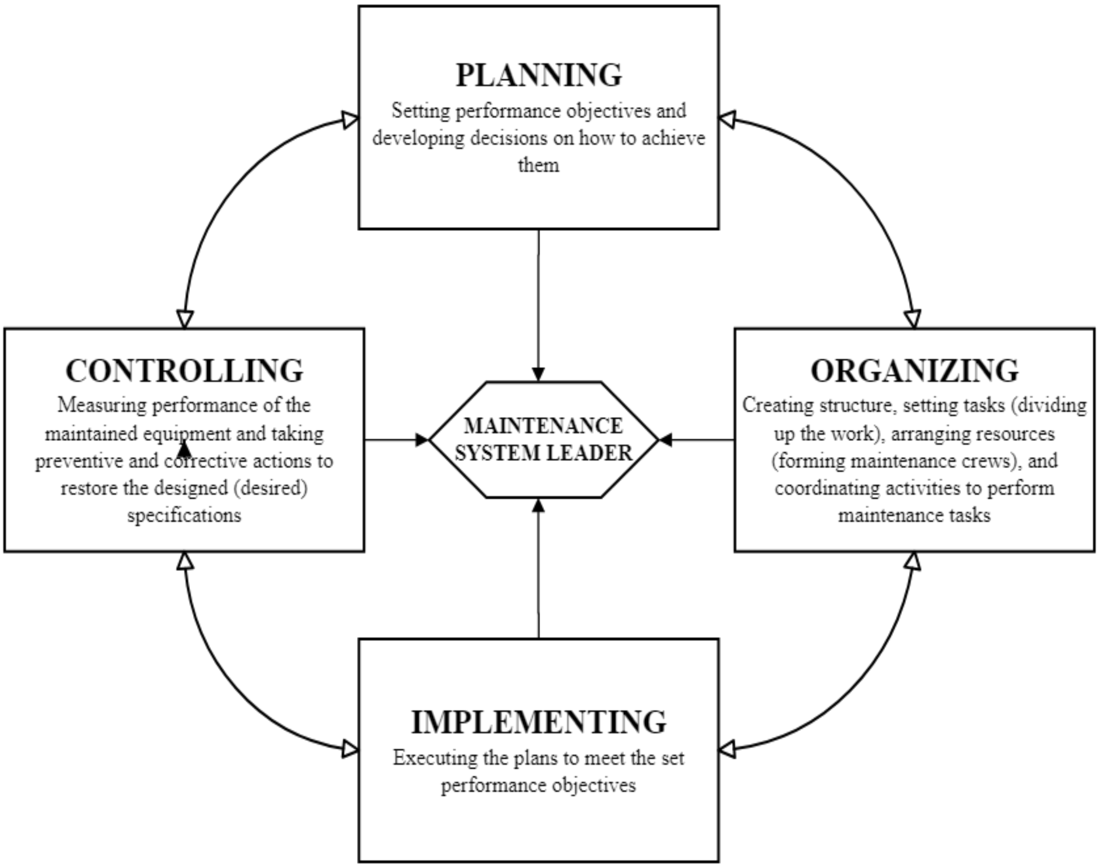



**Figure 2.2 Maintenance Management Functions (Ben-Daya et al., 2009)**

## 2.3.1 Planning

### 2.3.1.1 Capacity Planning

Maintenance Capacity planning incorporates the much-needed overall resources which include Human Resource, equipment, tools, and skillsets required to perform tasks. These then formulate the number and skills of the craftsmen such as engineers, foremen, supervisors, and technicians. Moreover, from historical data much can be assessed after analysis. Multiple diverse techniques can be used for capacity planning in line with the organizational structure of the organization and the centralized or decentralized form of maintenance planning. This in turn helps balance the maintenance workload over specified periods of time.

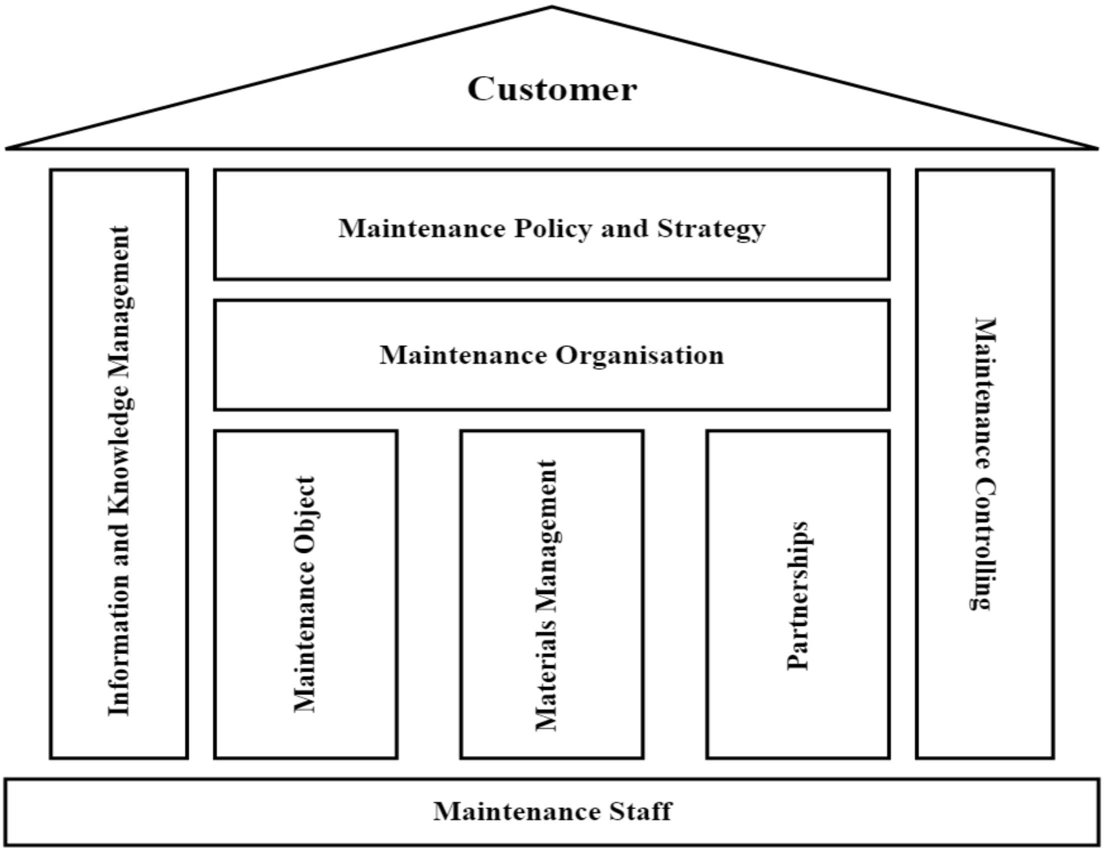



**Figure 2.3 House of Maintenance (Schuh et al., 2010)**

In order to plan for capacity in an organization House of Maintenance can be used which incorporates the customer and internal maintenance staff of the organization as the top and base respectively. This framework coordinates and encapsulates the existing knowledge and information of the organization with the present materials, objects, and control structures of the organization to formulate a Maintenance strategy that builds up partnerships in the corresponding departments of the organization.

This framework solves the problem of measuring and assessing the existing condition of the maintenance functions in the organization which makes the Maintenance management in the organization well organized with measurable success in the capacity planning.

#### 2.3.1.2 Maintenance strategy formulation

Perhaps the most important part of planning function of Maintenance Management is strategy formulation. In the primary and secondary literature there are frameworks proposed by authors to formulate maintenance strategies for the organizations in a wide variety of industrial settings with the special focus on choosing the success criteria effectively. The important strategy formulation markers as pointed towards by Waeyenbergh & Pintelon (2004) are:

- Holistic System Approach
- Structured strategy development
- Flexible process to incorporate feedback and improvements

Furthermore, according to Campbell & Reyes-Picknell (2015). Maintenance strategy formulation will benefit if following considerations would be adopted: Organizational knowledge and vision should be integrated with the baseline maintenance strategy After successful consideration of the vision with the maintenance strategy, organization should strive to achieve that vision In order to achieve a structured approach to maintenance strategy formulation, Salonen (2011) proposed work process with the result being a maintenance strategy composed of production related aspects, organizational mission and vision, strategic aspects, and measurable targets.

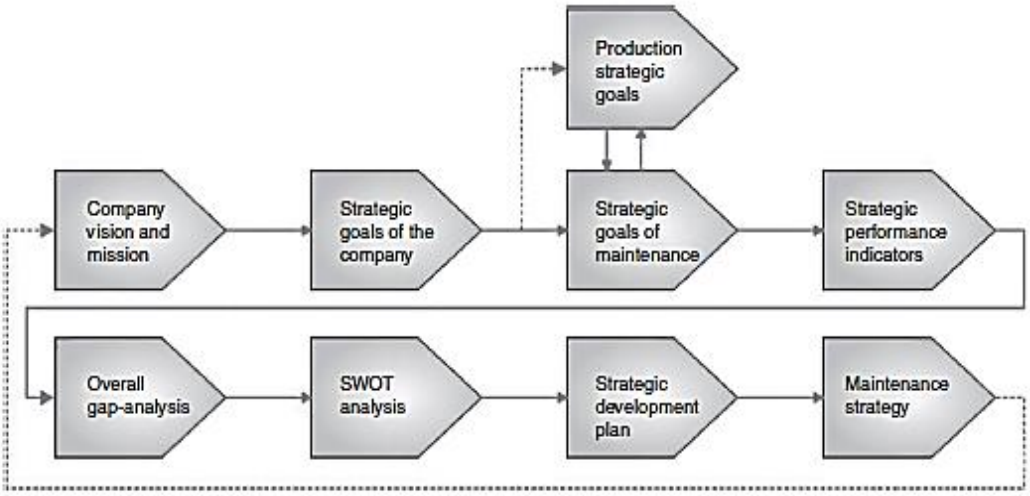



**Figure 2.4 Schematic view of work process when formulating a MS (Salonen, 2011)**

### 2.3.2 Organizing

Next Function of Maintenance Management is organizing which in broader perspective incorporates the organizational structure of the maintenance department with the overall organization. The main elements in an organization links resources available, planning capacities, organizational administrative structure with the existing knowledge of the organization together with the human factor. Human personnel and maintenance activities are managed according to the resources at hand and in accordance with the planned strategy. This in turn helps in maintaining an effective management scheme throughout the maintenance process.

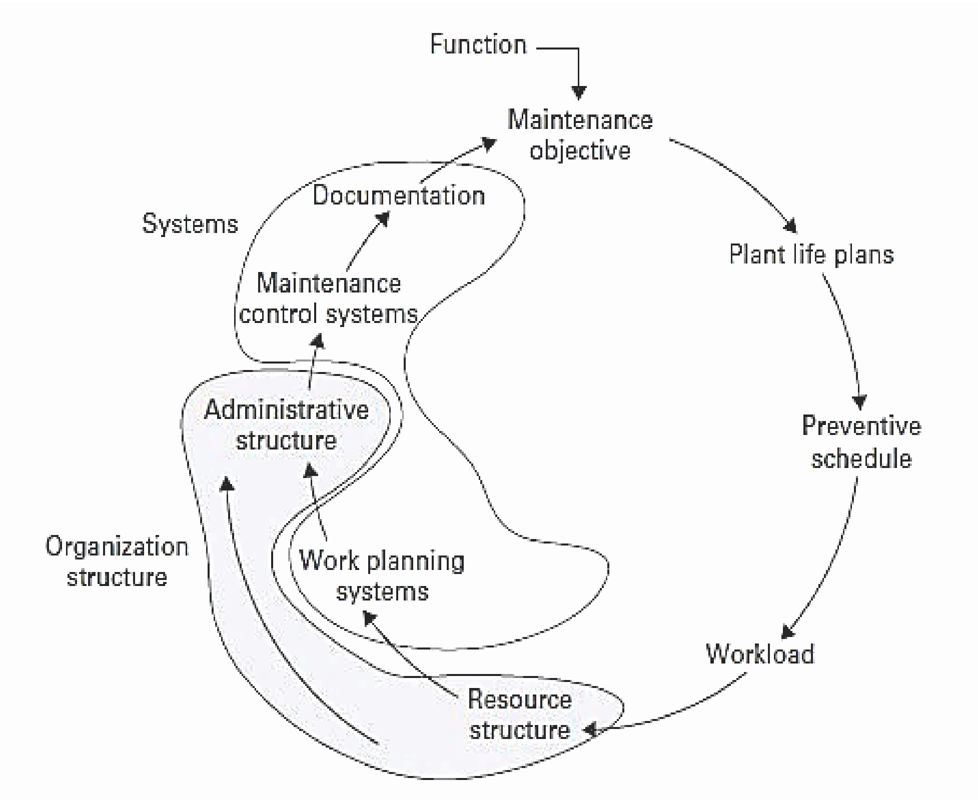



**Figure 2.5 Main elements of Maintenance Organization (Kelly, 2006)**

Moreover, organization of activities backed by advanced planning can have a good effect on the human resource of the organization and can serve as an important functional factor for Maintenance Management. Human factors are broad in spectrum and have strong effects on the organization for maintenance management. They can be categorized as:

**Table 2.1 Human factors on Maintenance Management (Kelly, 2006)**

| Individual Behavior Characteristics | Group Behavior Characteristics |
|---|---|
| Equipment ownership | Culture |
| Goodwill | Esprit de corps |
| Motivation | Horizontal Polarization |
| Morale | Vertical polarization |
| Resentment | |
| Protectionism | |
| Parochialism | |

Models by (Kelly, 2006), shows that the organizational hierarchy can be established in multiple ways according to the flexibility and resources of the organization. The depth and importance of maintenance activities can be a good predictor of the organization of maintenance teams in a facility. Organizing function in maintenance management also deals with the team members, their individual role, and collective roles in maintenance activities. Different departments are linked with different skilled personnel on many versatile levels to enhance the overall effectiveness of the maintenance activities.

### 2.3.3 Implementing

This phase of the Maintenance management Function deals with executing the maintenance activities on the equipment in the field or plant. Maintenance activities are implemented in accordance with the corporate values of the organization for a successful business approach. Advanced planning and organization become the inputs to maintenance implementation under maintenance management functions.

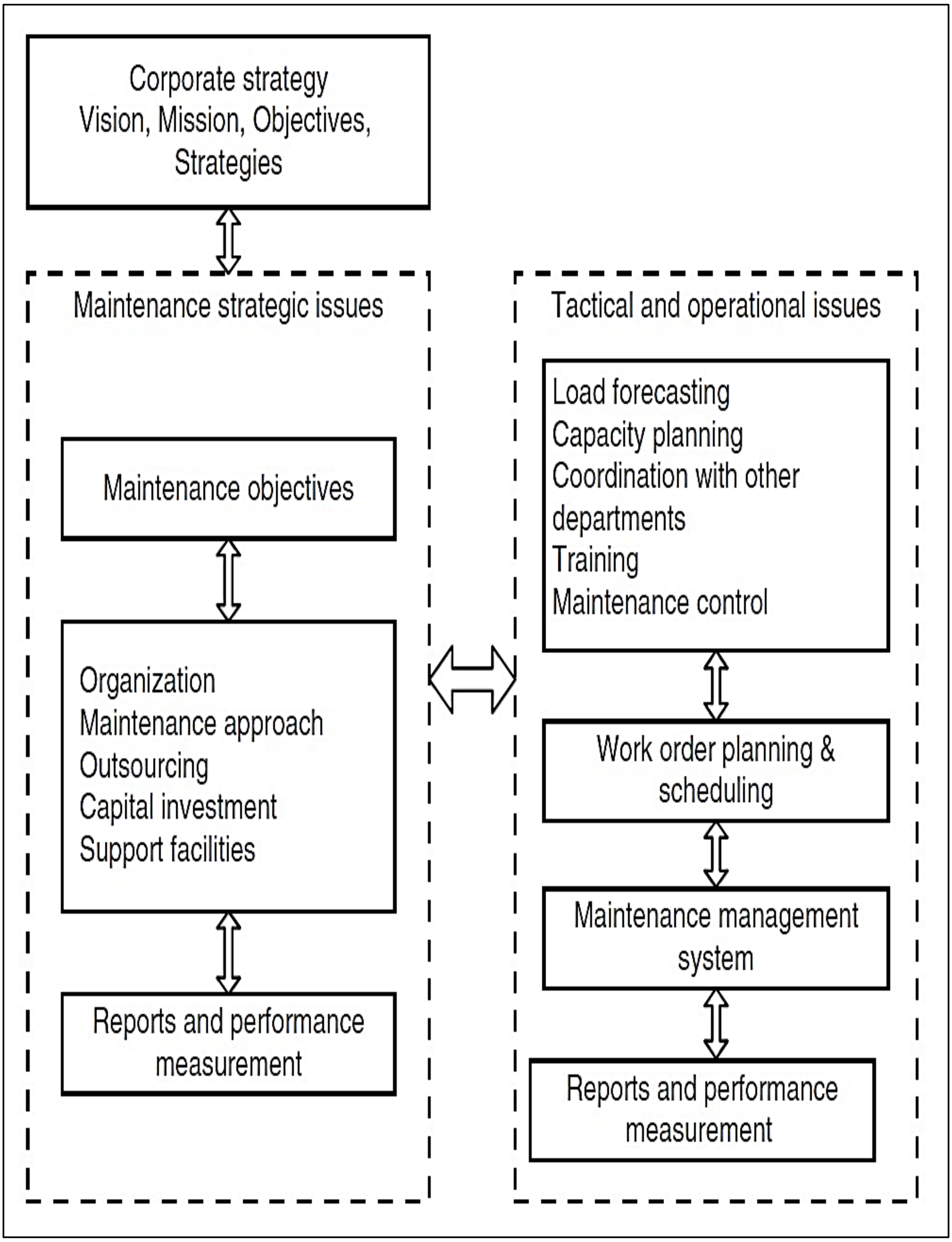



**Figure 2.6 Key issues in Maintenance Management (Ben-Daya et al., 2016)**

While implementation, maintenance objectives and responsibilities are focused. In the same way, management decisions are implemented and executed.

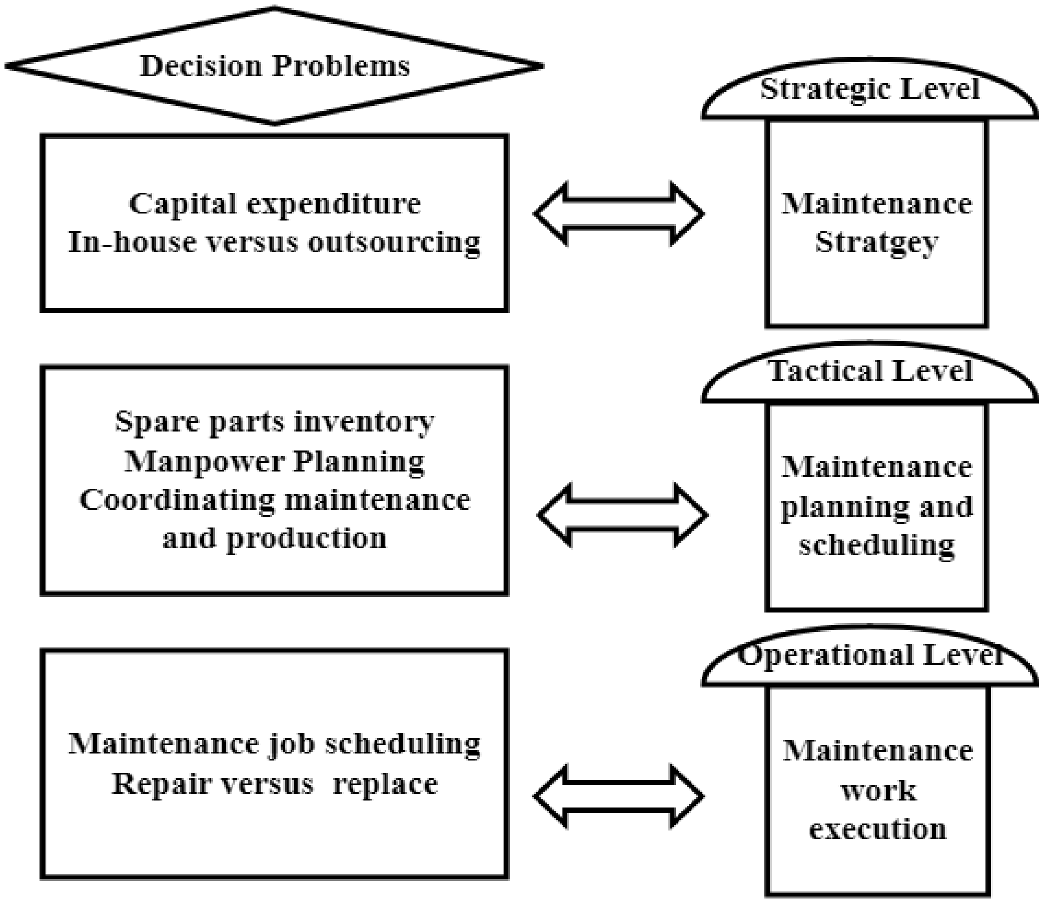



**Figure 2.7 Decision Problems in Maintenance (Ben-Daya et al., 2016)**

The Maintenance activities are decided then implemented on three different levels.

#### 2.3.3.1 Strategic Level

The strategic level relates to the overall organizational goals and values. Terms like company mission, values and objectives are focused. Upper-management directs the maintenance activities towards achieving strategic objectives of the organization.

#### 2.3.3.2 Tactical Level

At this level, maintenance activities are implemented to achieve small targets, timelines, and objectives. Tactical maintenance implementation can mean performing tasks on the ground, in the field directly on the equipment to achieve deadlines by middle managers.

#### 2.3.3.3 Operational Level

Operational level maintenance activities are the direct implementation and execution by the maintenance team on the equipment. All of the prior work, planning and scheduling, data recording and history, resource allocation and team building culminates at this level to physically execute the tasks such as lubrication, repairs and other specific of the sort of maintenance.

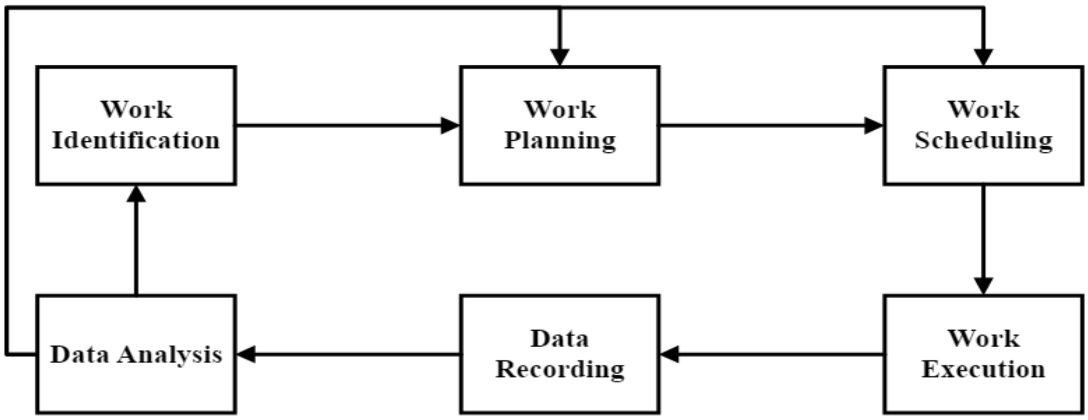



**Figure 2.8 Decision Implementation on operational level (Ben-Daya et al., 2016)**

## 2.3.4 Controlling

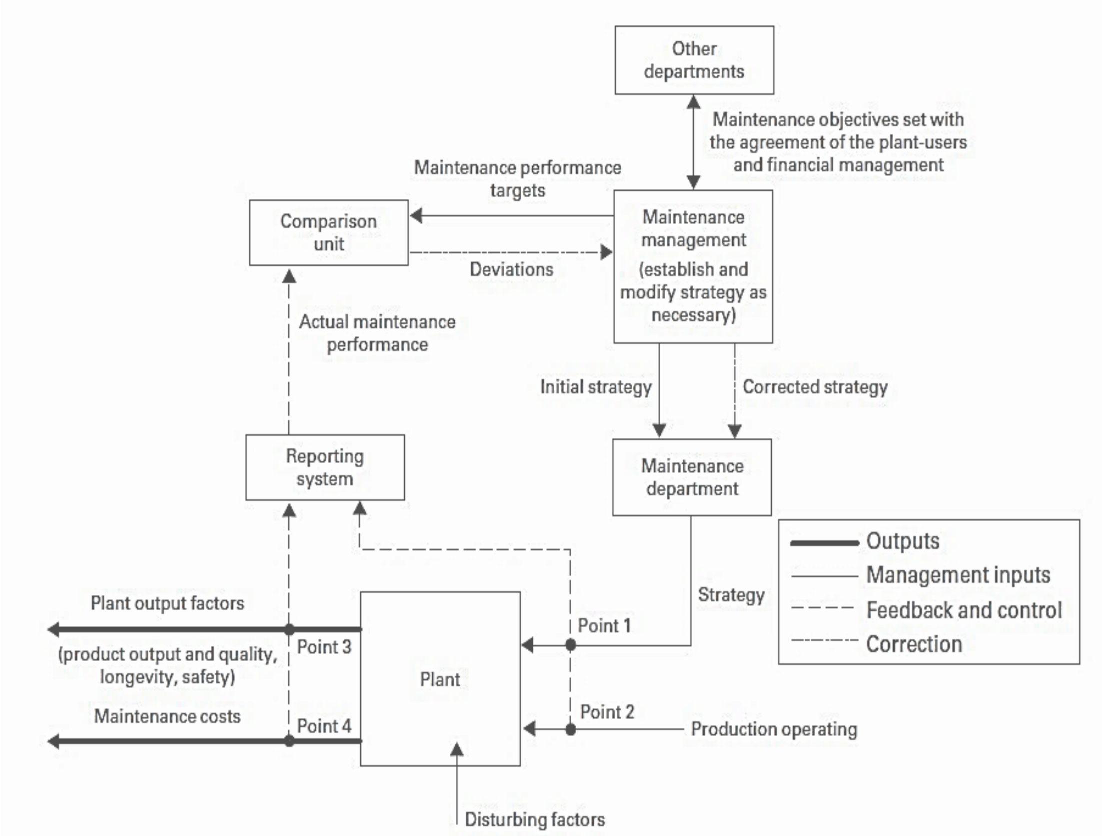



**Figure 2.9 Maintenance Management Control: A theoretical model (Kelly, 2006)**

The last function of maintenance management is the control of the activities performed after strategizing, planning, and scheduling, executing, and then measuring the important factors.  Exercising control enables the maintenance activities to achieve quality standards and meet specific and clear objectives with adequate performance. The main components of control function of maintenance management are reporting, documenting, and evaluating maintenance performance indicators. Documentation helps keep record of important information for future use and also helps in documenting issues that arise out of special circumstances. Reporting ensures the reliability of the execution of maintenance activities and help keep the balance of hierarchy. Finally, key performance indicators, Maintenance indicators in this case, provide a bigger picture with higher degree of control over the budgetary expenses incurred after maintenance has been performed. Also, specific targets relating to plant/facility efficiency are measured and maintained by keeping track of performance indicators. Maintenance Management functions, planning, organizing, implementing, and controlling work together to achieve organizational objectives and help accomplish responsibilities and targets set by the Maintenance practitioners and analysts. These functions contribute immensely towards developing a sound maintenance strategy.

**Table 2.2 Maintenance Management Frameworks**

| Stages | Framework | Authors |
|---|---|---|
| Maintenance Management | Integrated Management System | Niebel (1994) |
| | Maintenance Management Functions | Ben-Daya et al. (2009) |
| Planning | House of Maintenance | Schuh et al. (2009) |
| | Schematic view of work process when formulating a Maintenance Strategy | Salonen (2011) |
| Organizing | Main elements of Maintenance Organization | Kelly (2006) |
| | Two-dimensional resource Structure model | |
| | Three-dimensional organizational model | |
| Implementing | Key issues in Maintenance Management | Ben-Daya et al. (2016) |
| | Decision Problems in Maintenance | |
| | Decision Implementation on operational level | |
| Controlling | Maintenance Management Control: A theoretical model | Kelly (2006) |

## 2.4 MSS and MCDM

Multicriteria decision making has been popular among researchers in various fields in recent years and also with industry 4.0 among other interests. MCDM techniques are being used in multiple studies for maintenance with maintenance strategy selection as the popular area of interest as it has shown importance and superiority over other maintenance management functions recently. Mardani et al.

(2015) employed the systematic literature review methodology to gather and categorize research articles on MCDM techniques in multiple areas of research interests. Authors reviewed 393 articles from the timeline 2000-2014 in over 120 peer-reviewed journals. AHP has been the most popular singular technique while other the greatest number of studies used hybrid MCDM techniques. The popularity of the MCDM techniques with the researchers is self-evidence for their use in maintenance strategy selection as part of maintenance management function. The loss of time and resources during a breakdown causes a ripple effect that questions the reliability of the whole maintenance function. Therefore, maintenance should be planned and corrective measures should be taken accordingly. Gackowiec (2019) laid significance on the maintenance strategy formulation and effectively classified the existing literature into PM, CM, PDM, CBM and Proactive maintenance using a systematic literature review. The literature reviewed for the maintenance strategies indicate that the most scientific papers favored Preventive Maintenance (PM) over the rest and this trend seems to increase with the increasing contribution of the researchers most recent body of literature and this hopes to continue in the future. The author concluded that the importance of maintenance strategy formulation and implementation can be tackled by employing preventive maintenance (PM) as the effective strategy. Since the researchers in different settings with different methodology have favored PM as the most regarded/effective of the best maintenance strategies out there.

### 2.4.1 AHP and Hybrid-AHP

Maintenance Strategy selection for industrial production plants depends heavily on the identification of important critical factors. Experts play a crucial role in identifying those factors. According to Ohta (2018), AHP and Fuzzy AHP were compared for multiple criteria such as cost, quality, safety, value addition and viability against maintenance strategies namely CM, PM, PDM and Proactive Maintenance. In the comparison of AHP and Fuzzy AHP, both techniques provided similar results under similar circumstances and Corrective Maintenance (CM) was chosen as the best strategy with value added being the highest contributing criterion. Some discrepancies remained among the Consistency Ratios (CR) due to error or mistakes but overall, the authors found strong evidence that Fuzzy AHP can be used in AHP related studies as a solution to consistency issues for maintenance strategy selection. Galankashi et al. (2020) conducted the study on Cement manufacturer located in Iran which is categorized as a developing nation and authors claim that the literature on developing nations is less focused. The authors designed an AHP-Fuzzy AHP integrated methodology and then implemented it, firstly, to find the most suitable maintenance strategy through a questionnaire. The strategies that were considered were CM, RCM, TPM, PM and PDM along with multiple criteria. Secondly, AHP was used to rank the best strategy among the suitable strategies for designated equipment. Fuzzy AHP re-evaluated the findings under uncertain circumstances. The findings indicated that safety, cost, reliability, and availability were the most important criteria that were affecting the designated equipment maintenance. The authors recommended different strategies for different equipment based on AHP and Fuzzy AHP integrated approach along with managerial insights. Maintenance strategy helps immensely in reducing the downtime and accidental wastage of the resource inputs in various process industries. The wastages can be liquid chemicals, poisonous gasses and various other substances that may adversely affect the immediate environment. Panchal & Kumar (2017) strongly point out that reduced wastage can be achieved through the implementation of a suitable maintenance strategy. For the selection of the best possible maintenance strategy the authors propose a novel framework which involves, firstly, Fuzzy AHP to build a hierarchy or structure with ranking of criteria and sub-criteria using Geometric Means (GM). Secondly, the weights become input to another approach namely, Fuzzy CODAS. The proposed framework yield best alternative strategy for maintenance of the Ammonia Synthesis Unit (ASU) at urea fertilizer plant in North India. The candidates were CM, PDM, CBM, RCM and PM strategies. Finally, authors report that Preventive Maintenance (PM) as the best or suitable maintenance strategy that came out of the novel AHP-Fuzzy CODAS framework. Multicriteria decision making involves complex parameters for physical upkeep of the equipment. Maintenance strategy selection thus plays a vital role in decision implementation aspect of maintenance function.

Fouladgar et al. (2012) propose a new approach involving AHP and COPRAS and evaluate the case study under a fuzzy environment to assess the potential of the novel method. Weights of the criteria were calculated using Fuzzy AHP and alternatives were evaluated using COPRAS for the undertaken case study. Also, the methodology to work for the case study with much flexibility in decision making parameters. The study was executed for maintenance strategy selection but can be remodeled and applied to other aspects of maintenance management such as equipment and process selection, project and timeline selections. The selection of the best maintenance strategy can be affected immensely by the condition of the equipment under consideration.

Farajiparvar & Mayorga (2018) employed Fuzzy Failure Mode and Effect Analysis (FFMEA) and fuzzy-AHP to calculate risk priority number (RPN) for the equipment under consideration for selection of maintenance strategy. Firstly, FFEMA + Fuzzy-AHP were employed to calculate RPN for risk of equipment. Dimensions namely, severity, occurrence and sub-dimensions were weighted by industry experts. Secondly, important criteria were found using AHP. Lastly, a novel fuzzy approach was proposed to select the best maintenance strategy among the alternatives. The best maintenance strategy was reported to be CBM for some equipment and CM for others. The study seemed to conclude that risk and criticality were major players when it came to selecting the best maintenance strategy. Maintenance strategy selection has its importance as a function of maintenance management for engine rooms on ships. Complex machinery with different conditions presents challenges for maintenance engineers. Animah & Shafiee (2021) employed a hybrid-AHP-PROMETHEE approach compared with cost benefit analysis to select the best maintenance strategy. The model utilizes three maintenance alternatives and four comparison criteria for 17 machinery systems in the engine room. The results obtained from the proposed model were then compared with those obtained from cost-benefit analysis and a qualitative survey result from experienced marine engineers. The authors concluded that the proposed method was more robust in selection of maintenance strategy for ship engine room machinery systems. Selection of a suitable maintenance strategy is of utmost importance when there are multiple criteria involved and the decision making is complex. Azadeh & Zadeh (2016) proposed an integrated AHP distance-based fuzzy MCDM approach to select the best maintenance strategy from four common maintenance strategies namely condition-based, time-based, failure-based, and opportunistic maintenance. The criteria considered were derived from three different sources such as simulation, experts' opinion, and triangular fuzzy numbers. The study showed that Condition based maintenance was the best maintenance strategy as opposed to opportunistic maintenance, failure-based maintenance, and time-based maintenance. The authors further concluded that the proposed methodology is beneficial as it incorporates data from three different reliable sources and integrates them to obtain favorable results in the form of a best maintenance strategy. As different industries make use of effective maintenance strategy selection so does the maritime marine industry in engine rooms systems. Lazakis & Ölçer (2016) propose a novel reliability-criticality based maintenance strategy selected through a fuzzy-AHP multiple attributive group decision-making technique in three stages of rating, expert opinion aggregation and then selection of maintenance strategy while concluding that PM is the best approach for ship system maintenance closely followed by PDM and CM. The proposed method focuses on expert opinions and real-time data to come up with a suitable maintenance stagy considering multiple related/dependent attributes that help in pinpointing the best maintenance strategy as a function of maintenance management on maritime shipping industry. Existing maintenance strategies can also benefit from the well thought out and implemented maintenance strategy selection process and identifying important criteria affecting the maintenance operations. Mostafa & Fahmy (2020) use AHP to solve a maintenance strategy selection issue for a natural gas processing plant. The plant previously used time-based preventive maintenance strategy throughout its equipment and systems. Authors evaluated six maintenance strategy alternatives against criteria such as cost, damage, and applicability. After evaluation of the alternatives, it was found that the existing practice of time-based preventive maintenance for some equipment has to be re-considered with changes. Predictive maintenance (PM) and Corrective maintenance (CM) were concluded as reliable alternatives for different equipment based on the three aforementioned criterion against time-based preventive maintenance with major affecting criterion being cost. Agile thinking can be applied to minimize costs and optimize maintenance function based on the selection of a suitable maintenance strategy for various industries. Srivastava et al. (2018) used agile thinking and fuzzy-AHP to select the best maintenance strategy for a thermal power station. The authors consider CM, PM, CBM, PDM and OM as potential candidates for best maintenance strategy selection. The criteria used in fuzzy-AHP hierarchical structure were safety, execution capability, cost and added valve. The authors also reported that after considering the criteria into fuzzy-AHP with other sub-criteria some important and affecting criteria were shortlisted and PDM was selected as the best maintenance strategy. The authors also concluded that fuzzy-AHP was a reliable method to convert qualitative data into quantitative data in MCDM issues. Analytic Hierarchy process (AHP) coupled with other MCDM techniques present unique but effective results as in the case of maintenance strategy selection. Bertolini & Bevilacqua (2006) propose

AHP-Goal Programming technique to select the best maintenance strategy for centrifugal pumps in an oil refinery. For the AHP hierarchy optimal maintenance strategy was selected as the goal, occurrence, severity, and detectability were selected as criteria, and CM, PM and PDM were the alternatives used as candidates for the best maintenance strategy for centrifugal pump failures. The AHP-GP integrated approach proposed by the authors resulted in the selection of Predictive Maintenance as the best maintenance strategy for centrifugal pump failures.

### 2.4.2 AHSCM

AHCSM Analytic Hierarchy Constant Sum Method can be used to select the appropriate maintenance strategy in various industrial settings for overall effectiveness of maintenance management functions. The optimum or best maintenance strategy selection is imperative for best practices and World Class Maintenance System (WMS) to overcome challenges that arise due to the complex nature of production and maintenance systems. Kodali et al. (2009) propose and justify the use of Analytic Hierarchy Constant Sum Method (AHSCM) for WMS by analyzing the performance measures on an organization. Authors reported WMS is the best among the alternatives considered for the given circumstances. From the extensive analysis of the results from the model, implementing WMS would result in overall improvement in the performance of an organization. The AHSCM method can be employed by managers to adopt a WMS based on an effective Maintenance Strategy to achieve organizational strategic and tactical goals while overcoming challenges faced in a robust environment.

Martin et al. (2019) employed a semi-structured interview method to gather important criteria for maintenance management in the target organization. These criteria were then fed in AHCSM to rank the criteria according to their increasing importance which then helps in selecting the most desirable maintenance strategy. The important factors/criteria were productivity, quality, reliability, cost, safety and work environment, morale, inventory, and flexibility of operations. Total Productive Maintenance (TPM) was selected as the most desirable maintenance strategy for the target organization through the AHCSM method. AHCSM could provide useful results on selecting the most appropriate maintenance strategy with the integration of important criteria that affect the maintenance management of the organization.

### 2.4.3 ANP

Maintenance strategy selection becomes complex with multiple equipment as more variables get involved and different sets of equipment show dependency on other sets of equipment which calls for the use of dependency MCDM models.

Shafiee et al. (2019) combine ANP and cost-risk criticality analysis on four maintenance alternatives such as failure, time, risk, and condition based. Furthermore, two criteria were evaluated based on the model namely maintenance costs and failure criticality. Authors reported that for wind turbine maintenance, Failure-based maintenance was the most cost-effective strategy and Risk based maintenance as the best maintenance strategy for criticality. Furthermore, authors proposed that for future considerations environment to equipment relationship be considered, hybrid MCDM approaches can also be considered and fuzzy logic can be used to counter uncertainties.

In industries with safety critical equipment, such as aviation, shipping, nuclear and fossil fuel it becomes imperative to have a suitable maintenance strategy. Arjomandi et al. (2021) propose a novel MCDM approach based on DEMATEL-ANP to determine weights for criteria and then a VIKOR methodology to rank the candidate maintenance strategies. The maintenance strategies used as potential candidates were namely RTF, PM, CBM and RCM. Criteria were divided into economical, safety and sustainability categories. The authors reported that with the support of advanced technology for data gathering on maintenance functions RCM and CBM are the better maintenance strategies in fossil fuel/oil refineries. The new approach can be extended to other areas of interest and industries but RCM and CBM seem to need advanced data retrieval technologies and require their support to be effective in certain environments. Production and manufacturing environments have seen increased productivity in recent years with industry 4.0 and this calls for optimum maintenance strategies for production environments. Borjalilu & Ghambari (2018) employed fuzzy-ANP methodology on 5-MW powerhouse, paired with criteria such as organization, safety, administration, staff, and technical requirements. The maintenance strategy alternatives/options were PM, CM, CBM, RCM and PDM. Authors reported that after the ranking, through expert judgements, the most important criteria were administrative and staff requirements while the optimum maintenance strategy was selected to be PDM. Authors further concluded that the MCDM techniques prove useful in selection of maintenance strategies for different industries and the different approaches must frequently be compared to maximize results.

### 2.4.4 VIKOR

Maintenance strategy becomes much more effective if it covers important criteria that affect the maintenance management function. Having more criteria translated to complex system with inter-dependencies among maintenance management function. The proposed solution to this complexity is the sustainable approach. Nezami & Yildirim (2013) employ a sustainable approach to maintenance strategy selection by considering three important aspects namely economic, social, and environmental. Further criteria were evaluated by factor analysis and then the output was fed into Fuzzy VIKOR method for further evaluation. Authors reported that by reducing sub-criteria and employing VIKOR method under fuzzy conditions appropriate maintenance strategy should be a mix of social, environmental and ultimately economic aspects of the organization. Authors concluded the study arguing that more sub-criteria can be tried for factor analysis and ANP be employed as an alternative to the study's approach.

### 2.4.5 IFLAM

Maintenance management, used as an effective element, plays a central role in cost reduction, maximizing equipment uptime, quality improvement and enhancement, productivity and improving equipment efficiency, thus, striving for organizational goals and objectives. Bashiri et al. (2011) propose a novel approach of interactive fuzzy linear assignment method (IFLAM)for optimum maintenance strategy selection. This new method focused on interaction with the key maintenance personnel involved on ground to gather qualitative and quantitative data for ranking maintenance strategy alternatives. The authors used PM, CM, CBM, TBM and PDM as maintenance strategy alternatives. After ranking alternatives through the proposed IFLAM, Preventive Maintenance (PM) was selected as the best maintenance strategy. While IFLAM can be used as an effective method to rank maintenance strategy alternatives, it is calculation intensive and heavily based on interaction direct or indirect with the maintenance personal which can show data bias and increased number of dependent criteria.

### 2.4.6 TOPSIS

Combining more than one technique for MCDM problems often results in a progressive and robust approach. Panchal & Kumar (2017) employ fuzzy-AHP combined with fuzzy-TOPSIS methodology for coal fired thermal power plant to select the best maintenance strategy. Firstly, important related and affecting criteria were weighted by using fuzzy-AHP. Then secondly, alternative maintenance strategy candidates were ranked using fuzzy-TOPSIS methodology. The authors considered PM, CM, CBM, PDM and RCM as maintenance strategy candidates. The criteria that were ranked by using fuzzy-AHP namely, Costing issues, operational conditions, Reliability aspects, Quality issues and flexibility. These criteria were paired with other sub-criteria in fuzzy-AHP. For these criteria alternatives were ranked and CBM was selected as the best maintenance strategy for the coal fired thermal power plant using fuzzy-TOPSIS methodology. Experts and expert opinions matter much when selecting and implanting a cost-effective maintenance strategy in industries where challenging environment makes it difficult to maneuver. Asuquo et al. (2019) propose multi-attribute group decision-making (MAGDM) methodology to gather concise and robust feedback from experts and then employ fuzzy TOPSIS methodology to rank alternative maintenance strategies with respect to cost and implementation perspectives. The MAGDM and TOPSIS methodology resulted in RTF, PM, CBM and RCM as maintenance strategy alternatives with reliability, cost, safety, availability, and downtime as important criteria. Although the proposed hierarchal methodology concluded the ranking of alternatives and pointed out important criteria but it relied on past or historical data with expert feedback and judgement. The results obtained from such studies should then be relayed to the maintenance personnel on the ground to be implemented as seen suitable. AHP-GP-TOPSIS combined and integrated methodology results in an effective selection of maintenance strategy for sustainability sensitive operational equipment. Özcan et al. (2017) propose AHP-GP-TOPSIS combined methodology to select the best maintenance strategy based on three criteria for hydro-electric power plant namely occurrence, severity, and detectability. The alternatives for AHP hierarchy were PM, CM, PDM and Revision Maintenance (RM). A wide range of power generation equipment was studied for the best alternatives for maintenance strategy implementation. Different equipment was assigned different maintenance strategy alternative based on the results from the proposed approach for sustainable performance. Hydro-electric power plant showed increased efficiency and reduced costs due to the new approach and the potential of the proposed framework was shown through industry application. Just as AHP was useful for hydro-electric power plant maintenance strategy selection, it can be useful for steam powered coal-fired power plants which serve as the baseline generation power plants. Dachyar et al. (2018) used AHP-TOPSIS methodology to select the best maintenance strategy for coal-fired steam power plant in Indonesia. Experts from the industry were contacted and their input for important criteria and sub-criteria was gathered. This formed the basis for pairwise comparisons which then resulted in a normalized matrix, which then was fed into TOPSIS to determine the most suitable maintenance strategy. Four criteria namely, economic, technical, social, and environmental were weighted and the most important criterion chosen was technical. Three alternatives were considered namely, PM, PDM and RCM. The most suitable maintenance strategy chosen was RCM followed by PDM and then PM after normalizing through TOPSIS. AHP coupled with different MCDM approaches provide researchers with unique insights into Maintenance strategy selection problems in various industrial settings.

### 2.4.7 MACBETH

Carnero & Gómez (2017) employed MCDM technique to propose an effective maintenance strategy for health care facilities power distribution system. Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) with Continuous- time Markov Chain was the employed technique. MACBETH delivered a combination of CM, PM and PDM strategy for the health care facility. Also, with the new maintenance strategy authors were able to come up with an implementation plan for the energy distribution system. The proposed and demonstrated MACBETH-CT Markov Chain technique was effective but it constituted a deep modelling of the entire system and prior machine failure data, as that might not be the case every time. This shows that, the maintenance strategy when employed efficiently can support high priority systems such as health care systems.

### 2.4.8 Genetic Algorithm

Automated Guided Vehicles (AGVs) find increased usage among automated production lines to cut costs and material transportation time with the added benefit of high efficiency and accuracy in a specialized work environment. Their maintenance gets prioritized as their use increases. Yan et al. (2018) employed Genetic Algorithms (GA) approach to select the best maintenance strategy for three AGVs from an automated material distribution system. Authors demonstrated the effectiveness of CM and PM strategies with the help of Colored Petri Nets (CPNs). The important criteria that affected the optimization of maintenance function were the location selection for maintenance purposes and the optimal maintenance strategy employed. The authors reported that GA for the selection and optimization of maintenance strategy, paired with CPNs for multi-AGVs systems could help in reducing maintenance costs and increasing efficiency and productivity.

### 2.4.9 Other Methods

Thermal power plants have a vital stake in electric supply production and reliability for these plants to work on demand has increased dependence on multiple factors such as flexibility, continuous service, maintenance, and future development capacity. But more importantly consumers have to be supplied continuously which can affect the planned and run-to-failure maintenance activities. Zarei & Ghaedi-Kajuei (2017) employed two methodologies for maintenance strategy selection, deterministic and probabilistic. Both models are described and a comparison is presented. The comparison showed that probabilistic models were better than deterministic models in their abilities of reliability maximization and cost minimization. Authors further concluded that probabilistic models were closer to real time evaluation than deterministic models in selecting the best maintenance strategy for reliable maintenance of thermal power plants. The automotive industry can be subject to demands for cost reduction and increased customer satisfaction. In that respect the pressure increases on the effective maintenance management of production lines. This in turn lay emphasis on the cost criteria for maintenance strategy implementation and selection. Pophaley & Vyas (2010) aimed to select appropriate maintenance strategy by keeping cost of maintenance in focus while keeping CM, PM and PDM as candidates. Further cost related mathematical models supported the decision-making process. The authors reported cost of maintenance strategy implementation as the most important criteria affecting the selection process. The study concluded that cost of maintenance strategy implementation had controlling effect on the reliability of maintenance management function in automotive industry. Reliability and resource allocation are also very important perspectives when considering alternatives for maintenance strategy selection. Braglia et al. (2013) propose a unique model comprising FMECA for fault analysis and positions regarding the suitable maintenance strategy. Authors also calculate the costs and RPN for the faults. The maintenance strategy selection was done to mitigate faults. The proposed model resulted in optimally allocating the monetary resources, maintenance strategy selection and implementation for each failure with calculation of RPN. The study proposed was a type of RCM approach coupled with RPN calculation for the selection of best maintenance strategy for individual failures. MCDM techniques not only prove useful in selecting the best maintenance strategy selection but also for maintenance performance measurement as a function of maintenance management. Parida & Chattopadhyay (2007) proposed a framework for maintenance performance measurement by combining different approaches found in existing literature and then developing their own framework which can be used by maintenance engineers. The proposed framework links Hierarchal structure and different maintenance performance indicators under the maintenance management operation to present strategic, tactical, and functional aspects of maintenance performance measurement. Maintenance performance measurement can culminate into effective implementation of optimal maintenance strategy which is selected carefully as a function of maintenance management. Effective maintenance strategy can be used to minimize costs on operation and maintenance, also effective grouping and scheduling of maintenance activities can be achieved. Nguyen & Chou (2018) proposed a dynamic maintenance strategy for individual and group equipment along with maintenance schedules. The proposed approach was a mathematical model that optimized maintenance strategy by considering individual equipment repair activities and group equipment repairing activities. The authors reported that by the use of mathematical based optimized maintenance strategy the savings on wind turbine maintenance were 2.33% for individual and 4.56% on group activities. The proposed approach can be viewed as an effective tool for planning maintenance strategy but it takes on quantitative data into mathematical model, entirely leaving out the qualitative side of the maintenance management function.

**Table 2.3 MCDM Techniques literature count 2000-2014 (Mardani et al., 2015)**

| MCDM techniques | Frequency of application | Percentage |
|---|---|---|
| AHP | 128 | 32.57 |
| ELECTRE | 34 | 8.65 |
| DEMATEL | 7 | 1.78 |
| PROMETHEE | 26 | 6.62 |
| TOPSIS | 45 | 11.4 |
| ANP | 29 | 7.38 |
| Aggregation Methods | 46 | 11.70 |
| Hybrid MCDM | 64 | 16.28 |
| VIKOR | 14 | 3.56 |
| Total | 393 | 100 |

**Table 2.4 AHP used in literature from 2000-2014 (Mardani et al., 2015)**

| Application field | Number of papers | percentage |
|---|---|---|
| Energy, Environmental and Sustainability | 53 | 13.49 |
| Supply Chain Management | 23 | 5.85 |
| Materials | 21 | 5.34 |
| Quality Management | 12 | 3.05 |
| GIS | 14 | 3.56 |
| Construction and Project Management | 18 | 4.58 |
| Safety and Risk Management | 14 | 3.56 |
| Manufacturing Systems | 32 | 8.14 |
| Information Technology Management | 25 | 6.36 |
| Operations Research and Soft Computing | 109 | 27.74 |
| Strategic Management | 8 | 2.04 |
| Knowledge Management | 5 | 1.27 |
| Production Management | 18 | 4.58 |
| Tourism Management | 11 | 2.80 |
| Other Fields | 30 | 7.63 |
| Total | 393 | 100 |

## 2.5 Maintenance Types

### 2.5.1 Corrective Maintenance

The principal concept of corrective maintenance is that proper, complete repairs of all occurring maintenance issues and accidental problems are made on a required basis meaning done when the problem is just starting to manifest (Bevilacqua & Braglia, 2000). All repair activities are planned, implemented, and executed by skilled and trained technicians and maintenance personnel and verified before the machine or system is returned to service (Patil et al., 2022). CM covers electrical, electronic, and mechanical faults in the systems as these make up the majority of the faults and problems in the production system (G. Kumar & Maiti, 2012). The main objective of corrective maintenance is to eliminate breakdowns, deviations from optimum operating condition, and maintenance exercises (Shafiee, 2015b) and the optimization of the effectiveness of all critical machinery and systems (Zaim et al., 2012).

### 2.5.2 Preventive Maintenance

Preventive maintenance type is a strategic tool in maintenance management function that is intended to prevent the occurrence of a maintenance related problem. A comprehensive preventive maintenance type incorporates multiple activities such as regular evaluation of critical plant equipment, development and implementation of routine equipment checks (Bertolini & Bevilacqua, 2006). This allows the maintenance team to carefully evaluate and inspect the equipment and perform activities that prevent accidental breakdowns thus keeping the uptime of the machinery at the maximum (Thor et al., 2013).

### 2.5.3 Opportunistic Maintenance

Working on the machinery and other technical systems when an opportunity presents itself might be referred to as opportunistic maintenance. This approach to maintenance management is feasible when there are seasonal or time-based activities running in the production facility. For those activities that are affected by external factors outside the scope of production or maintenance processes, opportunistic maintenance may be an effective approach (Bertolini & Bevilacqua, 2006). Opportunistic maintenance can be made more effective with planned schedules and regular inspections of the equipment. This planning might point out the avenues where opportunistic maintenance can be carried out for the machinery.

### 2.5.4 Condition-Based Maintenance

Traditional and modern, both maintenance practices evidently guide the maintenance personnel to keep regular checks on equipment and carry out inspection periodically to gather much information about the condition the equipment is in at different times and after different periods of usage (Ilangkumaran & Kumanan, 2012), so that the machinery and equipment which is in the criteria of reception of maintenance activity must be singled out and maintained. This approach is called condition-based maintenance and it is highly effective where the time schedules of the running equipment are not known and cannot be planned beforehand, thus eliminating the chance to plan maintenance activities in advance.

### 2.5.5 Predictive Maintenance

Predictive maintenance is a type of maintenance program that uses regular evaluation of the actual operating condition of the production facility's equipment, production systems and administrative or maintenance management functions to come up with a strategic plan that helps predict the maintenance activities before they actual happen based on data and evidence historical or otherwise (Bashiri et al., 2011). This enables the maintenance personnel and decision makers to develop a proactive approach to incorporate and direct important or critical resources towards areas where there is an increased chance of failure or breakdown. Properly used, predictive maintenance can identify most, if not all, factors that limit effectiveness and efficiency of the total plant (Aghaee et al., 2020).

### 2.5.6 Outsourced Maintenance

The idea of outsourcing the maintenance activities to third party stakeholders may be referred to outsourced maintenance. This type of maintenance management strategy when well thought out might reduce the operational costs of the production facility for the short term and can be an effective tool to keep the machinery up for much longer for the peak seasons or production times (Shafiee, 2015b). However, the medium to long term prospects of outsourced maintenance might not be favorable in terms of finances and inhouse maintenance personnel skill development and capacity building. This approach might seem feasible for projects with short life cycles where more important resources can be allocated at important stations while keeping the focus on non-technical activities.

### 2.5.7 Energy Centered Maintenance

Energy centered maintenance (ECM) is a relatively new approach towards the maintenance management functions and strategies. ECM is about the gathering of information regarding the energy requirements of the equipment, in the maximum load conditions and no-load conditions (Alshakhshir & Howell, 2021b). Also, the information of equipment at the time of initial employment and later in the life cycle is required and the parameters that give energy perspective are continuously monitored. Especially, electrical and electronics equipment can be monitored and maintained when requirements in energy changes for the equipment. With special attention to the traditional and modern way of maintenance in mechanical equipment, it can be maintained effectively when the energy requirements for them also changes. Energy centered maintenance if studied, planned, developed, implemented, and executed effectively can change the energy costs incorporated in long term for the small and medium enterprises and production facilities with high production capacities and energy requirements (Howell & Alshakhshir, 2020).

### 2.5.8 Reliability Centered Maintenance

A reliability-centered maintenance (RCM) type presents a systematic approach to identify all of the related functions and includes failures associated with the production plant and its assets such as machinery and systems (Gandhare et al., 2018). RCM helps identify possible causes for accidental and unwanted failures or breakdowns (Ilangkumaran & Kumanan, 2012). Once the effects of the failures are measured and tracked, RCM guides all asset management options: on-condition task, scheduled restoration task, scheduled discard task, failure-finding task, and one-time change (to hardware design, operating procedures, personnel training, or other aspects of the asset outside the strict world of maintenance). In the regard that RCM differs from other maintenance types, it develops maintenance management functions in the facility and prepare equipment to be reliable and operate when needed and continue to operate effectively till the job is complete or another scheduled maintenance task is upon the system (Ahmadi et al., 2009).

### 2.5.9 Run to failure Maintenance

This sort of maintenance is also known as breakdown maintenance. For run-to-failure maintenance type, operations are more focused on the tipping point when actually the critical machinery breakdowns and then only the maintenance activities can start. The machine, when returned to its before failure condition, is considered sufficient as long as it keeps on running (Ahmadi et al., 2009). This marginal mentality keeps the machine on its limit and breakdowns become frequent. Run-to-failure maintenance has poor planning and it keeps the machinery in incomplete repair but it is the fastest response to any breakdown and costs less or more often. Just a quick fix could do the job at the cost of a few cents, but just for the time being but in the longer run the machinery shows more breakdowns and the cost to fix those breakdowns adds up in multitudes (Shafiee, 2015b).

### 2.5.10 Design Centered Maintenance

Modern concept of design centered maintenance is about designing the equipment in such a way that the equipment requires less maintenance throughout its life cycle of usage. This approach applies even to spare parts and replaceable items for the primary equipment (Ahmadi et al., 2009). Incorporating maintenance in design leaves room for other critical activities but increases time and efforts in the design and deployment phases of the equipment. The benefit of design centered maintenance is the ability of the equipment to perform at maximum efficiency throughout its employment with minimum requirement for maintenance activities thus reducing time and costs (Zaim et al., 2012).

# CHAPTER 3. RESEARCH METHODOLOGY

## 3.1 Introduction

The AHP, introduced by (Saaty 1980, 1990, 2008), has unquestionably emerged as a highly popular and remarkably effective approach in Multiple Criteria Decision Making (MCDM). Its allure lies in its robust mathematical properties, seamless data acquisition process, and the subsequent surge of interest it has garnered from researchers who recognize its immense potential (Triantaphyllou et al., 1995). Which is truly remarkable about the AHP, is its ability to transcend its original purpose of solving MCDM problems, adapting flawlessly to a wide array of domains, including the intricate realm of project ranking and pivotal decision-making scenarios (Al-Harbi, 2001; Palcic & Lalic, 2009; Zahedi, 1986). By skillfully harnessing the innate human capacity to form comprehensive judgments, the AHP ingeniously dissects complex problems into hierarchical structures, facilitating the process of making simple yet powerful paired comparisons (Al-Harbi, 2001; Bayazit, 2005). These invaluable pair-wise comparisons are precisely quantified using a meticulously crafted scale devised by none other than Saaty himself (1990), enabling decision makers to assign discrete numerical values to each choice, thereby capturing their true importance with remarkable precision. It is this remarkable fusion of subjective and objective assessment measures that endows the AHP with the remarkable ability to counteract biases that may taint the decision-making process, thus elevating its stature as a profoundly dependable methodology (Dalalah et al., 2010).

Nevertheless, even a method as impressive as the AHP has not been immune to critical scrutiny from scholars well-versed in the field (Belton & Gear, 1983; Dyer, 1990; Watson & others, 1982). Concerns have been raised, for instance, regarding the potential occurrence of rank reversal when comparable alternatives are introduced into the decision set, casting doubt on the method's reliability (Belton & Gear, 1983). Furthermore, the sheer magnitude of pair-wise comparisons required in complex problems has been deemed burdensome, posing a formidable challenge for practitioners (Macharis et al., 2004). However, it is worth noting that the very foundation of the AHP has been subjected to rigorous examination and comprehensive verification by esteemed scholars such as Harker & Vargas (1987) and, of course, Saaty himself (1990), effectively dispelling any lingering doubts and reinforcing its solid footing within the field. Given its remarkable suitability based on the aforementioned criteria, as well as the manageable number of criteria and alternatives, the AHP unquestionably stands as the most fitting choice for this study. To provide further insight, Table 3.2 elegantly showcases the scale proposed by Saaty, while intriguing psychological experiments have compellingly demonstrated the formidable challenge faced by individuals when simultaneously comparing more than seven objects (Baddeley et al., 1994). As a testament to its unparalleled utility, the AHP is often seamlessly integrated with the widely acclaimed Expert Choice® tool, making it the method of choice for countless decision-making and project planning endeavors in numerous countries across the globe (Saaty, 2001). It is, therefore, no surprise that the AHP has rightfully earned its place as one of the most frequently employed and highly regarded methods in the expansive realm of decision making (Ahmad & Pirzada, 2014).

## 3.2 AHP Hierarchy

The creativity in decision making and problem structuring lies in the structing of the hierarchy. This is usually done as a top-down approach. The decision problem structuring starts from the definition of the goal and then moves towards the selection of criteria in the subsequent lower level. Then the sub-criteria under the main criteria, if needed, are defined and their priorities are assigned. In the lower most level the alternatives are defined which are scored against the criteria to achieve the final synthesis resulting in the best possible alternative having the highest priority.

**Table 3.1 Analytic Hierarchy Model**

| | | |
|---|---|---|
| **Level # 1** | **Goal** | **Best Maintenance Strategy Selection for New Production Plant** |
| **Level # 2** | **Criteria** | **Main Criteria** |
| | | **Sub-Criteria** |
| **Level # 3** | **Alternatives** | **Potential Maintenance Strategies as candidates** |

## 3.3 Fundamental Scale

To record measurements into pair-wise comparison matrices, Saaty developed the fundamental scale. This scale consists of the values without units that are recorded into the pair-wise comparison matrices by the respondents, participants, or experts whose opinion is to be considered in order to derive the priorities of the main criteria contributing to the overall goal (Harker & Vargas, 1987).

Since the fundamental scale is used to record pair-wise judgements among the homogenous elements in the sub-criteria, this leads to the intensities for the main criteria which are over the sub-criteria level. These intensities of the main criteria show the importance of the criteria towards the achievement of the overall goal at the top level of the AHP hierarchy. Furthermore, the fundamental scale consists of values ranging from 1 to 1/9. Two homogenous elements are compared in terms of their importance towards the goal, if the elements thus compared are equal in importance the value assigned to them is 1, in this way the more important activity is given increasing values till 9. If the first activity or element is extremely important then the second is assigned the absolute value of 9. Similarly, the reciprocal values are recorded if the second activity is extremely important than the first value in the pair-wise comparison. This results in the values range of 1 till 1/9. The elements or activities must be homogenous as only two similar activities can be compared logically throughout.

**Table 3.2 Fundamental Scale (Saaty, 2008)**

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal Importance | Two activities contribute equally to the objective |
| 2 | Weak or slight | |
| 3 | Moderate importance | Experience and judgement slightly favour one activity over another |
| 4 | Moderate plus | |
| 5 | Strong importance | Experience and judgement strongly favour one activity over another |
| 6 | Strong plus | |
| 7 | Very strong or demonstrated importance | An activity is favored very strongly over another; its dominance demonstrated in practice |
| 8 | Very, very strong | |
| 9 | Extreme importance | The evidence favoring one activity over another is of the highest possible order of affirmation |
| Reciprocals of above | If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i | A reasonable assumption |
| 1.1-1.9 | If the activities are very close | May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities. |

### 3.3.1 Consistency Index and Consistency Ratio

Another important calculation in the derivation of the intensities of the main-criteria and the sub-criteria contributing to the overall goal is the consistency index (Saaty, 2008). It is a ratio calculated through the comparison of the Consistency index (C.I.) and Random Consistency Index (R.I.).

The R.I. is derived from a sample of randomly generated reciprocal matrices using the fundamental scale (Holder, 1990).

**Table 3.3 Random Consistency Index (Saaty, 2008)**

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Random Consistency Index (R.I.)** | **0** | **0** | **0.52** | **0.89** | **1.11** | **1.25** | **1.35** | **1.40** | **1.45** | **1.49** |

Consistency is the measure of usefulness or reliability of a judgment in the pair-wise comparisons by the experts. If the Consistency Ratio (C.R.) is less than 0.10 then the comparison is to be revisited for the judgements recorded. Consistency index is given by C.I. = $(\lambda_{max} - n)/ (n - 1)$, where $\lambda_{max}$ is the principal eigen value of the pair-wise comparison matrix. The C.R. is calculated by comparing the C.I. with the vales of the R.I. from the precalculated values. This results in a measure of inconsistency of the pair-wise judgements. The value of C.R. allowed is less than or equal to 0.10 for the comparisons to be reliable. Measure of inconsistency applies to the whole hierarchy in AHP which contributes towards the effectiveness of the selection of solutions or alternatives for the goal.

### 3.3.2 Advantages of AHP

(a) the ability of structuring a problem in a way that is easily manageable

(b) making the decision criteria explicit and the decision-making process transparent as a whole (Mu & Pereyra-Rojas, 2017)

(c) deriving priorities through a rigorous mathematical process using ratio scales

(d) allowing measuring and comparison of tangible and intangible elements

(e) sharing of decision-making process for feedback and buy-in (Saaty & Saaty, 2003)

### 3.3.3 Limitations of AHP

(a) the comparison process may be long if the decision is complex (Saaty, 1987)

(b) the comparison judgment may be unreliable if the participants are not fully engaged in the process

(c) the decision-making transparency may be counterproductive for managers who are interested in manipulating the results (Saaty, 2008)

(d) group decision-making may make it difficult to handle consistency problems

## 3.4 Summarized Procedure

Analytic Hierarchy Process (AHP) consists of subsequent steps that are, in their order of occurrence, summarized as Ahmad & Pirzada (2014).

Generally, the following steps are undertaken to apply the AHP:

- Definition of the decision problem and the main goal, clearly and according to requirements of the decision-making process
- Design of AHP hierarchal structure with the main goal on the top, in the next level main criteria are placed, the sub-criteria for the main criteria are placed in the next level if required, and in the last level the alternatives for the solutions/options are placed
- Construction of pair-wise comparison matrices of the size (n x n) for the sub-criteria level for each element in the criteria level. This gives a set of pair-wise comparison matrices for each of the criteria with the matrix elements being the sub-criteria. These matrices result in the priority value of each main criterion for the overall goal in the hierarchy (Harker & Vargas, 1987)
- Next step in AHP methodology is placing comparison values in the pair-wise comparison matrices for the sub-criteria under the main criteria. This results in the sets of valued pair-wise comparisons of individual respondents, participants, or experts whose judgements make up the AHP
- The values in the pair-wise comparison matrices come from the fundamental scale or other scales commonly or specially used in AHP. For the fundamental scale, values or scores range from 1 to 9 and their reciprocal values so the scale ultimately ranges from 1/9 to 9. Since the pair-wise comparisons are carried out by comparing one element with the other, the exceptional or absolute importance of one element over the other is assessed at 9 and if both elements are equal in importance, then number 1 is used to denote this equality. Reciprocal values are also assigned in order to assess the importance of the elements (Saaty, 1987)
- Total comparison matrices required are $n \times (n - 1) / 2$. Then to form the pair-wise comparison matrix, geometric mean of the comparisons is calculated.

Since arithmetic mean does not accurately represent the weights, geometric mean is calculated and used in the calculations of weights of the eigenvectors (Srdjevic & Srdjevic, 2023)

- Hierarchical synthesis is carried out to find the weightage of eigenvectors by the weights of the criteria and then sum of all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy is calculated to find the overall priority
- After carrying out pair-wise comparisons, the consistency is found by using the eigenvalue, $\lambda_{max}$. Consistency index (CI) is calculated using the formula involving matrix size n: $CI = (\lambda_{max} - n) / (n - 1)$. Judgment consistency is calculated by consistency ratio (CR) using the value of random index (RI) as ($CR = CI / RI$). The CR value below 0.10 is acceptable otherwise the judgment matrix is inconsistent which is required to be reviewed and improved (Harker, 1989)

## 3.5 Main-Criteria & Sub-Criteria

Subsequent to the goal level in AHP hierarchy design is the criteria level. Criteria can be further divided in to main-criteria and sub-criteria. The main-criteria represent the high level relevancy to the decision making process and the sub-criteria under main-criteria are the lower level relevant to the decision making process (Saaty, 1980). Furthermore, the sub-criteria contribute towards the priorities of the main-criteria thus contributing priorities towards the overall goal (Saaty, 1977).

For the current study, the process of making the AHP hierarchy consisted of identifying the main and sub-criteria. Firstly from the literature (Bevilacqua & Braglia, 2000; G. Kumar & Maiti, 2012; Mardani, Jusoh, Nor, et al., 2015; Panchal et al., 2017b; Patil et al., 2022; Shafiee et al., 2019; Triantaphyllou et al., 1997) and then secondly from the expert consultation (Abdul-Jawwad & AbuNaffa, 2022).

**Table 3.4 Analytic Hierarchy Model for Selecting Best Maintenance Strategy**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Goal** | **Best Maintenance Strategy Selection for New Production Plant** | | | | | | |
| **Criteria** | **Quality** | **Failures** | **Operations** | **Costs** | **Resources** | **Safety** | **Management** |
| **Sub-Criteria** | **Service Quality** | **Equipment Degradation** | **Equipment Setup Time** | **Software Costs** | **Skillful Human Resources** | **Personal Safety** | **Strategic Perspective** |
| | **Products Defects** | **Reliability** | **Equipment Efficiency** | **Personal Wages** | **Role Of Outsourcing Specialists** | **Occupational Illness** | **Management Commitment** |
| | **Quality Procedures** | **Maintainability** | **Criticality** | **Tool Costs** | **Spare Parts Availability** | **Environmental Effects** | **Employee Acceptance** |
| | **Impact On Process** | **Failure Frequency** | **Power Consumption** | **Staff Training Costs** | **Tools Availability** | **Equipment Safety** | **Quality Assurance** |
| | **Spare Parts Quality** | **Fault Identification** | **Machine Accessibility** | **Spare Parts Costs** | **Special Software** | **Infrastructure Safety** | **Financial Support** |
| | | | | **Operational Costs** | **Fault Detection Tools** | | |
| | | | | **Outsourcing Costs** | | | |
| **Alternatives** | **Maintenance Strategy MS-1**<br>**Maintenance Strategy MS-2**<br>**Maintenance Strategy MS-3**<br>**Maintenance Strategy MS-4**<br>**Maintenance Strategy MS-5** | | | | | | |

## 3.6 SuperDecisions (SD)

Since the development of AHP it has been used frequently in more than 50 countries of the world in various fields, directly or indirectly related to Decision Sciences (Saaty, 2008). In recent years many Multi-Criteria Decision-Making Techniques have been developed and researched, and also published, but the most widely applied is the AHP. With computers so much common these days, AHP is applied using various software. SuperDecisions (SD) is a software designed by the Creative Decisions Foundation in 2017 (Mu et al., 2018). SuperDecisions V3 is the latest version of the software package developed for analysis, synthesis, and justification of complex decisions based on the AHP methodology (Adams, 2011).

### 3.6.1 Advantages

SD, apart from being user-friendly computer software, has the main advantage of performing mathematical calculations for the researchers and practitioners. Researchers from inter-disciplinary fields and practitioners from all over the business world and executives from the government can easily make use of AHP with the help of the software but of course with little training (Adams & Saaty, 2003). Since the mathematics behind the AHP calculations might be advanced for many decision makers, the use of friendly interface of the software can help them to make decisions in their respective domains. Also, with the newer version of the software, it is possible not only to apply AHP but also ANP with fair accuracy where complex networks and sub-networks exist, for the decision problems (Adams, 2011). If the decision-maker were using a spreadsheet, the complexity of the consistency calculation and related adjustments would increase drastically. Here is where Super Decisions becomes extremely useful by allowing the user to work with a large number of criteria and alternatives while hiding the complexity of the AHP calculations (Cvetkovska, 2022).

### 3.6.2 Limitations

The limitations in the software are in accordance with the limitations of AHP. Such as in AHP and SD, as far as the group decisions are concerned, the consistency of the judgements is difficult to handle. Moreover, slight calculations for geometric mean are required in case of multiple participants (Mu & Pereyra-Rojas, 2017).

### 3.6.3 Procedure

SD have an elaborate procedure for the decision maker, which is in accordance with the steps involved in AHP (Mu et al., 2018). The procedure of the software involves using the graphical user interface, drag and drop objects and defining the problem in a hierarchal fashion (Saaty, 2001).

- Developing a model for the decision making
- Derive priorities for the criteria
- Derive priorities for the alternatives
- Synthesize the model
- Perform sensitivity analysis
- Making the final judgement

The different levels of the AHP hierarchy are named and added on the main screen. The top-most level is named as goal and the goal of the decision problem is placed in this block. Next block is placed with the name criteria and the main criteria are created, named, and placed in this block. If there are sub-criteria in the AHP hierarchy then another block named as sub-criteria is created and the elements are named and placed in this block. Lastly, the final block is created and named as alternatives with the alternatives or choices placed in this block. Moreover, each block is also known as a cluster (Saaty & Saaty, 2003). Next step in SD is to link the elements within the clusters to form a network which shows and connects the levels in the hierarchal structure of AHP for the decision problem. Once the network is complete and all the elements in the criteria level are connected to the goal element and the criteria are connected to the elements in the sub-criteria clusters and the all the alternatives in the alternatives cluster are connected to all the individual elements in the sub-criteria cluster then only the hierarchy is formed (Adams & Saaty, 2003). After completing the network linking for the elements and hierarchy, next pair-wise comparisons are made between the elements in each level. The results are displayed in the same window as the comparisons. Values from the fundamental scale are entered, ranging from 1 to 1/9 for the elements in pair-wise comparisons. The values from the fundamental scale for pair-wise comparisons can be recorded in five different ways (Adams, 2011).

- Graphical
- Verbal
- Matrix (used in this study)
- Questionnaire
- Direct (used in this study)

In Direct format, the comparison values are entered which might be previously calculated in past models, exercises or manually.

The pair-wise comparisons results yield the intensities of the elements in the level. For AHP, further calculations require that the inconsistency ratio for the comparisons be less than or equal to 0.10, so that the judgements can be considered reliable and coherent or unbiased. SD calculate the inconsistency ratio for the comparison judgements and can generate a report for the decision maker (Adams & Saaty, 2003). If the values of inconsistency report are less than or equal to 0.10 then the calculations can proceed otherwise the judgements have to be revisited and rerecorded in the pair-wise comparison steps to make the inconsistency ratio acceptable. The next step is to carry out the overall synthesis of the hierarchal model in order to get the overall priorities of the elements that contribute towards the overall goal (Saaty, 2001). Once the whole model has been synthesized and the priorities obtained, a sensitivity analysis can be performed in order to see the effect of changing priorities on the overall goal and outcome of the best alternative selection. The final step is to make the decision based upon the results of the SD AHP exercise (Saaty & Saaty, 2003). In general, the best alternative is the one with the highest general priority. The decision maker can now choose this alternative and at the same time can justify the reason for the selection. It presents an opportunity to explain the criteria used and the importance assigned and furthermore, explain what would have happened if the weights of the criteria had changed with the help of the sensitivity analysis.

## 3.7 Data Collection

For the purpose of data collection, firstly the facility was targeted and then respondents were contacted and their approval was gained while making them fully aware of the rounds of questionnaires they shall be facing in the coming months and the meetings they were about to attend and participate. Finally, after the purpose and methodology of the study was made easy to understand for the respondents, the questionnaires were administered in a non-intrusive way i.e., without disrupting daily activities of the respondents and operations of the production facility.

### 3.7.1 Case-Study Industry Setting

The fertilizer production is the part of Large-Scale Manufacturing (LSM) in Pakistan. LSMs in Pakistan make up 76 percent of the total contribution from the manufacturing sector to the economy. Fertilizers, make up 3.9 percent of the LSM contribution to the country’s economy (PACRA, 2023). The facility for the implementation of the research case study for the selection of suitable maintenance strategy for a new fertilizer plant was situated in city of Lahore, in Punjab province, and the production facility was designed for the manufacturing of Sulphur 80% WDG (Water Dispersible Granules). The facility can be categorized as an SME with working employees up to 250-300 personnel. At the time the study was conducted and experts/respondents were being interviewed, the facility was in the final stages of completion. The data collection was done at a new Sulphur Production Plant, first of its kind in Pakistan. Sulfur 80 WDG is a fungicide, insecticide and miticide for use on Citrus, Field, Fruit, Nut, Ornamental, Turf and Vegetable applications. It contains 80% Sulfur and it is a multi-faceted product designed for a variety of uses in a range of crops.

The site or production facility consisted of multiple production halls with varying capacities and builds. A team of electrical and mechanical staff was assigned maintenance duties which they performed with due diligence under the leadership of the Maintenance Executive and guidance of Group Director (Projects and Admin).

The facility was ISO 9001:2015 certified so they kept a record of maintenance related daily, weekly, and monthly activities with focus on Corrective maintenance (CM) and Preventive Maintenance (PM). The routine activities were recorded on maintenance complain basis on work orders (WO), which recorded the time, date and issue with the personnel dealing with the issue thus showing the maintenance activity life cycle. Based on the Work Order (WO) issuance, Corrective Maintenance (CM) and Preventive Maintenance (PM) requests were generated which resulted in failure analysis report by the maintenance team. The progress of the team was monitored with Human Resource Assessment Forms which decided their salary compensations, contract renewals and bonuses.

### 3.7.2 Respondents

In AHP decision making process, the decision problem, goal of the exercise and the criteria with reference to their importance are discussed by a panel of experts, sometimes called Respondents. These respondents or participants are industry experts with a wide range of skills and expertise under their belts. From the Agri-chemical production plant, a total of twelve (12) respondents were selected based upon their formal education and years of experience. These respondents were experts in their respective skills and had spent a considerable time in the Agri-chemical industry in Pakistan. These characteristics made them ideal for selection as respondents in the round of questionnaires that followed their selection process. The respondents ranged from decision makers in top management to the directly involved technical staff. The technical knowledge of the machinery involved in the new plant was taken as a positive marker of expertise and experience. Along with these markers, formal education was required up to matriculation level and a basic reading and writing skills in English language and numbers were set as a minimum threshold for the respondent to participate. In AHP methodology of decision making, more important respondents may be assigned more weights than the less important respondents participating in the expert judgement processes such as scoring of questionnaires and pair-wise comparisons.

But in this study for the selection of the suitable maintenance strategy, each respondent was given an equal scoring weight of one (1), which means that the response of every respondent is regarded as equal in terms of importance towards the achievement of the goal. The difference in management position of the respondent and level of formal education was matched by the years of experience gathered in the Agri-chemical industry, technical soundness of the personnel (assessed through scrutinizing the past three year technical and HR performance which in turn was tracked by annual HR performance reviews conducted regularly by the administration department) and the direct involvement with the machinery or production process (as this was considered important because of the direct failure reporting mechanism adopted by the organization). This consideration resulted in conclusive sessions among the respondents and the scoring automatically became reliable. The respondents were selected from all the departments related directly and indirectly to the new production plant. The first respondents interviewed were the Production Manager and Assistant Production Manager of the new Agri-chemical production plant, who was responsible for the most decision-making processes for the new production plant such as the financing, budgeting, human resource allocation, task assignments and daily, weekly, and monthly inspections and performance reviews. Next, from the production department, the production supervisor and machine operator were interviewed as they both were directly linked to the production processes, machinery, and quantities. They were going to be the first ones to point out and face the machinery failures as they were present on the production floor at times of machinery running. A safety officer at the production plant was also considered as a suitable respondent as he was well aware and educated, considered, and retained production or maintenance personnel and machine safety as the core activity. He also possessed expertise and experience in safety procedures, precautions, and guidelines in Agri-chemical production facilities. The last and the most directly involved department with the new production plant machinery was the maintenance department.

**Table 3.5 Respondents**

| No. | Designation | Education | Experience |
|---|---|---|---|
| R1 | Production Manager | 18 years | 15 years |
| R2 | Assistant Production Manager | 16 years | 12 years |
| R3 | Safety Officer | H.S.E. | 12 Years |
| R4 | Production Supervisor | 12 years | 8 years |
| R5 | Machine Operator | Matric | 3 years |
| R6 | Maintenance Manager | Engineering | 15 years |
| R7 | Mechanical Engineer | Engineering | 5 years |
| R8 | Electrical Engineer | Engineering | 3 years |
| R9 | Maintenance Supervisor Mechanical | B. Tech. | 8 years |
| R10 | Maintenance Supervisor Electrical | B. Tech. | 12 years |
| R11 | Senior Technician Mechanical | Diploma | 20 Years |
| **R12** | Senior Technician Electrical | Diploma | 15 Years |

Maintenance department was headed by a maintenance executive titled as Maintenance Manager and his education was Engineering with more than 15 years of experience in the field of Agri-chemical production machinery maintenance. Maintenance Manager was tasked with the budgeting, sourcing, and monitoring the spare parts, tools, coordinating maintenance activities with Mechanical and Electrical Engineers and their supervisors and technicians. Mechanical and Electrical Engineers categorized and performed their respective maintenance functions along with their technicians to solve the issues related to their respective area of study, expertise, and experience. Response of mechanical and electrical supervisors was considered important based on the fact that their vast experience on the machinery and their traditional way of solving maintenance issues was the outcome of their immense hands-on exposure on the machinery. Senior technicians guided and worked in teams with younger and diversified (based on experience and years spent in the Agri-chemical industry) to perform maintenance activities and they had the freshest or real-time look on the machine failure. Respondents had similar historical background and experience, they were considered as a reliable source of expert judgements on forming the hierarchy in AHP and thus performing the pair-wise comparisons for the subsequent levels in AHP hierarchy to determine the priorities of the main-criteria and sub-criteria ultimately resulting in the selection of the most suitable maintenance strategy for a new (without any historical machine failure data) Agri-chemical/fertilizer production plant Pakistan.

### 3.7.3 Questionnaires

Once the respondents were ready to participate in the decision-making process, they were exposed to a round of questionnaires with different scoring scales and methods.

The questionnaires were planned to assess the judgements of the experts of the production facility for different inputs in the hierarchy of the Analytic Hierarchy Process (AHP). The first questionnaire was regarding the criteria for the goal. The sub-criteria were ranked according to the contribution to the main-criteria with the minimum score being 1 and the maximum score being 5, thus representing the experts' perspective towards the contribution of the criteria towards the achievement of the overall goal. The second questionnaire was regarding the maintenance types which provided the experts with a list candidates of maintenance types from the literature and their inputs were recorded on a scoring scale from 1 -5. Value 1 represented the least important maintenance type for the maintenance strategy brainstorming and value 5 being the most important maintenance type candidate. The next questionnaire was regarding the maintenance strategy brainstorming, which focused on the development of a number of maintenance strategies suitable for the new Agri-chemical production plant. The final questionnaire was shared with the respondents to gather their opinion in regard to the relationship of the previously developed maintenance strategies with the selected or shortlisted sub-criteria. These questionnaires showed the response of the experts directly involved in the decision-making process for the selection of the suitable maintenance strategy for Agri-chemical/fertilizer production plant in Pakistan. Furthermore, the outputs of these questionnaires were used as inputs to the hierarchy of AHP for calculations of final priorities and values of alternatives to rank them according to their respective score.

## 3.8 Pair-wise Comparisons

### 3.8.1 Scoring

The elements in the levels of AHP are compared with each other to get the relevance and contribution of the element towards the overall goal. For this the elements are compared in Pair-wise Comparisons to get their relative importance (Srdjevic & Srdjevic, 2023). Pair-Wise Comparisons are matrices for recording the responses of the respondents. The respondents are briefed about the procedure and the scoring scale of the Pair-wise comparisons (Mu & Pereyra-Rojas, 2017). After the comparisons are made the results are compiled in pair-wise comparison matrices.

### 3.8.2 Group Decisions

Individual responses are rare in AHP and the decisions have to be made in group. Also, for this study group decision making was required. This is done by calculating the geometric means of responses by each respondent for the Pair-wise comparison Matrix (Cvetkovska, 2022). For this study there were twelve (12) respondents and the sum of their respective responses were also calculated for each comparison. Also, the arithmetic means and geometric means for each respondent were also calculated. The scoring was done according to the Fundamental Saaty Scale (Adams, 2011).

# CHAPTER 4. RESULTS AND ANALYSIS

## 4.1 Calculations

### 4.1.1 Maintenance Types scoring

The respondents were presented with 10 maintenance types to evaluate and discuss from with a scoring range of 1-5. Out of ten (10), seven maintenance types were selected with a cut off score at 3.0, leaving seven maintenance types relevant for the respondents to make maintenance strategies.

**Table 4.1 Maintenance Types Scoring for Maintenance Strategies Brainstorming**

| Serial no. | Maintenance Type | Score 1-5 | | | | | | | | | | | | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Corrective Maintenance | 4 | 3 | 4 | 5 | 4 | 4 | 5 | 4 | 5 | 4 | 4 | 4 | 4.16667 |
| 2 | Preventive Maintenance | 5 | 3 | 5 | 5 | 4 | 4 | 5 | 4 | 5 | 4 | 4 | 4 | 4.33333 |
| 3 | Opportunistic Maintenance | 3 | 2 | 4 | 3 | 3 | 5 | 4 | 3 | 2 | 3 | 2 | 3 | 3.08333 |
| 4 | Condition-Based Maintenance | 4 | 3 | 5 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4.66667 |
| 5 | Predictive Maintenance | 3 | 4 | 5 | 4 | 5 | 4 | 4 | 4 | 3 | 3 | 4 | 3 | 3.83333 |
| 6 | Outsourced Maintenance | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 1 | 1 | 2 | 1 | 1 | 1.83333 |
| 7 | Energy Centered Maintenance | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 1 | 2 | 2 | 1 | 3 | 2.25 |
| 8 | Reliability Centered Maintenance | 5 | 5 | 4 | 4 | 4 | 5 | 3 | 4 | 5 | 4 | 5 | 5 | 4.41667 |
| 9 | Run To Failure Maintenance | 3 | 4 | 3 | 3 | 5 | 2 | 3 | 3 | 2 | 3 | 2 | 4 | 3.08333 |
| 10 | Design Centered Maintenance | 2 | 2 | 1 | 5 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 4 | 2.08333 |

### 4.1.2 Criteria Scoring

Sub-criteria in the third level of AHP, 38 of them shortlisted from the literature review and then presented to respondents for scoring. After scoring them on the scoring range of 1-5 with a cut off score at 3.5 leaves twenty-three (23) for further calculations. This further scrutiny makes the AHP elements in the sub-criteria a lot less and makes the pair-wise comparisons easy to calculate and increases the consistency of the pair-wise comparisons. The respondents scored them on a scale from 1 to 5 and the sub-criteria with a score equal to or more than 3.50 were selected for further round of calculations. The scores then were compiled for the main-criteria which gave their priorities for the overall goal. The scores in the table for the sub-criteria response were summed and then the sub-criteria in the main-criteria were also summed. These latter scores were then divided by the former scores to obtain the main-criteria local weights which also represent the contribution of the main-criteria for the overall goal. Also, the local weights of the sub-criteria were also calculated by dividing each response by the sum of responses in the related main-criteria. Finally, the global weights of the sub-criteria were calculated by dividing the response score of each sub-criteria by the sum of all the response scores.

**Table 4.2 Main-Criteria and Sub-Criteria Scoring with weights for Local and Global Weights**

| Main Criteria | Main Criteria Local Weights | Sub-Criteria | Average Response score | Local weights of sub criteria within main criteria | Sub-Criteria Global Weight |
|---|---|---|---|---|---|
| Quality | 0.175 | Service Quality | 3.58 | 0.24 | 0.042 |
| | | Products defects | 3.75 | 0.25 | 0.044 |
| | | Quality Procedures | 3.83 | 0.26 | 0.045 |
| | | Impact on Process | 3.83 | 0.26 | 0.045 |
| Failures | 0.166 | Reliability | 3.58 | 0.25 | 0.042 |
| | | Maintainability | 3.58 | 0.25 | 0.042 |
| | | Failure Frequency | 3.50 | 0.25 | 0.041 |
| | | Fault identification | 3.58 | 0.25 | 0.042 |
| Operations | 0.228 | Equipment Setup time | 3.50 | 0.18 | 0.041 |
| | | Equipment Efficiency | 4.08 | 0.21 | 0.048 |
| | | Criticality | 3.92 | 0.20 | 0.046 |
| | | Power Consumption | 4.25 | 0.22 | 0.050 |
| | | Machine accessibility | 3.75 | 0.19 | 0.044 |
| Cost | 0.126 | Spare parts Cost | 3.58 | 0.33 | 0.042 |
| | | Operational Cost | 3.50 | 0.32 | 0.041 |
| | | Outsourcing Costs | 3.75 | 0.35 | 0.044 |
| Resources | 0.087 | Skillful human resources | 3.83 | 0.52 | 0.045 |
| | | Fault detection tools | 3.58 | 0.48 | 0.042 |
| Safety | 0.085 | Personal safety | 3.58 | 0.49 | 0.042 |
| | | Occupational illness | 3.67 | 0.51 | 0.043 |
| Management | 0.133 | Management commitment | 3.92 | 0.34 | 0.046 |
| | | Employee acceptance | 3.75 | 0.33 | 0.044 |
| | | Quality assurance | 3.75 | 0.33 | 0.044 |
| Sum | 1.000 | | 85.67 | 7.00 | 1.000 |

**Table 4.3 Sub-Criteria Scoring for Respondents with Average Scores**

| Sr | Sub-Criteria | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 | R11 | R12 | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Service Quality | 3 | 4 | 5 | 3 | 3 | 3 | 4 | 4 | 3 | 4 | 4 | 3 | 3.58 |
| 2 | Products defects | 2 | 3 | 4 | 3 | 5 | 4 | 3 | 4 | 5 | 5 | 3 | 4 | 3.75 |
| 3 | Quality Procedures | 5 | 3 | 3 | 5 | 4 | 3 | 5 | 4 | 4 | 3 | 5 | 2 | 3.83 |
| 4 | Impact on Process | 5 | 4 | 5 | 4 | 4 | 4 | 2 | 4 | 4 | 4 | 5 | 1 | 3.83 |
| 5 | Spare parts quality | 4 | 4 | 2 | 2 | 3 | 4 | 4 | 4 | 3 | 2 | 5 | 4 | 3.42 |
| 6 | Equipment Degradation | 3 | 4 | 3 | 3 | 2 | 3 | 5 | 3 | 2 | 4 | 3 | 5 | 3.33 |
| 7 | Reliability | 3 | 3 | 4 | 5 | 4 | 4 | 4 | 2 | 4 | 3 | 4 | 3 | 3.58 |
| 8 | Maintainability | 4 | 4 | 3 | 4 | 4 | 3 | 4 | 4 | 4 | 2 | 4 | 3 | 3.58 |
| 9 | Failure Frequency | 5 | 3 | 4 | 4 | 4 | 4 | 3 | 2 | 3 | 4 | 2 | 4 | 3.50 |
| 10 | Fault identification | 3 | 4 | 4 | 4 | 4 | 3 | 5 | 4 | 4 | 3 | 3 | 2 | 3.58 |
| 11 | Equipment Setup time | 3 | 3 | 3 | 3 | 4 | 4 | 2 | 5 | 4 | 3 | 4 | 4 | 3.50 |
| 12 | Equipment Efficiency | 4 | 5 | 5 | 4 | 3 | 3 | 3 | 4 | 5 | 5 | 3 | 5 | 4.08 |
| 13 | Criticality | 4 | 3 | 4 | 5 | 4 | 4 | 5 | 5 | 3 | 4 | 3 | 3 | 3.92 |
| 14 | Power Consumption | 3 | 4 | 4 | 5 | 5 | 3 | 4 | 5 | 4 | 5 | 5 | 4 | 4.25 |
| 15 | Machine accessibility | 5 | 5 | 5 | 4 | 4 | 4 | 2 | 5 | 2 | 2 | 5 | 2 | 3.75 |
| 16 | Software Cost | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 2 | 1 | 3 | 2.75 |
| 17 | Personal Wages | 2 | 4 | 4 | 1 | 3 | 3 | 4 | 3 | 3 | 3 | 4 | 4 | 3.17 |
| 18 | Tool Costs | 2 | 3 | 3 | 2 | 2 | 4 | 2 | 3 | 4 | 4 | 4 | 5 | 3.17 |
| 19 | Staff Training Cost | 4 | 3 | 2 | 3 | 4 | 5 | 3 | 4 | 5 | 5 | 1 | 1 | 3.33 |
| 20 | Spare parts Cost | 4 | 4 | 3 | 4 | 4 | 3 | 2 | 3 | 3 | 4 | 4 | 5 | 3.58 |
| 21 | Operational Cost | 4 | 3 | 2 | 3 | 4 | 4 | 4 | 4 | 3 | 2 | 5 | 4 | 3.50 |
| 22 | Outsourcing Costs | 5 | 3 | 4 | 5 | 5 | 3 | 5 | 4 | 2 | 1 | 4 | 4 | 3.75 |
| 23 | Skillful human resources | 4 | 4 | 5 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 3 | 3 | 3.83 |
| 24 | Role of outsourcing specialists | 2 | 3 | 4 | 2 | 2 | 3 | 4 | 2 | 3 | 2 | 4 | 4 | 2.92 |
| 25 | Spare parts availability | 3 | 4 | 3 | 4 | 3 | 2 | 5 | 4 | 1 | 4 | 1 | 2 | 3.00 |
| 26 | Tools availability | 4 | 4 | 2 | 3 | 4 | 3 | 2 | 3 | 4 | 1 | 3 | 3 | 3.00 |
| 27 | Special software | 2 | 3 | 5 | 2 | 1 | 3 | 5 | 2 | 3 | 4 | 1 | 4 | 2.92 |
| 28 | Fault detection tools | 3 | 3 | 5 | 2 | 2 | 4 | 3 | 3 | 4 | 5 | 4 | 5 | 3.58 |
| 29 | Personal safety | 2 | 4 | 4 | 3 | 2 | 5 | 5 | 3 | 3 | 4 | 4 | 4 | 3.58 |
| 30 | Occupational illness | 3 | 4 | 5 | 4 | 5 | 2 | 4 | 4 | 4 | 4 | 3 | 2 | 3.67 |
| 31 | Environmental effects | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 2 | 3 | 3.17 |
| 32 | Equipment safety | 3 | 4 | 2 | 2 | 3 | 3 | 5 | 2 | 2 | 2 | 1 | 4 | 2.75 |
| 33 | Infrastructure safety | 3 | 3 | 2 | 3 | 3 | 4 | 2 | 3 | 2 | 3 | 2 | 3 | 2.75 |
| 34 | Strategic perspective | 4 | 4 | 3 | 2 | 3 | 3 | 4 | 4 | 3 | 2 | 3 | 4 | 3.25 |
| 35 | Management commitment | 5 | 4 | 5 | 5 | 4 | 3 | 5 | 4 | 2 | 1 | 4 | 5 | 3.92 |
| 36 | Employee acceptance | 5 | 4 | 3 | 2 | 4 | 4 | 2 | 3 | 5 | 5 | 4 | 4 | 3.75 |
| 37 | Quality assurance | 5 | 3 | 4 | 5 | 5 | 3 | 2 | 4 | 4 | 4 | 3 | 3 | 3.75 |
| 38 | Financial support | 2 | 3 | 3 | 1 | 3 | 3 | 3 | 1 | 3 | 4 | 4 | 4 | 2.83 |

### 4.1.3 Pair-wise Comparison Matrices

After the scoring, the geometric means that were previously calculated are inserted into another matrix known as Pair-wise Comparison Matrix. Pair-wise Comparison Matrix is a square matrix with all the diagonal entries as one (1). The values of geometric means from the comparison matrices are inserted into the upper diagonal. Therefore, the lower diagonal consists of the reciprocal values of the upper diagonal entries. The geometric mean for these entries is calculated for all the Pair-wise comparison matrices. The weights for the entries for each entry are calculated by dividing individual geometric mean with the sum of geometric means in the respective matrix.

**Table 4.4 Pair-Wise Comparison Matrices for Sub-Criteria with Inconsistency Ratios**

| Sub-Criteria Pairwise Comparisons | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Quality** | | | | | | | | |
| | **Service Quality** | **Products Defect** | **Quality Procedures** | **Impact on Process** | | **GM** | **NW** | **Inconsistency Ratio** |
| **Service Quality** | 1.00 | 1.41 | 2.62 | 2.51 | | 1.75 | 0.39 | 3 % (acceptable) |
| **Products Defect** | 0.71 | 1.00 | 2.20 | 2.90 | | 1.46 | 0.32 | |
| **Quality Procedures** | 0.38 | 0.45 | 1.00 | 2.51 | | 0.81 | 0.18 | |
| **Impact on Process** | 0.40 | 0.34 | 0.40 | 1.00 | | 0.48 | 0.11 | |
| **Sum** | 2.49 | 3.21 | 6.22 | 8.92 | | 4.50 | 1.00 | |
| **Failures** | | | | | | | | |
| | **Reliability** | **Maintainability** | **Failure Frequency** | **Fault Identification** | | **GM** | **NW** | **Inconsistency Ratio** |
| **Reliability** | 1.00 | 1.67 | 2.31 | 3.42 | | 1.91 | 0.42 | 6 % (acceptable) |
| **Maintainability** | 0.60 | 1.00 | 3.02 | 1.80 | | 1.34 | 0.30 | |
| **Failure Frequency** | 0.43 | 0.33 | 1.00 | 2.81 | | 0.80 | 0.18 | |
| **Fault Identification** | 0.29 | 0.56 | 0.36 | 1.00 | | 0.49 | 0.11 | |
| **Sum** | 2.32 | 3.56 | 6.69 | 9.03 | | 4.54 | 1.00 | |
| **Operations** | | | | | | | | |
| | **Equipment Setup Time** | **Equipment Efficiency** | **Criticality** | **Power Consumption** | **Machine Accessibility** | **GM** | **NW** | **Inconsistency Ratio** |
| **Equipment Setup Time** | 1.00 | 3.34 | 2.16 | 2.61 | 2.21 | 2.11 | 0.37 | 9% (acceptable) |
| **Equipment Efficiency** | 0.30 | 1.00 | 2.40 | 2.47 | 2.44 | 1.34 | 0.24 | |
| **Criticality** | 0.46 | 0.42 | 1.00 | 1.80 | 2.53 | 0.97 | 0.17 | |
| **Power Consumption** | 0.38 | 0.40 | 0.56 | 1.00 | 2.79 | 0.75 | 0.13 | |
| **Machine Accessibility** | 0.45 | 0.41 | 0.40 | 0.36 | 1.00 | 0.48 | 0.09 | |
| **Sum** | 2.60 | 5.57 | 6.51 | 8.24 | 10.97 | 5.66 | 1.00 | |
| **Costs** | | | | | | | | |
| | **Spare Parts Cost** | **Operational Costs** | **Outsourcing Costs** | | | **GM** | **NW** | **Inconsistency Ratio** |
| **Spare Parts Cost** | 1.00 | 2.60 | 2.93 | | | 1.99 | 0.57 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Operational Costs** | **0.38** | **1.00** | **2.60** | **1.00** | **0.29** | **5 % (acceptable)** |
| **Outsourcing Costs** | **0.34** | **0.38** | **1.00** | **0.50** | **0.14** | |
| **Sum** | **1.73** | **3.98** | **6.53** | **3.50** | **1.00** | |
| **Resources** | | | | | | |
| | **Skillful Human Resources** | **Fault detection tools** | | **GM** | **NW** | **Inconsistency Ratio** |
| **Skillful Human Resources** | **1.00** | **7.83** | | **2.80** | **0.89** | **0.00 % (acceptable)** |
| **Fault detection tools** | **0.13** | **1.00** | | **0.36** | **0.11** | |
| **Sum** | **1.13** | **8.83** | | **3.16** | **1.00** | |
| **Safety** | | | | | | |
| | **Personal Safety** | **Occupational Illness** | | **GM** | **NW** | **Inconsistency Ratio** |
| **Personal Safety** | **1.00** | **7.00** | | **2.65** | **0.88** | **0.00 % (acceptable)** |
| **Occupational Illness** | **0.14** | **1.00** | | **0.38** | **0.13** | |
| **Sum** | **1.14** | **8.00** | | **3.02** | **1.00** | |
| **Management** | | | | | | |
| | **Management Commitment** | **Employee Acceptance** | **Quality assurance** | **GM** | **NW** | **Inconsistency Ratio** |
| **Management Commitment** | **1.00** | **3.29** | **2.97** | **2.17** | **0.61** | **2 % (acceptable)** |
| **Employee Acceptance** | **0.30** | **1.00** | **1.76** | **0.81** | **0.23** | |
| **Quality assurance** | **0.34** | **0.57** | **1.00** | **0.57** | **0.16** | |
| **Sum** | **1.64** | **4.86** | **5.73** | **3.55** | **1.00** | |

### 4.1.4 Inconsistency Ratios Check

The inconsistency of the pair-wise comparison matrices is calculated by the random value tables generated by Saaty for inconsistency ratio checks. Inconsistency of the matrices are the measure of the credibility values recorded in them by the respondents. The inconsistency values must lie between 0-1 or must be less than or equal to 10 percent. If the inconsistency is not in the limits, then the values in the comparison matrices must be re-recorded with the consent of the respondent and a request be made to the respondent to change their values so that the consistency can be achieved in the judgements.

### 4.1.5 Maintenance Strategy relationship with Sub-Criteria

Once the Maintenance Strategies (MS) are discussed and formulated as MS 1-5, then the respondents were asked to rate their formulated MS 1-5 as relevant to the sub-criteria and establish a relationship in the score ranging from 1-3, where 1 being the minimum relevance and 3 being the maximum relevance with the sub-criteria. After this the averages are compiled and then recorded as MSRS in the final selection table.

**Table 4.5 Maintenance Strategy relationship with Sub-Criteria**

| Serial no. | Sub-Criteria | MS | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 | R11 | R12 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **Service Quality** | **MS-1** | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | **1.33** |
| | | **MS-2** | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | **1.83** |
| | | **MS-3** | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 3 | 1 | **1.42** |
| | | **MS-4** | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | **2.83** |
| | | **MS-5** | 2 | 2 | 2 | 1 | 3 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | **1.75** |
| **2** | **Products defects** | **MS-1** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **1.00** |
| | | **MS-2** | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | **1.75** |
| | | **MS-3** | 1 | 3 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | **1.58** |
| | | **MS-4** | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 3 | 2 | **2.42** |
| | | **MS-5** | 2 | 3 | 2 | 1 | 2 | 2 | 2 | 2 | 1 | 0 | 1 | 1 | **1.58** |
| **3** | **Quality Procedures** | **MS-1** | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | **1.75** |
| | | **MS-2** | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | **1.67** |
| | | **MS-3** | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | **1.50** |
| | | **MS-4** | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | **2.50** |
| | | **MS-5** | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 3 | 1 | 2 | 2 | 2 | **1.92** |
| **4** | **Impact on Process** | **MS-1** | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | **1.42** |
| | | **MS-2** | 1 | 2 | 2 | 2 | 1 | 3 | 1 | 2 | 1 | 2 | 0 | 2 | **1.58** |
| | | **MS-3** | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 3 | **1.75** |
| | | **MS-4** | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 3 | **2.33** |
| | | **MS-5** | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 3 | 0 | 1 | 3 | 2 | **1.75** |
| **5** | **Reliability** | **MS-1** | 3 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | **2.08** |
| | | **MS-2** | 1 | 3 | 2 | 3 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | **2.50** |
| | | **MS-3** | 3 | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | **1.58** |
| | | **MS-4** | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | **2.83** |
| | | **MS-5** | 3 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 0 | 2 | 1 | 2 | **1.92** |
| **6** | **Maintainability** | **MS-1** | 2 | 2 | 1 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | **2.25** |
| | | **MS-2** | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 2 | 3 | 3 | 2 | **2.58** |
| | | **MS-3** | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 3 | 1 | 1 | 1 | 2 | **1.58** |
| | | **MS-4** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | **3.00** |
| | | **MS-5** | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 1 | 2 | 1 | 2 | **1.83** |
| **7** | **Failure Frequency** | **MS-1** | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | **1.25** |
| | | **MS-2** | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | **1.58** |
| | | **MS-3** | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | **1.50** |
| | | **MS-4** | 3 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 3 | 3 | 3 | 3 | **2.83** |
| | | **MS-5** | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 3 | **1.75** |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **8** | **Fault identification** | **MS-1** | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | **1.83** |
| | | **MS-2** | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | **1.92** |
| | | **MS-3** | 2 | 2 | 2 | 1 | 1 | 2 | 3 | 2 | 1 | 0 | 2 | 3 | **1.75** |
| | | **MS-4** | 3 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | **2.42** |
| | | **MS-5** | 2 | 2 | 3 | 2 | 2 | 2 | 1 | 3 | 2 | 2 | 3 | 2 | **2.17** |
| **9** | **Equipment Setup time** | **MS-1** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | **1.08** |
| | | **MS-2** | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | **1.50** |
| | | **MS-3** | 3 | 3 | 1 | 1 | 2 | 1 | 3 | 2 | 0 | 3 | 2 | 3 | **2.00** |
| | | **MS-4** | 3 | 2 | 1 | 3 | 3 | 2 | 3 | 2 | 2 | 2 | 3 | 2 | **2.33** |
| | | **MS-5** | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | **1.83** |
| **10** | **Equipment Efficiency** | **MS-1** | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | **1.58** |
| | | **MS-2** | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | **2.08** |
| | | **MS-3** | 3 | 1 | 1 | 1 | 2 | 2 | 2 | 0 | 0 | 2 | 1 | 3 | **1.50** |
| | | **MS-4** | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | **2.67** |
| | | **MS-5** | 2 | 1 | 3 | 2 | 2 | 2 | 3 | 1 | 1 | 1 | 2 | 1 | **1.75** |
| **11** | **Criticality** | **MS-1** | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | **2.33** |
| | | **MS-2** | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 1 | 2 | 3 | 3 | **2.50** |
| | | **MS-3** | 3 | 3 | 3 | 2 | 1 | 2 | 1 | 2 | 1 | 0 | 1 | 3 | **1.83** |
| | | **MS-4** | 2 | 2 | 2 | 3 | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 2 | **2.50** |
| | | **MS-5** | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | **2.42** |
| **12** | **Power Consumption** | **MS-1** | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | **0.42** |
| | | **MS-2** | 1 | 0 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **1.00** |
| | | **MS-3** | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | **1.17** |
| | | **MS-4** | 3 | 1 | 2 | 3 | 3 | 3 | 2 | 2 | 1 | 2 | 2 | 2 | **2.17** |
| | | **MS-5** | 2 | 2 | 1 | 2 | 1 | 2 | 0 | 1 | 2 | 1 | 1 | 1 | **1.33** |
| **13** | **Machine accessibility** | **MS-1** | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | **1.58** |
| | | **MS-2** | 2 | 1 | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | **1.92** |
| | | **MS-3** | 3 | 3 | 2 | 1 | 2 | 0 | 2 | 2 | 1 | 2 | 1 | 3 | **1.83** |
| | | **MS-4** | 3 | 3 | 1 | 3 | 3 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | **2.33** |
| | | **MS-5** | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 3 | 2 | 1 | 3 | **2.25** |
| **14** | **Spare parts Cost** | **MS-1** | 2 | 1 | 1 | 0 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | **1.08** |
| | | **MS-2** | 2 | 1 | 2 | 0 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | **1.33** |
| | | **MS-3** | 3 | 1 | 2 | 0 | 1 | 2 | 1 | 2 | 2 | 1 | 1 | 2 | **1.50** |
| | | **MS-4** | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 2 | 3 | **2.50** |
| | | **MS-5** | 2 | 2 | 1 | 3 | 2 | 2 | 3 | 1 | 1 | 1 | 1 | 3 | **1.83** |
| **15** | **Operational Cost** | **MS-1** | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | **1.17** |
| | | **MS-2** | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | **1.58** |
| | | **MS-3** | 3 | 1 | 3 | 1 | 3 | 3 | 1 | 1 | 2 | 1 | 1 | 1 | **1.75** |
| | | **MS-4** | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 3 | **2.25** |
| | | **MS-5** | 2 | 2 | 1 | 2 | 2 | 2 | 3 | 1 | 3 | 1 | 1 | 3 | **1.92** |
| **16** | **Outsourcing Costs** | **MS-1** | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | **0.83** |
| | | **MS-2** | 1 | 1 | 2 | 2 | 2 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | **1.50** |
| | | **MS-3** | 3 | 1 | 3 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | **1.50** |
| | | **MS-4** | 1 | 3 | 2 | 2 | 3 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | **1.92** |
| | | **MS-5** | 2 | 3 | 1 | 2 | 3 | 2 | 2 | 1 | 3 | 1 | 3 | 2 | **2.08** |
| **17** | | **MS-1** | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | **1.83** |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Skillful human resources** | **MS-2** | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | **1.83** |
| | | **MS-3** | 2 | 2 | 1 | 1 | 2 | 1 | 3 | 1 | 2 | 2 | 2 | 1 | **1.67** |
| | | **MS-4** | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | **2.92** |
| | | **MS-5** | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | **2.25** |
| **18** | **Fault detection tools** | **MS-1** | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 2 | 2 | **1.92** |
| | | **MS-2** | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | **1.92** |
| | | **MS-3** | 3 | 2 | 3 | 2 | 2 | 2 | 3 | 2 | 1 | 1 | 3 | 2 | **2.17** |
| | | **MS-4** | 3 | 3 | 2 | 2 | 3 | 1 | 2 | 2 | 3 | 3 | 2 | 3 | **2.42** |
| | | **MS-5** | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | **1.83** |
| **19** | **Personal safety** | **MS-1** | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | **1.33** |
| | | **MS-2** | 3 | 3 | 3 | 3 | 1 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | **2.42** |
| | | **MS-3** | 3 | 2 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | 1 | 1 | 2 | **1.92** |
| | | **MS-4** | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 2 | **2.75** |
| | | **MS-5** | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 3 | **1.92** |
| **20** | **Occupational illness** | **MS-1** | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | **1.83** |
| | | **MS-2** | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | **2.25** |
| | | **MS-3** | 2 | 3 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 3 | 2 | **1.92** |
| | | **MS-4** | 3 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | **2.75** |
| | | **MS-5** | 2 | 3 | 1 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | **1.75** |
| **21** | **Management commitment** | **MS-1** | 3 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | **2.33** |
| | | **MS-2** | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 2 | **2.33** |
| | | **MS-3** | 1 | 1 | 2 | 1 | 1 | 1 | 0 | 1 | 2 | 0 | 1 | 1 | **1.00** |
| | | **MS-4** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | **3.00** |
| | | **MS-5** | 3 | 2 | 2 | 2 | 0 | 2 | 2 | 1 | 2 | 1 | 2 | 2 | **1.75** |
| **22** | **Employee acceptance** | **MS-1** | 2 | 2 | 2 | 2 | 3 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | **1.83** |
| | | **MS-2** | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 3 | 2 | **2.08** |
| | | **MS-3** | 2 | 1 | 3 | 2 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 2 | **1.42** |
| | | **MS-4** | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | **2.50** |
| | | **MS-5** | 3 | 3 | 3 | 3 | 2 | 1 | 3 | 3 | 2 | 3 | 3 | 3 | **2.67** |
| **23** | **Quality assurance** | **MS-1** | 1 | 2 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | **2.08** |
| | | **MS-2** | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 1 | 2 | 3 | **2.25** |
| | | **MS-3** | 1 | 2 | 3 | 1 | 1 | 0 | 1 | 1 | 2 | 1 | 2 | 1 | **1.33** |
| | | **MS-4** | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 2 | 2 | 2 | 3 | **2.58** |
| | | **MS-5** | 2 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | **1.67** |

## 4.2 Maintenance Strategy Selection

For the selection of suitable maintenance strategy for a new Agri-chemical or fertilizer plant in Pakistan by the employment of Analytic Hierarchy Process (AHP), firstly the site for data collection was selected in Pakistan, an Agri-chemical and fertilizer production plant which were in the process of establishing a new Agri-chemical or fertilizer production plant and wanted to plan the maintenance strategy for the machinery and upkeep of the production plant. But with no historical data on machine failure the administration was unable to coordinate the management control activities with the maintenance functions and as well as the human resource could not be direct in the right direct and with compliance with company traditions. So, the researcher presented them with a methodology already established in literature by practical applications and established theoretical and mathematical background. The respondents were selected based upon their formal education and experience in the Agri-chemical industry or allied industries. This provided a credible expert panel for making the decision and judgements in AHP methodology. Once the panel has been decided then the respondents are informed and briefed about the forthcoming round of questionnaires and discussions. The first round of questionnaires was regarding the ranking of criteria both main-criteria and sub-criteria to short list the relevant criteria from the criteria introduced in the questionnaire from literature review. This helped in assessment of the most relevant criteria for the achievement of the overall goal. A further round of questionnaires was regarding the consideration of Maintenance types and their selection for Maintenance Strategy Formulation through brainstorming. This resulted in the formulation of maintenance strategies MS 1,2,3,4,5 by the experts as alternatives in AHP hierarchical model. After the questionnaires have been gathered and brainstorming or discussion sessions have been completed, the pair-wise comparisons were done using fundamental scale, the values were recorded to form pair-wise comparison matrices for group decision making process through AHP. After the formulation of pair-wise comparison matrices, the weights of criteria and eigen values were recorded and relationship between sub-criteria and alternatives was established through scoring along with the local and global weights. Lastly, the final calculations were conducted and placed in a table for overall analysis. The final values were marked as Maintenance Strategy Score (MSS) compiled by multiplying Maintenance Strategy relationship with sub-criteria (MSRS) with Global weights (GW). After the final calculations, the Maintenance Strategy MS-4 had the most priority value or ranking for achievement of the overall goal of selection of the suitable maintenance strategy for the new Agri-chemical/fertilizer production plant in Pakistan.

***MS-4***

Using Preventive maintenance to plan and schedule maintenance activities while keeping track of hours the machinery has been run and applying Condition-based maintenance for the equipment after specific planned hours with keeping room for improvement in planning and scheduling tasks targeting for reliability in equipment performance, also applying Corrective maintenance actions for chance breakdowns.

**Table 4.6 Maintenance Strategy Selection Scores to select the best Maintenance Strategy (MS)**

| | Local Weight of Main | Local weight for sub | Global weight for sub | MS-Relationship score with Sub-criteria | | | | | MS overall Score (MSS) = MSRS * GW | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | MSRS | | | | | MSS | | | | |
| **Main and Sub-Criteria** | **MW** | **NW** | **GW** | **MS-1** | **MS-2** | **MS-3** | **MS-4** | **MS-5** | **MS-1** | **MS-2** | **MS-3** | **MS-4** | **MS-5** |
| **Quality** | 0.175 | | | | | | | | | | | | |
| **Service Quality** | | 0.388 | 0.068 | 1.333 | 1.833 | 1.416 | 2.833 | 1.750 | 0.090 | 0.124 | 0.096 | 0.192 | 0.119 |
| **Products defects** | | 0.324 | 0.057 | 1.000 | 1.750 | 1.583 | 2.417 | 1.583 | 0.057 | 0.099 | 0.090 | 0.137 | 0.090 |
| **Quality Procedures** | | 0.181 | 0.032 | 1.750 | 1.667 | 1.500 | 2.500 | 1.917 | 0.055 | 0.053 | 0.047 | 0.079 | 0.061 |
| **Impact on Process** | | 0.107 | 0.019 | 1.417 | 1.583 | 1.750 | 2.333 | 1.750 | 0.027 | 0.030 | 0.033 | 0.044 | 0.033 |
| **Failures** | 0.166 | | | | | | | | | | | | |
| **Reliability** | | 0.420 | 0.070 | 2.083 | 2.500 | 1.583 | 2.833 | 1.917 | 0.145 | 0.174 | 0.110 | 0.198 | 0.134 |
| **Maintainability** | | 0.296 | 0.049 | 2.250 | 2.583 | 1.583 | 3.000 | 1.833 | 0.111 | 0.127 | 0.078 | 0.147 | 0.090 |
| **Failure Frequency** | | 0.176 | 0.029 | 1.250 | 1.583 | 1.500 | 2.833 | 1.750 | 0.036 | 0.046 | 0.044 | 0.083 | 0.051 |
| **Fault identification** | | 0.108 | 0.018 | 1.833 | 1.917 | 1.750 | 2.417 | 2.167 | 0.033 | 0.034 | 0.031 | 0.043 | 0.039 |
| **Operations** | 0.228 | | | | | | | | | | | | |
| **Equipment Setup time** | | 0.373 | 0.085 | 1.083 | 1.500 | 1.750 | 2.333 | 1.833 | 0.092 | 0.127 | 0.149 | 0.198 | 0.156 |
| **Equipment Efficiency** | | 0.237 | 0.054 | 1.583 | 2.083 | 1.500 | 2.667 | 1.750 | 0.086 | 0.113 | 0.081 | 0.144 | 0.095 |
| **Criticality** | | 0.172 | 0.039 | 2.333 | 2.500 | 1.833 | 2.500 | 2.417 | 0.092 | 0.098 | 0.072 | 0.098 | 0.095 |
| **Power Consumption** | | 0.133 | 0.030 | 0.417 | 1.000 | 1.167 | 2.167 | 1.333 | 0.013 | 0.030 | 0.035 | 0.066 | 0.040 |
| **Machine accessibility** | | 0.085 | 0.019 | 1.583 | 1.917 | 1.833 | 2.333 | 2.250 | 0.031 | 0.037 | 0.036 | 0.045 | 0.044 |
| **Costs** | 0.126 | | | | | | | | | | | | |
| **Spare parts Cost** | | 0.571 | 0.072 | 1.083 | 1.333 | 1.500 | 2.500 | 1.833 | 0.078 | 0.096 | 0.108 | 0.180 | 0.132 |
| **Operational Cost** | | 0.286 | 0.036 | 1.167 | 1.583 | 1.750 | 2.250 | 1.917 | 0.042 | 0.057 | 0.063 | 0.081 | 0.069 |
| **Outsourcing Costs** | | 0.143 | 0.018 | 0.833 | 1.500 | 1.500 | 2.083 | 2.083 | 0.015 | 0.027 | 0.027 | 0.038 | 0.038 |
| **Resources** | 0.087 | | | | | | | | | | | | |
| **Skillful human resources** | | 0.887 | 0.077 | 1.833 | 1.833 | 1.667 | 2.917 | 2.250 | 0.141 | 0.141 | 0.129 | 0.225 | 0.174 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Fault detection tools** | | 0.113 | 0.010 | 1.917 | 1.917 | 2.167 | 2.417 | 1.833 | 0.019 | 0.019 | 0.021 | 0.024 | 0.018 |
| **Safety** | 0.085 | | | | | | | | | | | | |
| **Personal safety** | | 0.875 | 0.074 | 1.333 | 2.417 | 1.917 | 2.750 | 1.917 | 0.099 | 0.180 | 0.143 | 0.205 | 0.143 |
| **Occupational illness** | | 0.125 | 0.011 | 1.833 | 2.250 | 1.917 | 2.750 | 1.750 | 0.019 | 0.024 | 0.020 | 0.029 | 0.019 |
| **Management** | 0.133 | | | | | | | | | | | | |
| **Management commitment** | | 0.612 | 0.081 | 2.250 | 2.333 | 1.000 | 3.000 | 1.750 | 0.183 | 0.190 | 0.081 | 0.244 | 0.142 |
| **Employee acceptance** | | 0.228 | 0.030 | 1.833 | 2.083 | 1.417 | 2.500 | 2.667 | 0.056 | 0.063 | 0.043 | 0.076 | 0.081 |
| **Quality assurance** | | 0.161 | 0.021 | 2.083 | 2.250 | 1.333 | 2.583 | 1.667 | 0.044 | 0.048 | 0.028 | 0.055 | 0.036 |
| **Sum** | 1.000 | 7.000 | 1.000 | 36.083 | 43.916 | 36.916 | 58.916 | 43.917 | 1.564 | 1.939 | 1.566 | 2.631 | 1.895 |
| **Maintenance Strategy Percentage** | | | | | | | | | 16.30 | 20.20 | 16.32 | 27.42 | 19.75 |

## 4.3 Comparison of Results

The Results computed via MS Excel with numerical analysis were credible as the judgements were appropriate and consistency of judgements were in desirable limits as checked through inconsistency ratios. The results were further validated by SuperDecisions (SD) Software to check for any errors that might be present in the numerical analysis.

### 4.3.1 Hierarchal Model

The first step in SuperDecisions (SD) is to develop a hierarchal model on the basis of the original model developed previously. The hierarchical model is developed in four levels. The top level being the goal level which is to select the suitable maintenance strategy for a new Agri-chemical/fertilizer production plant in Pakistan.

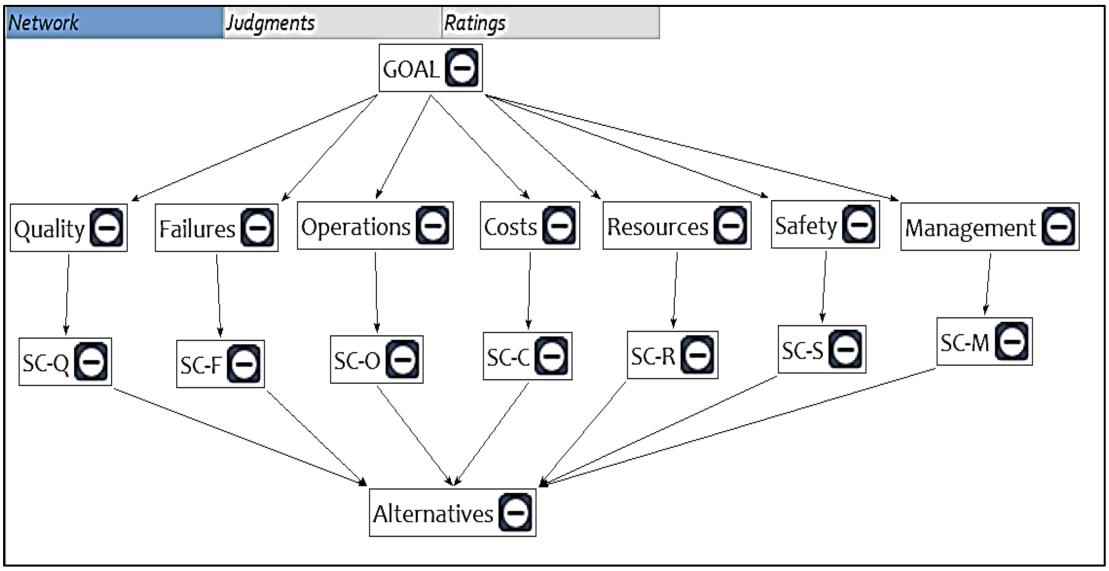



**Figure 4.1 Analytic Hierarchy Process AHP Hierarchal Model in SuperDecisions (SD)**

### 4.3.2 Main-Criteria

The next level is the main-criteria which are made in separate blocks in SuperDecisions (SD). Each element in the main-criteria is placed in a separate block in the same level of the hierarchy.

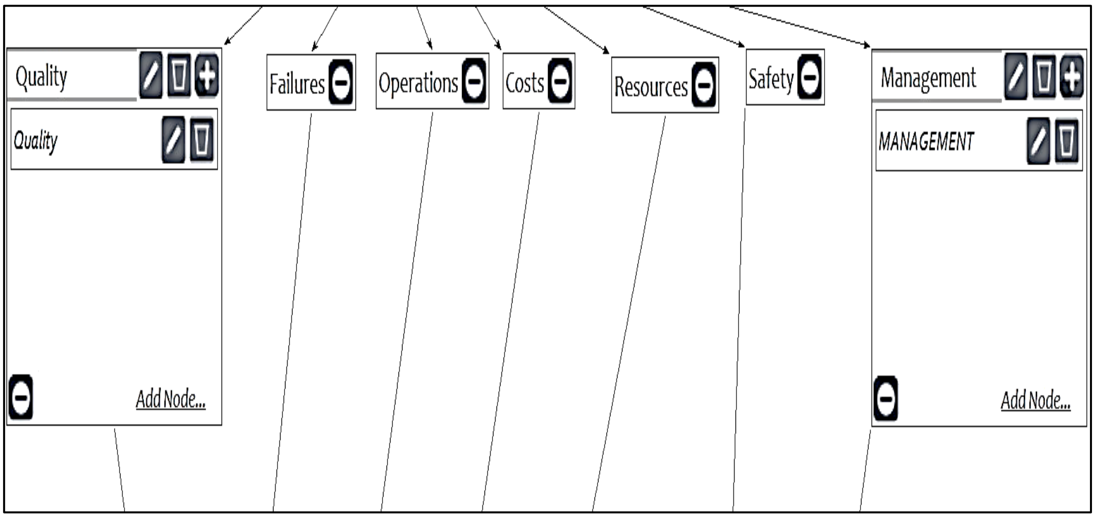



**Figure 4.2 Main-Criteria blocks in second hierarchy level in SuperDecisions (SD)**

### 4.3.3 Sub-Criteria

The next level is the sub-criteria and similarly, all the sub-criteria elements are placed in their respective main-criteria block.

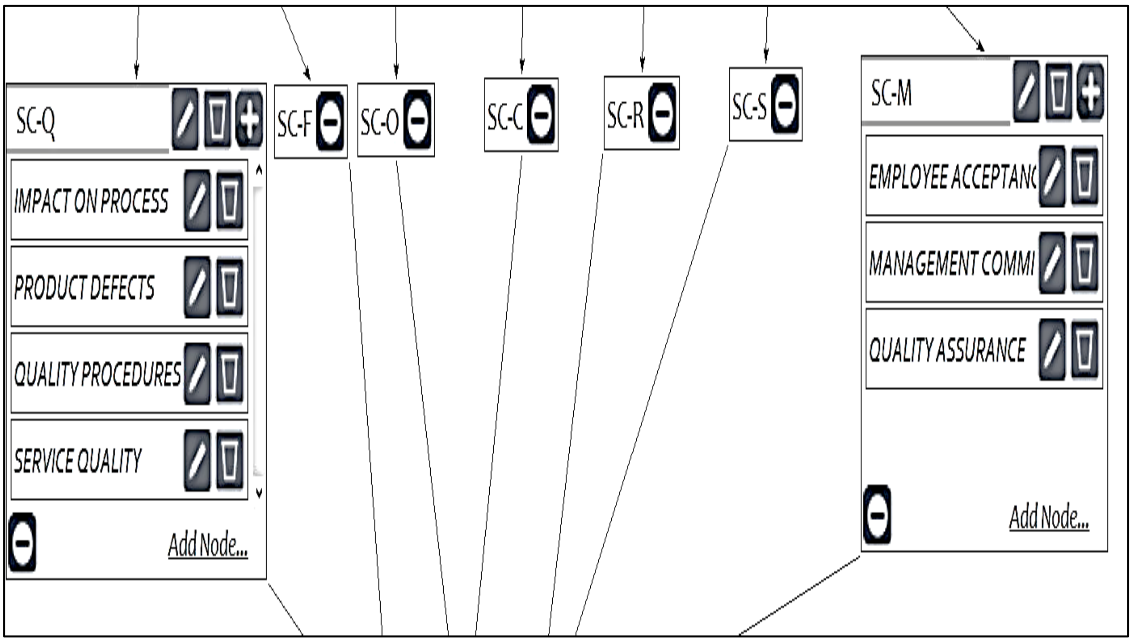



**Figure 4.3 Sub-Criteria blocks in third hierarchy level in SuperDecisions (SD)**

### 4.3.4 Alternatives

Finally, alternatives are placed in the lowest block of the AHP hierarchy in a single block.

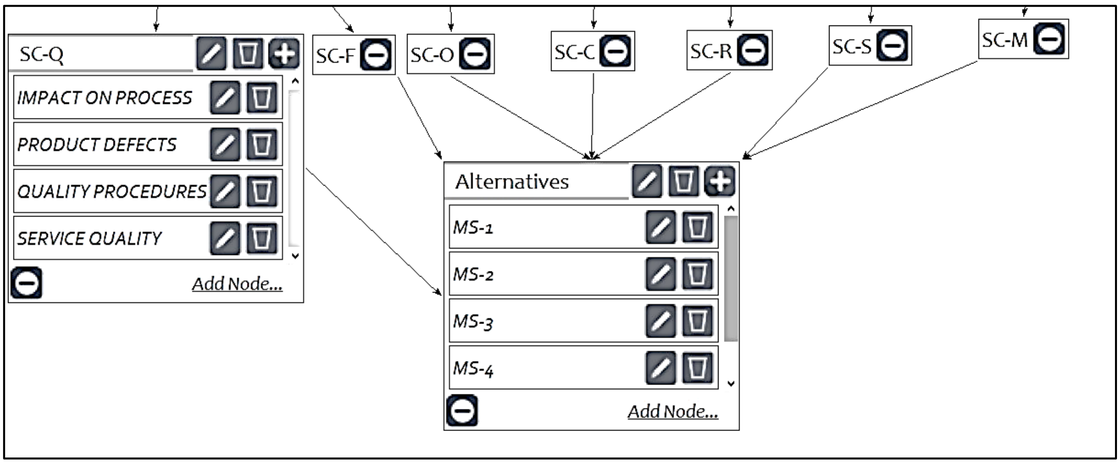



**Figure 4.4 Hierarchy Alternatives' blocks in the last level in SuperDecisions (SD)**

### 4.3.5 Connections and Network

Once the hierarchy is made and the blocks are defined, the network in the SuperDecisions (SD) has to be made to link up the blocks and complete the hierarchy.

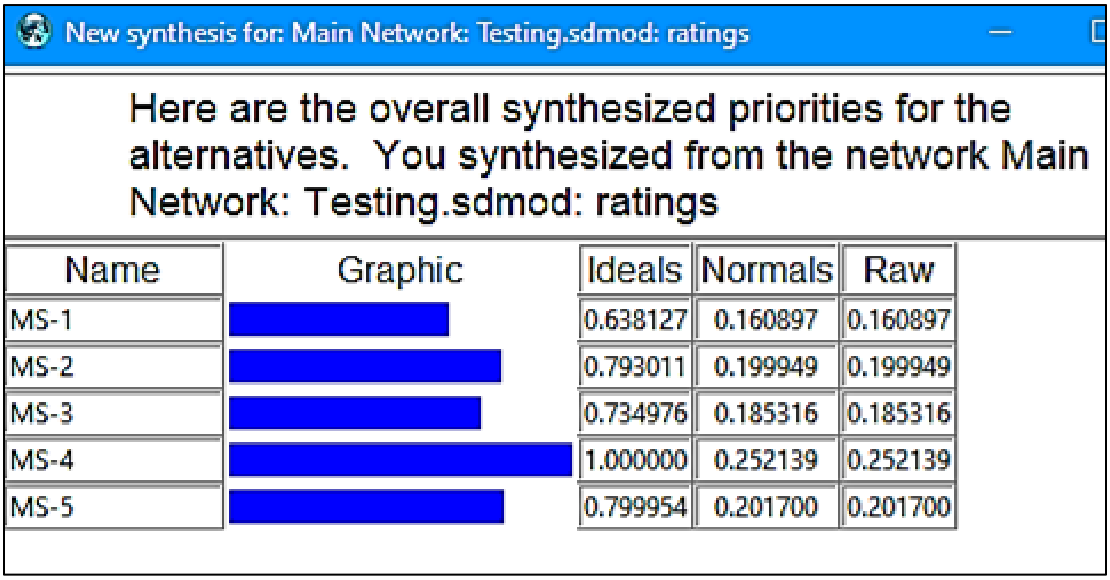
### 4.3.6 Judgements

After the network is complete the judgement can be recorded in four different modes.

For this study, the pair-wise comparison values for the main-criteria level were recorded via direct mode as they were previously calculated in numerical analysis. For the pair-wise comparisons of the sub-criteria level, the judgements were recorded in the matrix mode. These judgements were taken from the pair-wise comparison matrices of the numerical analysis. Next, the ratings for alternatives were completed and then the whole model was synthesized while keeping the inconsistency ratios in check.

## 4.4 Final Results

Complete synthesis yields the results in favor of MS-4, just as seen in the numerical analysis. Results were closer in comparison with the results seen in numerical analysis, for the SuperDecisions (SD) Software. SuperMatrix was compiled by software which shows the priorities of all the elements of the hierarchy either actual or normalized. Comparison between the Software and the numerical calculations yields close enough results to make the AHP decision making credible enough for the production plant administration to make maintenance strategy decisions for their new production plant.




| Name | Graphic | Ideals | Normals | Raw |
|---|---|---|---|---|
| MS-1 | | 0.638127 | 0.160897 | 0.160897 |
| MS-2 | | 0.793011 | 0.199949 | 0.199949 |
| MS-3 | | 0.734976 | 0.185316 | 0.185316 |
| MS-4 | | 1.000000 | 0.252139 | 0.252139 |
| MS-5 | | 0.799954 | 0.201700 | 0.201700 |

**Figure 4.5 Final Results for the best Maintenance Strategy (MS) in SuperDecisions (SD)**

## 4.5 Sensitivity Analysis

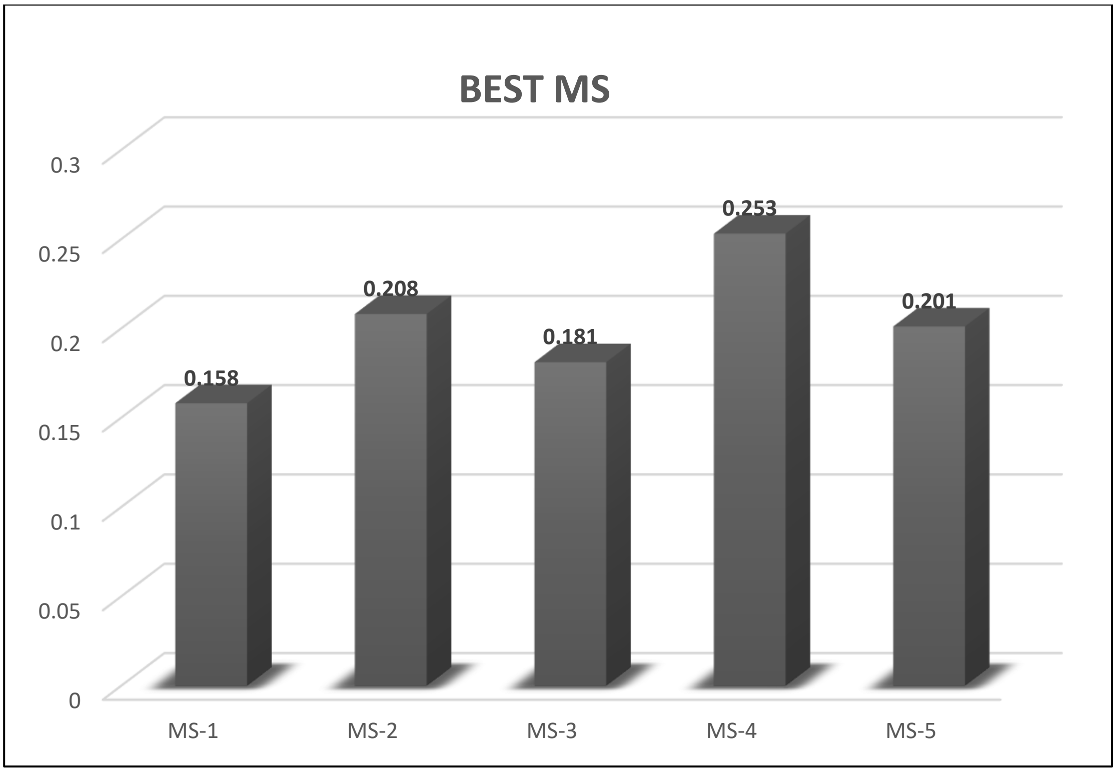



**Figure 4.6 Ideal sensitivity *graphs* for Maintenance Strategy (MS) in SuperDecisions (SD)**

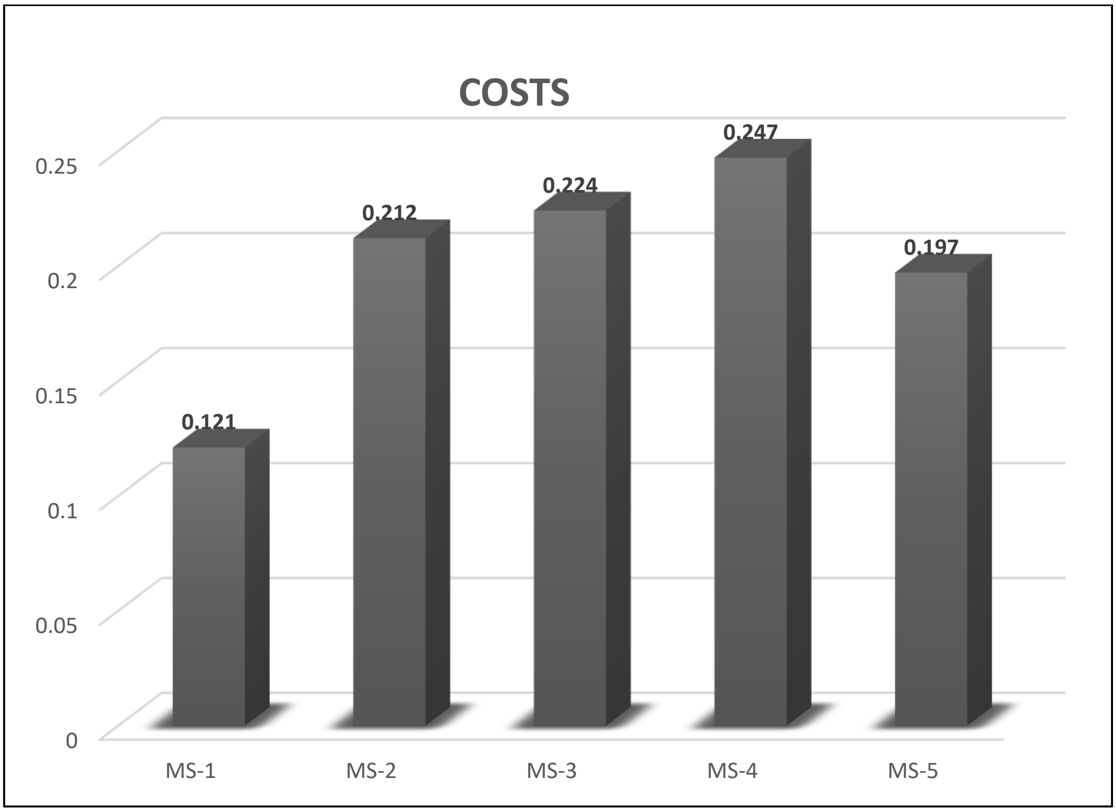



**Figure 4.7 Cost criteria sensitivity graph for Maintenance Strategy (MS) in SuperDecisions (SD)**

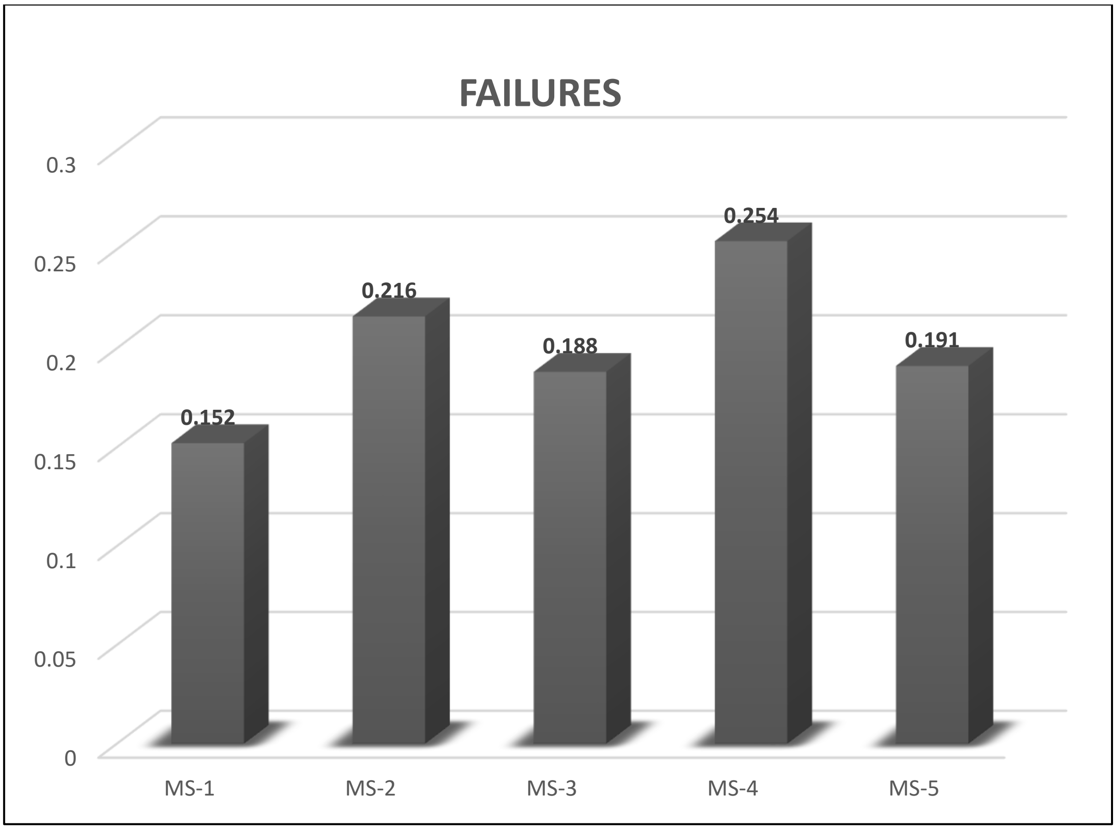



**Figure 4.8 Failure criteria sensitivity graph for Maintenance Strategy (MS) in SuperDecisions (SD)**

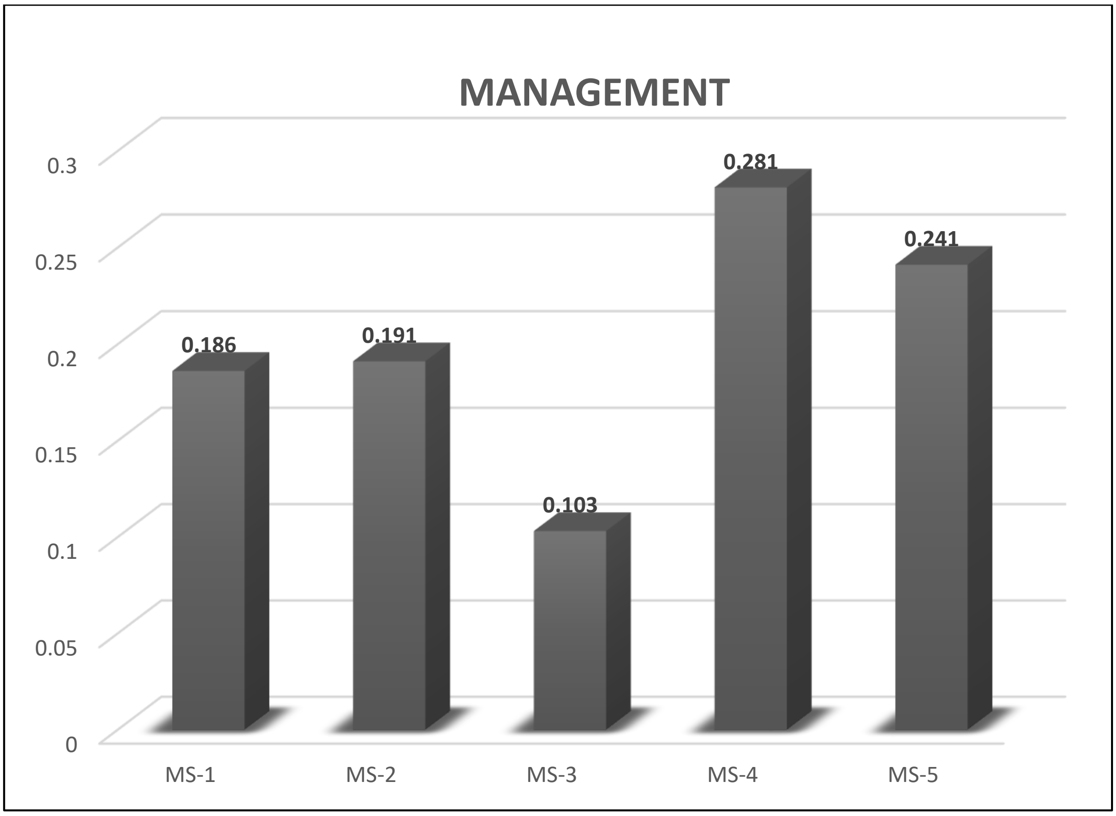



**Figure 4.9 Management criteria sensitivity graph for Maintenance Strategy (MS) in SuperDecisions (SD)**

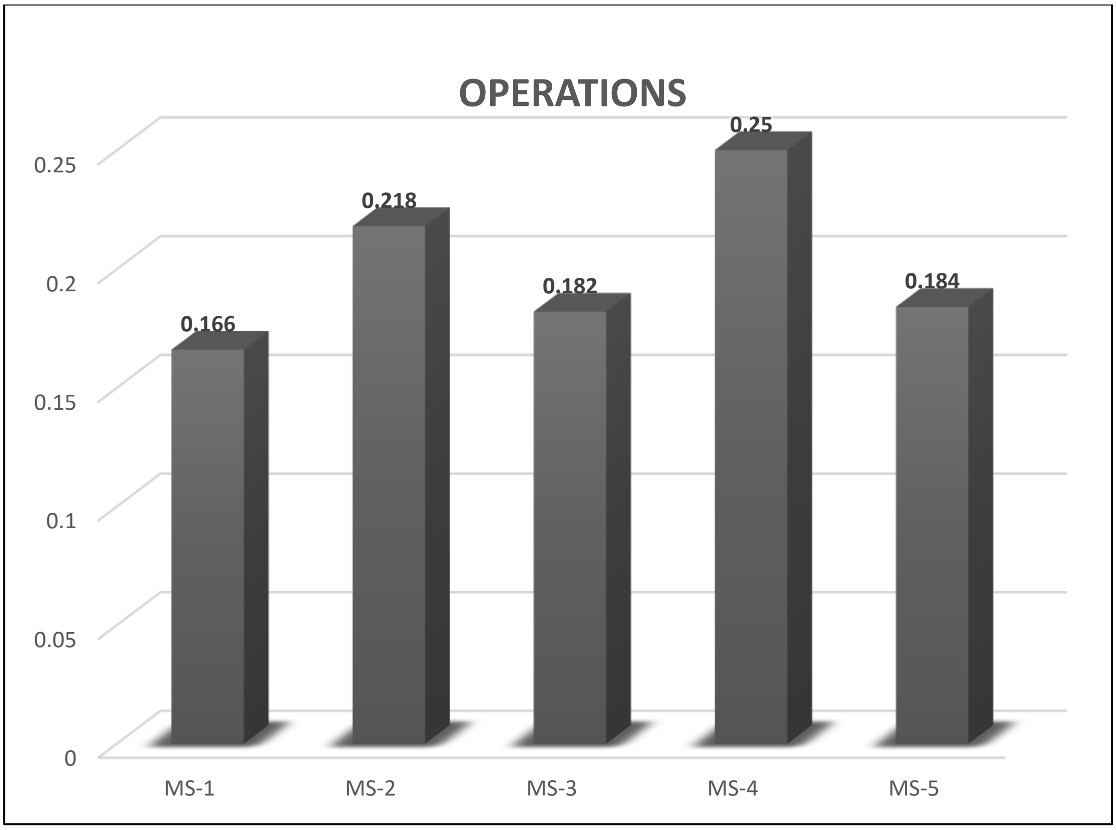



**Figure 4.10 Operations criteria sensitivity graph for Maintenance Strategy (MS) in SuperDecisions (SD)**

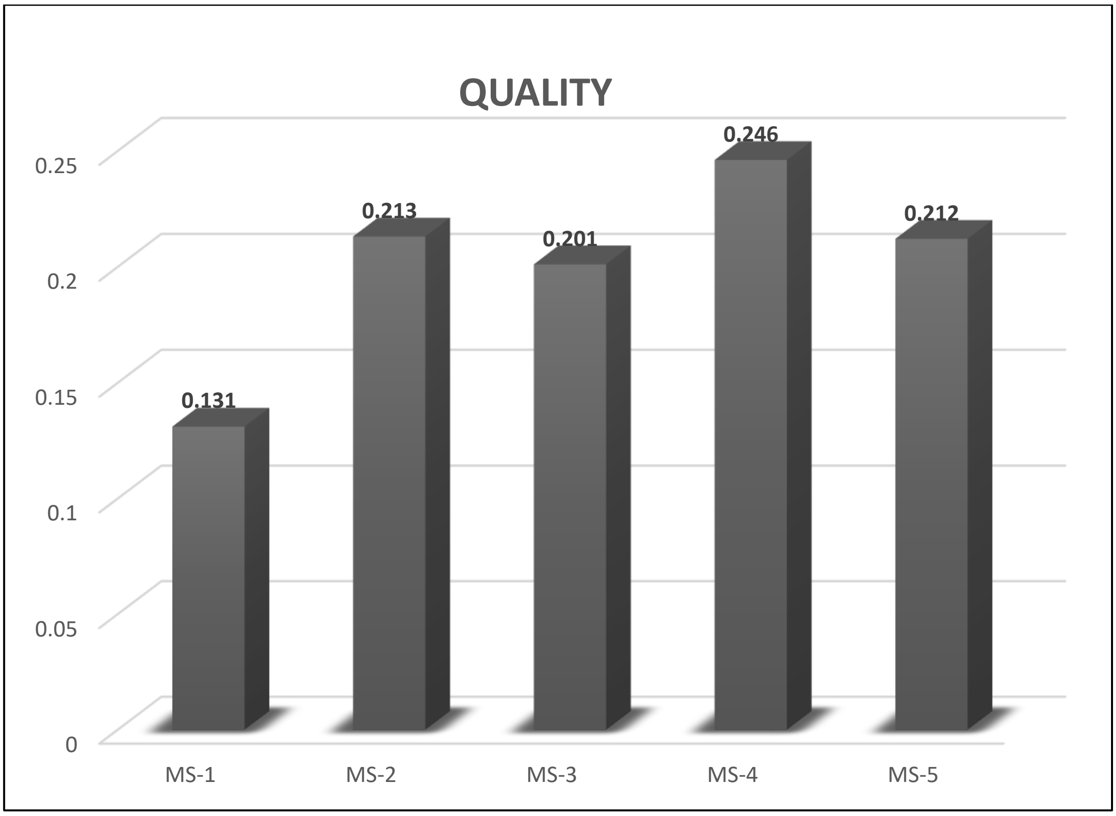



**Figure 4.11 Quality criteria sensitivity graph for Maintenance Strategy (MS) in SuperDecisions (SD)**

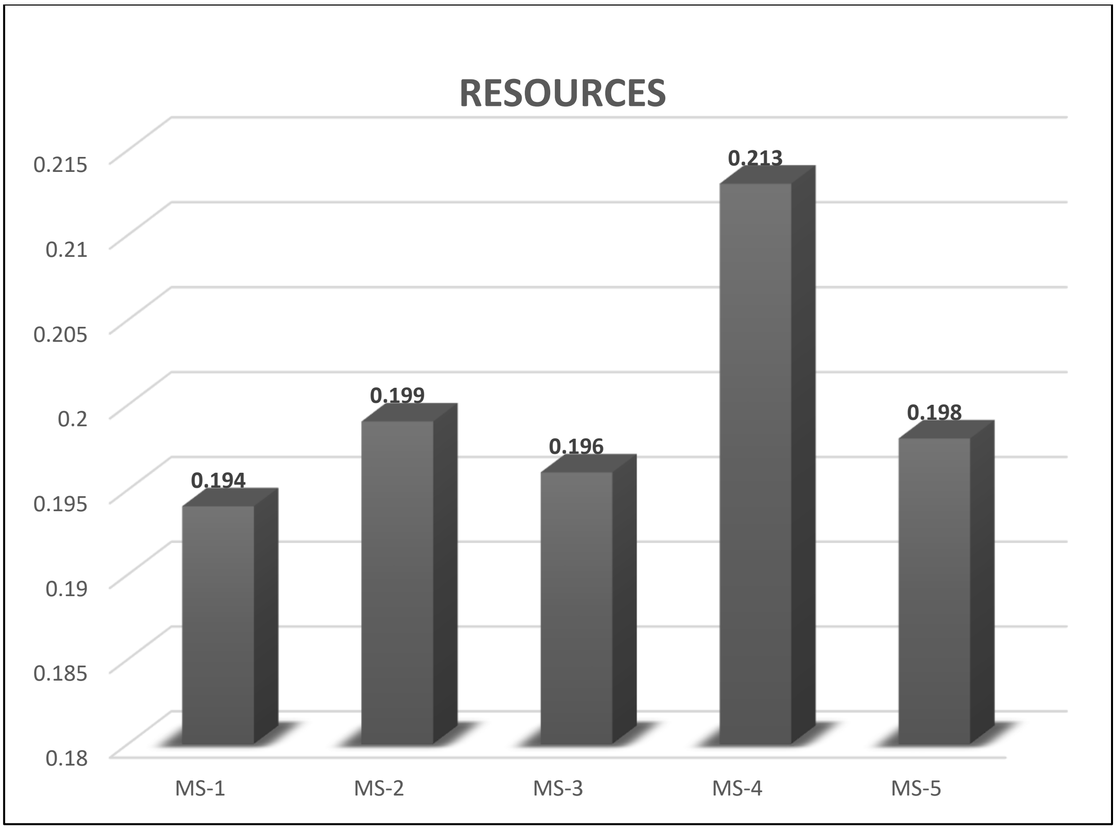



**Figure 4.12 Resources criteria sensitivity graph for Maintenance Strategy (MS) in SuperDecisions (SD)**

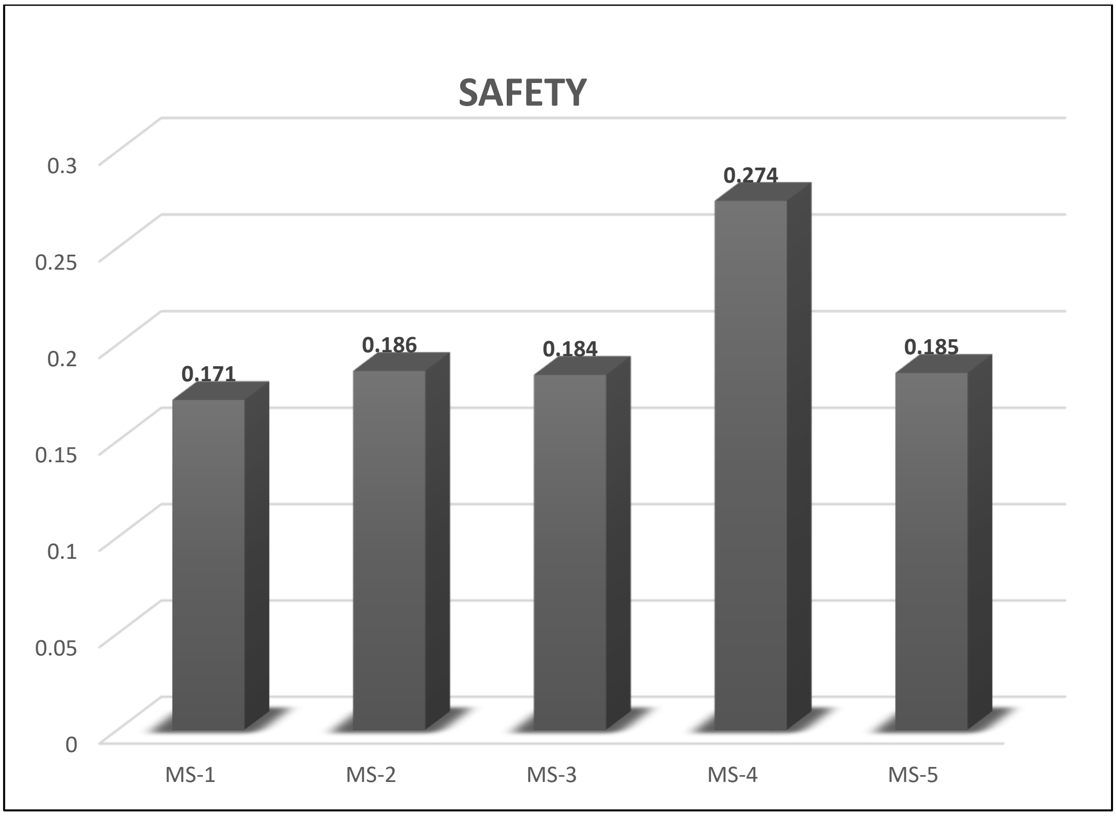



**Figure 4.13 Safety criteria sensitivity graph for Maintenance Strategy (MS) in SuperDecisions (SD)**

## 4.6 Discussions

The hierarchy in Analytic Hierarchy Process (AHP) gives the levels by which the decision makers can be led to a suitable or best possible solution to the decision problem (Ishizaka & Labib, 2011). For the undertaken study, the hierarchy consists of the elements mainly selected from the literature, as the literature on the criteria in Agri-chemical industry and maintenance practices in general is very strong and has a wide scope of practice and application (Abdul-Jawwad & AbuNaffa, 2022). The hierarchy of AHP is fundamental in organizing the decision problem into manageable parts and the process of assigning or calculating priorities to the elements in the hierarchy leads to the best outcome for the decision problem (Triantaphyllou et al., 1995). During the course of the study the most challenging part with the respondents was to brief them about the pair-wise comparisons and to guide them to fill in the reciprocal matrices as the respondents sometimes have difficulty in understanding the outcome of the pair-wise comparison matrices (Mu & Pereyra-Rojas, 2017b). Also, avoidance of the inconsistency in the pair-wise comparison matrices was a task requiring special attention as the final judgements relied heavily on these inconsistency ratios being equal to or less than 10 percent for all matrices (Harker & Vargas, 1987).

### 4.6.1 Energy-Centered Maintenance (ECM)

The novelty in research is the consideration of Energy-Centered Maintenance (ECM) (M. Howell & Alshakhshir, 2017) for potential maintenance type candidates in local and foreign literature. This is a relatively newer maintenance type and thus requires much intense data collection from the machinery deployed (Alshakhshir & Howell, 2021a). With the advances in data analysis tools and techniques it might be possible to incorporate ECM into modern and current practices for maintenance strategies in energy dependent or energy intensive industries (Firdaus et al., 2019). Unfortunately, in this study, ECM could not move pass the respondents in maintenance type candidates scoring. Perceivable causes might be lack of awareness in the maintenance personnel and lack of training for the maintenance teams. There is much gap in literature for the analysis and testing of ECM applications and potential in manufacturing and production industries (Alshakhshir & Howell, 2021b).

### 4.6.2 Maintenance Strategies

Until now the maintenance types have been ranked by the respondents based upon their importance and contribution towards the achievement of the overall goal in AHP methodology of selecting the suitable maintenance strategy for the new Agri-chemical or fertilizer production plant without prior existence of historical machine failure and breakdown data. Next phase for the respondents was to come up with five (5) maintenance strategies incorporating and integrating the ranked and selected maintenance types. This was done in a meeting of all the respondents moderated by the researcher and the number of maintenance strategies which was five (5) was mutually accepted because it left room for more options in the alternatives level of the AHP hierarchy and at the same time accommodated the opinion of all the respondents with much detail.

The maintenance strategies devised by the respondents were:

### 4.6.3 MS-1

Applying opportunistic maintenance during planned and unplanned shutdowns, also combining the condition-based maintenance with planned inspections and applying corrective maintenance activities whenever needed.

### 4.6.4 MS-2

Combining activities to deploy a mix of Preventive Maintenance and Corrective maintenance with root cause analysis activities.

### 4.6.5 MS-3

Benefitting from staff experience and history to devise activities based on predictive maintenance and combine with corrective actions to minimize equipment breakdown.

### 4.6.6 MS-4

Using Preventive maintenance to plan and schedule maintenance activities while keeping track of hours the machinery has been run and applying Condition-based maintenance for the equipment after specific planned hours with keeping room for improvement in planning and scheduling tasks targeting for reliability in equipment performance, also applying Corrective maintenance actions for chance breakdowns.

### 4.6.7 MS-5

Run-to-failure maintenance can be used for equipment breakdown as it can keep teams on high alert and activities get automatically prioritized as they come up in real time.

### 4.6.8 Main-Criteria

Once the AHP hierarchy is developed and the goal is defined, the next step is to identify the elements of the next level which consists of the criteria contributing towards the main goal. For the current study, seven (7) main-criteria were identified from the literature and presented to the respondents for scoring and discussions.

The main-criteria are the main contributors towards the selection of suitable maintenance strategy for a new Agri-chemical or fertilizer production plant in Pakistan. These criteria must be relevant and have enough significance as they are sub divided into other sub-criteria.

### 4.6.9 Sub-Criteria

After the main-criteria are identified, the next step is to identify the sub-criteria which contributes to the priorities of the main-criteria which in turn contributes towards the overall goal achievement. A list of thirty-eight (38) sub-criteria were presented to the respondents, selected in advance from the literature. Out of these twenty-three (23) were selected to proceed for further round of calculations.

# CHAPTER 5. CONCLUSION

The study conducted by the researcher delves into the Multi-Criteria Decision Making (MCDM) techniques and uses Analytic Hierarchy Process (AHP) methodology to select a suitable maintenance strategy for a newly completed fertilizer production facility in Pakistan, thus, resulting in multiple rounds of questionnaires with various scales and types, to gauge the responses of the experts and come up with the best maintenance strategy with the help of a mix of maintenance types which formulate the alternatives. Then finally, from those alternatives, with the help of experts and calculated priorities through pair-wise comparison matrices, the AHP renders a best or most suitable single maintenance strategy for the new fertilizer production facility, even with the non-existing historical record of machine failure and regular issues. Also, the calculations were performed through two methods, numerical and software based. The results from the numerical method were validated by the software and they were found to be in acceptable deviations. The foremost conclusion given by the study is in the form of visible lack of knowledge of maintenance personnel in Pakistan regarding the formulation and implementation of maintenance strategies, in general for the whole industrial infrastructure and in specific for the fertilizer industry of Pakistan. Maintenance is an issue effecting the cost of inputs side for the manufacturing and process industries and is taken seriously by the organizations and personnel; however, negligible focus is rendered for the formulation, implementation, execution and feedback loops to improve and organize the maintenance activities. The study seems to provide another conclusion, such that, there is little understanding of maintenance types in the fertilizer industries in Pakistan, both the organizational leadership and the maintenance engineers have little to no understanding of maintenance types or at least not enough understanding to formulate a practical and actionable strategy. The most relied upon maintenance type is run-to-failure and maintenance personnel seems to be comfortable with this type. However, the adverse effects on supply chain and maintenance costs appear in the quarterly and annual maintenance expenditure reports.

The study thus completed, further concluded that the panel of experts formed the most important part of the whole decision-making process and the most challenges were also associated with the management of the human factor. As the schedules and willingness at times of the experts to contribute towards the questionnaires and responses differed almost regularly. It also became a bit of a work to gather all the respondents at the same time and at the same table to brainstorm maintenance strategies while at the same time briefing them about the inherent differences of the maintenance types used in development of maintenance strategies for best alternative selection. The final conclusion made by the researcher can be attributed to the immense use of practical MCDM techniques such as Analytic hierarchy Process (AHP) for decision making in complex and uncertain environments such as fertilizer production plants. This approach can be used in multiple industrial settings among the SME and LSM industry of Pakistan to initiate an academic and research movement, hopefully, to bring about change in the traditional maintenance styles and mindsets of the maintenance management personnel in the rapidly evolving industries in developing nations such as Pakistan

## 5.1 Future Research

At the end of the study, it becomes imperative to take into perspective and consider the amount of time and effort that went into the study, to layout and explore the avenues that might provide some insight to the future implications of the study. Broader issues can be addressed and modern solutions to traditional problems can be researched, experimented upon, and implemented for the betterment of the industry in specific and the world around us in general. Along with the Analytic Hierarchy Process (AHP), Thomas L. Saaty with multiple researchers also presented Analytic Network Process (ANP). In ANP process, the criteria have evident dependence on one another. This dependence makes the criteria more volatile in comparison to each other. The network ultimately becomes complex and the normal AHP does not render credible priorities.

Thus, ANP provides another avenue for the researchers to select practical and suitable maintenance strategy for the process and manufacturing industries in Pakistan. For the co-dependent criteria with broader scope and high specific impact on the maintenance activities in fertilizer or other process industries ANP can be effective way for not only maintenance strategy selection but also for other decision-making process that influence the industry in great effect. In recent times, Artificial intelligence is being incorporated in all the technical fields within the reach of mankind. The immense impact, scope and utility of Artificial intelligence has produced impressive results for the technological advances in almost all the primary and allied fields of study. This can be a great avenue to make use of this technology and the others like it for maintenance functions. Similarly, for the maintenance strategy selection the AI tools and techniques can be incorporated into existing practices to enhance the decision-making process and obtain precise results. This could further lead the researchers into a broad scope of action especially in Pakistan. Digitalization and sustainability are important topics for manufacturing industries as they are affecting all parts of the production chain. Various initiatives and approaches are set up to help companies adopt the principles of the fourth industrial revolution with respect to sustainability. Within these actions the use of modern maintenance approaches such as Maintenance 4.0 is highlighted as one of the prevailing smart & sustainable manufacturing topics. The latest trends within the area of maintenance management from the perspective of the challenges of the fourth industrial revolution and the economic, environmental, and social challenges of sustainable development can be seen through the lens of maintenance 4.0. Intelligent and sustainable maintenance can be considered in three perspectives. The first perspective is the historical perspective, in relation to which evolution has been presented in the approach to maintenance in accordance with the development of production engineering. The next perspective is the development perspective, which presents historical perspectives on maintenance data and data-driven maintenance technology. The third perspective presents maintenance in the context of the dimensions of sustainable development and potential opportunities for including data-driven maintenance technology in the implementation of the economic, environmental, and social challenges of sustainable production. This presents the researchers and academics as well as the industry practitioners with a lot of potential areas to advance their individual and collective knowledge for pragmatic approaches towards the industry. With the advances in the maintenance related activities and monitoring of those activities, therein lies a potential for the researchers to gather and make capable use of the massive amount of data. This maintenance data can potentially be a rich source of much better decision making and more complex systems can be easily monitored and better decisions regarding the uptime of machinery and reduction in costs of maintenance functions can be achieved. Based upon the gathered data the researchers can aim to build comprehensive and decisive Maintenance Decision Support Systems (MDSS) for the LSMs and SMEs to enhance the productivity in their maintenance functions and thus keeping the machinery in ready and working condition for the longer than intended periods. MDSS can be made to possess the capability of storing multiple data gathered from multiple points. Those multiple points can be sensors from an internet of Things (IOT) system deployed anywhere, in any kind of industrial setting to monitor the condition of important machinery, power consumption, reliability centered activities and other maintenance activities. The data gathered from these IOT systems can be input and organized in the MDSS to make important decisions regarding the maintenance systems that are much more complex to handle otherwise. The created MDSSs will make information available to the public and private sector organizations thus setting an exemplary industrial database for the rapid positive transformation of the industrial sector. Especially, for Pakistan as an agrarian state, the increase in farm mechanization has brought about a revolution in the millennia old traditional farming. Farmers are starting to incorporate modern machinery, either imported or indigenized to improve crop yields and save input costs.

The modern farms in Pakistan have seen a diverse group of machinery installation for providing different benefits on the localized farm environment. The different machinery and equipment installation systems on the farm require special initiatives for maintenance. Thus, special research efforts should be made to develop maintenance strategies and maintenance strategy selection techniques for the new mechanized farms with no historical data for machine failure and machinery breakdown. This would help extend the lessons learned from the current study in the much-neglected area of the country’s economy, ultimately providing the small farmers the means to reduce their input costs. After mechanized farms the next revolution in agricultural farming technologies and techniques are shifting towards precision agriculture. Smart IOT farms and orchids are being deployed all over Pakistan to develop the skills and human resource necessary to bring about the agricultural revolution that Pakistan has been waiting for. Precision Agriculture requires the deployment of smart sensors that collect soil nutrients deficiency data, moisture data, monitoring of weather-related parameters for rainfall and season change predictions, smart irrigation systems involving relatively sensitive machinery on the farm, mechanized heavy machinery such as tractors, field and lab electronics, renewable energy resources, drone technology and advanced spectral-imagery. These points provide a lot of potential for data gathering and the system on IOT farms for precision agriculture also require maintenance and there is a massive gap in literature for academia and researchers to tap into. This provides massive opportunities to develop research and practical capacity for the academia and the skills for human resource to provide maintenance services in the field of Precision Agriculture. In accordance with the United Nations' Sustainable Development Goals 2030 (UN SDGs 2030), the development of sustainable agriculture falls under the SDG # 2 and the industry, innovation and infrastructure SDG # 9, SDG # 17 corresponds to partnerships for the goals through which the UN agenda 2030 will be made possible.

Maintenance management can fall under the jurisdiction of SDG # 9 dealing with industrial capacity building, innovation, and sustainable manufacturing. For this SDG the maintenance function for the production plants in Pakistan can be focused for research and academia to form partnerships between research institutions, academic institutions, government support and industrial partners. The learning and progress can be extended into the maintenance management of agricultural sector in Precision Agriculture, Farm Mechanization and Agri-chemicals or fertilizer production facilities for the increased supply at lower cost, thus affecting positively the economic factors involved in the manufacturing and logistical supply chains. As seen from above discussion, there lies a lot of potential in direct and indirect relation to the research, academics and industry for the local researchers, academicians and industry practitioners to foster maintenance management, develop maintenance functions, formulate, implement, execute and improve the maintenance strategy selection process via MCDM techniques such as AHP for the fertilizer industry in specific, and all the industrial sectors in general, thus contributing effectively to the country's economic prosperity.

# References

Abdul-Jawwad, A. K., & AbuNaffa, I. (2022). Applying analytical hierarchy process (AHP) in selecting best maintenance strategies for newly established chemical fertilizers plants. *Journal of Quality in Maintenance Engineering*, *28*(3), 545–566. https://doi.org/10.1108/JQME-06-2020-0056

Adams, B. (2011). SuperDecisions limit matrix calculations. *USA: Decision Lens Inc*.

Adams, W. J. L., & Saaty, R. (2003). Super decisions software guide. *Super Decisions*, *9*, 43.

Aghaee, A., Aghaee, M., Fathi, M. R., Shoa'bin, S., & Sobhani, S. M. (2020). A novel fuzzy hybrid multi-criteria decision-making approach for evaluating maintenance strategies in petrochemical industry. *Journal of Quality in Maintenance Engineering*, *27*(2), 351–365. https://doi.org/10.1108/jqme-04-2019-0036

Ahmad, Y., & Pirzada, D. S. (2014). Using Analytic Hierarchy Process for Exploring Prioritization of Functional Strategies in Auto Parts Manufacturing SMEs of Pakistan. *SAGE Open*, *4*(4), 215824401455356. https://doi.org/10.1177/2158244014553560

Ahmadi, A., Arasteh Khouy, I., Kumar, U., & Schunnesson, H. (2009). Selection of maintenance strategy, using analytical hierarchy process. *Communications in Dependability and Quality Management*, *12*(1), 121–132.

Al-Harbi, K. M. A.-S. (2001). Application of the AHP in project management. *International Journal of Project Management*, *19*(1), 19–27.

Ali, M., Ahmed, F., Channa, H., & Davies, S. (Eds.). (2015). *The Role of Regulations in the Fertilizer Sector of Pakistan*. https://doi.org/10.22004/ag.econ.211559

Alshakhshir, F., & Howell, M. T. (2021a). Chapter 2 Different Maintenance Types and the Need for Energy Centered Maintenance. In *Data Driven Energy Centered Maintenance* (pp. 21–30).

Alshakhshir, F., & Howell, M. T. (2021b). *Data Driven Energy Centered Maintenance*. CRC Press.

Animah, I., & Shafiee, M. (2021). Maintenance strategy selection for critical shipboard machinery systems using a hybrid AHP-PROMETHEE and cost benefit analysis: A case study. *Journal of Marine Engineering & Technology*, *20*(5), 312–323. https://doi.org/10.1080/20464177.2019.1572705

Arjomandi, M. A., Dinmohammadi, F., Mosallanezhad, B., & Shafiee, M. (2021). A fuzzy DEMATEL-ANP-VIKOR analytical model for maintenance strategy selection of safety critical assets. *Advances in Mechanical Engineering*, *13*(4), 168781402199496. https://doi.org/10.1177/1687814021994965

Asuquo, M. P., Wang, J., Zhang, L., & Phylip-Jones, G. (2019). Application of a multiple attribute group decision making (MAGDM) model for selecting appropriate maintenance strategy for marine and offshore machinery operations. *Ocean Engineering*, *179*, 246–260. https://doi.org/10.1016/j.oceaneng.2019.02.065

Ayub, M. A. (1975). An Econometric Study of the Demand for Fertilizers in Pakistan. *The Pakistan Development Review*, *14*(1), 135–141. https://doi.org/10.30541/v14i1pp.135-141

Ayub, M., Nadeem, M. A., Sharar, M. S., & Mahmood, N. (2002). Response of maize (Zea mays L.) fodder to different levels of nitrogen and phosphorus. *Asian Journal of Plant Sciences*, *1*(4), 352–354.

Azadeh, A., & Abdolhossein Zadeh, S. (2016). An integrated fuzzy analytic hierarchy process and fuzzy multiple-criteria decision-making simulation approach for maintenance policy selection. *SIMULATION*, *92*(1), 3–18. https://doi.org/10.1177/0037549715616686

Azizi, A., & Fathi, K. (2014). Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process. *Management Science Letters*, *4*(5), 893–898. https://doi.org/10.5267/j.msl.2014.3.028

Baddeley, A., Shiffrin, R. M., Nosofsky, R. M., & Miller, G. A. (1994). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *101*(2,343-352).

Bashiri, M., Badri, H., & Hejazi, T. H. (2011). Selecting optimum maintenance strategy by fuzzy interactive linear assignment method. *Applied Mathematical Modelling*, *35*(1), 152–164. https://doi.org/10.1016/j.apm.2010.05.014

Bayazit, O. (2005). Use of AHP in decision-making for flexible manufacturing systems. *Journal of Manufacturing Technology Management*, *16*(7), 808–819.

Belton, V., & Gear, T. (1983). On a short-coming of Saaty's method of analytic hierarchies. *Omega*, *11*(3), 228–230.

Ben-Daya, M., Duffuaa, S. O., Raouf, A., Knezevic, J., & Ait-Kadi, D. (2009). *Handbook of maintenance management and engineering* (Vol. 7). Springer.

Ben-Daya, M., Kumar, U., & Murthy, D. P. (2016). *Introduction to maintenance engineering: Modelling, optimization and management*. John Wiley & Sons.

Bertolini, M., & Bevilacqua, M. (2006). A combined goal programming—AHP approach to maintenance selection problem. *Reliability Engineering & System Safety*, *91*(7), 839–848. https://doi.org/10.1016/j.ress.2005.08.006

Bevilacqua, M., & Braglia, M. (2000). The analytic hierarchy process applied to maintenance strategy selection. *Reliability Engineering & System Safety*, *70*(1), 71–83. https://doi.org/10.1016/S0951-8320(00)00047-8

Borjalilu, N., & Ghambari, M. (2018). Optimal maintenance strategy selection based on a fuzzy analytical network process: A case study on a 5-MW powerhouse. *International Journal of Engineering Business Management*, *10*, 184797901877617. https://doi.org/10.1177/1847979018776172

Braglia, M., Castellano, D., & Frosolini, M. (2013). An integer linear programming approach to maintenance strategies selection. *International Journal of Quality & Reliability Management*, *30*(9), 991–1016. https://doi.org/10.1108/IJQRM-05-2012-0059

Campbell, J. D., Reyes-Picknell, J. V., & Kim, H. S. (2015). *Uptime: Strategies for excellence in maintenance management*. CRC Press.

Carnero, M. C., & Gómez, A. (2017). Maintenance strategy selection in electric power distribution systems. *Energy*, *129*, 255–272. https://doi.org/10.1016/j.energy.2017.04.100

Cvetkovska, V. (2022). Book review of "Practical Decision Making: An Introduction to the Analytic Hierarchy Process (AHP) Using Super Decisions v2" by Enrique Mu and Milagros Pereyra-Royas (2017). *Management: Journal of Sustainable Business and Management Solutions in Emerging Economies*, *27*(2), 83–85.

Dachyar, M., Nurcahyo, R., & Tohir, Y. (2018). Maintenance strategy selection for steam power plant in range of capacity 300-625 MW in Indonesia. *ARPN Journal of Engineering and Applied Sciences*, *13*(7), 2571–2580.

Dalalah, D., Al-Oqla, F., & Hayajneh, M. (2010). Application of the Analytic Hierarchy Process (AHP) in multi-criteria analysis of the selection of cranes. *Jordan Journal of Mechanical & Industrial Engineering*, *4*(5).

Dorri, M., Kazemipour, H., & Peydaei, M. M. (2014). Proposing a model for the selection of repair & maintenance strategy for it systems with the help of dematel & ANP fuzzy process. *Kuwait Chapter of the Arabian Journal of Business and Management Review*, *3*(6), 202.

Dyer, J. S. (1990). Remarks on the analytic hierarchy process. *Management Science*, *36*(3), 249–258.

Farajiparvar, N., & Mayorga, R. V. (2018). Maintenance policy selection using fuzzy failure modes and effective analysis and key performance indicators. *International Journal of Productivity and Quality Management*, *25*(2), 170–197.

Fertilizers Sector Study. (2023). In *Pacra.com*. Pakistan Credit Rating Agency. https://www.pacra.com/sector_research/Fertilizers%20-%20PACRA%20Research%20-%20Jan'23_1676028125.pdf

Firdaus, N., Samat, H. A., & Mohamad, N. (2019). Maintenance for Energy efficiency: A Review. *IOP Conference Series: Materials Science and Engineering*, *530*(1), 012047. https://doi.org/10.1088/1757-899X/530/1/012047

Fouladgar, M. M., Yazdani-Chamzini, A., Lashgari, A., Zavadskas, E. K., & Turskis, Z. (2012). Maintenance Strategy Selection using AHP and COPRAS under FUZZY Environment. *International Journal of Strategic Property Management*, *16*(1), 85–104. https://doi.org/10.3846/1648715X.2012.666657

Gackowiec, P. (2019). General overview of maintenance strategies – concepts and approaches. *Multidisciplinary Aspects of Production Engineering*, *2*(1), 126–139. https://doi.org/10.2478/mape-2019-0013

Galankashi, M. R., Khorramrouz, F., Esmaeilnezhad, M., Rafiei, F. M., & Hisjam, M. (2020). *Maintenance strategy selection in a cement company: An integrated AHP-FAHP approach*. 030197. https://doi.org/10.1063/5.0000519

Gandhare, B. S., Akarte, M. M., & Patil, P. P. (2018). Maintenance performance measurement – a case of the sugar industry. *Journal of Quality in Maintenance Engineering*, *24*(1), 79–100. https://doi.org/10.1108/JQME-07-2016-0031

Harker, P. T. (1989). The Art and Science of Decision Making: The Analytic Hierarchy Process. In B. L. Golden, E. A. Wasil, & P. T. Harker (Eds.), *The Analytic Hierarchy Process: Applications and Studies* (pp. 3–36). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-50244-6_2

Harker, P. T., & Vargas, L. G. (1987). The theory of ratio scale estimation: Saaty's analytic hierarchy process. *Management Science*, *33*(11), 1383–1403.

Holder, R. D. (1990). Some Comments on the Analytic Hierarchy Process. *Journal of the Operational Research Society*, *41*(11), 1073–1076. https://doi.org/10.1057/jors.1990.167

Howell, M., & Alshakhshir, F. S. (2017). Chapter 3 The Energy Centered Maintenance Origin and Model. In *Energy Centered Maintenance—A Green Maintenance System* (pp. 35–42).

Howell, M. T., & Alshakhshir, F. (2020). *Energy Centered Maintenance: A Green Maintenance System*. CRC Press.

Ilangkumaran, M., & Kumanan, S. (2012). Application of Hybrid VIKOR Model in Selection of Maintenance Strategy. *International Journal of Information*

*Systems and Supply Chain Management*, *5*(2), 59–81. https://doi.org/10.4018/jisscm.2012040104

Ishizaka, A., & Labib, A. (2011). Review of the main developments in the analytic hierarchy process. *Expert Systems with Applications*, *38*(11), 14336–14345. https://doi.org/10.1016/j.eswa.2011.04.143

Jawwad, A. A., & Saleem, M. (2019). *Criticality Analysis of Medical Equipment: A Case Study at King Hussein Cancer Center (KHCC) Amman-Jordan*.

Karsak, E. E., & Tolga, E. (2001). Fuzzy multi-criteria decision-making procedure for evaluating advanced manufacturing system investments. *International Journal of Production Economics*, *69*(1), 49–64. https://doi.org/10.1016/s0925-5273(00)00081-5

Kelly, A. (2006). *Plant Maintenance Management Set*. Butterworth-Heinemann.

Kodali, R., Prasad Mishra, R., & Anand, G. (2009). Justification of world-class maintenance systems using analytic hierarchy constant sum method. *Journal of Quality in Maintenance Engineering*, *15*(1), 47–77. https://doi.org/10.1108/13552510910943886

Kumar, D., & Pandey, P. C. (1993). Maintenance planning and resource allocation in a urea fertilizer plant. *Quality and Reliability Engineering International*, *9*(5), 411–423. https://doi.org/10.1002/qre.4680090505

Kumar, G., & Maiti, J. (2012). Modeling risk based maintenance using fuzzy analytic network process. *Expert Systems with Applications*, *39*(11), 9946–9954.

Lazakis, I., & Ölçer, A. (2016). Selection of the best maintenance approach in the maritime industry under fuzzy multiple attributive group decision-making environment. *Proceedings of the Institution of Mechanical Engineers, Part M:*

*Journal of Engineering for the Maritime Environment*, *230*(2), 297–309. https://doi.org/10.1177/1475090215569819

Macharis, C., Springael, J., De Brucker, K., & Verbeke, A. (2004). PROMETHEE and AHP: The design of operational synergies in multicriteria analysis.: Strengthening PROMETHEE with ideas of AHP. *European Journal of Operational Research*, *153*(2), 307–317.

Mardani, A., Jusoh, A., MD Nor, K., Khalifah, Z., Zakwan, N., & Valipour, A. (2015). Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014. *Economic Research-Ekonomska Istraživanja*, *28*(1), 516–571. https://doi.org/10.1080/1331677X.2015.1075139

Mardani, A., Jusoh, A., Nor, K., Khalifah, Z., Zakwan, N., & Valipour, A. (2015). Multiple criteria decision-making techniques and their applications–a review of the literature from 2000 to 2014. *Economic Research-Ekonomska Istraživanja*, *28*(1), 516–571.

Martin, H., Mohammed, F., Lal, K., & Ramoutar, S. (2019). Maintenance strategy selection for optimum efficiency – application of AHP constant sum. *Facilities*, *38*(5/6), 421–444. https://doi.org/10.1108/F-05-2018-0060

Mobley, R. K. (Ed.). (2002). Contents. In *An Introduction to Predictive Maintenance (Second Edition)* (Second Edition, pp. v–xii). Butterworth-Heinemann. https://doi.org/10.1016/B978-075067531-4/50000-2

Mostafa, M. F., & Fahmy, S. A. (2020). Maintenance Strategy Selection Using AHP: A Case Study in the Oil and Gas Industry. *2020 IEEE 7th International Conference on Industrial Engineering and Applications (ICIEA)*, 1049–1053. https://doi.org/10.1109/ICIEA49774.2020.9101952

Mu, E., & Pereyra-Rojas, M. (2017a). *Practical decision making using super decisions v3: An introduction to the analytic hierarchy process*. Springer.

Mu, E., & Pereyra-Rojas, M. (2017b). Understanding the Analytic Hierarchy Process. In E. Mu & M. Pereyra-Rojas (Eds.), *Practical Decision Making: An Introduction to the Analytic Hierarchy Process (AHP) Using Super Decisions V2* (pp. 7–22). Springer International Publishing. https://doi.org/10.1007/978-3-319-33861-3_2

Mu, E., Pereyra-Rojas, M., Mu, E., & Pereyra-Rojas, M. (2018). Building AHP Models Using Super Decisions v3. *Practical Decision Making Using Super Decisions v3: An Introduction to the Analytic Hierarchy Process*, 23–42.

Nezami, F. G., & Yildirim, M. B. (2013). A sustainability approach for selecting maintenance strategy. *International Journal of Sustainable Engineering*, *6*(4), 332–343. https://doi.org/10.1080/19397038.2013.765928

Nguyen, T. A. T., & Chou, S.-Y. (2018). Maintenance strategy selection for improving cost-effectiveness of offshore wind systems. *Energy Conversion and Management*, *157*, 86–95. https://doi.org/10.1016/j.enconman.2017.11.090

Niebel, B. W. (2014a). *Engineering Maintenance Management* (2nd ed.). CRC Press. https://doi.org/10.1201/9781482293531

Niebel, B. W. (2014b). *Engineering Maintenance Management* (2nd ed.). CRC Press. https://doi.org/10.1201/9781482293531

Oecd, F. (2022). *OECD-FAO Agricultural Outlook 2022-2031*.

Ohta, R. (2018). SELECTION OF INDUSTRIAL MAINTENANCE STRATEGY: CLASSICAL AHP AND FUZZY AHP APPLICATIONS. *International Journal of the Analytic Hierarchy Process*, *10*(2). https://doi.org/10.13033/ijahp.v10i2.551

Özcan, E. C., Ünlüsoy, S., & Eren, T. (2017). A combined goal programming – AHP approach supported with TOPSIS for maintenance strategy selection in hydroelectric power plants. *Renewable and Sustainable Energy Reviews*, *78*, 1410–1423. https://doi.org/10.1016/j.rser.2017.04.039

Pakistan Stock Exchange (PSX). (2022). *PSX-year-2022.xlsx* [Analysis Report]. Pakistan Stock Exchange (PSX). https://dps.psx.com.pk/download/analysis_report/year-2022.xlsx

Palcic, I., & Lalic, B. (2009). Analytical Hierarchy Process as a tool for selecting and evaluating projects. *International Journal of Simulation Modelling (IJSIMM)*, *8*(1).

Panchal, D., Chatterjee, P., Shukla, R. K., Choudhury, T., & Tamosaitiene, J. (2017a). Integrated Fuzzy AHP-Codas Framework for Maintenance Decision in Urea Fertilizer Industry. *Economic Computation & Economic Cybernetics Studies & Research*, *51*(3).

Panchal, D., Chatterjee, P., Shukla, R. K., Choudhury, T., & Tamosaitiene, J. (2017b). Integrated Fuzzy AHP-Codas Framework for Maintenance Decision in Urea Fertilizer Industry. *Economic Computation & Economic Cybernetics Studies & Research*, *51*(3).

Panchal, D., & Kumar, D. (2017a). Maintenance decision-making for power generating unit in thermal power plant using combined fuzzy AHP-TOPSIS approach. *International Journal of Operational Research*, *29*(2), 248–272.

Panchal, D., & Kumar, D. (2017b). Maintenance decision-making for power generating unit in thermal power plant using combined fuzzy AHP-TOPSIS approach. *International Journal of Operational Research*, *29*(2), 248–272. https://doi.org/10.1504/IJOR.2017.083958

Parida, A., & Chattopadhyay, G. (2007). Development of a multi-criteria hierarchical framework for maintenance performance measurement (MPM). *Journal of Quality in Maintenance Engineering*, *13*(3), 241–258. https://doi.org/10.1108/13552510710780276

Park, M. (2001). *The fertilizer industry*. Woodhead Publishing.

Patil, A., Soni, G., Prakash, A., & Karwasra, K. (2022). Maintenance strategy selection: A comprehensive review of current paradigms and solution approaches. *International Journal of Quality & Reliability Management*, *39*(3), 675–703. https://doi.org/10.1108/IJQRM-04-2021-0105

Pophaley, M., & Vyas, R. K. (2010). Choice criteria for maintenance strategy in automotive industries. *International Journal of Management Science and Engineering Management*, *5*(6), 446–452. https://doi.org/10.1080/17509653.2010.10671136

Saaty, R. W. (1987). The analytic hierarchy process—What it is and how it is used. *Mathematical Modelling*, *9*(3), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Saaty, R. W., & Saaty, T. L. (2003). Super decisions. *Software for Decision Making with Dependence and Feedback. Tutorial*.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, *15*(3), 234–281. https://doi.org/10.1016/0022-2496(77)90033-5

Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, priority setting, resource allocation*. McGraw-Hill International Book Company.

Saaty, T. L. (1987). Rank generation, preservation, and reversal in the analytic hierarchy decision process. *Decision Sciences*, *18*(2), 157–177.

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, *48*(1), 9–26.

Saaty, T. L. (2001a). Decision making with the analytic network process (ANP) and its super decisions software: The national missile defense (NMD) example. *ISAHP 2001 Proceedings*, 2–4.

Saaty, T. L. (2001b). Decision making with the analytic network process (ANP) and its super decisions software: The national missile defense (NMD) example. *ISAHP 2001 Proceedings*, 2–4.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, *1*(1), 83. https://doi.org/10.1504/IJSSCI.2008.017590

Salonen, A. (2011). Service transition strategies of industrial manufacturers. *Industrial Marketing Management*, *40*(5), 683–690.

Schuh, G., Lorenz, B., Winter, C.-P., & Gudergan, G. (2010). The House of Maintenance-Identifying the potential for improvement in internal maintenance organizations by means of a capability maturity model. *Engineering Asset Lifecycle Management: Proceedings of the 4th World Congress on Engineering Asset Management (WCEAM 2009), 28-30 September 2009*, 15–24.

Seiti, H., Hafezalkotob, A., Najafi, S. E., & Khalaj, M. (2019). Developing a novel risk-based MCDM approach based on D numbers and fuzzy information axiom and its applications in preventive maintenance planning. *Applied Soft Computing*, *82*, 105559.

Seiti, H., Tagipour, R., Hafezalkotob, A., & Asgari, F. (2017). Maintenance strategy selection with risky evaluations using RAHP. *Journal of Multi-Criteria Decision Analysis*, *24*(5–6), 257–274. https://doi.org/10.1002/mcda.1618

Shafi, M., Bakht, J., Jan, M. T., & Shah, Z. (2007). Soil C and N dynamics and maize (Zea may L.) yield as affected by cropping systems and residue management in North-western Pakistan. *Soil and Tillage Research*, *94*(2), 520–529.

Shafiee, M. (2015a). Maintenance strategy selection problem: An MCDM overview. *Journal of Quality in Maintenance Engineering*, *21*(4), 378–402. https://doi.org/10.1108/JQME-09-2013-0063

Shafiee, M. (2015b). Maintenance strategy selection problem: An MCDM overview. *Journal of Quality in Maintenance Engineering*, *21*(4), 378–402. https://doi.org/10.1108/JQME-09-2013-0063

Shafiee, M., Labib, A., Maiti, J., & Starr, A. (2019). Maintenance strategy selection for multi-component systems using a combined analytic network process and cost-risk criticality model. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *233*(2), 89–104. https://doi.org/10.1177/1748006X17712071

Srdjevic, B., & Srdjevic, Z. (2023). Prioritisation in the analytic hierarchy process for real and generated comparison matrices. *Expert Systems with Applications*, *225*, 120015. https://doi.org/10.1016/j.eswa.2023.120015

Srivastava, P., Khanduja, D., & Agrawal, V. P. (2018). Integrating agile thinking into maintenance strategy performance analysis. *International Journal of Process Management and Benchmarking*, *8*(2), 228–245.

*The fertilizer industry, world food supplies and the environment*. (1998). IFA : UNEP.

Thor, J., Ding, S.-H., & Kamaruddin, S. (2013). Comparison of multi criteria decision making methods from the maintenance alternative selection perspective. *The International Journal of Engineering and Science*, *2*(6), 27–34.

Triantaphyllou, E., Kovalerchuk, B., Mann, L., & Knapp, G. M. (1997). Determining the most important criteria in maintenance decision making. *Journal of Quality in Maintenance Engineering*, *3*(1), 16–28.

Triantaphyllou, E., Mann, S. H., & others. (1995). Using the analytic hierarchy process for decision making in engineering applications: Some challenges. *International Journal of Industrial Engineering: Applications and Practice*, *2*(1), 35–44.

Waeyenbergh, G., & Pintelon, L. (2004). Maintenance concept development: A case study. *Manufacturing Strategy*, *89*(3), 395–405. https://doi.org/10.1016/j.ijpe.2003.09.008

Wakeel, A., Kiran, A., Shahid, M. R., Bano, Z., & Zia, M. H. (2022). Chapter 5—Trends in nitrogen use and development in Pakistan. In T. Aziz, A. Wakeel, M. A. Watto, M. Sanaullah, M. A. Maqsood, & A. Kiran (Eds.), *Nitrogen Assessment* (pp. 73–97). Academic Press. https://doi.org/10.1016/B978-0-12-824417-3.00002-2

Watson, S. & others. (1982). Assesing attribute weights. *Omega*, *10*(6), 582–583.

Werbińska-Wojciechowska, S., & Winiarska, K. (2023). Maintenance Performance in the Age of Industry 4.0: A Bibliometric Performance Analysis and a Systematic Literature Review. *Sensors*, *23*(3), 1409. https://doi.org/10.3390/s23031409

Yan, R. D., Dunnett, S. J., & Jackson, L. M. (2018). Optimising the maintenance strategy for a multi-AGV system using genetic algorithms. In S. Haugen, A. Barros, C. van Gulijk, T. Kongsvik, & J. E. Vinnem, *Safety and Reliability – Safe Societies in a Changing World* (1st ed., pp. 547–554). CRC Press. https://doi.org/10.1201/9781351174664-67

Zahedi, F. (1986). The analytic hierarchy process—A survey of the method and its applications. *Interfaces*, *16*(4), 96–108.

Zaim, S., Turkyılmaz, A., Acar, M. F., Al-Turki, U., & Demirel, O. F. (2012). Maintenance strategy selection using AHP and ANP algorithms: A case study. *Journal of Quality in Maintenance Engineering*, *18*(1), 16–29. https://doi.org/10.1108/13552511211226166

Zarei, S., & Ghaedi-Kajuei, P. (2017). Evaluation of Various Maintenance Strategies for Reliability Assessment of Thermal Power Plants. *Indonesian Journal of Electrical Engineering and Computer Science*, *7*(3), 617. https://doi.org/10.11591/ijeecs.v7.i3.pp617-624

# Appendices

| Main Criteria | No. | Sub-Criteria | Description | Score |
|---|---|---|---|---|
| Quality | 1 | Service Quality | Efficiency of maintenance activities | |
| | 2 | Products defects | Defects as indications for maintenance problems | |
| | 3 | Quality Procedures | Acceptance for maintenance activity as indicator | |
| | 4 | Impact on Process | Influence of maintenance activities on production process | |
| | 5 | Spare parts quality | The ability for spare parts to fit maintenance or operation needs within machines | |
| Failures | 6 | Equipment Degradation | The ability for spare parts to fit maintenance or operation needs within machines | |
| | 7 | Reliability | The ability for a component to perform its functions over a specified time | |
| | 8 | Maintainability | The ease for equipment to be maintained | |
| | 9 | Failure Frequency | Rate of failure with respect to time | |
| | 10 | Fault identification | The ability to have full diagnosis for each failure | |
| Operations | 11 | Equipment Setup time | Time needed to prepare machine to work | |

| | | | | |
|---|---|---|---|---|
| | **12** | **Equipment Efficiency** | **The percentage between input and output** | |
| | **13** | **Criticality** | **Bottleneck machines that mainly effect production quantities** | |
| | **14** | **Power Consumption** | **Effect of maintenance on machine power consumption** | |
| | **15** | **Machine accessibility** | **The allowance for maintenance staff to reach and repair machine** | |
| **Cost** | **16** | **Software Cost** | **Cost of needed programs for operation** | |
| | **17** | **Personal Wages** | **Wages paid for maintenance staff** | |
| | **18** | **Tool Costs** | **The cost of maintenance tools** | |
| | **19** | **Staff Training Cost** | **Professional training cost** | |
| | **20** | **Spare parts Cost** | **Cost of spare parts** | |
| | **21** | **Operational Cost** | **The effect of maintenance activities on plant operation** | |
| | **22** | **Outsourcing Costs** | **Cost of outsourcing maintenance activities and staff** | |
| **Resources** | **23** | **Skillful human resources** | **Cost of hiring/training skillful maintenance crew** | |
| | **24** | **Role of outsourcing specialists** | **Professionalism of outsourcing staff** | |
| | **25** | **Spare parts availability** | **Availability of spare parts** | |
| | **26** | **Tools availability** | **Availability of tools** | |
| | **27** | **Special software** | **Availability of special software for complicated** | |

| | | | | |
|---|---|---|---|---|
| | | | failure diagnosis and repair | |
| | 28 | Fault detection tools | Ability to perform condition monitoring | |
| Safety | 29 | Personal safety | Any harm caused to personnel | |
| | 30 | Occupational illness | Chronic hazards related to maintenance activities | |
| | 31 | Environmental effects | Influences of maintenance activities on environment | |
| | 32 | Equipment safety | Any damage caused to maintenance equipment | |
| | 33 | Infrastructure safety | Any damage to facilities | |
| Management | 34 | Strategic perspective | Qualified vision for the top management related to maintenance activities | |
| | 35 | Management commitment | The commitment from top management toward maintenance department | |
| | 36 | Employee acceptance | The acceptance and understanding from all employees to the maintenance activities | |
| | 37 | Quality assurance | Root-cause analysis and defect identification | |
| | 38 | Financial support | Top management budgeting and financial support to maintenance department | |

# List of Respondents

| No. | Designation | Education | Experience |
|---|---|---|---|
| R1 | Production Manager | 18 years | 15 years |
| R2 | Assistant Production Manager | 16 years | 12 years |
| R3 | Safety Officer | H.S.E. | 12 Years |
| R4 | Production Supervisor | 12 years | 8 years |
| R5 | Machine Operator | Matric | 3 years |
| R6 | Maintenance Manager | Engineering | 15 years |
| R7 | Mechanical Engineer | Engineering | 5 years |
| R8 | Electrical Engineer | Engineering | 3 years |
| R9 | Maintenance Supervisor Mechanical | B. Tech. | 8 years |
| R10 | Maintenance Supervisor Electrical | B. Tech. | 12 years |
| R11 | Senior Technician Mechanical | Diploma | 20 Years |
| R12 | Senior Technician Electrical | Diploma | 15 Years |

| Score | Relationship |
|---|---|
| **3** | **Maintenance Strategy has a Strong Positive contribution toward meeting the particular criterion** |
| **2** | **Maintenance Strategy has a Relatively Strong Positive contribution toward meeting the particular criterion** |
| **1** | **Maintenance Strategy has a Poor Contribution toward meeting the particular criterion** |
| **0** | **Maintenance Strategy has a Negative effect toward meeting the particular criterion** |

| Maintenance Strategies' Relationship with Sub-Criteria | | | | | | |
|---|---|---|---|---|---|---|
| **Sr no.** | **Sub-criteria** | **MS-1** | **MS-2** | **MS-3** | **MS-4** | **MS-5** |
| **1** | **Service Quality** | | | | | |
| **2** | **Products defects** | | | | | |
| **3** | **Quality Procedures** | | | | | |
| **4** | **Impact on Process** | | | | | |
| **5** | **Spare parts quality** | | | | | |
| **6** | **Equipment Degradation** | | | | | |
| **7** | **Reliability** | | | | | |
| **8** | **Maintainability** | | | | | |
| **9** | **Failure Frequency** | | | | | |
| **10** | **Fault identification** | | | | | |
| **11** | **Equipment Setup time** | | | | | |
| **12** | **Equipment Efficiency** | | | | | |
| **13** | **Criticality** | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **14** | **Power Consumption** | | | | | |
| **15** | **Machine accessibility** | | | | | |
| **16** | **Software Cost** | | | | | |
| **17** | **Personal Wages** | | | | | |
| **18** | **Tool Costs** | | | | | |
| **19** | **Staff Training Cost** | | | | | |
| **20** | **Spare parts Cost** | | | | | |
| **21** | **Operational Cost** | | | | | |
| **22** | **Outsourcing Costs** | | | | | |
| **23** | **Skillful human resources** | | | | | |
| **24** | **Role of outsourcing specialists** | | | | | |
| **25** | **Spare Parts availability** | | | | | |
| **26** | **Tools availability** | | | | | |
| **27** | **Special Software** | | | | | |
| **28** | **Fault detection tools** | | | | | |
| **29** | **Personal safety** | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **30** | **Occupational illness** | | | | | |
| **31** | **Environmental effects** | | | | | |
| **32** | **Equipment safety** | | | | | |
| **33** | **Infrastructure safety** | | | | | |
| **34** | **Strategic perspective** | | | | | |
| **35** | **Management Commitment** | | | | | |
| **36** | **Employee acceptance** | | | | | |
| **37** | **Quality Assurance** | | | | | |
| **38** | **Financial Support** | | | | | |

# Pairwise comparisons between Sub-Criteria

**Quality**

| Criterion | Service Quality | Products Defect | Quality Procedures | Impact on Process |
|---|---|---|---|---|
| Service Quality | | | | |
| Products Defect | | | | |
| Quality Procedures | | | | |
| Impact on Process | | | | |

**Failures**

| Criterion | Reliability | Maintainability | Failure Frequency | Fault Identification |
|---|---|---|---|---|
| Reliability | | | | |
| Maintainability | | | | |
| Failure Frequency | | | | |
| Fault Identification | | | | |

**Operations**

| Criterion | Equipment Setup Time | Equipment Efficiency | Criticality | Power Consumption | Machine Accessibility |
|---|---|---|---|---|---|
| **Equipment Setup Time** | | | | | |
| **Equipment Efficiency** | | | | | |
| **Criticality** | | | | | |
| **Power Consumption** | | | | | |
| **Machine Accessibility** | | | | | |

**Cost**

| Criterion | Spare Parts Cost | Operational Costs | Outsourcing Costs |
|---|---|---|---|
| **Spare Parts Cost** | | | |
| **Operational Costs** | | | |
| **Outsourcing Costs** | | | |

**Resources**

| Criterion | Skillful Human Resources | Fault detection tools |
|---|---|---|
| **Skillful Human Resources** | | |
| **Fault detection tools** | | |

**Safety**

| Criterion | Personal Safety | Occupational Illness |
|---|---|---|
| Personal Safety | | |
| Occupational Illness | | |

**Management**

| Criterion | Management Commitment | Employee Acceptance | Quality assurance |
|---|---|---|---|
| Management Commitment | | | |
| Employee Acceptance | | | |
| Quality assurance | | | |

## Candidates for Maintenance Strategies for New Plant

| Serial no. | Maintenance Type | Score 1-5 |
|---|---|---|
| 1 | Corrective Maintenance | |
| 2 | Preventive Maintenance | |
| 3 | Opportunistic Maintenance | |
| 4 | Condition-Based Maintenance | |
| 5 | Predictive maintenance | |
| 6 | Outsourced Maintenance | |
| 7 | Energy Centered maintenance | |
| 8 | Reliability Centered Maintenance | |
| 9 | Run to failure Maintenance | |
| 10 | Design Centered Maintenance | |