UNIVERSITY OF STRATHCLYDE

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Using Multi-Criteria Decision Analysis to Assess the Health of High Volume, Low Cost Power Network Assets

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ABSTRACT

When power system assets come toward to the end of their lives, actions to maximize their utilisation and extend the lifetime of the assets to limit the capital and operational expenditure are required. The health profile of the assets can be an indicator of whether an asset requires replacement or refurbishment. To obtain the health profile of high volume, low cost assets, such as wood poles, whose maintenance strategies are predominantly age-based, and at the same time, without enough historical and monitoring data provided to monitor the asset condition, this thesis developed an adaptable approach using an improved- Analytic Hierarchy Process (AHP) and Swing Weight (SW) to elicit individual expert judgments on different age/condition criteria which contribute to the overall asset health.

The individual expert judgments are then processed using Delphi method or Logarithmic Pooling Method to derive a synthesised result, which is a score for an asset's health to inform such replacement decisions.

The results show that the health assessment derived from a combination of age and condition altered the replacement and refurbishment maintenance strategy compared to an age-based only approach. The introduction of 'condition' in the health assessment (in addition to 'age') is to ensure the replacement of relatively 'young' assets (with a relatively shorter service length) in poor condition (deterioration occurred) and avoid the replacement of 'older' assets (with a relatively longer service length) which are actually in a good condition (serviceable condition), resulting in inefficient targeting of asset investment. Younger assets, at an age of 9, are required to be replaced after introducing age and condition while only assets above the age of 54 were required to be replaced with age-based only approach. The thesis presents the methodology developed for and applied to wood poles as one more generally suitable for high volume, low cost assets without enough historical and monitoring data provided to monitor the asset condition; where the health of the assets can be assessed by introducing condition criteria into the assessment approach. It uses multiple experts' judgments derived by AHP/SW along with Delphi/Logarithmic Pooling Method to maximize the utilisation and extend the lifetime of the assets and consequently limit the capital and operational expenditure associated with asset replacement and refurbishment.

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CONTENTS

ABBREVIATIONS

UK	United Kingdom
HVHC	High Volume High Cost
HVLC	High Volume Low Cost
LVHC	Low Volume High Cost
MCDA/MCDM	Multiple Criteria Decision Analysis
MEJA	Multiple Experts Judgments Aggregation
DNOs	Distribution network operators
TNOs	Transmission Network Operators
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
Ofgem	Office of Gas and Electricity Markets
DPCR5	Distribution Price Control Review 5
RIIO	Revenue set to deliver strong Incentives, Innovation and Outputs’
CM	Corrective Maintenance
TBM	Time-based Maintenance
CBM	Condition-Based Maintenance
RCM	Reliability-Centred Maintenance
RBM	Risk-Based Maintenance
CBRM	Condition-Based Risk Management

HI	Health Index
LI	Load Index
FR	Fault Rate
AHP	Analytic Hierarchy Process
PC	Pairwise Comparison
C.I.	Consistency Index
R.I.	Random Index
C.R.	Consistency Ratio
SW	Swing Weights
BCS	Best-Case Scenario
WCS	Worst-Case Scenario
EM	Eigenvalue Method
AM	Arithmetic Mean
GM	Geometric Mean
LS	Least Squares
LogPM	Logarithmic Pooling Method
LiPM	Linear Pooling Method
R/R	Refurbishment/Replacement
MTBF	Mean Time between Failure
PoF	Probability of Failure
E.I.	Error Index

CCM	Cooke Method or Cooke’s Classical Model

1 INTRODUCTION

1.1 Motivation

Since the expansion of the UK power network 85 years ago, a large number of assets have been installed and are now coming toward to the end of their lives. This has increased the pressures on network operators and power generators to take actions to maximize the utilisation and extend the lifetime of their assets with limited capital and operational expenditure available, and at the same time maximize any return on investment.

In order to make the best use of assets and the available maintenance and replacement budget, it is essential to assess assets by continual or periodic condition-based monitoring. Risk may be defined as 'the possibility of incurring misfortune or loss' in the dictionary. In the context of a power system, the thesis author uses 'risk' to measure of the probability of faults in power distribution or transmission system occurring and the severity of the consequences it causes to connected consumers. The risk of asset failure involves consideration of the health or condition of assets, the criticality of assets, the cost of assets and the perceived risk of asset failure. The translation from the monitoring data into a risk measurement therefore becomes a key part of the assessment. In the past, especially for high volume, low cost assets, there has been a lack of condition data and assets are commonly replaced or refurbished purely on age or as a result of a failure. This can result in failure to replace relatively 'young' assets in poor condition and similarly, 'older' assets which are actually in a good condition, resulting in inefficient targeting of asset investment. Decisions affecting asset maintenance, refurbishment or replacement are predominantly age-based, though easily informed, may not provide an accurate representation of the health profile of an asset base. Therefore, a workable approach is required to measure the asset risk robustly by integrating a variety of asset risk factors and utilising organisational expertise to offset the lack of asset condition monitoring data, which is commonplace within organisations, particularly when considering high volume, low cost assets.

1.2 Research Objectives

In order to derive the asset risk measurement of high volume, low cost assets without enough historical and monitoring data provided, the objectives of the research focused on:

- Developing an adaptable approach which can produce a health profile of such assets based on expert judgments;
- Providing decision support in the replacement or refurbishment actions to individual asset.

The thesis will firstly document, evaluate and adapt the existing condition-based methodology from a power system utility for the assignment of health index classifications to low volume, high cost (LVHC) assets and then develop a methodology for high volume, low cost (HVLC) assets. The candidate asset type is HV Wood Poles in this thesis, and potentially switchgear in the future. Currently, data available for HV Wood Poles represent pole age and defect types which are derived from on patrol inspections; however, decisions made on replacement are mainly age-based. The required methodology will generate a new health profile contributed to by both age and defect to assist managers in making more accurate and risk mitigating replacement or refurbishment decisions to maximize revenues, minimize expenditures and ensure stable electricity delivery to customers.

1.3 Research Contributions

This thesis proposes an asset assessment method using an expert-based scoring mechanism to address the main objectives outlined in the previous section. The key contributions are highlighted below:

- Develops a robust expert-based multi-criteria decision analysis (MCDA) health assessment methodology. This methodology is designed to inform and support industry decision makers and asset managers in the prioritisation of non-load related asset replacement.
    - Apply different expert knowledge aggregation techniques on power system asset health assessment using a mathematical and behavioural approach.

    - Coordinates the use of MCDA and Multiple Expert Judgments Aggregation (MEJA) techniques to assess asset health based on multiple health criteria, and to manage the subjectivity and conflict associated with individual and joint expert judgment.

- The methodology is designed for asset health assessment where historical condition and maintenance data required for probabilistic/stochastic asset degradation modelling is not available.
    - Developed a generic process and tool for the development of scoring mechanisms for power system assets health assessment. This tool reduces workload and 'unacceptable' consistency while expert judgments were made using MCDA techniques. The inconsistency of the output from MCDA techniques ordinarily requires the repetition of the whole process which is inefficient and time-consuming. An improved process has been developed to reduce the need for such repetition, which makes this conventional approach unscalable when considering large number of criteria.
- Assess the health of asset which classified as high volume low cost (HVLC) asset, using expert judgment where on-line condition monitoring systems are not available or cost-effective.

1.4 Thesis Organization

Chapter 1 introduces the background, motivation, key objectives, and contributions of the thesis.

Chapter 2 summarises the background knowledge related to asset management and health assessment. Furthermore, it focuses on the power system assets including both low volume high cost (LVHC) and high volume low cost (HVLC) assets and different approaches appropriate to these asset categories. It introduces existing health assessment methodologies on assets such as circuit breakers, cables, transformers, and wood poles associated with generation, transmission, and distribution systems.

In Chapter 3, the approach used in the thesis is introduced.

Section 3.1 describes the general concept of MCDA and three major MCDA techniques firstly. The suitability of MCDA techniques is dependent upon the application and the nature of the criteria affecting the decision-making process and the available data. This chapter deconstructs these techniques and appraises them regarding their relative merits and shortcomings, offering an opinion on the specific types of decision-making for which they are most suitable.

Section 3.2 introduces the existing scaling methods for priorities in hierarchical structures.

Section 3.3introduces the concept of MEJA techniques. For projects with multiple experts involved, it is necessary to synthesise their judgments to form a unified consensus using either a mathematical approach or an iterative behavioural approach. This chapter will describe these approaches in detail, with application demonstrated in Chapter 4.

Chapter 4 and Chapter 5 applies two MCDA techniques in the assessment of asset health which, based on expert judgment, have been applied to power system assets as part of this research. This approach is of particular use in assessing the health of HVLC assets (i.e., HV Wood Poles owned by a power system utility) where the capture and storage of quantitative on-line condition monitoring data for this purpose is not available and generally considered not to be cost-effective. All data and experts involved in the application are from a leading UK utility. The experts' experience of conducting inspections across the organisation's population of HV Wood Poles, attaining extensive and varied degrees of knowledge relating to Wood Pole condition and health. In this chapter, MCDA based scoring mechanisms are developed based on four different approaches (arithmetic, eigenvector, geometric mean, and least square) to derive priorities (of 'importance') attached to different health assessment criteria. The results are then compared and analysed. The MCDA scoring mechanism is applied to individual experts with MEJA for the synthesis and aggregation of multiple expert judgments (individual scores) into a single consensus (group score) to provide a final quantitative measure of HV Wood Poles' health.

Chapter 6 presents the conclusions of the work and provides several suggestions for the future research work, i.e., the on-going distribution network transformers health assessment case study and potential distribution network switchgear health assessment project; and possible further improvement of the proposed approach, such as the application of Cooke Method to improve the degree of accuracy of the health assessment.

2 POWER SYSTEM ASSET MANAGEMENT BACKGROUND

This chapter introduces the asset management carried out in power system. A general asset management cycle is illustrated, and four maintenance strategies are briefly explained in Section 2.1 and Section 2.2. Official asset management guidelines now used in the UK with details are described in Section 2.3 to Section 2.5.

2.1 Asset Management

The term 'asset management' developed in many different industries, including water, finance, gas and electricity, since it is a process that requires trade-off decisions between cost, performance and risk. These decisions should ensure efficient investment and allow effective services to be sustained. The Institute of Asset Management defines an asset management system as:

'systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their lifecycles for the purpose of achieving its organisational strategic plan.' [1]

In a power system, the definition can be explained as stakeholders such as Distribution Network Operators (DNOs), Transmission Network Operators (TNOs) and power suppliers taking systematic and coordinated activities and making practice management decisions to use their power system resources and asset system in an optimal and sustainable way. This will, therefore, fulfil pre-defined requirements, such as the quality of service delivered to customers, the stability of a power system network and success of planned budget, in the strategic plan over the lifecycle of the assets.

The development of management decisions is not necessarily straightforward but may involve a series of processes called the Asset Management Framework Cycle (Figure 1). There are three parts and each one includes several decisions.

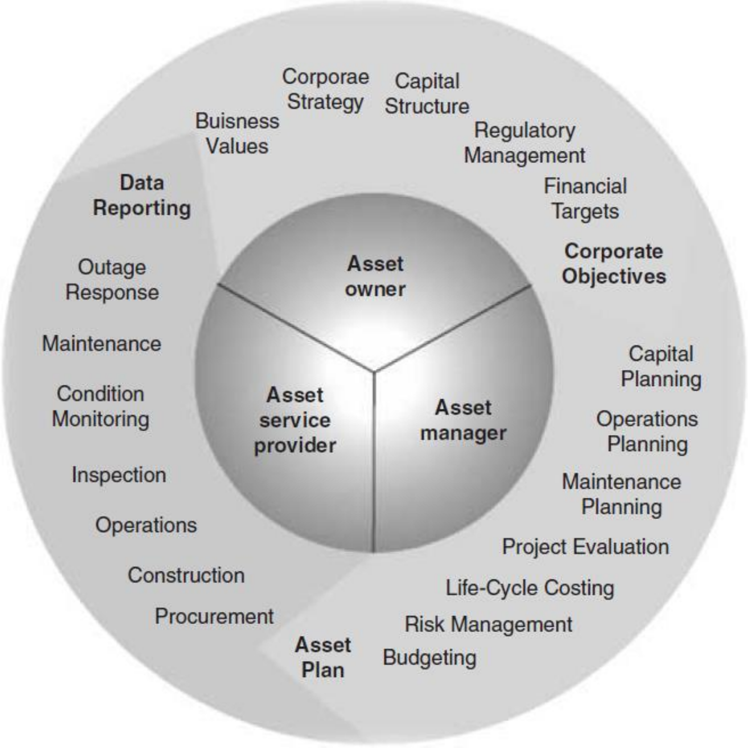

Figure 1: Asset Management Framework Cycle [2]

This framework shows that the three divisions are asset service provider, asset owner and asset manager. The asset owner defines the investment, technical and risk criteria in terms of performance, cost and risk, with a focus on corporate objectives. The asset manager determines the most efficient and economical plan to satisfy these objectives with a focus on planning. The asset service provider finally executes the asset plan and delivers monitoring, performance, and cost data information with a focus on data reporting. These three parts are internally linked and aligned together. The utilisation of asset management contributes to the improvement and adaption of the occurrences as they arise in the power system, i.e., the ageing of system assets, development of new technologies and shifting industrial structures.

As mentioned before, the UK power network expanded over 50 years ago and a large number of assets that were installed are now coming towards the end of their lifespans. These ageing assets will decrease the quality of service that can be delivered, i.e. aged assets may struggle to provide a secure supply of electricity, this may become a major problem. Figure 2 is a causal loop diagram to visualise the relationship between asset ageing, performance, and investment and Figure 3 illustrates the ageing states during the whole lifecycle of assets.

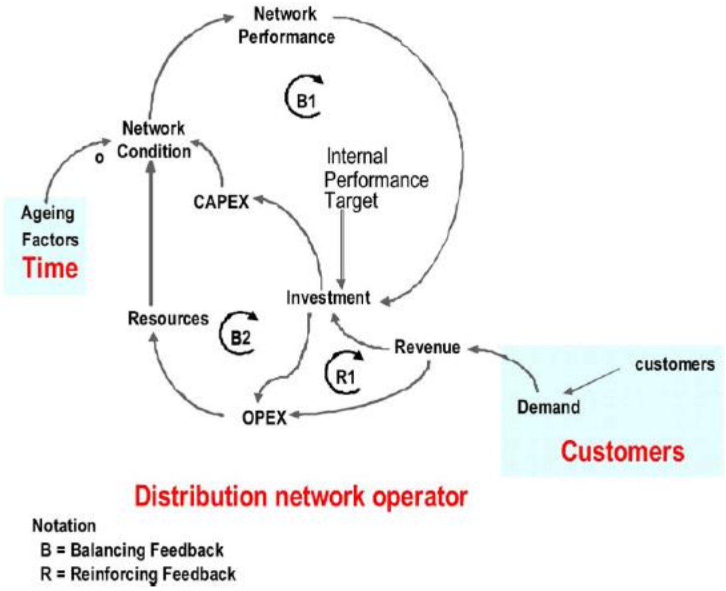

Figure 2: Causal Loop Diagram [3]

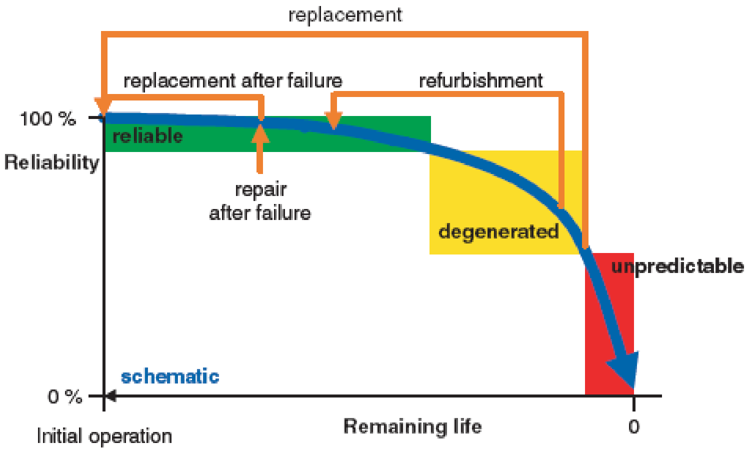

Figure 3: General Ageing Model [3]

In Figure 2, the ageing factors, at the left-hand side of the diagram, affect the network condition and further impact network performance. Once the targeted internal performance is not met, the amount of investment including capital expenditures (CAPEX) and operational expenditures (OPEX) must increase in order to improve the network condition. Future investment will come from the money customers are willing to pay, which is often depending on the quality of service. Therefore, dissatisfaction can disrupt this cycle as asset managers are required to maintain a sustainable level of service for the customers.

As shown in Figure 3, there are three states on the reliability curve: reliable, degenerated, and unpredictable. The concept of reliability in the power system can be defined as the probability of a system or asset which operates at a pre-defined level of performance, lasting for a specified period of time. Reliability always decreases over time without intervention. Adequate maintenance actions can result in an asset remaining in a reliable state longer, i.e., past its operational lifetime, and the asset will be replaced after it moves to the unpredictable state.

As for the structure in industries, in the UK, power system companies are regulated by Office of Gas and Electricity Markets (Ofgem), a new office formed in the late 1980s, whose responsibility is to use asset management to limit customers from experiencing unreasonable electricity prices. Ofgem set Distribution Price Control Review (DPCR5) for 2010-2015 and then move on to a new model, called, '**R**evenue set to deliver strong **I**ncentives, **I**nnovation and **O**utputs' or RIIO-ED1[4], where 'ED1' presents the first electricity distribution price control. RIIO-ED1 price control will review and set the outputs for the 14 electricity DNOs required to deliver to the customers and the revenues accordingly are allowed to collect from 1 April 2015 to 31st March 2023.

2.2 Maintenance Strategies

Maintenance strategies are critically important and widely used by system operators for asset management. The availability of data details, maintenance costs and asset types for each strategy vary. Figure 4 shows the classification of maintenance strategies.

The simplest maintenance strategy is corrective maintenance (CM) which replaces or refurbishes assets after failure detection, however, the simple fix may not be the cheapest, where a replacement can generate a large maintenance cost compared with refurbishment. CM is recommended to use for assets that have a low importance and low cost for repair in short-term while at the same time, minimum plan is required. However, long-term cost can be high and unscheduled repair may cause other failure or rush in time.

An upgraded maintenance strategy includes time-based maintenance (TBM), where regular inspection or maintenance of assets is based on a fixed time interval. This can keep assets to operate efficient, prolong the lifetime, and avoid the occurrence of unforeseen breakdown. TBM can be time consuming especially when assets are in good condition that may not require maintenance as planned. However, the maintenance frequency can be reduced accordingly to the actual asset condition and the understanding of the failure and the causes to them to save time if maintenance is not required.

Another maintenance strategy is condition-based maintenance (CBM) which involves continuous or occasional monitoring of the condition of assets to act when maintenance required. This involves the application of large number of sensors to monitor the real time condition of assets. CBM can be expensive and need more workforce to track the monitoring and maintain the sensors themselves. For assets play an important role or cost higher for replacement than sensors and labour fee, CBM is a good option.

Finally, a more advanced maintenance strategy is reliability-centred maintenance (RCM), which considered both the condition and importance of the asset, it focuses on ways to classify the risk and corresponding consequences and identify maintenance actions to extend the lifetime of an asset. RCM is cost-effective but requires the intelligence to achieve optimum maintenance. Without doubt, RCM can increase assets' availability, maximise the lifetime and minimise the cost by implementing a tailored maintenance strategy to the most important assets in a facility.

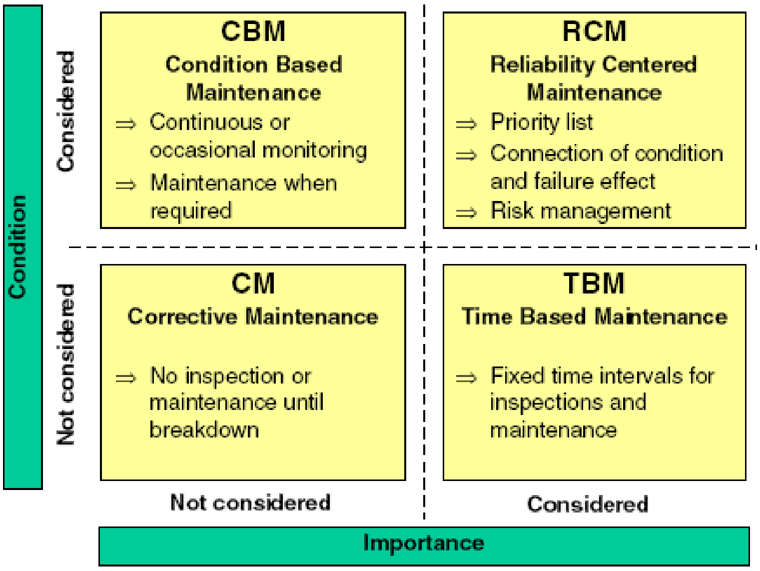

Figure 4: Overview of the Classification of Four Maintenance Strategies [3]

The applied maintenance strategy for the project in this thesis can be considered to be a combination of CBM and RBM (risk-based maintenance). Risk-based maintenance (RBM) methodology reduces life cycle cost and involves the following steps [5-7]:

- Data about the assets are captured by inspection;
- Data then used to develop a risk assessment analysis process involving expert judgments;
- Rank evaluated risk assessment;

- Create maintenance plans according to the risk assessment;
- Implement the maintenance strategy in the management system.

This combined maintenance strategy can also be called CBRM (condition-based risk management), a maintenance strategy that has been developed by EA Technology, a specialist in asset management solutions for owners and operators of electrical assets. which combines asset data information and expert judgments into the optimisation overview of an asset management plan. It introduces the concept of a health index (HI) to classify assets based on their condition and then to schedule maintenance plans.

2.3 Official AM Guidelines

An ideal scenario is that the promised service quality to customers can be satisfied with controlled and acceptable system risks while maximising network profits and minimising investment costs. An adequate asset management strategy is necessary to achieve this target. By following the first guideline for optimization physical asset management called ‘PAS-55’ which has been developed by the British Standards Institute in 2004 [8, 9] and has been accepted broadly since then, ISO 55000 series are developed by the International Standards Organisation based on the PAS-55 and have becoming the current standard for any asset type since 2014 [10]. This guideline defined a common language and provided recommendations relating to asset management practice at both strategic levels and at an operational level (i.e., from lifecycle strategy to daily maintenance). Assets deteriorate not only because of ageing but also due to environmental conditions, the number of customers, etc. This, in turn, will affect the risk of asset failure, both in terms of likelihood and consequence.

The condition of assets will be defined and affected by many criteria. In the power system, the overall risk can be split into two criteria: the likelihood of failure and consequence of failure. Furthermore, based on the utility approaches, criteria of age, environmental conditions and fault rate etc. can provide indications to determine the likelihood of failure; and criteria of safety, spares and network security etc. can help to define the consequence of failure. The definitions of the risk of failure for different assets may vary. The problem is how to quantify the risk. It is still necessary to refer the measured risk to a common base that will enable different assets to be compared directly, and subsequently enable the scheduling of a replacement to be made across different asset types.

2.4 Price Control

In order to build an asset management system, the cost can be high. It may occur that the payback in return is not enough to cover the effort and cost by an inefficient asset management system.

Therefore, Ofgem set a price control limit for every five years which identifies the maximum revenues from customers for DNOs to allow an efficient business to finance activities. DNOs are also being encouraged to innovate in a more efficient, secure and reliable way to provide better service.

Distribution Price Control Review 5 (DPCR5) [11], is Price Control Policy that was published in 2009 and put into use after 1st April 2010. DNOs, TNOs, generators, electricity suppliers and other stakeholders are impacted by this schedule. It dictates the CAPEX, OPEX and ultimately the cost of electricity for consumers.

After DPCR5, Ofgem moved to RIIO-ED1, in 2015 [12]. RIIO-ED1 aims at attracting a wider range of parties and determine how to regulate energy network companies to achieve sustainable and low carbon energy delivery in an efficient and economical way while still maximising return on investment.

2.5 Health Index (HI)

Ofgem uses HI and load index (LI) and criticality (FR) [13] as indicators in the form of secondary deliverable for reliability , to understand if the network risk level affects the delivery to customers by DNOs. In the meantime, it can also help managers to determine if DNOs have successfully achieved cost savings during the price control period.

- HI is a framework for checking and tracking distribution assets health (or condition) over their lifetime;
- LI is a framework for collating information on the utilisation of the distribution assets, checking the loading and firm capacity;
- Criticality is a measure of the financial consequence of an asset failing.

This project is focused on assessing the health of the asset; therefore, it has a focus on the HI output.

The HI framework includes five health classifications, i.e., HI 1-HI 5, Table 1. Each asset will be checked, tracked and assigned into the relevant HI level. The classifications of HI are based on the DNO’s own assessments which are based on the factors which affect the health of assets.

Table 1: Definition of Asset Health Index and Descriptions [14]

HI Classifications	Descriptions
HI 1	New or as new
HI 2	Good or serviceable condition
HI 3	Deterioration. Requires assessment or monitoring
HI 4	Material deterioration, intervention requires consideration
HI 5	End of serviceable life, intervention required

Ofgem also provides a weighted health index as well, which can be found in Table 2:

Table 2: Health Index versus Weighted Health Index [14]

Health Index				
1	2	3	4	5
Weighted Health Index				
1	10	30	70	100

That means, for example, if an asset moves from HI5 to HI1, the total point for the asset is 100-1=99 points. This value is then multiplied by the pre-defined unit cost for the asset.

Based on the score of each metric, assets will be assigned into different HI classifications depending on their final scores. The results, therefore, provide the decision-makers with an understanding of the relative health between assets. The techniques applied here are MCDA techniques which will be introduced in Chapter 3.

2.6 Conclusion

This chapter provides an introduction of the current power system asset management framework, along with those maintenance strategies used in the power system. There is also a brief description about when and which maintenance strategy to choose over different situations. ISO 55000 series and RIIO-ED1 are the latest standards to follow for power system DNOs. The approaches in this thesis are developed to meet the requirements of the standards.

2.7 References

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3 THE APPROACH USED IN THE THESIS

The approach used in this thesis is a combination of multiple criteria decision analysis with selected priority scaling method and expert elicitation methods.

Section 3.1 introduces different and selected multiple criteria decision analysis, which provides the structure of the approach.

Section 3.2 describes six different priority scaling methods. A comparison between the methods is made in order to show how the method performs in each case.

Section 3.3 provides different ways to combine multiple experts' judgments, how and when to apply.

3.1 Multiple Criteria Decision Analysis

3.1.1 Introduction

Multiple criteria decision analysis (MCDA), also known as multiple criteria decision-making (MCDM), addresses complex decision problems involving multiple criteria. Criteria can be conflicting, which indicates differing opinions. MCDA helps the decision maker to consider multiple criteria to reach a better decision with reasonable justification and explanations.

MCDA utilises human judgments to support the decision-making process for those complex problems; therefore, MCDA does not provide an objective final decision. This is explained by V.Belton and T.J.Stewart [15]:

> *Subjectivity is inherent in all decision making, in particular in the choice of criteria on which to base the decision, and the relative 'weight' given to those criteria. MCDA does not dispel that subjectivity; it simply seeks to make the need for subjective judgements explicit and the process by which they are taken into account transparent (which is again of particular importance when multiple stakeholders are involved).*

The process of MCDA is presented in Figure 5. The problem-structuring phase allows brainstorming to establish any thinking and to identify key issues that relate to the decision problem. The model-building phase extracts the key thoughts from the problem-structuring phase, which can help in evaluating the problem more precisely. Iterations can occur between both of these phases. The third phase uses the final outcomes of the model-building phase to collect related information, elicit judgments by challenging human intuition, and to analyse robustness and sensitivity. The outcome of this phase is a final action plan.

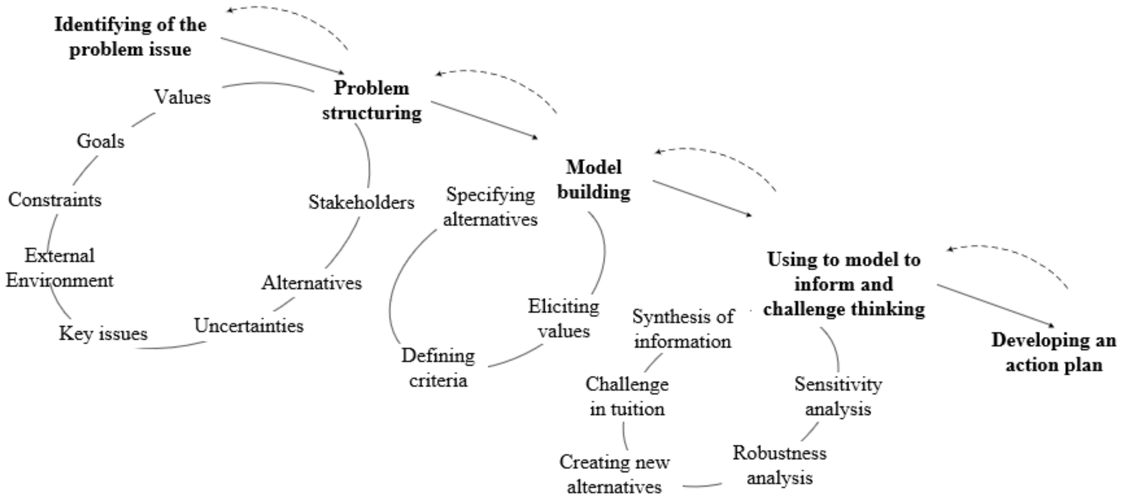


Figure 5: The Process of MCDA [15]

3.1.2 Different MCDA models:

Models of MCDA can be classified into categories, as follows [15]:

- *Value measurement models.* Numeric scores are derived from this kind of model. The scores represent the preference of decision options;
- *Goal, aspiration, or reference level models.* These models evaluate possible decision options and find out the closest one;
- *Outranking models.* The output of these models is similar to those from value measurement models, and a preference order will be generated. The main difference between outranking and value measurement models is that there is no score calculation function for outranking models.

The case study research in this thesis requires numeric scores as health assessment outputs to be assigned in different numeric ranges. Therefore, the value measurement models are detailed in Section 3.1.3.

3.1.3 Analytic Hierarchy Process

3.1.3.1 Fundamental of AHP

Analytic hierarchy process (AHP) is one of the value measurement models originally developed by Saaty [16] to solve decision-making problems. It has been studied and used widely since then. From environmental area [17-19] to business, management and social science [20, 21], engineering and energy area [22-24], and medicine and biological science[25, 26]. The output of the AHP is a numeric score, which represents the quantification of the weighting of criteria. A hierarchical structure and questionnaire are developed specially for each decision-making problem. Experts involved in each decision-making problem are asked to compare criteria in pairs with relative importance to construct a pairwise comparison (PC) matrix. This matrix will then generate a set of numeric scores that represent the quantification of the weighting of the criteria under consideration. The scores are then used to make the decision.

The fundamental steps of AHP are as follows:

1. Collect available information/data with alternatives related to the decision-making problem;
2. Identify useful information/data that contribute to the decision-making problem as criteria;
3. Develop a hierarchical structure. The structure consists of three parts: the overall goal of the decision-making problem on the goal level; identified criteria on the criteria level; and alternatives on the bottom level;
4. Apply pairwise comparisons to capture judgments on criteria (with respect to the goal) and alternatives (with respect to the criteria);
5. Derive priorities of the PC-Matrix using the priority scaling method, i.e., eigenvalue method in the context of AHP (developed by Saaty);
6. Check the consistency ratio to ensure the consistency of the judgments is acceptable, where consistency means the quality of always having the same judgments;

7. Calculate the overall scores of the alternatives to obtain the overall ranking of the alternatives.

To begin, there are some assumptions and axioms of AHP, as follows:

Assumptions of AHP:

1. Assume set A is comprised of a finite number of alternatives, denoted as $A_i, i = 0,1,\ldots,n$;
2. Assume set C is comprised of a finite number of criteria, denoted as $C_{i,}$;
3. Let $\mathrm{C}_i > \mathrm{C}_n$ represent criterion C_i, which is more important/preferred than criterion C_j;
4. Let $P_c(C_i, C_n)$ represent the comparison of $C_i \ to \ C_n$;
5. Let $P_c(A_i, A_n)$ represent the comparison of $A_i \ to \ A_n$, with respect to a criterion $C_i \in C$;
6. Assume set w is comprised of a finite number of relative weightings, denoted as $w_i, i = 0,1,\ldots,n$; with respect to a criterion $C_i \in C$

$i = 0,1,\ldots,n$

$A_i,\ A_n \in A$

$C_i,\ C_n \in C$

$w_i,\ w_n \in w > 0$

Axioms of AHP:

1. The axiom $P_c(C_i, C_n) = \frac{1}{P_c(C_n, C_i)}$ maintains the basis of AHP, i.e., reciprocal of the matrix. For example, if an adult is judged to be three times higher than a child, then the child should also be judged as one-third the height of the adult;
2. For a known set of alternatives $A_i,\ i = 0,1,\ldots,n$, with known relative weightings $w_1, w_2, \ldots, w_n$ the pairwise comparison matrix A can be represented as:

$$A = \begin{bmatrix} {}^{w_1}\!/_{w_1} & {}^{w_1}\!/_{w_2} & \cdots & {}^{w_1}\!/_{w_n} \\ {}^{w_2}\!/_{w_1} & {}^{w_2}\!/_{w_2} & & {}^{w_2}\!/_{w_n} \\ \vdots & & \ddots & \vdots \\ {}^{w_n}\!/_{w_1} & {}^{w_n}\!/_{w_2} & \cdots & {}^{w_n}\!/_{w_n} \end{bmatrix}$$

   Therefore, with the transpose matrix of $w,\ w^T = (w_1, w_2, \ldots, w_{n)}$, the following expression forms,

$$Aw^T = nw^T$$

3. For an unknown set of w, the solution of $(A - nI)w = 0$ is required. For a non-zero solution, n must be a non-zero eigenvalue of A. This is known as the

maximum eigenvalue of A, denoted as λ_{max}, thus $\lambda_{max} = n$ when A is consistent, i.e., the relationship of ${}^{w_i}/_{w_j} \times {}^{w_j}/_{w_k} = {}^{w_i}/_{w_k}$ is satisfied.

4. In the case of the non-satisfaction of the consistent relationship, i.e., ${}^{w_i}/_{w_j} \times {}^{w_j}/_{w_k} \neq {}^{w_i}/_{w_k}$, λ_{max} is not equal to the number of alternatives n. Therefore, the check of the consistency of the pairwise comparison matrix, consistent ratio (C.R.) is required. C.R. can be calculated with Equation (3 - 2) by deriving a consistent index (C.I.) with λ_{max} and n with Equation (3 - 1), as follows:

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \tag{3 - 1}$$

$$C.R. = \frac{C.I.}{R.I.} \tag{3 - 2}$$

where R.I. is the random index (generated at Oak Ridge National Laboratory) with a sample size of 100 for matrices of order 1-15 [16]. The value of R.I. can be found in Table 3. The pairwise comparison matrix is acceptable when C.R. is less than 0.1.

Table 3: Table of Random Index (R.I.)

R.I.															
Order of Matrix	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0.00	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

AHP can be applied to a case which involves comparison of more than one criterion. A simple power system related example is provided. The goal of the example is to choose from two different transformers with four different criteria: efficiency (%), volume (m^3), weight (kg) and material cost (kUSD). The alternatives consist of two types of transformers, SST (solid-state transformer) and LFT (low-frequency distribution transformer). Details of the two transformers are show in Table 4.

Table 4: Details of Two Transformers [27]

Details of Two Transformers		
	SST	LFT
Efficiency (%)	96.3	98.7
Volume (m^3)	2.67	3.43
Weight (kg)	2600	2590
Material Cost (kUSD)	52.7	11.4

To represent and implement the application of AHP with a more general concept, a holiday destination selection example is provided. The goal of the example is to choose the most suitable holiday destination. Consider ‘transportation fee in pounds’, ‘transportation time in hours’ and ‘number of changes during travel’. In addition, alternatives consist of five holiday destinations, namely London, Glasgow, Edinburgh, Aberdeen, and Newcastle. Details of the five destinations are shown in Table 5.

Table 5: Details of Five Holiday Destinations

Details of Five Holiday Destinations					
	London	Glasgow	Edinburgh	Aberdeen	Newcastle
Transportation Fee (£)	325	20	25	50	95
Transportation Time (h)	6	1	1.5	2	3
# Changes During Travel	2	0	1	0	1

For this example, the overall goal is to choose the most suitable place to go on holiday. In addition, according to the available information/data listed in Table 5, there are three criteria and five alternatives. The three criteria are on Criteria Level 1 and contribute to the overall goal; while five destinations are on the Alternative Level. Therefore, the corresponding hierarchical structure is generated, and presented in Figure 6.

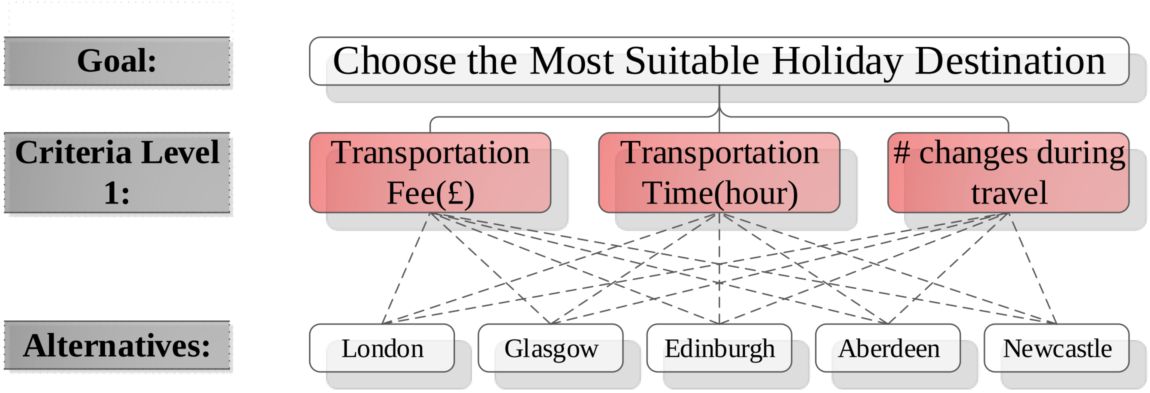


Figure 6: Hierarchical Structure of Holiday Destination Example

With the built hierarchical structure, the decision maker, the one whose requirement is to choose a holiday destination in this example, is asked to perform two different types of comparisons:

1. One is to conduct the pairwise comparison between criteria, i.e., in this example, ‘transportation fee in pounds’, ‘transportation time in hours’ and ‘number of changes during travel’ are compared in pairs. From this, the priorities are derived, i.e., the relative importance of the criteria in choosing the most suitable holiday destination;
2. The other is to compare the alternatives with respect to every single criterion. From the example, London, Glasgow, Edinburgh, Aberdeen, and Newcastle are compared in pairs with respect to cost, weather, and ease. From this, the priorities are derived, i.e., the relative strength of the five destinations with respect to the corresponding criterion.

For the first type of pairwise comparison, the three criteria generate three comparisons: comparing ‘transportation fee’ with ‘transportation time’, ‘transportation fee’ with ‘number of changes during travel’, and ‘transportation time’ with ‘number of changes during travel’. The calculation of the number of comparisons is $\frac{n(n-1)}{2}$, where n is the number of criteria. In each pairwise comparison, the decision maker selects the criterion which is judged to be the least important and assigns it a scale of 1, then scales the other criteria relative to this (a value no smaller than 1 and no greater than 9). The scales with corresponding descriptions of importance [16] for this example are presented in Table 6.

Table 7 presents the scale chosen for each pairwise comparison. For instance, ‘transportation time’ is considered with a scale of 1 while ‘transportation fee’ is scaled ‘9’. From the decision-maker’s opinion, ‘transportation fee’ is more important than ‘transportation time’.

Table 6: PC Scale Table of Importance [28, 29]

PC Scale	Descriptions of importance
1	equally important
3	weakly more important than
5	strongly more important than
7	demonstrably or very strongly more important than
9	absolutely more important than
2,4,6,8	can be used to facilitate compromise between slightly differing judgments

Table 7: Comparison of Decision-Making Criteria with respect to Choosing Holiday Destination (i.e., the goal)

Criteria Compared with respect to the Goal			
Transportation Fee (£)	9	Transportation Time(hour)	1
Transportation Fee (£)	5	# Changes during Travel	1
Transportation Time (h)	1	# Changes during Travel	3

The scales are then used to construct the PC-Matrix shown in Table 8.

Table 8: PC-Matrix of the Comparison of Decision-Making Criteria with respect to Choosing Holiday Destination (i.e., the goal)

PC-Matrix of Criteria Compared with respect to the Goal				
	Transportation Fee (£)	Transportation Time (h)	# Changes During Travel	Priorities
Transportation Fee (£)	1	9	5	0.7514
Transportation Time (h)	1/9	1	1/3	0.0704
# Changes during Travel	1/5	3	1	0.1782
C.R. = 0.0251< 0.1, i.e., acceptable.				

The scales on the diagonal of the PC-Matrix are 1's, because criteria are equally important by themselves. Scales in the symmetric positions (for example, position = Row 1, Column 2, and position = Row 2, Column 1), are reciprocals. Therefore, the scale for 'transportation time' compared with 'transportation fee' is 1/9, reciprocal to 9.

The checked C.R. is 0.0251, which is lower than the threshold (i.e., 0.1); therefore, the consistency of this PC-Matrix is acceptable.

For the second type of pairwise comparison, five alternatives generated ten comparisons with respect to each criterion. The calculation of the number of comparisons is $\frac{n(n-1)}{2}$, where n is the number of alternatives. Taking 'transportation fee' as an example, the 'transportation fee' for London is compared with the 'transportation fee' of Glasgow to Newcastle; the transportation fee' of Glasgow is compared with the 'transportation fee' of Edinburgh to Newcastle, and so on. All the ten comparisons are listed in Table 9. To scale the comparisons, a PC Scale Table is also required for 'transportation fee' as ‘importance’ in Table 6. The range of the scale is maintained at 1 to 9, while the descriptions differ. Text expressions are used in Table 6, because ‘importance’ is a non-numeric, qualitative term, and direct calculation and normalisation (if required) are used for numeric numbers. An explanation of the normalisation is described, as follows:

1. Find out the highest and lowest ‘transportation fee’ for five destinations (these are London and Glasgow, with £325 and £20, respectively;
2. Calculate how many times London is greater than Glasgow (325/20 = 16.25 in this example);
3. Normalise 16.25 to scale 9, because 16.2” is beyond the scale limit, and assign 9 to Glasgow for this comparison (a higher scale indicates a greater advantage of the place with respect to ‘transportation fee’);
4. Repeat Step 2 for London compared to Edinburgh, Aberdeen, and Newcastle, for which the multiples are 13, 6.5, and 3.42, respectively;
5. Normalise 13, 6.5, and 3.42 to 7.2, 3.6, and 1.89, according to Step 3;
6. Round up 7.2, 3.6, and 1.89 to 7, 4, and 2, because the scales are integers.

Apply Steps 3 to 6 to the remaining five pairwise comparisons to derive the scales. All the results are shown in Table 9.

Table 9: Comparison of Alternatives with respect to the Decision-Making Criteria Transportation Fee (£)

Alternatives Compared with respect to Transportation Fee (£)			
London	1	Glasgow	9
London	1	Edinburgh	7
London	1	Aberdeen	4
London	1	Newcastle	2
Glasgow	1	Edinburgh	1
Glasgow	2	Aberdeen	1
Glasgow	3	Newcastle	1
Edinburgh	1	Aberdeen	1
Edinburgh	2	Newcastle	1
Aberdeen	1	Newcastle	1

The converted PC-Matrix from Table 9 is presented in Table 10.

Table 10: PC-Matrix of the Comparison of Alternatives with respect to the Decision-Making Criteria Transportation Fee (£)

PC-Matrix of Alternatives d with respect to Transportation Fee (£)						
	London	Glasgow	Edinburgh	Aberdeen	Newcastle	Priorities
London	1	1/9	1/7	1/4	1/2	0.0467
Glasgow	9	1	1	2	3	0.3573
Edinburgh	7	1	1	1	2	0.2764
Aberdeen	4	1/2	1	1	1	0.1883
Newcastle	2	1/3	1/2	1	1	0.1313
C.R. = 0.0238 < 0.1, i.e., acceptable.						

The C.R. for the PC-Matrix of alternatives compared with ‘transportation fee’ is 0.0238, within the acceptable range.

A similar process is applied to ‘transportation time’ and ‘number of changes during travel’, with the resultant PC-Matrices presented in Table 11 and

Table 12, with acceptable C.R. equal to 0.0037 and 0.0173.

Table 11: PC-Matrix of the Comparison of Alternatives with respect to the Decision-making Criteria Transportation Time (h)

PC-Matrix of Alternatives Compared with respect to Transportation Time (h)						
	London	Glasgow	Edinburgh	Aberdeen	Newcastle	Priorities
London	1	1/6	1/4	1/3	1/2	0.0618
Glasgow	6	1	2	2	3	0.3929
Edinburgh	4	1/2	1	1	2	0.2204
Aberdeen	3	1/2	1	1	2	0.2081
Newcastle	2	1/3	1/2	1/2	1	0.1167
C.R. = 0.0037 < 0.1, i.e., acceptable.						

Table 12: PC-Matrix of the Comparison of Alternatives with respect to the Decision-Making Criteria # Changes during Travel

PC-Matrix of Alternatives Compared with respect to # Changes During Travel						
	London	Glasgow	Edinburgh	Aberdeen	Newcastle	Priorities
London	1	1/8	1/4	1/8	1/4	0.0362
Glasgow	8	1	4	1	4	0.3741
Edinburgh	4	1/4	1	1/4	1	0.1078
Aberdeen	8	1	4	1	4	0.3741
Newcastle	4	1/4	1	1/4	1	0.1078
C.R. = 0.0173 < 0.1, i.e., acceptable.						

A summary of the priorities for criteria and alternatives is presented in Table 13.

Table 13: Summary of Priorities of Criteria and Alternatives

Criteria	Priorities	Alternatives	Priorities with respect to criterion
Transportation Fee (£)	0.7514	London	0.0467
		Glasgow	0.3573
		Edinburgh	0.2764
		Aberdeen	0.1883
		Newcastle	0.1313
Transportation Time (h)	0.0704	London	0.0618
		Glasgow	0.3929
		Edinburgh	0.2204
		Aberdeen	0.2081
		Newcastle	0.1167
# Changes During Travel	0.1782	London	0.0362
		Glasgow	0.3741
		Edinburgh	0.1078
		Aberdeen	0.3741
		Newcastle	0.1078

The final score for London is the summation of the following calculations:

- London’s priority with respect to transportation fee is 0.7514 × 0.0467 = 0.0351;
- London’s priority with respect to transportation time is 0.0704 × 0.0618 = 0.0044;
- London’s priority with respect to number of changes during travel is 0.1782 × 0.0362 = 0.0667.

Therefore, the final score for London is 0.0351 + 0.0044 + 0.0667 = 0.0459. The final scores for all the five holiday locations are presented in Table 14.

Table 14: Final Scores for all Holiday Locations

Priorities with respect to Criteria				
Alternatives	Transportation Fee (£)	Transportation Time (h)	# Changes During Travel	Final Score
London	0.0351	0.0044	0.0065	0.0459
Glasgow	0.2685	0.0277	0.0667	0.3628
Edinburgh	0.2077	0.0155	0.0192	0.2424
Aberdeen	0.1415	0.0147	0.0667	0.2228
Newcastle	0.0987	0.0082	0.0192	0.1261

These result shows that Glasgow has the highest score and London has the lowest. This indicates that among five locations, and with respect to three criteria, Glasgow is the best choice to take a holiday.

3.1.3.2 Application of AHP

AHP has been studied and applied across a wide range of fields where multiple criteria decision-making problems exist. This includes alternative selections, planning decisions in general management, financial projects, resource allocation, and ranking.

For small scale or personal projects, AHP is a technology that can provide reasonable assessment as a useful tool. In a study by [30], five contractors were five alternatives to be prequalified under six criteria in a project management scenario. The application of AHP was simple and clear with a final choice of contractor (D) to perform the project. A complex car selection problem in [31] involved three models of car to be evaluated under seven criteria on Level 1, each criterion then had 47 sub-criteria. AHP was applied in two groups (cases): the first group, Case I, comprised 13 experienced managers working in a sales department for more than 10 years; the second group, Case II, comprised 22 customers with experiences over seven years assessing their satisfaction with their own cars. The results showed that Case I was more appropriate for the car selection project. Another interesting case assessed the possibility of winning a bid in [32], involving three competitor alternatives (A, B, and C) with four criteria (service level, plant performance, financial conditions, and contractual conditions) on Level 1 and 13 criteria in total on Level 2. Competitor C had only a 2.3% possibility of winning the bid whereas competitor A has the highest possibility (at 69.5%), with competitor B at 28.2%.

AHP has been used in large-scale projects, such as manufacturing, designing, and marketing. Because markets have become much more competitive, manufacturing companies, product design companies, and retailers are expected to be capable of accommodating varied customer demands to survive in the market. Therefore, many companies are keen to investigate new technologies or strategies. For example, [33] shows the application of AHP in evaluating the investment of time compression technologies to achieve efficient design development and production. In [34], a Spanish solar power investment company used AHP to investigate the benefit of commencing a particular solar-thermal power plant project and at the same time investigating the priority of other projects in the company. The decision maker in this example found the technique very useful in understanding and clarifying the complexity of the problem, finally reaching a decision to choose projects B and C (rather than A) while investing in project B prior to C.

For projects concerning education and health, AHP is also applicable and can be found in many cases. Studies in [35, 36] relate to education, and [37, 38] are environment examples. In [35], the application of AHP was introduced to evaluate seven different teaching strategies in terms of three highest level criteria (skills development, interest and knowledge developments, and preparation for exams and jobs). There are four teaching objectives on Level 2 for the former two criteria, and two for the third criteria. The teaching objectives and teaching techniques were identified by 133 student responses and staff surveys. It is interesting to note that focusing on individual problem-solving and interaction with students were the most effective techniques to satisfy teaching objectives, whereas the least two effective techniques were multi-media aids and incomplete handouts. After lectures and tutorials, taking an exam was considered the way to evaluate teaching results; therefore, [36] provides an example of how to compose an exam problem with the help of AHP. The teacher in charge of the composition of the exam paper took the AHP questionnaire and conducted the pairwise comparisons to evaluate each question regarding four criteria: answer possibility, necessity time, difficulty balance, and appropriateness.

From the health perspective, [37] applied AHP along with the Delphi group method to assess and select a preferred environmentally friendly supplier. Three pilot tests were involved in this project, as follows: tests about an automotive manufacturer, a paper manufacturer, and an apparel manufacturer. In pilot test 2 (the paper manufacturer), none of the suppliers were preferred, with the conclusion that this was because of the tight restrictions of government regulation in the pulp industry. Thus, the government would need to revoke restrictions to overcome any problem. Therefore, expert judgments may not work under this situation. For pilot tests 1 and 3, a preferred supplier could be derived via AHP with respect to six environmental criteria. This requires future research to obtain a better supplier with respect to criteria other than the environment. Another environment-related problem was described in [38]. The main issue for manufacturers is whether or not to accept the ISO 14001 Environmental Management System (EMS) standard. An AHP model was developed in this paper to evaluate the benefits/costs ratio of implementing the standard. With alternatives of ‘whether or not to implement ISO 14001

EMS standard' to be the goal, 'implement' and 'not implement' to be the alternatives, two hierarchical structures were developed: benefit hierarchy and cost hierarchy. Both hierarchical structures had the same four criteria on Level 1 and a total of 14 criteria on Level 2. Level 3 comprised benefit-related objectives and cost-related objectives. The resultant benefits/costs ratio for implementing the standard was 1.238 and 0.548 for not implementing.

In the field of electrical power systems, [39-44] present several examples of the application of AHP in power systems. In [39], AHP was used to explore the planning strategies and analysis of distributed generations in three cases: conventional grid, hybrid DG operation, and micro-grid. The criteria included incremental losses, capital costs, and percentage time, for which demand was not served for all cases. The project involved three criteria at Level 1, three criteria at Level 2, and six alternatives (i.e., six strategies). The result shows that two strategies—hybrid DG with low load and micro-grid with low load—were both acceptable with minor differences. For power system substations, [40] identified age, load factor, the amount of obsolete equipment, equipment showing symptoms of failure, the same type equipment as that which has failed, noise levels, and the amount of PCB-contaminated insulation oil were the seven criteria, and the AHP health assessment procedure was applied across 74 substations. The utilisation of AHP was continued on site to keep track of the health condition of the substations. For distribution restoration problems, AHP was introduced in [41] to make restoration decisions apart from common approaches such as expert systems or heuristic searches, and in [42] it was applied to identify remotely controlled switch allocation along the distribution networks. The introduction of AHP in [41] derived a quantitative comparison of different restoration plans and gave a perceptual intuition of how good or bad a restoration plan was, while in [42], five options for the allocation of the remotely controlled switches were compared and ranked (option 5 being the best solution, followed by options 3, 1, 4, and 2). For demand side management, AHP was used to simulate a complex decision-making process of demand curtailment allocation problems with a three-level AHP structure [43]. This involved three criteria at Levels 1 and 2, five criteria including loading ration, capacity, critical load, deferrable load, and interruptible load on Level 3, and five substation alternatives. Results verified the application of AHP, which satisfied the different load curtailment requirements. Another application of AHP detailed in [44] assessed the probability of a generator failure. This was another complex project that involved eight degradation sites as eight alternatives, five failures on Level 1, and 21 criteria on Level 2 to achieve the goal (namely, to assess the origin of the failure). For an actual failure, the results derived by the AHP model were similar to the practical failure.

Despite the popular application of AHP, three specific shortcomings of AHP in its application to the High Value Low Volume power system HV Wood Poles case study have been identified, which are summarised as follows:

1. In a majority of cases, criteria such as height, distance, or weight (which can be compared easily depending on the quantity) are not represented numerically and quantitatively; therefore, there exists a quantification pre-processing of criteria either consciously or unconsciously by experts while comparing every time, which increases the workload of pairwise comparisons;
2. A large number of criteria to be pairwise compared, such as nine criteria, indicates $\sum_{k=0}^{n=8} \mathrm{n} = 36$ pairwise comparisons; this increases the scope for inconsistency across an expert's complete set of pairwise comparisons, which requires repeating of the PC process;
3. The inconsistency cannot be eliminated with the improved AHP process.

The shortcomings outlined above can also have the effect of making this a time-consuming and onerous process with which experts engage. This can frustrate experts, causing them to disengage and so potentially compromise the accuracy of the expert judgments captured. As evidenced here, as the number of criteria subject to examination and comparison increases, this approach may become increasingly cumbersome.

Therefore, inspired by Keeney [45], Belton [15], Parnell [46] [47] [48], an alternative MCDA technique known as the swing weights method (SW), is introduce in the next section.

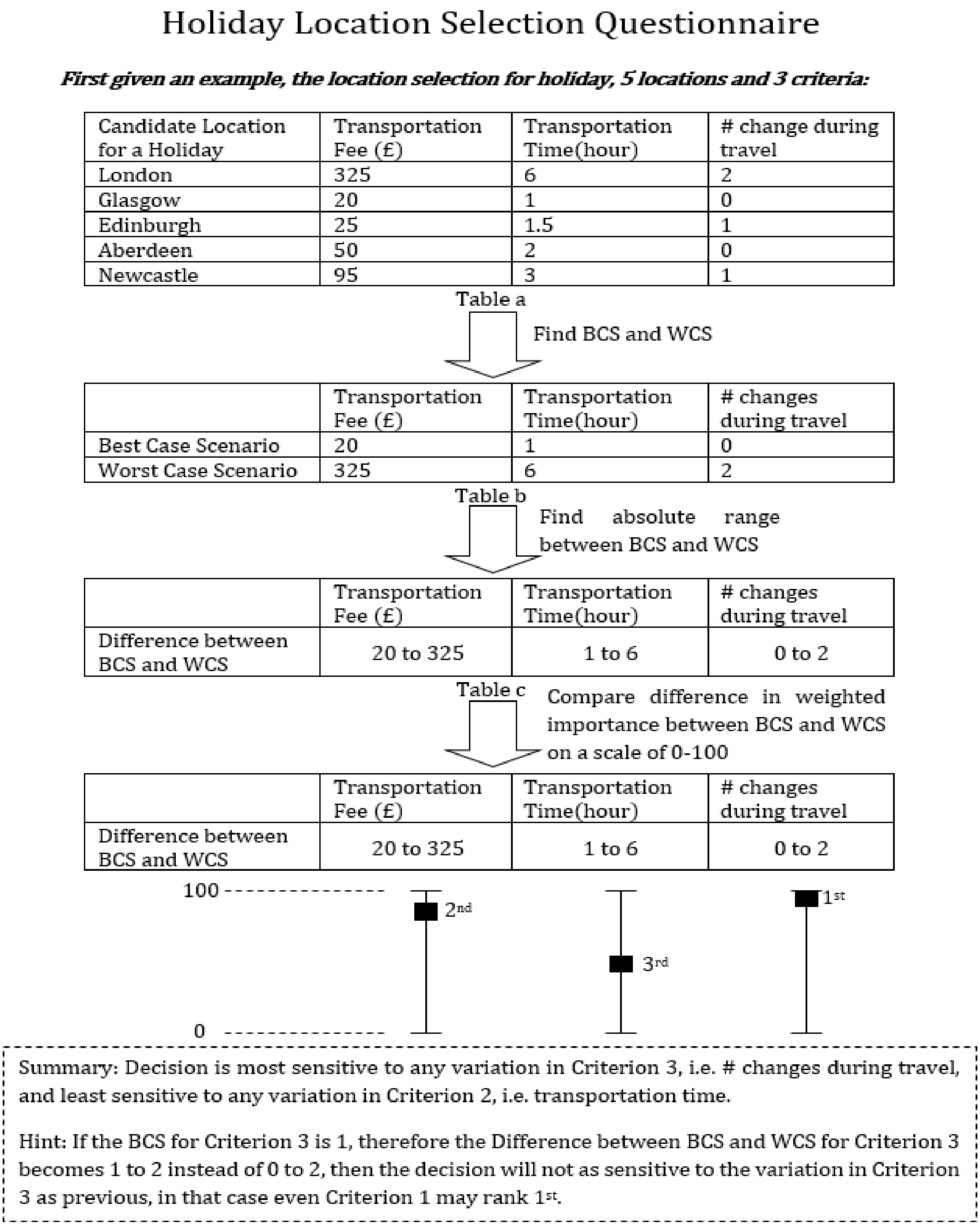
3.1.4 Swing Weights Method

The Swing Weights(SW) method is another value measurement method that delivers quantitative outcomes to evaluate alternatives. The differences between SW and AHP are that SW compares the 'swing' representing the change from the two reference points (i.e., the best-case scenario (BCS) and worst-case scenario (WCS)). The SW method requires fewer comparisons than AHP, which is clearly an advantage when a large number of criteria are involved. In addition, the setting of reference points is to some extent a process of quantification for criteria, which are not numeric measurements. It is important for experts to have an accurate and consistent understanding of BCSs and WCSs and provide a clear description of this for each criterion. It is then necessary to complete an SW questionnaire, which records the description of BCS and WCS for each criterion, as defined by group consensus from multiple experts. This can be used for future reference to ensure an expert's comparisons are based on the pre-defined 'swing'.

To explain swing in an understandable way, Figure 3 presents an example from the first page of the SW questionnaire to ensure experts understand the concept correctly. The example lists five locations to choose for a holiday with three criteria in Table a: 'transportation fee', 'transportation time', and 'number of changes during travel'. These are all expressed in numeric figures. As can be seen for each criterion, the BCS and WCS can be found and listed in Table b. Therefore, the swing of each criterion is the variance from BCS to WCS, as indicated in Table c. In the example, the ranking of the three swings in terms of the 'importance' (i.e., how much the criterion will affect the decision depend on the swing), is as follows: 'the number of changes during travel' is ranked first, 'transportation fee' is ranked second, and 'transportation time' is last. The scores of 'the swing of the number of changes during travel' is then set to be 100, and 'the swing of the transportation fee' is compared to 'the swing of the number of changes during travel' with a score of 80. The next step is to take 'the swing of the number of changes during travel' to 100 and compare 'the swing of transportation time' to 'the swing of the number of changes during travel', where the assigned score is 70. To derive the priorities of the three criteria, the scores are to be normalised from [100, 80, 70] to [100, 80, 70/100*80 = 56]. Priorities can then be calculated as:

[100/(100 + 80 + 56), 80/(100 + 80 + 56), 56/(100 + 80 + 56)] = [0.424, 0.339, 0.237].

A summary and hint are detailed underneath the assigned scores, emphasising the concept of 'swing' and how sensitive the decision depends on the swing.



Holiday Location Selection Questionnaire

First given an example, the location selection for holiday, 5 locations and 3 criteria:

Candidate Location for a Holiday	Transportation Fee (£)	Transportation Time(hour)	# change during travel
London	325	6	2
Glasgow	20	1	0
Edinburgh	25	1.5	1
Aberdeen	50	2	0
Newcastle	95	3	1

Table a

Find BCS and WCS

	Transportation Fee (£)	Transportation Time(hour)	# changes during travel
Best Case Scenario	20	1	0
Worst Case Scenario	325	6	2

Table b

Find absolute range between BCS and WCS

	Transportation Fee (£)	Transportation Time(hour)	# changes during travel
Difference between BCS and WCS	20 to 325	1 to 6	0 to 2

Table c

Compare difference in weighted importance between BCS and WCS on a scale of 0-100

	Transportation Fee (£)	Transportation Time(hour)	# changes during travel
Difference between BCS and WCS	20 to 325	1 to 6	0 to 2

Summary: Decision is most sensitive to any variation in Criterion 3, i.e. # changes during travel, and least sensitive to any variation in Criterion 2, i.e. transportation time.

Hint: If the BCS for Criterion 3 is 1, therefore the Difference between BCS and WCS for Criterion 3 becomes 1 to 2 instead of 0 to 2, then the decision will not as sensitive to the variation in Criterion 3 as previous, in that case even Criterion 1 may rank 1st.

Figure 7: SW Travel Example

Both AHP and SW are applied in this thesis in Chapter 4 on a power system asset project. The project involves two criteria on Level 1, 14 criteria on Level 2, and a large number of alternatives (assets).

3.1.5 Conclusion

This chapter provides a brief introduction of common MCDA models used widely across the world and a detailed introduction of two value measurement models AHP and SW which produce numeric results. Both models consist of a hierarchical structure but different comparing approach.

In this thesis, both AHP and SW methods are being used to derive the health assessment of HV Wood Poles. Within the hierarchical structure, there are two criteria levels involved, Level 1 consists of two criteria, ‘age’ and ‘condition’ while Level 2 consists of the sub-criteria of ‘age’ (different ages) and ‘condition’ (different defects). AHP is applied to derive the relative weightings of age and condition on Level 1, requiring the comparison of only these two criteria; making the AHP process fairly simple to apply. Similarly, AHP is used to determine the relative weightings between different ages (which are quantitative in nature) in order to obtain the probability of failure curve on Level 2 under criteria ‘age’. For the relative weightings between different defects on Level 2 under criteria ‘condition’ (where defects are qualitative in nature), both AHP and SW are applied. An ‘improved-AHP’ was also developed during the application, which can alert one to inconsistencies associated with expert judgements as they arise, as opposed to waiting until the end of, what can be, a lengthy process of pairwise comparison associated with the ‘traditional’ AHP approach. The detailed applications of both models are in Chapter 4.

3.2 Priority Scaling Methods

Since two-value measurement models, i.e., AHP and SW, are used in this thesis, priorities are required to be computed either for AHP or SW. As introduced in Section 3.1.4, the calculation of the priorities of SW is straightforward; however, there are several priority scaling methods that can be used to derive the priorities of an AHP PC-Matrix. T.L. Saaty, the developer of AHP, suggests that the priority order is equivalent to the eigenvector of the PC-Matrix associated with largest eigenvalues ([49], [16] p. 17). Consequently, the largest eigenvalues can be used to calculate the consistency, i.e., C.R, of the PC-Matrix. To obtain the eigenvector precisely, i.e., apply the eigenvector method (EM), the appropriate software such as Matlab or Python, is needed to carry out the calculation. Therefore, Saaty listed four alternative methods that can be used to estimate the eigenvector and corresponding maximum eigenvalue in the absence of available software

([16] pp. 19). Saaty defines the accuracy of obtaining the estimated eigenvectors of the four methods from ‘crudest’ to ‘good’. In addition to the EM and alternative four methods introduced by Saaty, an additional Least Squares (LS) method, which estimates the eigenvector, is introduced in this thesis. The details of the six priority scaling methods are described in Sections 3.2.1 to 3.2.6, and results are compared in Section 3.2.7.

3.2.1 Eigenvector Method

The Eigenvector Method (EM) is the original priority scaling method used in hierarchical structures associated with a PC-Matrix, which was first proposed by T.L. Saaty [49]. In this paper, Saaty introduced the following methods and concepts:

- Defined each scaling number, from 1-9, and compared this scaling system with other scaling systems;
- Utilised a priority scaling method that uses a principal eigenvector to calculate the priorities of a PC-Matrix (i.e., EM);
- Introduced the C.R. concept, which reviews how to determine the maximum eigenvector, λ_{max}, with the necessary conditions required for consistency;
- Implemented his theory with examples.

Three years later, he published a book [16] consisting of three parts which expands on these concepts. An explanation of how to find the eigenvalue and eigenvector of a positive square matrix, i.e., PC-Matrix, is explained below:

Consider an n–dimensional, $n \in Z^{+}$, square matrix (4 - 1):

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \cdots & \cdots & \cdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \qquad (4 - 1)$$

with corresponding eigenvector (4 - 2):

$$v = \begin{bmatrix} v_1 \\ \cdots \\ v_n \end{bmatrix} \qquad (4 - 2)$$

and scalar eigenvalue λ. A linear transformation is applied to A and is expressed by the following linear equation (4 - 3):

$$Av = \lambda v \qquad (4 - 3)$$

To find the v and λ for matrix A, linear algebra properties are applied to arrive at the expression (4 - 4):

$$(A - \lambda I)v = 0 \tag{4 - 4}$$

where I is an n–dimensional identity matrix. Find the λ that satisfies the zero determinant of matrix $(A - \lambda I)$ to derive corresponding non-zero solution of v with equation (4 - 5):

$$det(A - \lambda I) = 0 = det\begin{bmatrix} a_{11} - \lambda & \dots & a_{1n} \\ \dots & \dots & \dots \\ a_{n1} & \dots & a_{nn} - \lambda \end{bmatrix} \tag{4 - 5}$$

The algebraic operation (4 - 5) then yields eigenvalues and eigenvectors in (4 - 6):

$$\lambda_1, \dots, \lambda_n \text{ and } v_{\lambda_1} = \begin{bmatrix} v_{\lambda_1 1} \\ \cdots \\ v_{\lambda_1 n} \end{bmatrix}, \dots, v_{\lambda_n} = \begin{bmatrix} v_{\lambda_n 1} \\ \cdots \\ v_{\lambda_n n} \end{bmatrix} \tag{4 - 6}$$

The linear equation and algebraic operations used to find the eigenvalue/eigenvector pairs are needed to understand Saaty's λ_{max} theory. Therefore, the next step is to determine the λ_{max} from $\lambda_1, \dots, \lambda_n$ and its associated $v_{\lambda_{max}} = \begin{bmatrix} v_{\lambda_{max} 1} \\ \cdots \\ v_{\lambda_{max} n} \end{bmatrix}$. Once λ_{max} is found, it is used to check the C.R. by using Equation (3 - 1) and (3 - 2), introduced in Section 3.1.3.1. A result of the holiday destination example, found in Table 8 (Section 3.1.3.1, Page 16), is: $\lambda_{max} = 3.0290$ and $v_{\lambda_{max}} = \begin{bmatrix} 0.7514 \\ 0.0704 \\ 0.1782 \end{bmatrix}$. Since a complex computation is required to find accurate eigenvalues of matrix A with dimension larger than n=3, Saaty introduced four additional methods that can be used to estimate λ_{max} and $v_{\lambda_{max}}$. These four methods are introduced and applied to Table 8 to derive estimated priorities, respectively.

3.2.2 Crude Method

The first method can be used to do the estimation is the method, which Saaty referred to as the 'crudest' estimation method [2]. The principle of the 'crude method' is to sum all the entries of the PC-Matrix first to derive the total sum using equation (4 - 7):

$$A_{sum} = \sum a_{nn} \tag{4 - 7}$$

And the row sum of the PC-Matrix using equation (4 - 8):

$$\begin{bmatrix} a_{11}+\cdots+a_{1n} \\ \cdots \\ a_{n1}+\cdots+a_{nn} \end{bmatrix} \tag{4 - 8}$$

The row sum is then divided by A_{sum} to form (4 - 9) as the estimated priorities:

$$\frac{1}{\sum a_{nn}}\begin{bmatrix} a_{11}+\cdots+a_{1n} \\ \cdots \\ a_{n1}+\cdots+a_{nn} \end{bmatrix} \tag{4 - 9}$$

From Table 8, the calculated $v_{\lambda_{max}}$=$\begin{bmatrix}0.7266\\0.0700\\0.2034\end{bmatrix}$ and its associated λ_{max} is in (4 - 10):

$$\frac{1}{3}\times\left(\frac{[1\quad 9\quad 5]\times\begin{bmatrix}0.7266\\0.0700\\0.2034\end{bmatrix}}{0.7266}+\frac{[1/9\quad 1\quad 1/3]\times\begin{bmatrix}0.7266\\0.0700\\0.2034\end{bmatrix}}{0.0700}+\frac{[1/5\quad 3\quad 1]\times\begin{bmatrix}0.7266\\0.0700\\0.2034\end{bmatrix}}{0.2034}\right)=3.0453 \tag{4 - 10}$$

3.2.3 Reciprocal Method

As introduced by Saaty, a ‘better’ method than the crudest method is the reciprocal method. The reciprocal method derives the reciprocals of the sum of each column of PC-Matrix first as expressed in (4 - 11):

$$\begin{bmatrix}\frac{1}{a_{11}+\cdots+a_{n1}} & \cdots & \frac{1}{a_{1n}+\cdots+a_{nn}}\end{bmatrix} \tag{4 - 11}$$

Then, the reciprocals are normalised by dividing them by the sum of all the reciprocals of the matrix, which forms a row vector in (4 - 12):

$$\begin{bmatrix}\frac{\frac{1}{a_{11}+\cdots+a_{n1}}}{\frac{1}{a_{11}+\cdots+a_{n1}}+\cdots+\frac{1}{a_{1n}+\cdots+a_{nn}}} & \cdots & \frac{\frac{1}{a_{1n}+\cdots+a_{nn}}}{\frac{1}{a_{11}+\cdots+a_{n1}}+\cdots+\frac{1}{a_{1n}+\cdots+a_{nn}}}\end{bmatrix} \tag{4 - 12}$$

Transpose (4 - 12) into a column vector which then become to the estimated priorities.

The results using the data from Table 8 are $v_{\lambda_{max}}=\begin{bmatrix}0.7646\\0.0771\\0.1583\end{bmatrix}$ and λ_{max} is in (4 - 13):

$$\frac{1}{3}\times\left(\frac{[1 \quad 9 \quad 5]\times\begin{bmatrix}0.7646\\0.0771\\0.1583\end{bmatrix}}{0.7646}+\frac{[1/9 \quad 1 \quad 1/3]\times\begin{bmatrix}0.7646\\0.0771\\0.1583\end{bmatrix}}{0.0771}+\frac{[1/5 \quad 3 \quad 1]\times\begin{bmatrix}0.7646\\0.0771\\0.1583\end{bmatrix}}{0.1583}\right)=3.0521 \tag{4 - 13}$$

3.2.4 Arithmetic Mean

Apart from the ‘crude’ and ‘reciprocal’ methods above, the remaining two methods are rated as ‘good’ methods by Saaty. The first is also known as arithmetic mean (AM) method and is introduced in this section. This method first divides each element of Column A by the sum of the Column A to form another matrix (4 - 14):

$$\begin{bmatrix}\frac{a_{11}}{a_{11}+\cdots+a_{n1}} & \cdots & \frac{a_{1n}}{a_{11}+\cdots+a_{n1}}\\ \cdots & \cdots & \cdots\\ \frac{a_{n1}}{a_{11}+\cdots+a_{n1}} & \cdots & \frac{a_{nn}}{a_{11}+\cdots+a_{n1}}\end{bmatrix} \tag{4 - 14}$$

with the same size n as the original PC-Matrix. This new matrix is then row-wise averaged to derive the estimated priorities in (4 - 15):

$$\begin{bmatrix}\dfrac{\frac{a_{11}}{a_{11}+\cdots+a_{n1}}+\cdots+\frac{a_{1n}}{a_{11}+\cdots+a_{n1}}}{n}\\ \cdots\\ \dfrac{\frac{a_{n1}}{a_{11}+\cdots+a_{n1}}+\cdots+\frac{a_{nn}}{a_{11}+\cdots+a_{n1}}}{n}\end{bmatrix} \tag{4 - 15}$$

Therefore, $v_{\lambda_{max}}=\begin{bmatrix}0.7482\\0.0714\\0.1804\end{bmatrix}$ and λ_{max} is calculated in (4 - 16):

$$\frac{1}{3}\times\left(\frac{[1\quad 9\quad 5]\times\begin{bmatrix}0.7482\\0.0714\\0.1804\end{bmatrix}}{0.7482}+\frac{[1/9\quad 1\quad 1/3]\times\begin{bmatrix}0.7482\\0.0714\\0.1804\end{bmatrix}}{0.0714}+\frac{[1/5\quad 3\quad 1]\times\begin{bmatrix}0.7482\\0.0714\\0.1804\end{bmatrix}}{0.1804}\right)=3.0293 \tag{4 - 16}$$

3.2.5 Geometric Mean

The other ‘good’ priority scaling method is known as the geometric mean (GM) method. In this method, the geometric mean is used to estimate $v_{\lambda_{max}}$ and λ_{max}. This method multiplies all the elements of the same row and then take the *n*th root of the product as shown in (4 - 17):

$$\begin{bmatrix}(a_{11}\times \ldots \times a_{1n})^{1/n}\\ \ldots \\ (a_{n1}\times \ldots \times a_{nn})^{1/n}\end{bmatrix} \tag{4 - 17}$$

Further normalisation is required so that resultant priorities are in (4 - 18) and sum to unity:

$$\begin{bmatrix}\dfrac{(a_{11}\times \ldots \times a_{1n})^{1/n}}{(a_{11}\times \ldots \times a_{1n})^{1/n}+\cdots+(a_{n1}\times \ldots \times a_{nn})^{1/n}}\\ \ldots \\ \dfrac{(a_{n1}\times \ldots \times a_{nn})^{1/n}}{(a_{11}\times \ldots \times a_{1n})^{1/n}+\cdots+(a_{n1}\times \ldots \times a_{nn})^{1/n}}\end{bmatrix} \tag{4 - 18}$$

Thus, $v_{\lambda_{max}}=\begin{bmatrix}0.7514\\0.0704\\0.1782\end{bmatrix}$ and the associated λ_{max} is shown in (4 - 19):

$$\frac{1}{3}\times\left(\frac{[1\quad 9\quad 5]\times\begin{bmatrix}0.7514\\0.0704\\0.1782\end{bmatrix}}{0.7514}+\frac{[1/9\quad 1\quad 1/3]\times\begin{bmatrix}0.7514\\0.0704\\0.1782\end{bmatrix}}{0.0704}+\frac{[1/5\quad 3\quad 1]\times\begin{bmatrix}0.7514\\0.0704\\0.1782\end{bmatrix}}{0.1782}\right)=3.0291 \tag{4 - 19}$$

3.2.6 Least Squares

The Least squares (LS) method in AHP is used to minimise the square of the error between the actual judgments and the calculated estimates of the PC-Matrix. The normalisation step of EM, AM and GM is the unit constraint of the priorities in LS. This step introduces the Lagrange Multiplier Method to find the optimised priorities which meet the minimisation function. The process begins with a PC-Matrix A, with expert judgments a_{ij}, and priorities W_i and W_j, which are estimated priorities of criteria i and j where $i = 1, 2 \ldots, n$ and $j = 1, 2 \ldots, n$. If matrix A is strictly consistent, then $a_{ij} = \frac{w_i}{w_j}$.

Now it is assumed matrix A is not strictly consistent, then there is error, $e_{i,j}$, such that there exists Equation (4 - 20):

$$a_{ij} W_j - W_i = e_{i,j} \tag{4 - 20}$$

Since $e_{i,j}$ can either be positive or negative, the square of the error is used in Equation (4 - 21):

$$min \sum_{i=1}^{n} \sum_{j=1}^{n} \left(a_{ij} W_j - W_i\right)^2 \tag{4 - 21}$$

There is a constraint condition to sum the priorities from $\mathrm{W_1}$ to $\mathrm{W_n}$ to one, i.e., $\sum_{i=1}^{n} W_i - 1$. The second order equation with an equality constraint can be solved with the help of the Lagrange Multiplier method, a mathematical optimization method to find local extrema. The Lagrange Multiplier function with multiplier parameter λ is found in Equation (4 - 22).

$$L(W, \lambda) = \sum_{i=1}^{n} \sum_{j=1}^{n} (a_{ij} W_j - W_i)^2 - 2\lambda \left(\sum_{i=1}^{n} W_i - 1 \right) \tag{4 - 22}$$

The first order partial derivative of $L(W, \lambda)$ is therefore in (4 - 23):

$$\begin{cases} \dfrac{\partial L}{\partial W_i} = \displaystyle\sum_{j=1}^{n}\left(-2a_{kj}W_j + 2W_k\right) - 2\lambda \\ (replace\ W_j\ by\ W_k\ as\ an\ independent\ variable\ ) \\ \dfrac{\partial L}{\partial W_j} = \displaystyle\sum_{i=1}^{n}(2{a_{ik}}^2 W_k - 2a_{ik}W_i) \\ (replace\ W_j\ by\ W_k\ as\ an\ independent\ variable\ ) \\ \dfrac{\partial L}{\partial \lambda} = -2\left(\displaystyle\sum_{i=1}^{n} W_i - 1\right) \end{cases} \tag{4 - 23}$$

Therefore, the squared error, which is a second order non-linear function, is transformed into a first order linear function. To find the extrema, let the first order partial derivative, i.e., the slope of the tangent line, be zero. The first order partial derivative then becomes:

$$\begin{cases} \dfrac{\partial L}{\partial W} = \displaystyle\sum_{i=1}^{n}({a_{ik}}^2 W_k - a_{ik}W_i) - \sum_{j=1}^{n}\left(a_{kj}W_j - W_k\right) - \lambda \\ \left(replace\ W_j\ by\ W_i\ as\ i\ and\ j\ are\ same\ variables\right) \\ \quad = \displaystyle\sum_{i=1}^{n} {a_{ik}}^2 W_k - \left(\sum_{i=1}^{n} a_{ik}W_i + \sum_{i=1}^{n} a_{ki}W_i\right) + \sum_{i=1}^{n} W_k - \lambda = 0 \\ \dfrac{\partial L}{\partial \lambda} = \displaystyle\sum_{i=1}^{n} W_i - 1 = 0 \end{cases} \tag{4 - 24}$$

When $\mathrm{i} = \mathrm{k}$, $\frac{\partial L}{\partial W}$ can be rewritten into Equation (4 - 25):

$$\begin{aligned} \frac{\partial L}{\partial W} = \sum_{i=1}^{n}({a_{kk}}^2 W_k - a_{kk}W_k) \\ - \sum_{i=1}^{n}(a_{kk}W_k - W_k) = \left(\sum_{i=1}^{n} {a_{kk}}^2 - 2a_{kk} + n\right) W_k \end{aligned} \tag{4 - 25}$$

.

Since a_{kk} are elements on the diagonal line of the PC-Matrix, $a_{kk} = 1$ for all $k = 1,2,\cdots n,$ therefore $-2a_{kk} = -2$.

When $i \neq k,$ $\frac{\partial L}{\partial W}$ can be rewritten into Equation (4 - 26):

$$\frac{\partial L}{\partial W} = -\sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{a_{ik}} + \mathrm{a_{ki}}) W_i \tag{4 - 26}$$

The matrix form of the linear function is thus $Bw' = m$.

Where

$\mathrm{w}' = (\mathrm{W_1}, \mathrm{W_2}, \cdots, \mathrm{W_n}, \lambda)^{\mathrm{T}}$;

$\mathrm{m} = (0,0, \cdots ,0,1)^{\mathrm{T}}$;

$\mathrm{B} = [\mathrm{b_{ik}}]_{(\mathrm{n}+1)\times(\mathrm{n}+1)}$;

$\mathrm{b_{ik}} = -(\mathrm{a_{ik}} + \mathrm{a_{ki}}), (\mathrm{i}, \mathrm{k} = 1,2, \cdots, \mathrm{n}, \mathrm{i} \neq \mathrm{k})$;

$\mathrm{b_{ii}} = (\mathrm{n} - 2) + \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{a_{ik}}^2 , (\mathrm{k} = 1,2, \cdots, \mathrm{n})$;

$\mathrm{b_{i.n+1}} = -1, (\mathrm{i} = 1,2, \cdots, \mathrm{n})$;

$\mathrm{b_{n+1.k}} = -1, (\mathrm{k} = 1,2, \cdots, \mathrm{n})$;

$\mathrm{b_{n+1.n+1}} = 0$.

Replace *k* by *j* since *k* and *j* are the same variables, then the matrix becomes (4 - 27):

$$\mathrm{B} = \begin{bmatrix} (\mathrm{n}-2) + \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{a_{i1}}^2 & -(\mathrm{a_{12}} + \mathrm{a_{21}}) & \cdots & -(\mathrm{a_{n1}} + \mathrm{a_{1n}}) & -1 \\ -(\mathrm{a_{21}} + \mathrm{a_{12}}) & (\mathrm{n}-2) + \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{a_{i2}}^2 & \cdots & \cdots & -1 \\ \cdots & \cdots & \cdots & -\left(\mathrm{a_{(n-1).n}} + \mathrm{a_{n.(n-1)}}\right) & \cdots \\ -(\mathrm{a_{n1}} + \mathrm{a_{1n}}) & \cdots & -\left(\mathrm{a_{n.(n-1)}} + \mathrm{a_{(n-1).n}}\right) & (\mathrm{n}-2) + \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{a_{in}}^2 & -1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \tag{4 - 27}$$

$$\mathrm{B} \times \begin{bmatrix} W_1 \\ W_2 \\ \cdots \\ W_n \\ \lambda \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \cdots \\ 0 \\ 1 \end{bmatrix}.$$

In order to prove $L(W, \lambda)$ has the global minima, the second order partial derivative is calculated in (4 - 28):

$$\begin{cases} \frac{\partial^2 \mathrm{L}}{\partial \mathrm{W}^2} = \sum_{i=1}^{n} \left({a_{ij}}^2 - 1 \right) - \sum_{j=1}^{n} \left(a_{ij} - 1 \right) = \sum_{i=1}^{n} {a_{ij}}^2 - \sum_{j=1}^{n} a_{ij} \\ \frac{\partial^2 \mathrm{L}}{\partial \mathrm{W}\, \partial \lambda} = -n \\ \frac{\partial^2 \mathrm{L}}{\partial \lambda\, \partial \mathrm{W}} = n \\ \frac{\partial^2 \mathrm{L}}{\partial \lambda^2} = 0 \end{cases} . \tag{4 - 28}$$

The corresponding Hessian matrix for the second order derivative of $L(W, \lambda)$ is $H(W, \lambda)$ in (4 - 29):

$$H(W, \lambda) = \begin{bmatrix} \frac{\partial^2 \mathrm{L}}{\partial \mathrm{W}^2} & \frac{\partial^2 \mathrm{L}}{\partial \mathrm{W}\, \partial \lambda} \\ \frac{\partial^2 \mathrm{L}}{\partial \lambda\, \partial \mathrm{W}} & \frac{\partial^2 \mathrm{L}}{\partial \lambda^2} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 \mathrm{L}}{\partial \mathrm{W}^2} & -n \\ n & 0 \end{bmatrix}. \tag{4 - 29}$$

Since $a_{ij} = \frac{1}{a_{ji}}, \frac{1}{9} \leq a_{ij} \leq 9$, the elements on the diagonal line, i.e., $a_{ii} = 1, a_{ii} - 1 = 0$, can be ignored. Then there are $\frac{n^2 - n}{2}$ elements that are a_{ij}, $\frac{n^2 - n}{2}$ are a_{ji}.

Assume (4 - 30):

$$2 \leq a_{ij} \leq 9, \frac{1}{9} \leq a_{ji} \leq \frac{1}{2}, i \neq j \tag{4 - 30}$$

Then (4 - 31) can be derived:

$$1 \leq a_{ij} - 1 \leq 8, -\frac{8}{9} \leq a_{ji} - 1 \leq -\frac{1}{2}, i \neq j \tag{4 - 31}$$

Therefore (4 - 32):

$$\begin{gathered} \tfrac{1}{9} \leq (a_{ij} - 1) + (a_{ji} - 1) \leq \tfrac{15}{2} \\ \frac{n^2 - n}{2} (a_{ij} - 1) + \frac{n^2 - n}{2} (a_{ji} - 1) > 0 \end{gathered} \tag{4 - 32}$$

This can also be expressed in (4 - 33):

$$\frac{\partial^2 \mathrm{L}}{\partial \mathrm{W}^2} = \sum_{i=1}^{n} {a_{ij}}^2 - \sum_{j=1}^{n} a_{ij} = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \left(a_{ij} - 1 \right) > 0 \tag{4 - 33}$$

In addition, (4 - 29) can yield (4 - 34):

$$H(W,\lambda) = n^2 > 0 \tag{4 - 34}$$

This means that $H(W,\lambda)$ is non-singular and positive-definite matrix. Since $H(W,\lambda)$ does not change with $W\ and\ \lambda$, then the Lagrange Multiplier function $L(W,\lambda)$ has a global minima and eligible solutions for $W_1\ to\ W_n$.

Therefore, this proves that using Equation (4 - 27) can find the priorities of the PC-Matrix.

By using LS, the estimated $v_{\lambda_{max}}$ is $\begin{bmatrix}0.7622\\0.0813\\0.1565\end{bmatrix}$ and estimated λ_{max} is in (4 - 35):

$$\frac{1}{3}\times\left(\frac{[1 \quad 9 \quad 5]\times\begin{bmatrix}0.7622\\0.0813\\0.1565\end{bmatrix}}{0.7622}+\frac{[1/9 \quad 1 \quad 1/3]\times\begin{bmatrix}0.7622\\0.0813\\0.1565\end{bmatrix}}{0.0813}+\frac{[1/5 \quad 3 \quad 1]\times\begin{bmatrix}0.7622\\0.0813\\0.1565\end{bmatrix}}{0.1565}\right)=3.0672 \tag{4 - 35}$$

The six methods are explained and then applied to the holiday destination example for comparison. The results of the application are compared in the next section.

3.2.7 Comparison of Different Priority Scaling Methods

To summarise, six sets of results are shown in Table 15.

Table 15: Results of Six Priority Scaling Methods

Priority	EM	Crude	Reciprocal	AM	GM	LS
Transportation Fee(£)	0.7514	0.7266	0.7646	0.7482	0.7514	0.7622
Transportation Time(hour)	0.0704	0.0700	0.0771	0.0714	0.0704	0.0813
# Changes During Travel	0.1782	0.2034	0.1583	0.1804	0.1782	0.1565
λ_{max}	3.0290	3.0453	3.0521	3.0293	3.0291	3.0672

Table 15 shows that for the λ_{max}, AM- and GM-based results are much closer to the EM-based results than other three methods. In terms of priorities, GM yields a result that is approximately the EM result.

Since the development of EM, there have been many research studies related to EM and similar methods. For example, G. Crawford and C. Williams [50] compared EM to GM. They concluded that GM has similar theoretical qualities with EM. By using their models, GM is preferable to EM. Another research study by G. Crawford [51] further expanded his theory of using GM instead of EM to estimate priorities. De Jong [52] advocates GM as well. In addition, other scaling methods exit that have been championed by others as priority scaling methods providing accurate estimation of eigenvectors and maximum eigenvalues. For example, R.E. Jensen [53] argued for LS, while A.T.W. Chu *et al* [54] argued for weighted LS, and K.O. Cogger and P.L. Yu [55] supported AM. As the developers of EM, T.L Saaty and L.G. Vagas insisted on the superiority of EM [56-58]. There is no conclusion about the ‘best’ or ‘optimal’ method that can be used for scaling priorities, therefore, multiple methods should be applied, and results should be reported to find the most acceptable solution.

Among the applications of AHP, in the field of power system engineering, [39, 41-43, 59-61] applied EM embedded with AHP as their approach. GM has been utilised as an alternative to EM in [40]. On the EM side, [42] developed a computer programme to allocate remotely controlled switches in Distribution Networks with a real case using EM. Other applications, such as those found in [43], applied AHP with EM when deciding on demand curtailments that the centre load dispatch centre requires within an electric utility service area. Also, [41] and [59] applied AHP to rate restoration plans, from the most desirable to the least desirable ones. While [41] is based on the existing Grey Relational Analysis for distribution system restoration and [59] is based on a fuzzy cause-effect network. Apart from restoration plans, AHP is also applied in evaluating a multitude of generation expansion plans. One research is based on data envelopment analysis as detailed in [60], and the other evaluated six different Distributed Generations options with three attributes [39] . All of them utilised EM in their approaches. In [61], two MCDA models, i.e., AHP and TOPSIS, are combined to evaluate vulnerability factors for a power control system derived by probability risk assessment, in which the priorities are calculated by EM. Although there are less electrical power system applications that use GM, [40] assessed the condition of the equipment in a power system substation with seven criteria, four experts who made the PC judgments, and five groups of substations grouped by age as five alternatives.

3.2.8 Conclusion

This chapter describes six different priority scaling methods mostly used and the performances are being compared based on the holiday destination selection example in Section 3.1. Since the ‘crude’ and ‘reciprocal’ method are not qualified as ‘good’ method by Saaty, in this thesis, EM, AM, GM, and LS are applied to a power system related real case study in Chapter 4 along with AHP. Results are also analysed and compared using an error index (E.I.), the results shown which method provides a minion error according to the expert judgments. The details are explained in Chapter 4.

3.3 Expert Elicitation

Expert elicitation is a synthesisation methodology that can be used in various projects to synthesise the belief or opinions of multiple experts where the project involves uncertainties. The area of the application of expert elicitation is multidisciplinary especially when expert knowledge is required.

Decision-making projects often involve more than one expert to capture their expertise to form a consensus. In that case, multiple opinions cannot co-exist, and a technique is required to obtain the desired single consensus, Multiple Experts Judgments Aggregation (MEJA) is a technique used to encapsulate multiple experts’ judgments into one final judgment. The MEJA technique can either bring a group of experts together to discuss and reach a consensus or elicit judgment from every individual expert and then find the single final consensus in a mathematical way. O'Hagan, Anthony *et al* [62], summarised different aggregation methods into two categories: the former aggregation is also known as a behavioural approach, which can be considered as a combination of experts while the latter is a mathematical approach to combine judgment from individual experts. Both approaches contain several alternative methods; details are introduced in the remaining sections of this chapter.

3.3.1 Behavioural Approaches

A behavioural approach is generally an approach that combines a group of experts together to elicit a single consensus. Differences between different behavioural methods can be the involvement of restrictions while interacting with experts. The most common behavioural method is Group Elicitation because it is easy to carry out, as described in

Section 3.3.2. The other behavioural method, the Delphi Method, involves typical elicitation procedures as used in this thesis, and is detailed in Section 3.3.3.

3.3.2 Group Elicitation

Group Elicitation is a simple and straight forward behavioural aggregation method, the most common form is a round-table discussion. The main idea of it is to bring a group of experts together to yield one correct or agreed outcome or answer to a task through group interactions.

Because the group interactions take place between individual experts directly, Group Elicitation can be effective if experts possess similar knowledge and no psychological bias is involved. On the other hand, difficulties in deriving a consensus may occur because of disagreements between experts, or a biased consensus is obtained due to the dominance of one or more experts towards other experts during discussions.

Because of the weaknesses of Group Elicitation, behavioural aggregations in which expert interactions are more controllable are required. Among these, the Delphi Method is applied in this thesis; the details are in the following section.

3.3.3 The Delphi Method

The application of the Delphi Method is multidisciplinary and can be widely used across a variety of decision-making projects with multiple experts, such as policy decision-making or industrial technology development. The Delphi Method was introduced in the 1960s, at that time, Dalkey and Helmer [63] had an experiment that featured Group Elicitation, i.e., the Delphi Method, using a small group of seven experts. An additional feature was introduced called ‘controlled feedback’ earlier in the 1950s. Six years later, Dalkey [64] conducted a larger experiment to study the Delphi Method. This involved 10 experiments, with 14 groups of experts with group size varying from 11 to 30 members. From those experiments, the Delphi Method was proved to have the ability to reduce the effect of an individual dominant expert, and at the same time, minimise the impact of the results from previous iterations and group pressure. From the ‘Delphi Guidance’ created by Linstone and Turoff [65], several features of a project lends it to the application of the Delphi Method, among which, the following points describe the features of the project in this thesis:

1. The solution of the project is a forecasting result;

2. The solution of the project requires collection of multiple experts' judgments;
3. The carrying out of frequent face-to-face group meetings is infeasible;
4. Anonymity is required to avoid the 'bandwagon effect', i.e., minimise the probability of deriving a biased result by quantity dominance or personality dominance.

From the guidance, it can be shown that, after comparing with Group Elicitation, the Delphi Method has the following characteristics that can minimise the disadvantage of Group Elicitation:

1. Capture the knowledge of experts in the domain, utilise expert experiences and knowledge sufficiently;
2. Anonymity is a unique characteristic of the Delphi Method among behavioural approaches, i.e., experts are interviewed separately without knowing each other;
3. The Delphi Method involves several iterations between experts and decision maker to reach a consensus, which usually requires three or four iterations.

To understand the rationale of the Delphi Method, the general procedure of the Delphi Method is described below:

1. Form an experts' group who have a great deal of knowledge in the domain. Experts can be those who work in the first line and deal with everyday affairs in the domain, high-level managers in the domain or invited from outside;
2. Conduct a session with experts separately to keep anonymity as a preparation before capturing expert judgments. This session should describe the purpose and corresponding requirements of the project to experts and at the same time meet their requests. It is vital to make sure that details are delivered properly to every expert. Therefore, all the experts are equipped with the same understanding of the projects and requirements. This helps experts provide their knowledge in a context compatible with others;
3. Work out a questionnaire consisting of questions to capture expert judgments. These questions should be as simple as possible, relate to the project, and able to be answered by experts;
4. Pass the questionnaire to experts and ask them to provide their judgments by answering the questions, and at the same time, remain anonymous. If the session

preparation is adequate, experts can seize the point of the questions and provide judgments efficiently;

5. Collect the questionnaires completed by experts and summarise their judgments. Experts are asked to compare their own judgments with the summary and reconsider if they would like to change their mind after comparing. The questionnaires are also sent back to them for modification if they so desire;
6. Repeat collecting, summarising, and sending back the summary along with questionnaires until there are no modifications from experts, keeping anonymous all the time;
7. Complete the final summation of the expert's judgments.

The advantages of the Delphi Method are as follows:

1. Collect wider opinions from multiple experts than a single expert with a proper knowledge elicitation approach to improve the accuracy of judgments;
2. The anonymity can effectively avoid the following scenarios as in face-to-face group discussion:
    a. Authorities affect other experts, therefore result in biased judgments. This can happen either because others are not convinced by themselves and can easily be influenced by others, especially authorities, or they are 'forced' by the discussion atmosphere;
    b. Some experts would not like to comment on others' opinion face to face, therefore a waste of resource;
    c. Some experts would not like to change their original opinions in public because of lack of confidence in themselves, therefore inaccurate judgments.

There exist disadvantages of the Delphi Method:

1. The Delphi Method can be time-consuming if the disagreement between multiple experts cannot be reduced after several iterations, therefore consensus is failed to be reached;
2. Conversely, prolonged process involving a large number of iterations can make experts tend to compromise with others to 'speed up the process', therefore resulting in an unrepresentative result;

3. The disagreements between multiple experts can discourage the experts with opposing opinions to insist and therefore leads to a biased consensus;

Preparing the questionnaire and exploring the disagreements between multiple experts properly can reduce the possibility of the derivation of a biased consensus, and so one solution to address the potential the failure of the Delphi Method caused by the deadlock between different opinions is to employ mathematical approaches, which are described in Section 3.3.4.

3.3.4 Mathematical Approaches

Mathematical approaches are applied when behavioural approaches cannot provide a reasonable consensus among multiple experts. Because it is a mathematical approach, numbers are dealt with by using mathematical equations. There are two mathematical approaches introduced and detailed below.

3.3.5 Logarithmic Pooling Method (LogPM) and Linear Pooling Method (LiPM)

LogPM and LiPM are two opinion-pooling techniques, LogPM is also known as the Geometric Pooling Method (GPM), it creates the synthesised PC-Matrix by calculating the geometric mean (GM) of the same compared pair from multiple experts while LiPM calculates the arithmetic mean (AM) instead of the GM. Equations are (5 - 1) and (5 - 2), respectively:

$$C_{ij-LogPM} = \left(\prod_{k=1}^{m} C_{ij-expk}\right)^{\frac{1}{m}} \tag{5 - 1}$$

$$C_{ij-LiPM} = \frac{1}{m}\left(\sum_{k=1}^{m} C_{ij-expk}\right) \tag{5 - 2}$$

where

i, j: row and column array of the elements, $i \in Z^{+}, j \in Z^{+}$;

m: number of experts.

Table 16 shows two experts judgments and with LogPM and LiPM results respectively. Both methods can develop a reasonable synthesised matrix where LogPM can maintain the Axiom 1 of AHP, i.e., keeps the matrix reciprocal. For example, for judgments with scale 3 and 5 and the reciprocal part with scale 1/3 and 1/5, the GM is $\sqrt{(3 \times 5)} =$

3.873 and $\sqrt{(1/3 \times 1/5)} = 1/\sqrt{15} = 1/3.873$ respectively, and the AM is $(3+5)/2 = 4$ and $(1/3 + 1/5)/2 = 4/15 = 1/3.75$ respectively. It can be seen that GM keeps the reciprocal relationship of the original matrix but not AM. Therefore, the logarithmic pooling is chosen to aggregate the multiple experts' PC matrices, the choice of LogPM has also been described in [40].

Table 16: LogPM and LiPM example

PC-Matrix Expert 1

	A1	A2	A3
A1	1	3	5
A2	1/3	1	3
A3	1/5	1/3	1

PC-Matrix Expert 2

	A1	A2	A3
A1	1	5	7
A2	1/5	1	2
A3	1/7	1/2	1

Apply LogPM

Apply LiPM

PC-Matrix LogPM

	A1	A2	A3
A1	1	3.87	5.92
A2	1/3.87	1	2.45
A3	1/5.92	1/2.45	1

PC-Matrix LiPM

	A1	A2	A3
A1	1	4	6
A2	1/3.75	1	2.5
A3	1/5.83	1/2.4	1

3.3.6 Cooke Method

The Cooke method, or so-called Cooke's classical model (CCM), was developed by Cooke in 1991 [66]. To aggregate multiple expert judgments, CCM is another method other than purely linear or logarithmic pooling. CCM is a performance-based method that depends on experts' judgement. It can potentially generate a more representative aggregated result from a group of experts. CCM uses a set of seed variables to calculate individual expert calibration and information scores which are then used to calculate an expert's relative weighting in terms of his/her expertise. Seed variables are the actual answers to a question, these are prepared and provided by the decision-maker. Once the expert's relative weighting has been calculated, individual experts are then asked to predict the quantiles for a target variable, typically the 5th, 50th and 95th percentiles [67]. The prediction then being used to produce a calibration component and an information component based on K-L distance [68-71]. This is then used to derive the performance-based weightings, if expert who provided a poorly calibrated estimation or too wide that gives little information, then the expert will be downweighed and therefore being allocated a lower performance-based weighting. The performance-based weighting is the combined with expert's individual judgments to derive the decision-maker's assessment of that variable.

A guide for the implementation of CCM to synthesise experts' judgments can be found in [67].

3.3.7 Applications

As mentioned before, the Delphi Method is a forecasting method used when historical data are hard to obtain and therefore experts' judgments are the only reliable domain knowledge that can be captured to inform predictions.

In the area of business scenarios analysis, [72] this was used in the prediction of goods transport scenarios in 2050 for Sweden - analysed with the help of the Delphi Method. Experts involved in this project were from academia, industry, and government. The scenarios for the project show an interest in the desire for connectivity and sustainability of goods transport; while [73] analysed the global transportation infrastructure scenarios in 2030, [74] was concerned about carbon capture, utilisation, and storage scenarios in 2030, with the identification of policy challenges and opportunities.

As for health care, there were 32 physicians who participated in the decision on the treatment for Alzheimer's disease using the Delphi Method. This application took three questionnaire iterations before a consolidated result was derived [75]. Apart from Alzheimer's disease, a study of identifying the proper actions and organisational factors for patients with intellectual disabilities was conducted and 82% agreement was reached with a two-round Delphi Method [76]. In the area of exercise therapy, joint replacement surgery, the therapeutic validity of total joint replacement on the recovery of functioning was estimated using the Delphi Method with four iterations [77]. A criteria list with 9 items, reduced from 206 items, was derived by a three-round Delphi Method questionnaire completed by 21 health experts. This list aims to minimise the reference standard for randomized clinical trials in health treatment.

Moving to the policy decision-making project, a health policy in terms of the transferability of success factors of private food marketing to public food marketing was undertaken. More than 30 experts participated in a two-round Delphi Method, the results show that low-costing is of most interest, other than that, building of trust, cooperation and consistency, public and marketing campaigns coupled with structural changes are important factors as well which should be combined in a good and sustainable way[78].

Another policy project, which related to the electricity market, researched the main issues in the medium-term future of the European electricity market presented in [79]. The factors that influence the European electricity market competition were uncovered, along with the future electricity management during a Delphi procedure in two iterations.

The Delphi Method has also been applied in other areas, for example, a future Lake Management in 2030 is predicted using the Delphi Method with lake experts to improve the quality of freshwater from eutrophication [80].

3.3.8 Conclusion

To sum up, the historical asset data of the wood poles considered in this thesis was not readily obtainable; which is common for such High Volume Low Cost assets where condition monitoring is not considered economically viable, the Delphi Method was considered a robust method of conducting an expert-based appraisal of the future asset health, and as such is applied and detailed in Chapter 4 of this thesis.

3.4 References

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4 VALIDATION OF PROPOSED MCDA HEALTH ASSESSMENT APPROACH

4.1 Asset Health Assessment Using a Joint MCDA and MEJA Approach

4.1.1 Introduction

Expert judgment is integral to asset health assessment in asset-based organisations. The health assessment approach proposed in this thesis required to inform refurbishment or replacement decisions affecting power system assets is based on the combination of MCDA and MEJA techniques as introduced previously in Chapters 3. It firstly captures multiple expert judgments individually using MCDA and then synthesises these judgments to achieve a consensus via MEJA. Figure 8 shows the interaction between MCDA (individual assessment) and MEJA (group assessment) in arriving at an overall consensus on asset health assessment involving a number of experts.

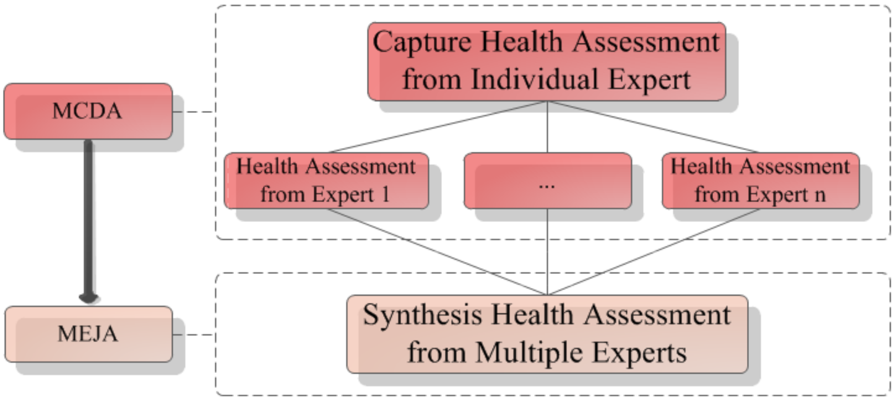


Figure 8: Combination of MCDA and MEJA

Experts are required to make decisions on prioritising assets for refurbishment/replacement (R/R) based on asset health. MCDA is a decision-making technique that can support experts in this task. Specifically, MCDA requires *individual* experts to define criteria enabling the assessment of asset health, on which R/R decisions are then based. MCDA relies completely on individual experts to define the asset health assessment criteria based on their own experience of the domain, and then assign asset specific scores and weightings which represent the relative contribution made to the asset health assessment and R/R decision attached to each criterion. The MCDA techniques utilised here are AHP and the SW method, which utilise the previously defined health assessment criteria to arrive at a single quantitative value providing a measure of asset health (health assessment score) which are representative of an individual's own *personal expert judgment*. Assets can then be measured relatively against each other on this basis and prioritised for R/R.

However, it is necessary to utilise the full breadth of expertise available, while managing potentially conflicting opinions derived from varying levels of domain knowledge and experience across the expert group. MEJA techniques can be employed to manage any conflicts of opinion between *multiple* experts in order to arrive at an agreed *expert group consensus*. The MEJA technique utilised here is the Delphi Method which has been introduced in Chapter 3.3. This is a *behavioural technique*, which firstly surveys multiple experts: asking them for quantitative judgments in order to assess the health of an asset while remaining anonymous. Prior to conducting the survey, it is necessary to clearly explain the details and requirements of the survey to the experts. In addition, the MCDA method is explained, including important terms and procedures used to capture their judgments on asset health assessment. The anonymity gives experts freedom to convey their true judgments without risk of biasing from other participants. The surveys are assimilated from *multiple* experts, analysed and summarised. Experts are then presented with the summary. This gives the opportunity for them to now reconsider and modify their personal judgments based on the summary, whilst remaining anonymous.

This iterative process requires the continued participation of experts and is repeated until a consensus is reached. However, there exist instances where a consensus cannot be reached utilising this behavioural technique. In these cases, a *mathematical approach* can be applied to derive quantitative values, i.e., aggregated priorities, representing relative contributions of health assessment criteria. Here, the mathematical approach of the LiPM and LogPM introduced in Section 3.3.4 are applied. These are mathematical approaches, unlike behavioural approaches, do not require continued iterations involving multiple experts after the initial delivery of the survey. These approaches aggregate the priorities from individual expert of the criteria of MCDA directly and mathematically, to reach a single quantitative output. Since the proposed approach is a combination of MCDA on individual expert and MEJA techniques on multiple experts, this chapter begins by introducing the application of the MCDA method involving individual experts in Section 4.1.2.

4.1.2 Hierarchical Structure of the Proposed MCDA Approach

The most important component of the two proposed MCDA methods, i.e., AHP and SW, is the hierarchical structure of the asset health assessment, further applications of AHP and SW are based on the structure. Referring to the holiday destination example which shows a general hierarchical structure and process in Figure 6 in Section 3.1, this can be applied to assess the health of HVLC power system assets with hierarchical structure shown in Figure 9. Asset which are classified as HVLC are assets where on-line condition monitoring systems are not available or cost-effective. Therefore, historical condition monitoring data is limited while domain expertise and experience are much more readily available. The thesis demonstrates how MCDA captures the expert judgment in a logical and hierarchical way. This hierarchical structure is developed for an individual expert for general HVLC asset health assessment.

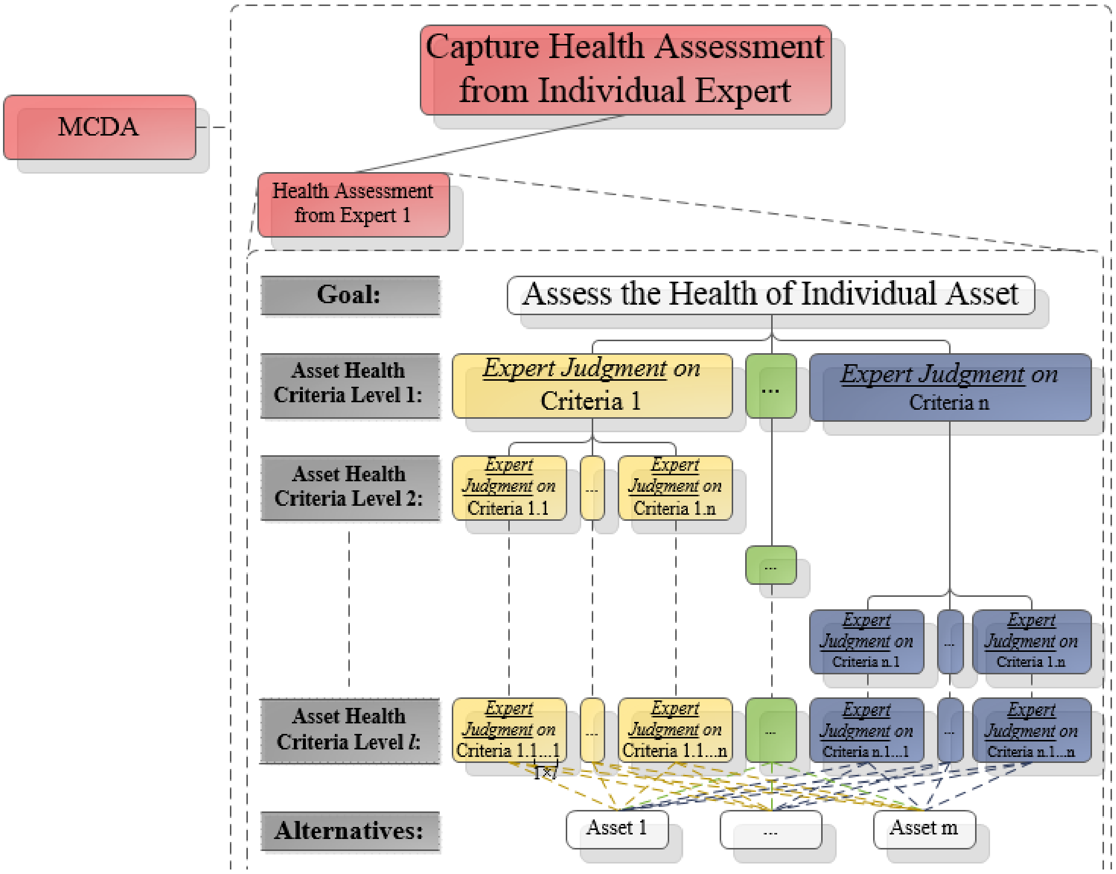


Figure 9: General Hierarchical Structure of HVLC Asset Health Assessment

Figure 9 shows the three basic hierarchical levels of the structure: a ‘goal’ level, an ‘asset health criteria’ level with several ‘sub-criteria’ levels, and an ‘alternatives’ level. It is similar to Figure 6 which consists of a ‘goal’ level, one ‘holiday selection criteria’ level, and an ‘alternatives’ level. This structure applies to AHP and SW as MCDA techniques. The number of asset health criteria levels depends on the number of asset health criteria identified by experts. The ‘goal’ represented in the AHP or SW hierarchy is to assess the health of every HVLC asset. At the bottom level of the hierarchy, ‘alternatives’ represent all assets to be assessed and ranked in terms of their relative state of health assessment. Between the ‘goal’ and ‘alternatives’ levels, are criteria that influence/define the asset health. The number of criteria levels depends on how experts define the relationship among criteria.

As discussed previously, for multiple experts, the Delphi Method (behavioural approach) can be used to aggregate their judgments, following an iterative approach to reaching a consensus of expert judgments. When this approach fails to reach a consensus, the LogPM (mathematical approach) can help to aggregate multiple experts’ judgments to derive a new comparison set of synthesised judgment by calculating the geometric mean of the multiple experts’ judgments.

This thesis proposes a novel joint MCDA and MEJA approach to assessing the health of a wide range of HVLC power system assets where historical condition monitoring data is limited, but where domain expertise and experience is much more readily available.

4.1.3 Power System Asset Health Assessment Using a Joint MCDA and MEJA Approach

When applying MCDA on power system asset health assessment, a hierarchical structure is created to assess the health of the particular power system asset in question. Information collected by field staff inspection is then required to populate the ‘values’ (representing aspects of asset health/condition) of the asset health criteria for a given asset. An example of this hierarchical structure for power system asset health assessment can be found in Figure 10 (based on the general hierarchy of Figure 9). In this example, the goal is to assess the health of the asset. In this case, age, condition, environment are three high-level health criteria identified by an expert.

‘Age’ is an indicator of the natural degradation of assets, different age points are the subordinate criteria, denoted as A1 to An.

‘Condition’ is very asset specific and affects asset health in many different ways. For example, in the case of transformer assets, the visual inspection and monitoring criteria focuses on rusting, oil leak, compound leak, sight glass and partial discharge monitoring.

‘Environment’ has a further subordinate asset health criteria level consists of three criteria: terrain, climate and temperature. As examples, the ‘terrain’ criterion can be defined as solid ground or near wet rivers; ‘climate’ can be defined as tropical rain climate or warm temperate maritime climate; and ‘temperature’ can range across the year for assets installed outdoor.

The visual inspection and monitoring criteria for cables as another asset type focuses on partial discharge monitoring, dielectric loss measurement, insulation resistance measurement and external damages.

In Figure 10, subordinate criteria used to evaluate ‘condition’ are denoted as C1 to Cn. Similarly, TER1 to TERn, CL1 to CLn, TEM1 to TEMn are used to represent the subordinate criteria used to evaluate the terrain, climate and temperature affecting the asset health. The ‘alternatives’ in the hierarchical structure represent all assets under inspection.

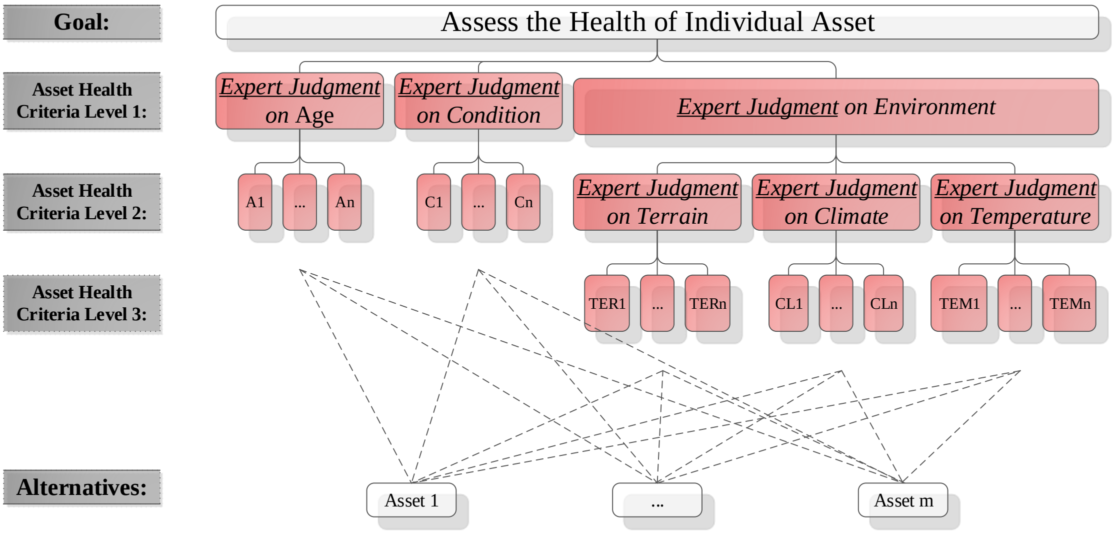


Figure 10: General Hierarchical Structure of Health Criteria for Power System Assets

In the next section, a real-world power system asset health assessment case, HV Wood Poles, are introduced. The process of collection of historical maintenance and inspection data and identification of asset health criteria for this real case of HV Wood Poles is described in detail, while the remainder of Chapter 4 demonstrates the application of MCDA and MEJA on the specific case of HV Wood Poles.

4.2 Asset Health Assessment Data of HV Wood Poles

4.2.1 Data Collection

The joint of MCDA and MEJA health assessment methodology is applied here to the health assessment of distribution HV Wood Poles owned, maintained and refurbished by an electric utility company. **R**evenue set to deliver strong **I**ncentives, **I**nnovation and **O**utputs (RIIO), requires power system assets to be classified as HI 1-5 in terms of their overall health. The existing approach to HI classifications is entirely age-based but the utility sought to involve other useful criteria to provide a more representative, accurate and robust health assessment strategy, while continuing to recognise the effects of natural degradation due to asset aging.

HV Wood Poles can be considered as HVLC assets. Therefore condition monitoring is not considered to be cost-effective and so none is currently installed. In order to maximise the utilisation of assets and stretch their available lifetime while minimising the cost of maintenance and maximising any return on investment, it is necessary to periodically assess the health of these assets. The utility sets up an inspection project for HV Wood Poles. The inspection information is available from the HV Wood Poles line patrol database owned by the utility. The information in the raw data shows wood pole inspection date, reference number, ID, year of installation, defects, comments, and the inspection status for each individual HV Wood Pole. These defects affect the pole, stay, conductor and plant. The collected raw data are not ready to be used directly as wood pole health assessment criteria, and so the next step requires the selection and identification of the criteria which contribute to the overall health assessment of HV Wood Poles by experts.

4.2.2 Criteria Selection and Identification

From the defects, experienced experts from the utility were able to limit the defects considered relevant in the asset health assessment required to inform R/R decisions. After several iterations with experts, conducted separately, a final agreement is reached, i.e., a total of ten defects were identified as relevant by domain experts in providing an insight into the asset condition. Among these ten defects, one of them is considered as an exception, i.e., defect ‘*Seriously Damaged*’. Experts decided that assets with this ‘*Seriously Damaged*’ defect description should be replaced immediately regardless of the age and existence of other defects. Therefore, the remaining criteria require further evaluation to establish their relative contribution to the health assessment of these wood pole assets, using the proposed joint MCDA and MEJA technique can be found in Table 17.

Table 17: Identified Criteria of HV Wood Poles

Identified Criteria	
Age	Condition

Identified Subordinate Criteria of Condition
Foundation Eroded
Animals Rubbing
Pole Off Plumb
Pole Top Rot
Broken/rusty rod
Broken/rusty wire
Slack Stay
Damaged permali insulator
Broken porcelain stay insulator

Section 4.3 and Section 5.4 implement the combination of AHP (as one of the chosen MCDA techniques) with the MEJA technique and then SW (as the other chosen MCDA techniques) with the MEJA technique respectively, to determine the relative contribution of the criteria in Table 17 in the assessment of the health of HV Wood Poles.

4.3 Using AHP and MEJA Approach to HV Wood Pole Health Assessment

The relationship between AHP and MEJA is that AHP will produce a matrix which reflects individual expert judgment, and MEJA is used to synthesise multiple PC-Matrixes from multiple experts.

The flowchart below demonstrates how AHP is applied to the HV Wood Poles case study to determine the relative contribution of each criterion to the overall health assessment of wood poles. The procedure starts by data collection, selection and criteria identification, followed by the construction of the hierarchical structure and pairwise comparison. Finally, it is necessary to calculate the eigenvalue and eigenvector as discussed in Chapter 3.2; which can be normalised to determine the weightings associated with different criteria, which define the relative contribution to the asset health assessment, and ultimately used to derive a quantitative Health Assessment Score which can be used to prioritise asset replacement and refurbishment (i.e., generating a ranked list of assets). The flowchart is shown below in Figure 11.

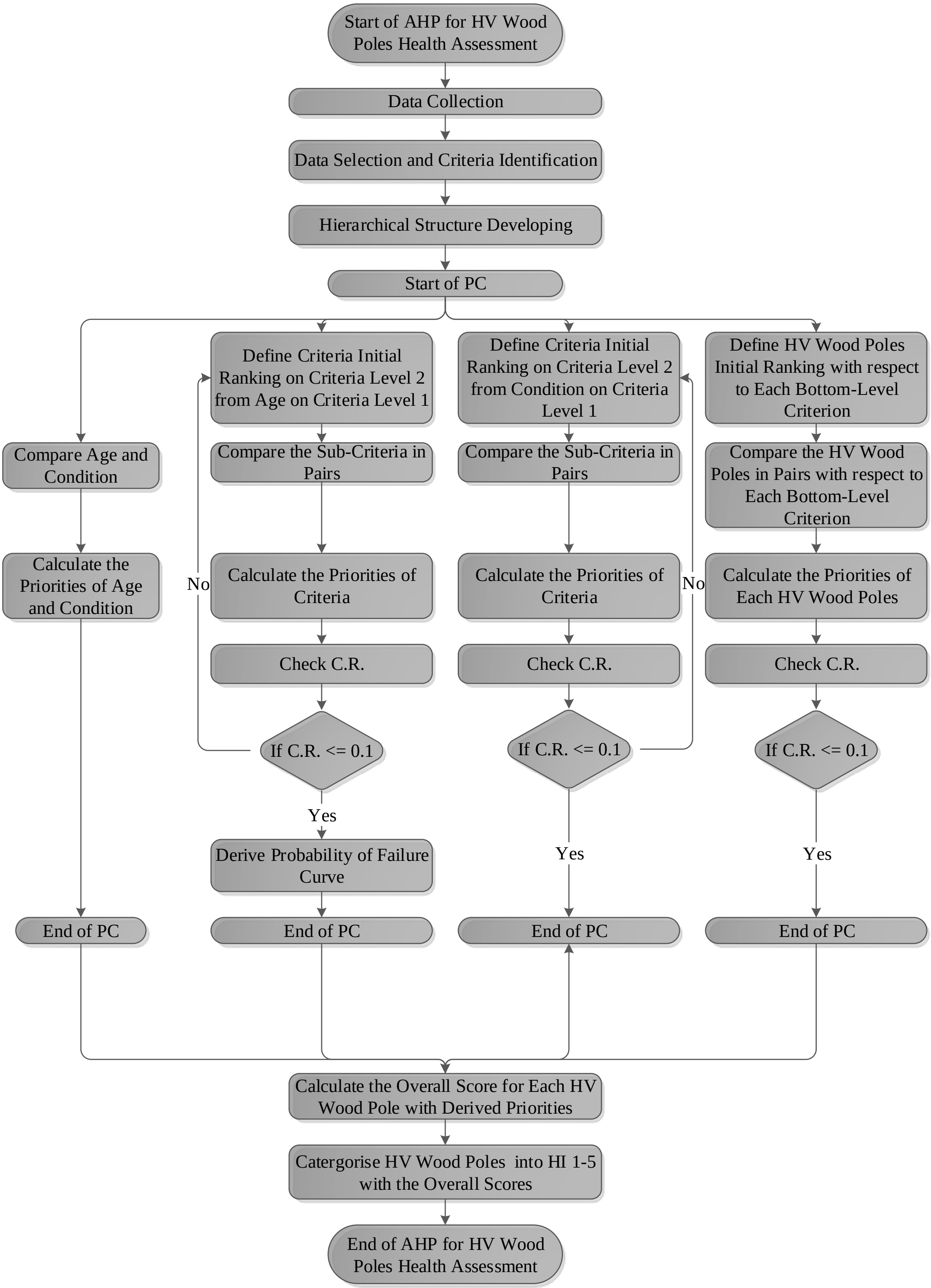


Figure 11: Flowchart of AHP for HV Wood Poles Health Assessment

AHP can be divided into three main stages: the first stage is the collection and selection of data and developing of hierarchical structure, the second stage focuses on conducting PC, and the third stage is the composition of priorities. The implementation of each stage of the flowchart in sections are detailed below:

- For the first two steps of the first stage, i.e., ‘data collection’ and ‘data selection and criteria identification’ have been demonstrated in Section 4.2, allowing the hierarchical structure of HV Wood Poles to be constructed (represented in Figure 12).

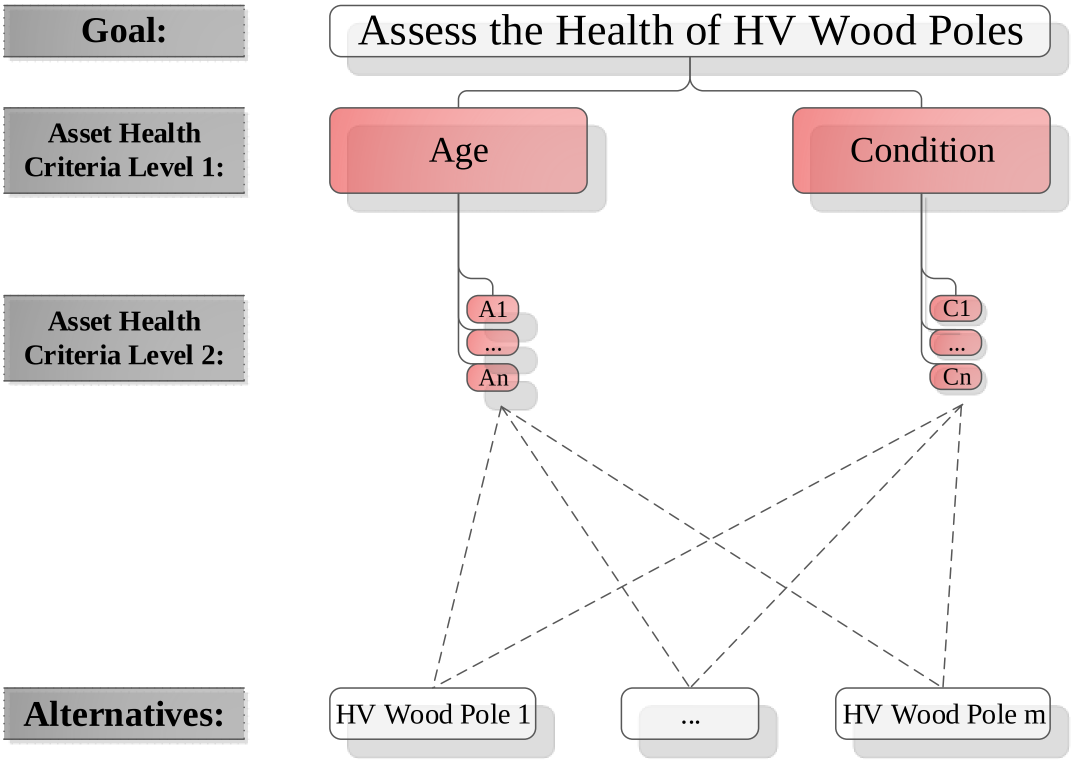


Figure 12: Hierarchical Structure of HV Wood Poles

  This hierarchical structure consists of the goal of the application (i.e., HV wood pole health assessment); two health criteria levels which define the decision-making criteria defining/characterising asset health; and all the alternatives (i.e., wood poles under consideration for refurbishment). As shown in the structure, experts identified ‘age’ and ‘condition’ as higher-level health assessment criteria characterising the overall health assessment of HV Wood Poles.

- The second stage of AHP (i.e., conducting PC), is applied repeatedly. It is firstly applied to ‘age’ and ‘condition’ (shown in Section 4.3.1) to derive their relative contribution to asset health assessment. Identification of the subordinate ‘age’ criteria is then detailed in Section 4.3.2 along with the pairwise comparison between five criteria (A1…An) to derive a probability of failure curve based on asset age. In Section 5.1, pairwise comparison is applied between the nine subordinate ‘condition’ criteria, i.e., C1…C9 defects of HV Wood Poles, to ascertain the relative contribution made by these defects to asset condition. Finally in Section 5.2, alternatives are compared via PC to obtain the relative contribution of each bottom level criteria on all assets.

- The composition of priorities which is derived using PC, generates the overall score of each HV Wood Pole that is used to classify them as HI 1-5 in accordance with the regulator’s requirements.

Figure 12 is the hierarchical structure of HV Wood Pole health assessment used to conduct the second stage of AHP, i.e., PC. In the hierarchical structure, the top-level decision-making criteria (level 1) will make different degrees of contribution to the overall decision affecting priorities of asset R/R; the lower-level decision-making criteria (level 2) consists of a group of subordinate criteria affiliated with each higher-level decision-making criteria shown in level 1. It is necessary to establish the contribution each of these subordinate criteria has on the affiliated, higher-level (parent) criterion.

As described above, Section 4.3 utilises AHP to capture individual expert’s judgments along with the chosen MEJA technique to aggregate multiple experts’ judgments. Section 4.3.1 details the application of the proposed AHP with MEJA approach to determine the relative contribution of the high-level health criteria, i.e., ‘age’ and ‘condition’ to asset health assessment.

4.3.1 Determine the Relative Contribution Made by Age and Condition

‘Age’ and ‘condition’ are two high-level health criteria on the first hierarchical level and so are compared with each other to ascertain the priorities that represent their relative contribution to asset health assessment. According to the AHP procedures, a PC Scale Definition Table for age and condition is firstly developed in Table 18.

Table 18: PC Scale Definition Table for Age and Condition

Scale	Pairwise Comparison Definition

1	just as important
3	slightly more important
5	significantly more important
7	much more important
9	absolutely more important
2,4,6,8	are intermediate values

In order to capture the judgments, the following question was asked of multiple experts independently of the wider group (maintaining individuals' anonymity):

'Is the condition considered to be ***just as/slightly more/significantly more/much more or absolutely much more important*** *than age when assessing the health of a pole?'*

The corresponding scale in the definition table is used to derive the priorities representing the relative contribution made by 'age' and 'condition' to asset health assessment. The resultant priorities are shown in Table 19 showing both age and condition contributing equally to asset health assessment. All the experts participating in the survey agreed with the equal contribution to health assessment offered by this high-level health criterion, i.e., priorities are 0.5 for both.

Table 19: PC-Matrix for Age and Condition

Pairwise Comparison Matrix			
	Age	Condition	Priorities
Age	1	1	0.5000
Condition	1	1	0.5000

In order to confirm the PC-Matrix filled with an expert's judgments is consistent, i.e., to confirm expert can make judgments in the same way, the C.R. must be derived and checked. In this instance, there is only one comparison required between these two high-level health criteria, i.e., 'age' and 'condition', the check of C.R. is not necessary. However, while conducting pairwise comparison on more than two criteria requires at least three comparisons to complete the PC-Matrix, will possibly increase the possibility for the judgments of being inconsistent. This affirming the need to constantly monitor the consistency ratio as a critical index to verify the consistency of expert's/synthesised judgments. In addition to applying the AHP method to elicit and quantify the relative contributions of these different health criteria from individual experts, the Delphi Method is applied to reach a consensus among multiple experts. The application of the Delphi

Method on the PC question in the questionnaire between ‘age’ and ‘condition’ reaches a high agreement with the assertions that equality between age and condition contribute equally to the health assesment of the HV Wood Pole asset; this indicates no mathematical approach (LogPM) calculation is required as discussed in Chapter 3.2.

4.3.2 Ascertain Expert Judgment in the Derivation of an Asset Probability of Failure Curve

The criterion ‘age’, is often related to asset failure rate, reliability or probability of failure, demonstrated by the widely acknowledged ‘Bathtub Curve’ [81] in the reliability engineering literature (shown in Figure 13). The curve has an x-axis of time and y-axis of failure rate and is a combination of three hazard functions consisting of:

1. Early infant mortality hazard function with decreasing failure rate.

   The early infant mortality section causes failures that happen to newly manufactured assets. These failures may be caused by manufacturing issues. Sometimes this section is ignored in the Bathtub Curve while describing the increasing failure rate of an asset (group) with time since the assets with manufacturing weakness will show up during burn-in tests.

2. Useful life hazard function with low constant failure rate.

During the section with low constant failure rate, assets are expected to function and perform as intended and the failure rate can be calculated by introducing mean time between failures (MTBF), which is a parameter based on known failure data describing the average continuous working time between failures for repairable assets. The measure of MTBF is the total operational time, i.e., cumulative ‘time between failures’, divided by the number of failures. The equations are in Equation (6 - 1) and (6 - 2).

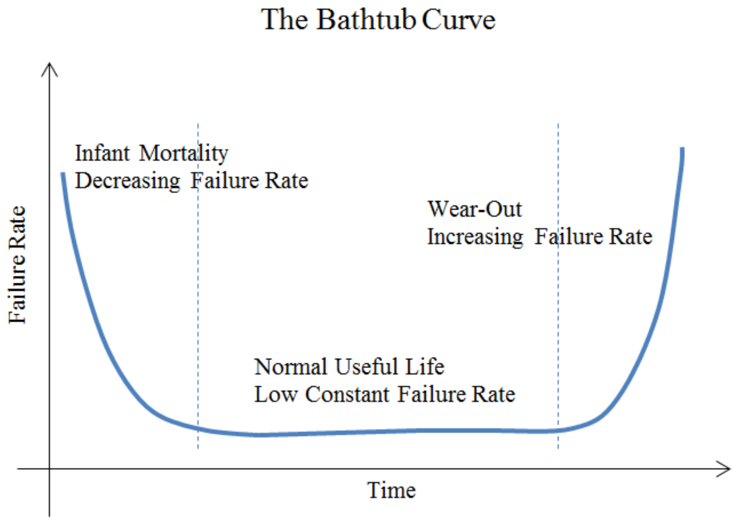


Figure 13: The Bathtub Curve

$$MTBF = \frac{Total\ operational\ time}{number\ of\ failures} = \frac{\sum(downtime - uptime)}{number\ of\ failures} \tag{6 - 1}$$

$$failure\ rate = \frac{1}{MTBF} \tag{6 - 2}$$

3. Late wear-out hazard function with increasing failure rate.

   The wear-out period describes the degradation of an asset (group) approaching the end of its life. This section can be extended by applying an adequate maintenance strategy.

The three sections of the Bathtub curve can be expressed by a two-parameter Weibull Distribution. The function of the failure rate can be expressed in Equation (6 - 3):

$$h(t) = \left(\frac{k}{\lambda}\right)\left(\frac{t}{\lambda}\right)^{k-1}, t \geq 0 \tag{6 - 3}$$

Where

λ: >0, scale parameter

k:>0, shape parameter

t: time

It can be seen that when 0<k<1, the failure rate decreases as time increases, representing the early infant mortality period; when k=1, hazard function $h(t) = \left(\frac{k}{\lambda}\right)$, the failure rate is constant for the normal useful life period; when k>1, the failure rate increases, representing the late wear-out period.

The corresponding probability density function $f(t)$ (PDF) and cumulative distribution function $F(t)$ (CDF) is in Equation (6 - 4) and (6 - 5).

$$f(t) = \begin{cases} \left(\frac{k}{\lambda}\right)\left(\frac{t}{\lambda}\right)^{k-1} e^{-\left(\frac{t}{\lambda}\right)^{k}} & ,t \geq 0 \\ 0 & ,t < 0 \end{cases} \tag{6 - 4}$$

$$F(t) = \begin{cases} 1 - e^{-\left(\frac{t}{\lambda}\right)^{k}} & ,t \geq 0 \\ 0 & ,t < 0 \end{cases} \tag{6 - 5}$$

According to Equation (6 - 3), (6 - 4) and (6 - 5), the hazard function can also be expressed as Equation (6 - 6):

$$h(t) = \frac{f(t)}{1 - F(t)} \quad ,t \geq 0 \tag{6 - 6}$$

The change of *shape parameter* k alters the shape of $h(t)$, $f(t)$ and $F(t)$, and these shapes are illustrated in Figure 14 to Figure 16. It can be seen that:

- When *0<k<1*, both failure rate and PDF decreases which represent the *early infant part* of Bathtub curve;
- When *k=1*, the failure rate changes from early infant to *useful life* section of the Bathtub curve, it remains the same with a low value with random failures, It is evident that as time increases, the assets enter into a steady state with approximately zero probability of failure;
- When *1<k<2*, the early degradation begins. PDF increases to a peak and then decreases, failure rate increases gradually;
- When *k=2*, the PDF reaches a Rayleigh Distribution, where the shape is similar to that when *1<k<2*, but with a higher peak value and the failure rate increases as a linear function;
- When *k>2*, the shape of PDF changes from a bell-shaped distribution to an extreme value-shaped distribution, and the failure rate represents the *late wear-out part*.

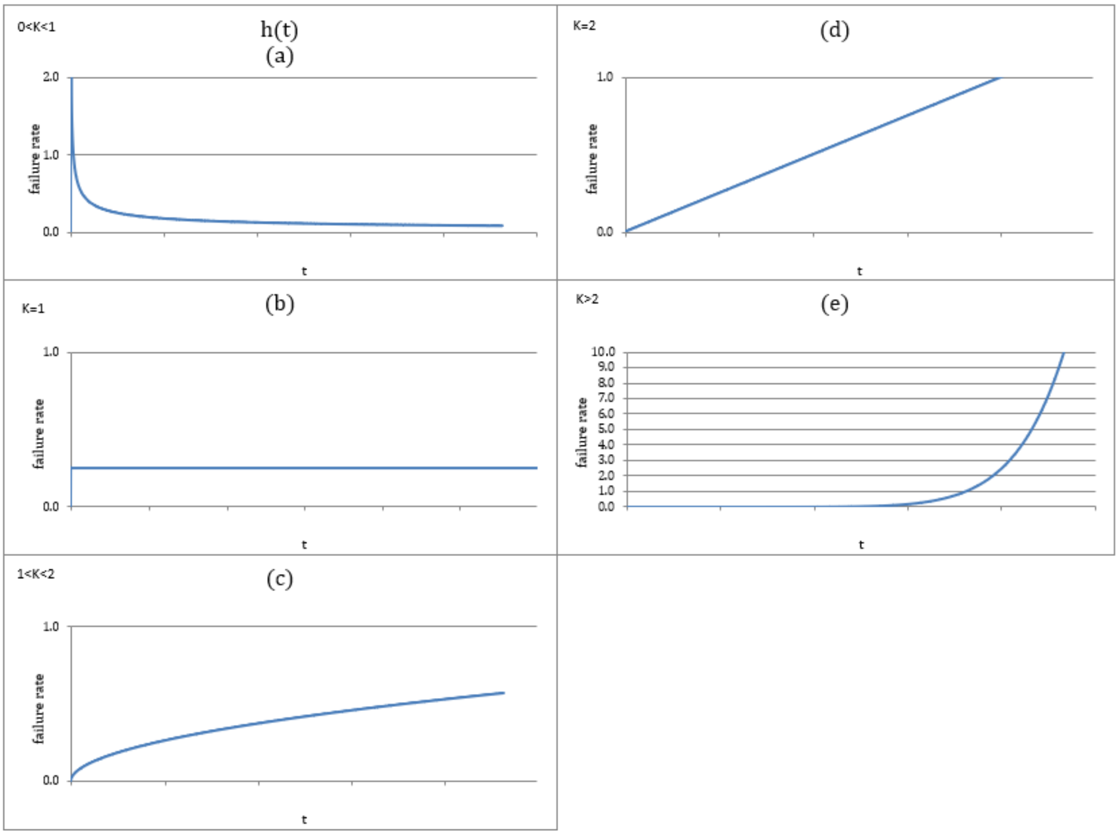


Figure 14: Fault Rate with various k

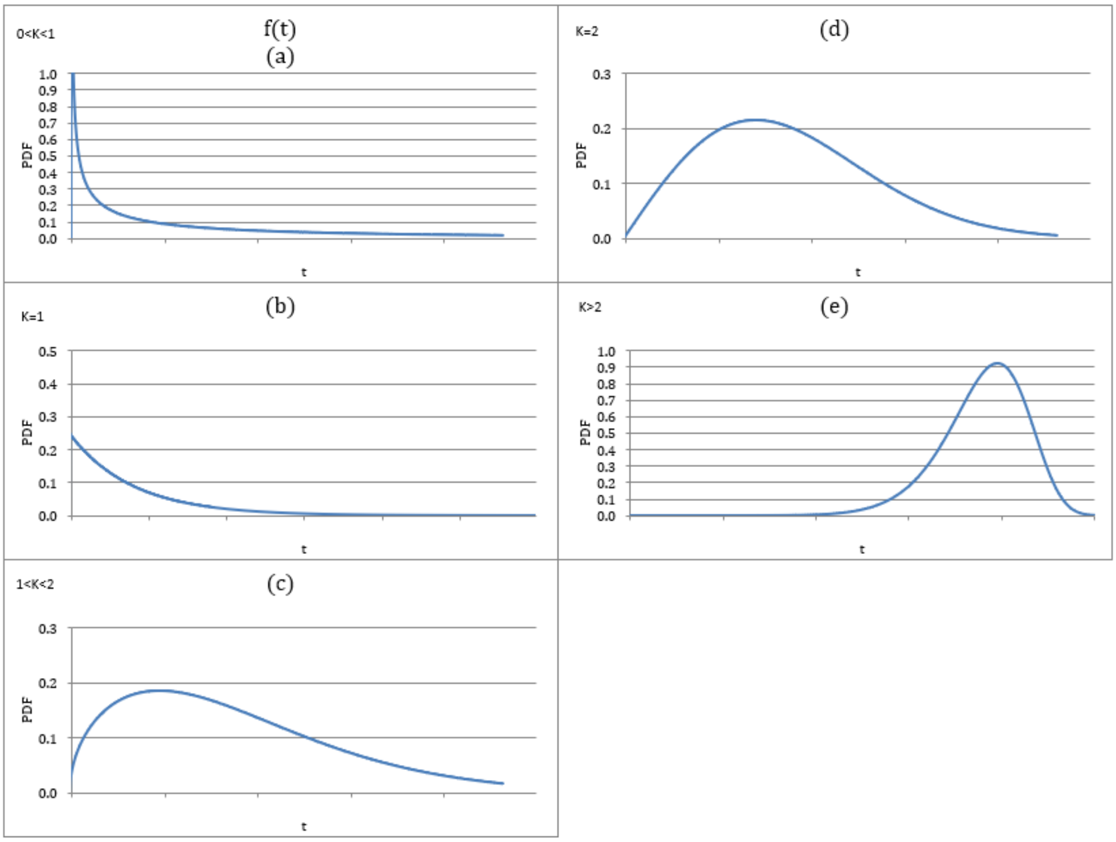


Figure 15: PDF with various k

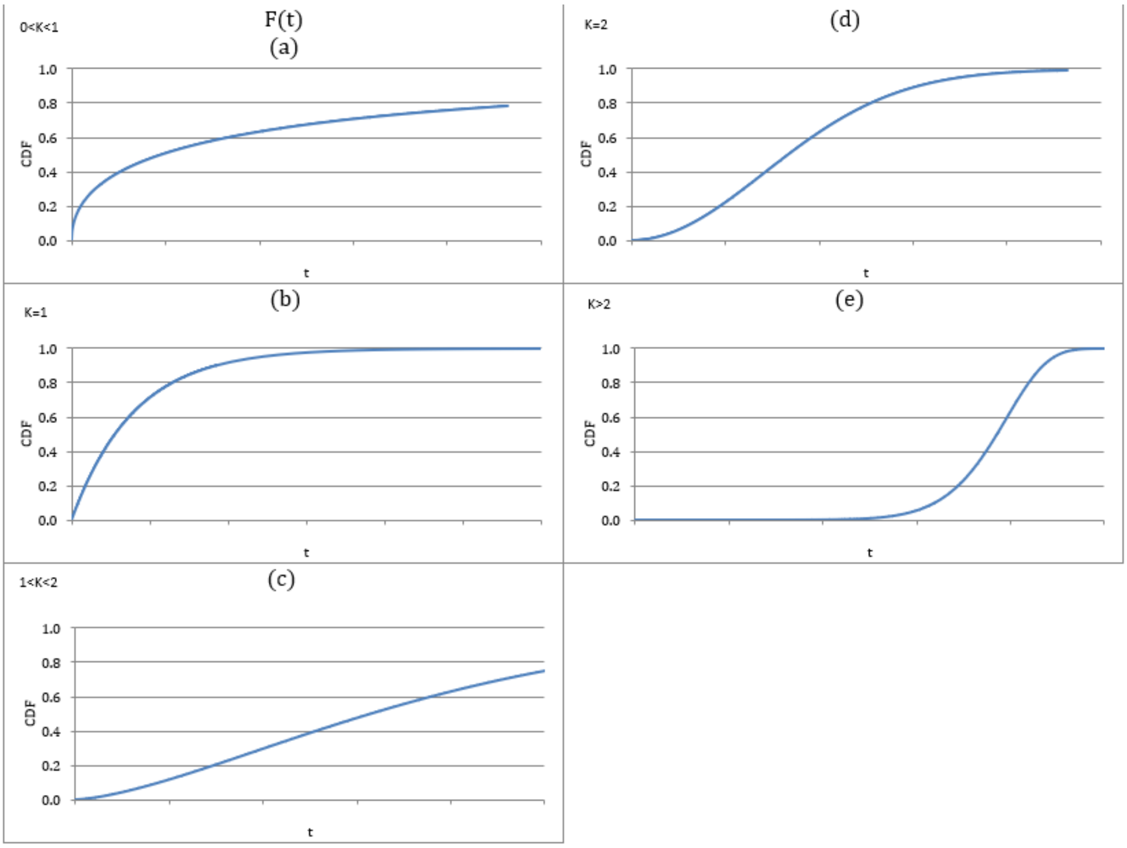


Figure 16: CDF with various k

To apply the failure rate, PDF and CDF on the assets to be evaluated, the thesis makes three assumptions relating to the three sections of the bathtub curve:

1. Early infant section: the assets to be evaluated has no early infant period or has passed the period when 0<k<1. This is because the asset health assessment considers the contribution of natural asset degradation (over time) when assessing age and is not concerned with the early life of the asset;
2. Useful life section: the asset to be evaluated is already in the steady state with low constant failure rate, PDF=0 and CDF =0 as *t* increases when *k=1*;
3. Late wear-out section: the assets to be evaluated follow the failure rate, PDF and CDF of Weibull Distribution when *k>2.*

Therefore, the failure rate distribution of interest in determining the probability of failure associated with natural asset degradation consists of the combination of the ‘normal useful life’ section when *k=1* and ‘late wear-out section’ when *k>2* of the PDF and CDF. Figure 17 shows the outline shapes of these curves for the assets. Since CDF evaluates the area under PDF for the assets from -∞ to *t*, it represents the probability of failure of assets at any age. This thesis uses the term probability of failure (PoF) when referring to a point on the CDF for a particular asset type.

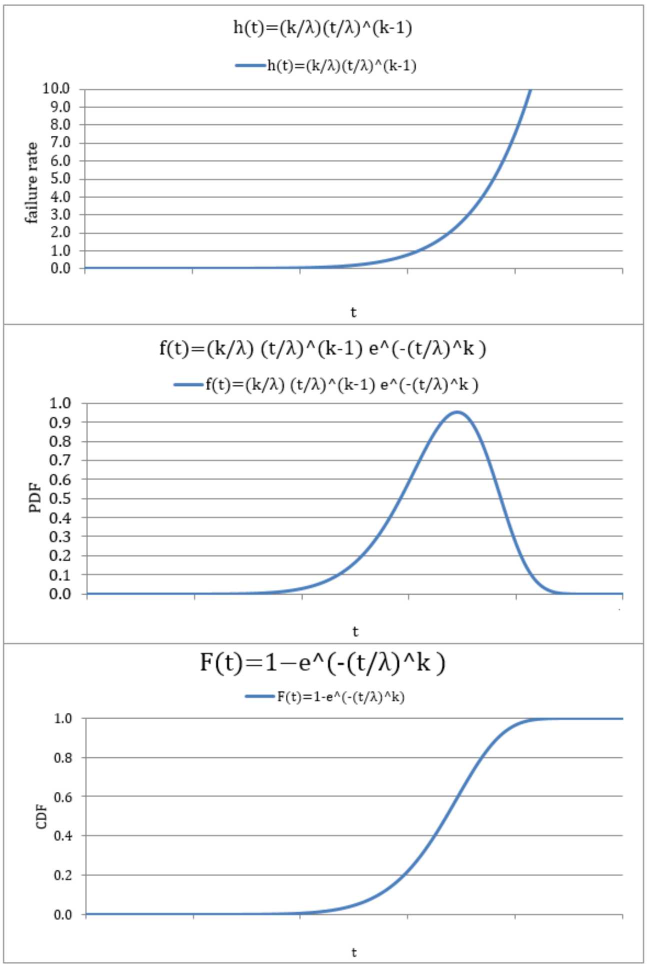


Figure 17: Expected Fault Rate, PDF and CDF Shape for the Assets

Where a sufficient volume of historical data is available, a Weibull Distribution can be derived from a set of historical asset failure and maintenance data. For the HV Wood Poles health assessment case study, the inspection information provides one set of historical data including age and detected defects, although maintenance and failure information is not available, therefore, calculation of the scale parameter λ and shape parameter k for the failure rate, PDF and CDF functions is not possible from this limited historical data alone.

Given the lack of failure data, which is common amongst power asset management, this thesis proposes to use expert judgments to elicit probability of failure associated with at certain ages of HV Wood Poles. The utilization of the distribution fitting toolbox of software MATLAB can produce a PoF curve versus age with corresponding scale and shape parameters. In order to create the pairwise comparison between different ages, two age points are chosen by experts, the detailed survey with questions to select the age points is in Section 4.3.2.1. In order to identify these two age points from experts, Delphi Method is applied, and details of each iteration are described below.

4.3.2.1 Delphi Method Iterations for Choosing Age Points

1st iteration

The questionnaire sent to the individual experts (while maintaining their anonymity) included the following questions:

- 1st: *'At which age does pole failure typically start to occur?'* Denoted as Point A;
- 2nd: *'At which age will a pole typically reach the end of life?'* Denoted as Point E.

The age points B, C and D are even distributed between A and E respectively. The five age points are treated as five subordinate criteria of health criteria 'age'. Figure 18 illustrates the relationship between A, B, C, D, E and the expected PoF curve.

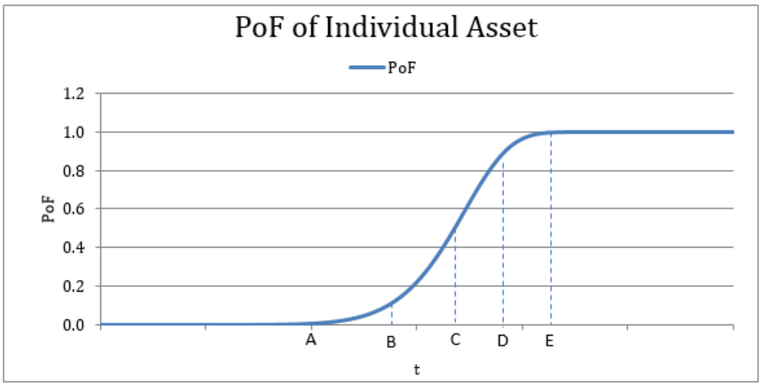


Figure 18: Expected PoF Curve with Point A, B, C, D and E

The result from the first iteration shows that two different opinions are formed on choosing A and E among multiple experts. A summary is in Table 20.

Table 20: Different Expert Opinions on Choosing A and E – Iteration 1

Age Point	A	E
Opinion 1	30	65
Opinion 2	30	55

It shows that both opinions agreed that assets start to fail at age 30 but shows different views on when the HV Wood Pole asset reaches the end of life. Opinion 1 shows an age of 65, ten years longer than that of opinion 2.

2^{nd} Iteration

The summarised table is then sent to experts to keep them updated with other judgments, but the anonymity of expert opinions is maintained. The experts then have an opportunity to change their minds after considering the other opinions. The results can be found in Table 21.

Table 21: Different Opinions on Choosing A and E – Iteration 2

Age Point	A	E
Opinion 1	30	62
Opinion 2	30	60

Disagreement still exist here, and so another iteration is required to attempt to reach consensus.

3^{rd} Iteration

After updating experts with Table 21, there is a further adjustment from Opinion 1, and this forms Table 22.

Table 22: Different Opinions on Choosing A and E – Iteration 3

Age Point	A	E
Opinion 1	30	60
Opinion 2	30	60

Although a final consensus is reached with three iterations, the confirmation iteration, i.e., 4th iteration, in this case, is required from experts to confirm that the opinions from the 3rd iteration are final results.

With the confirmation of no further changes, the chosen A, E and subsequently even distributed B, C and D are in Table 23.

Table 23: Expert Judgments on Age Points A, B, C, D and E

Point	Age
A	30
B	37.5
C	45
D	52.5
E	60

Therefore, Figure 12 can be modified to Figure 19 with identified age points as subordinate criteria of age.

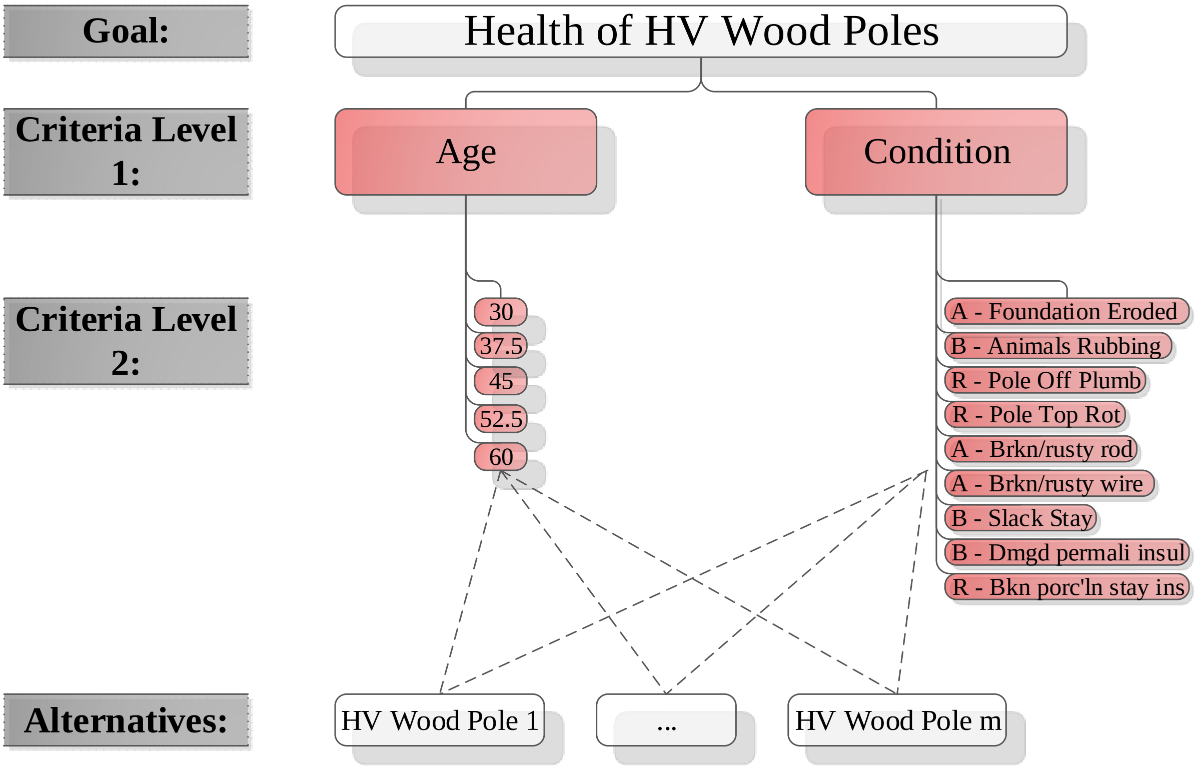


Figure 19: Hierarchical Structure of HV Wood Poles with Identified Age Points

4.3.2.2 Delphi Method Iterations for Deriving Age PC-Matrix

The next step is mapping these age points to corresponding PoF values of these five points using PC, and thus a PC Scale Definition Table is developed. The corresponding PC Scale Definition Table is developed and shown in Table 24 with the PC scale representing qualitative description of the likelihood of failure.

Table 24: PC SCALE Definition Table for PoF

Scale	Pairwise Comparison Definition
1	just as likely to fail
3	slightly more likely to fail
5	significantly more likely to fail
7	much more likely to fail
9	absolutely more likely to fail
2,4,6,8	are intermediate values

According to the table, an initial ranking is developed with age decreasing from oldest to youngest; and so the subsequent the comparisons follow the comparison of an asset of an older age to one of a younger age. By comparing in this way, the older asset will gain a larger score than a younger asset indicating greater PoF relative to the younger asset at the end of the assessment; this complies with the HI requirements, i.e., the asset with a higher score has a worse health than an asset with a lower score.

The pairwise comparison is conducted on the identified age criteria (age points) by using the Delphi Method questionnaire to ask experts the following questions:

*'A pole of age E is (***how much more likely to fail***) than a pole of age A?'*

Ten similar questions are required to complete the pairwise comparison process (i.e., comparing E to A, B, C and D, D to A, B and C, C to A and B and B to A). Experts are asked to choose a description from the PC Scale Definition Table describing the 'how much more likely to fail' is one pole of a particular age to fail than another. By following this process, these expert judgments are used to create a PC-Matrix which is used to calculate five priorities for five ages; these 'priorities' represent the relative likelihood of failure of poles of different vintage in order to produce the PoF curve for the HV Wood Pole asset type.

4.3.2.3 Apply Priority Scaling Method on the Derivation of PoF from Individual Expert

Since five age points yield ten questions, there is greater possibility that a consensus cannot be reached after several MEJA Delphi Method iterations among multiple experts. In case of no consensus, the Delphi Method is still a useful mean of capturing diverse experts' judgments. Following which, a mathematical approach can be taken to aggregate different experts' judgments into a single distribution. Table 25 shows the PC result from questioning of Expert 1.

Table 25: PC-Matrix for Age – Expert 1

PC-Matrix for Age – Expert 1					
Age	30	37.5	45	52.5	60
30	1	1/2	1/4	1/9	1/9
37.5	2	1	1/3	1/8	1/8
45	4	3	1	1/5	1/5
52.5	9	8	5	1	1
60	9	8	5	1	1

This reciprocal PC-Matrix shows that Expert 1 judges a 60-year-old HV Wood Pole to be 'absolutely more likely to fail' (scale 9) than a 30-year old one, while at the same time, considers poles with age 60 and 52.5 to be just as likely to fail.

To find the ‘priorities’ of different age points, i.e., the relative likelihood of failure of poles of different vintage, four priority scaling methods are applied as introduced in 3.2; they are AM(Arithmetic Mean), EM(Eigenvalue Method), GM(Geometric Mean) and LS(Least Squares). Therefore, four sets of normalised priorities are calculated for the PC-Matrix of Age from Expert 1 as shown in Table 26 and graphically presented in Figure 20.

Table 26: PC-Matrix of Age from Expert 1 with Calculated Priorities

Expert 1									
	30	37.5	45	52.5	60	Arithmetic Mean	Eigenvector	Geometric Mean	Least Squares
30	1	1/2	1/4	1/9	1/9	0.035	0.034	0.034	0.043
37.5	2	1	1/3	1/8	1/8	0.052	0.050	0.050	0.050
45	4	3	1	1/5	1/5	0.111	0.109	0.108	0.086
52.5	9	8	5	1	1	0.401	0.403	0.404	0.411
60	9	8	5	1	1	0.401	0.403	0.404	0.411
Sum						1.000	1.000	1.000	1.000
λ_{max}						5.119	5.117	5.117	5.228
C.R.						0.027	0.026	0.026	0.051

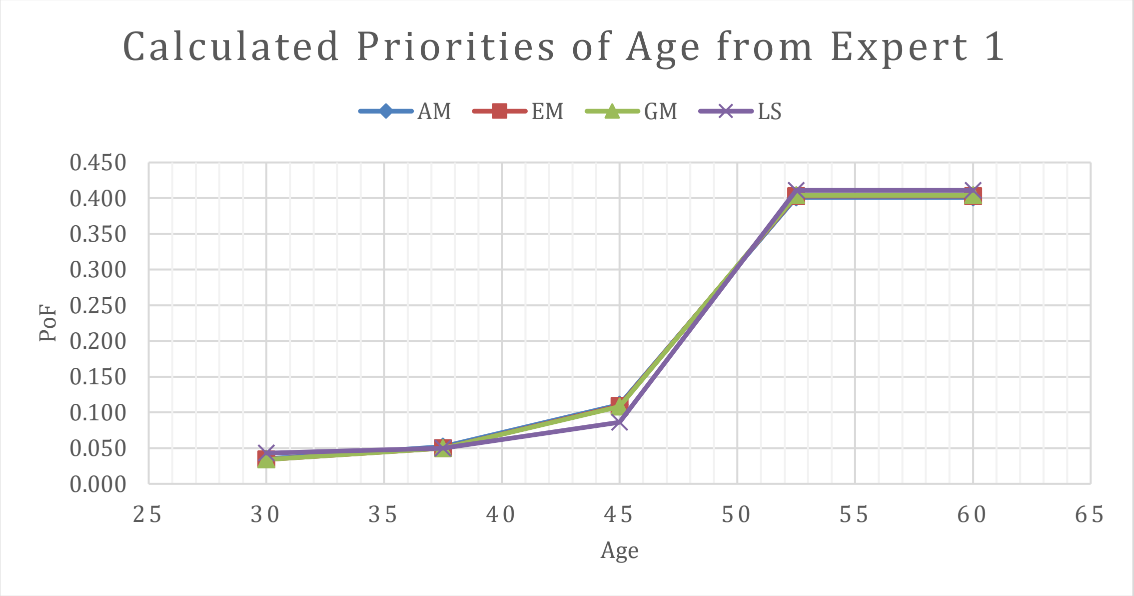


Figure 20: Calculated Priorities of Age from Expert 1

Differences can be found between the four sets of priorities. Firstly, EM and GM are quite similar to each other. Furthermore, there is a small difference between AM and EM or GM while LS is quite different from the other three.

At the same time, the maximum eigenvalue $\lambda_{\max}$ of all methods is around five which is the dimension of the PC-Matrix, and four corresponding C.R.s are shown above, where all of them are smaller than 0.1. This indicates that although differences of priorities exist between all four scaling methods, the consistency of the PC-Matrix following each approach is acceptable. All the results of EM and GM are close in value while AM is slightly different, and LS is substantially different. LS has a largest C.R. which indicates that using LS to derive the priorities show some inconsistency in the PC conducted with the expert.

Further analyses use the priorities to calculate the error between PC-Matrix and priorities. The PC-Matrix is established based on expert judgments by involving the comparison of criteria in pairs to determine the relative contribution of each criterion to the health assessment of a particular asset type. An error matrix is developed for each scaling method. Considering AM as an example, the details of how the error matrix is established are shown as follow. Denote expert judgments as a_{ij}, priorities as p_i, Table 26 can then be transferred into Table 27.

Table 27: Derivation of Error 1

	30	37.5	45	52.5	60	Arithmetic Mean
30	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	p_1
37.5	a_{21}	a_{22}	a_{23}	a_{24}	a_{25}	p_2
45	a_{31}	a_{32}	a_{33}	a_{34}	a_{35}	p_3
52.5	a_{41}	a_{42}	a_{43}	a_{44}	a_{45}	p_4
60	a_{51}	a_{52}	a_{53}	a_{54}	a_{55}	p_5

The a_{ij}, corresponding $p_{ij} = \frac{p_i}{p_j}$, error=$a_{ij} - p_{ij}$, and error^2 = $(a_{ij} - p_{ij)}{}^{2}$ are shown in Table 28.

Table 28: The Derivation of Error 2

a_{ij}		p_{ij}		$a_{ij} - p_{ij}$		$(a_{ij} - p_{ij)}{}^{2}$
a_{11}	1	$p_{11} = \frac{p_1}{p_1}$	$\frac{0.035}{0.035} = 1$	$a_{11} - p_{11}$	0	0
a_{12}	1/2	$p_{12} = \frac{p_1}{p_2}$	$\frac{0.035}{0.052} = 0.673$	$a_{12} - p_{12}$	-0.173	0.030

…	…	…	…	…	…	…
a_{15}	1/9	$p_{15}=\frac{p_1}{p_5}$	$\frac{0.035}{0.401}=0.087$	$a_{15}-p_{15}$	0.024	0.001
a_{21}	2	$p_{21}=\frac{p_2}{p_1}$	$\frac{0.052}{0.035}=1.486$	$a_{21}-p_{21}$	0.514	0.264
⋮	⋮	⋮	⋮	⋮	⋮	⋮
a_{55}	1	$p_{55}=\frac{p_5}{p_5}$	$\frac{0.401}{0.401}=1$	$a_{55}-p_{55}$	0	0

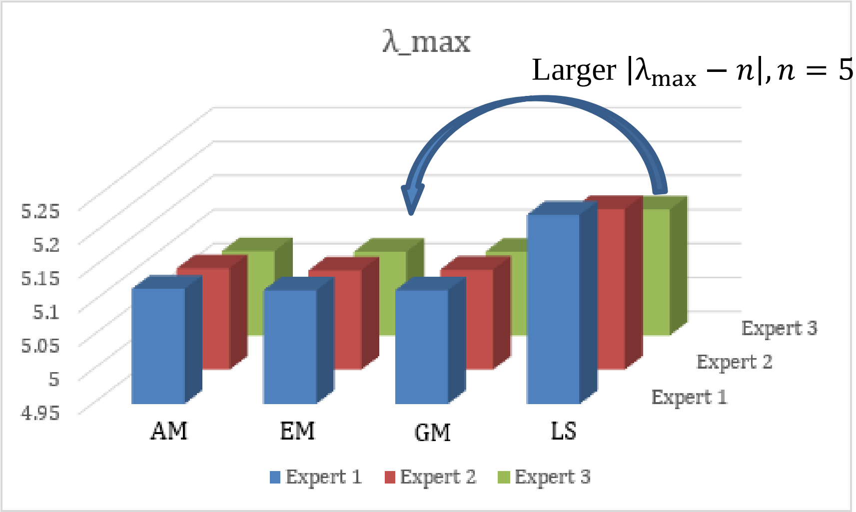
The calculated $\sum(a_{ij}-p_{ij)}{}^{2}$ of AM is the Error Index (E.I.) used to quantify the level of agreement between the PC-Matrix and the priorities. If the PC-Matrix is strictly consistent with $\lambda_{\max}$ equals the dimension of the matrix, five in this case, then E.I.=0, i.e., the priorities follow the comparing judgments entirely. Alternatively, if the $\lambda_{\max}$ of the PC-Matrix is not exactly the dimension of the matrix which creates a non-zero C.R., the E.I. will be non-zero at the same time. Strict consistency in a PC-Matrix is not common, therefore, there exists a non-zero E.I. The E.I. for all four scaling methods from Expert 1 are calculated respectively and compared in Table 29.

Table 29: Error Index of Four Scaling Methods of Expert 1

Priority Scaling Method	AM	EM	GM	LS
E.I.	17.857	21.327	21.528	7.411

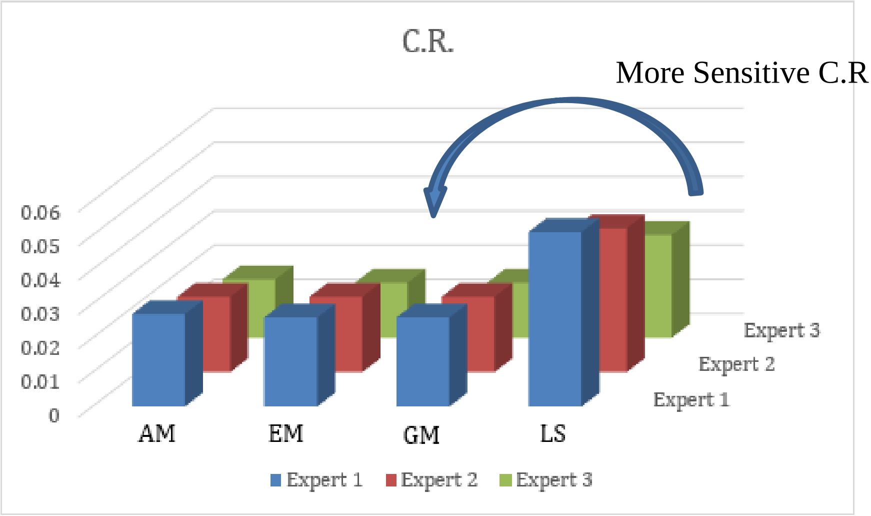
It can be seen that the summarised E.I. of EM and GM are quite close because their priorities are similar. This suggests GM can be an alternative scaling method to EM while an efficient eigenvector calculation software is not available. The software used in this thesis to find the maximum eigenvalue and the corresponding eigenvector is MATLAB. AM has a slightly smaller E.I. than EM and GM and at the same time much larger than LS. The smallest E.I.=7.411 of LS is approximately one-third of EM or GM and less than half of AM. This indicates that the priorities calculated by LS are the closest to expert comparing judgments among four scaling methods and in other words reflect expert judgments more accurate than other three.

The same analyses are applied for all the PC-Matrix of Age from every expert, parameters like $\lambda_{\max}$, corresponding C.R., and E.I. are calculated. Results are summarised Figure 21 to Figure 23 respectively.



Larger $|\lambda_{\max} - n|, n = 5$

Figure 21: A Summary of $\lambda_{\max}$ of All Experts



More Sensitive C.R.

Figure 22: A Summary of C.R. of All Experts

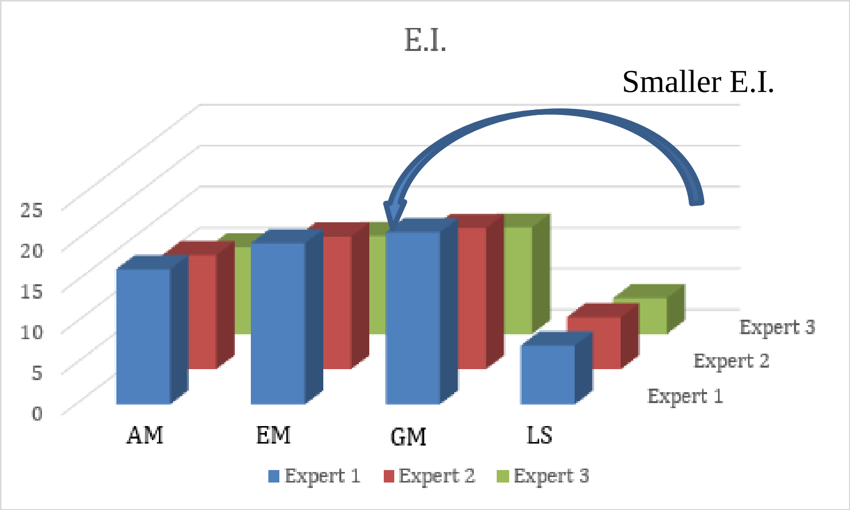


Figure 23: A Summary of E.I. of All Experts

The results of Expert 2 and 3 are similar to Expert 1, i.e., LS has a more sensitive C.R. and smallest E.I. than others priority scaling methods. The sensitivity provides a potential possibility that LS can sense the unacceptable consistency of the PC-Matrix while other three methods accept the matrix. At the same time, the small E.I. suggests LS to be the best scaling method to reflect the level of agreement of expert judgments and priorities. In that case, this thesis uses the priorities of LS to create the expected PoF curve.

The curve is produced by using a distribution tool ‘dfittool’ in MATLAB software. The process of the curve generating is:

1. Input the age points and corresponding calculated priorities into the ‘data’ column to create a dataset;
2. Select ‘new fit’ bottom then choose ‘Weibull Distribution’ and apply; this will generate the two parameters of a Weibull Distribution, i.e., scale parameter λ and shape parameter k;
3. Select to display CDF, i.e., PoF for an individual asset, with corresponding λ and k; the curve is then generated.

The three sets of parameters associated with each expert’s opinion are shown in Table 30. Recalling Equation (6 - 3), (6 - 4), and (6 - 5) of Section 4.3.2, these are used to plot the failure rate, PDF and PoF curves are shown in Figure 24 to Figure 26 respectively.

Table 30: Two Parameters of Weibull Distribution

Two Parameters of Weibull Distribution		
	Scale Parameter λ	Shape Parameter k
Expert 1	51.3411	12.2166
Expert 2	52.0057	10.8353
Expert 3	51.6337	13.2088

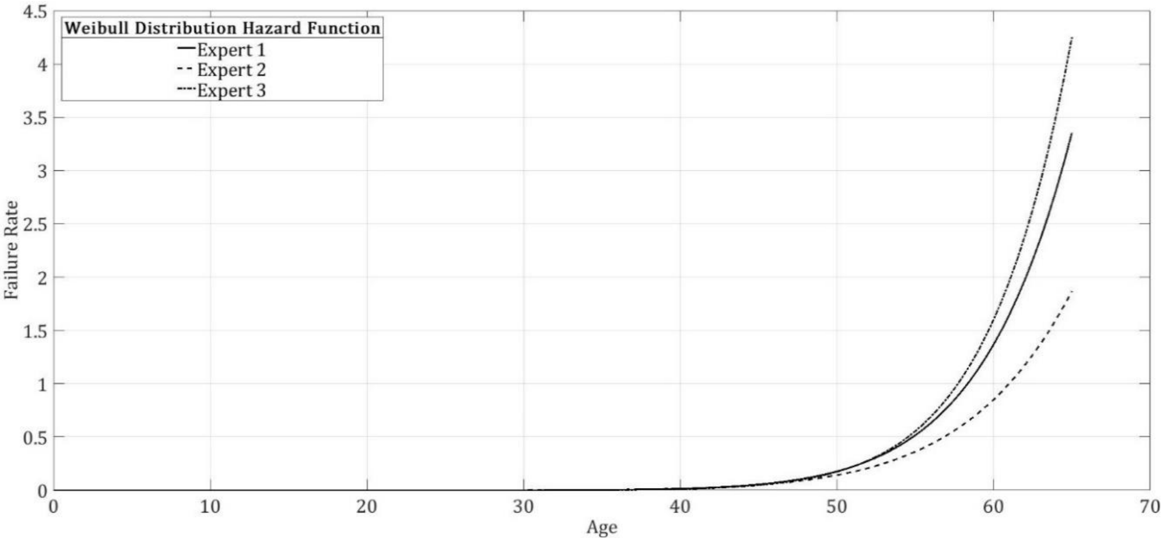


Figure 24: Hazard Function of Weibull Distribution

The growth of the hazard function $h(t)$ shown in Figure 24 shows that the PoF of HV Wood Poles rises over time due to asset wear out. With increasing age, the failure rate increases exponentially after age = λ.

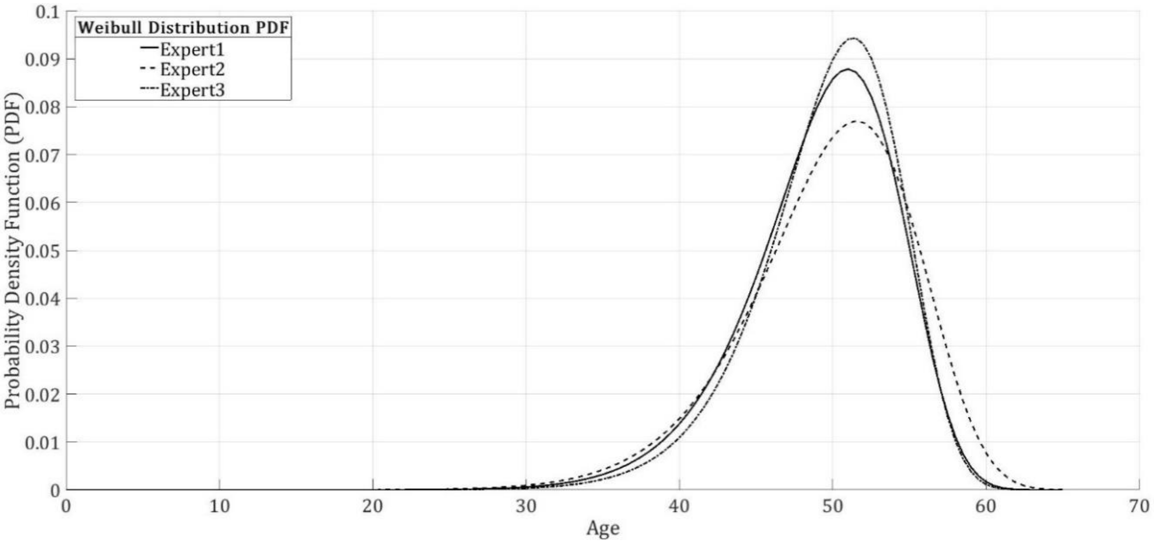


Figure 25: PDF of Weibull Distribution

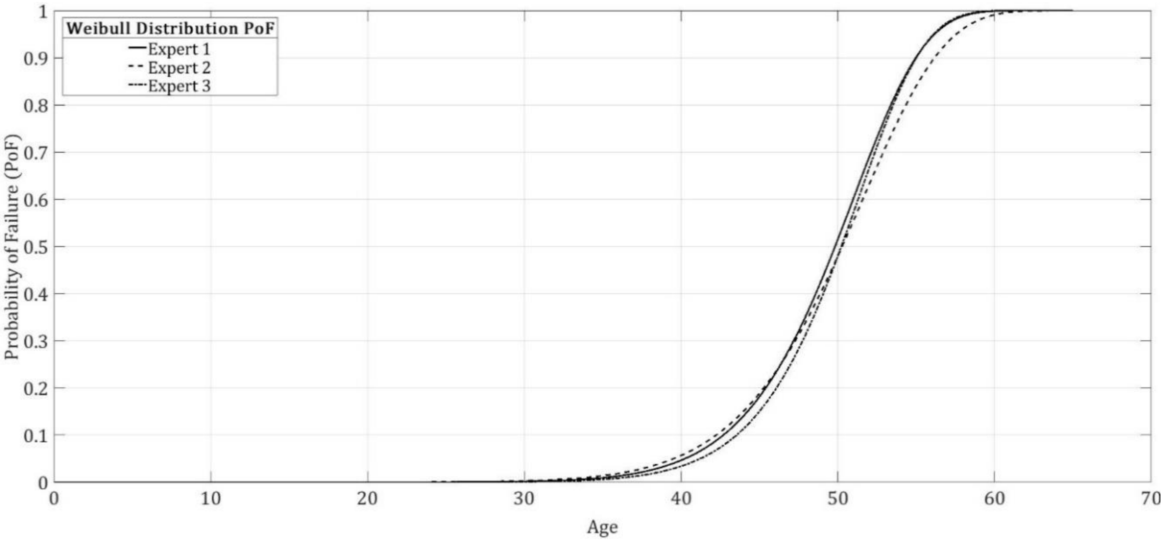


Figure 26: PoF of Weibull Distribution

The curves show that three PoF are close to each other showing a high level of agreement between experts, achieved through the 4 iterations of the Delphi Method. It can be seen that at age = 30, the curve starts to rise and reaches PoF=1 around age = 60.

4.3.2.4 Synthesise the PoF based on Asset Age from Multiple Experts

In order to synthesise the PoF from multiple experts, i.e., three experts, in this case, can be achieved in two ways. One is to synthesise the PC-Matrix of Age from multiple experts into an aggregated PC-Matrix of Age in order to calculate an aggregated set of priorities to generate the PoF using MATLAB. The other is to find the average value of the two parameters of the Weibull Distribution, i.e., scale parameter λ and shape parameter k. Both approaches are applied and compared next.

I. Synthesise the PC-Matrix of Age from Multiple Experts – Approach 1

As analysed in Section 3.3.4, LogPM is the aggregation method proved to be the one can keep the reciprocal of PC-Matrix in mathematical approach. Therefore, the synthesised PC-Matrix from three experts is formed by applying LogPM and shown in Table 31. The reciprocal characteristic is preserved. The priorities associated with the four scaling methods are calculated at the same time. In addition, parameters like $\lambda_{\max}$, C.R. and E.I. are also compared.

Table 31: Synthesised PC-Matrix of Age with Calculated Priorities

						Aggregation			
	30	37.5	45	52.5	60	AM	EM	GM	LS
30	1.000	0.500	0.250	0.111	0.111	0.036	0.035	0.035	0.043
37.5	2.000	1.000	0.333	0.125	0.125	0.052	0.051	0.051	0.050
45	4.000	3.000	1.000	0.232	0.215	0.117	0.115	0.114	0.094
52.5	9.000	8.000	4.309	1.000	1.000	0.394	0.396	0.397	0.404
60	9.000	8.000	4.642	1.000	1.000	0.401	0.403	0.403	0.409
Sum						1.000	1.000	1.000	1.000
λ_{max}						5.095	5.073	5.093	5.177
C.R.						0.021	0.016	0.021	0.040
E.I.						13.258	15.407	16.632	5.807

LS has a larger C.R. showing it is more sensitive to the inconsistency of the matrix than others, and at the same time has the smallest E.I. indicates that the priorities calculated by LS reflect the expert judgments more accurately than others. Therefore, the priorities used to create the PoF is the LS version. The PoF curve is then generated in MATLAB with parameters in Table 32 and will be plotted in the next section in order to make a comparison.

Table 32: Weibull Parameters for Approach 1

	Synthesised PC-Matrix	
	Scale Parameter λ	Shape Parameter k
Synthesised	51.673	11.787

II. Synthesise the Parameters of Weibull Distribution – Approach 2

The AM and GM values of scale parameter λ and shape parameter k are calculated and shown in Table 41.

Table 33: Weibull Parameters for Approach 2

	Synthesised Two Parameters of Weibull Distribution	
	Scale Parameter λ	Shape Parameter k
Synthesised AM	51.660	12.0869
Synthesised GM	51.659	12.0472

The differences between the results of AM and GM are small, especially for scale parameter λ. In order to keep accordant with the synthesisation of PC-Matrix with LogPM polling method, the GM values of approach 1 in Table 32 are chosen to simulate the wear-out phase of Bathtub curve in MATLAB. The curve is in Figure 27. The express of PoF is in Equation (6 - 7)

$$PoF = \begin{cases} 1 - e^{-\left(\frac{t}{51.673}\right)^{11.787}} & ,t \geq 0 \\ 0 & ,t < 0 \end{cases} \tag{6 - 7}$$

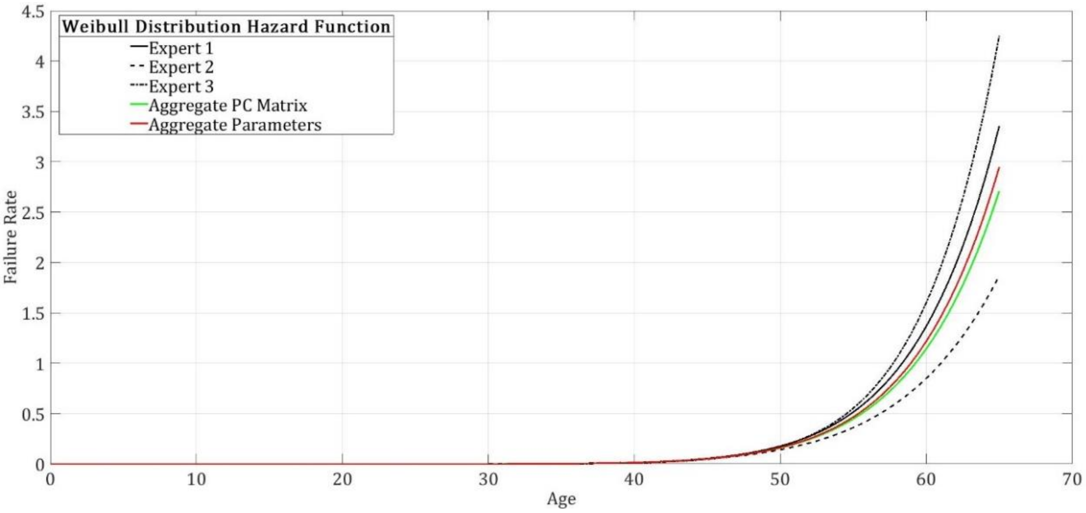


Figure 27: Synthesised Hazard Function

The green curve is the result of the aggregation of PC-Matrix (Approach 1), and the red one is the aggregation of two parameters (Approach 2). The two synthesised failure rate curves are very close to each other. The similarity can be seen in Figure 28 and Figure 29 above, from the synthesised PDF and PoF curves.

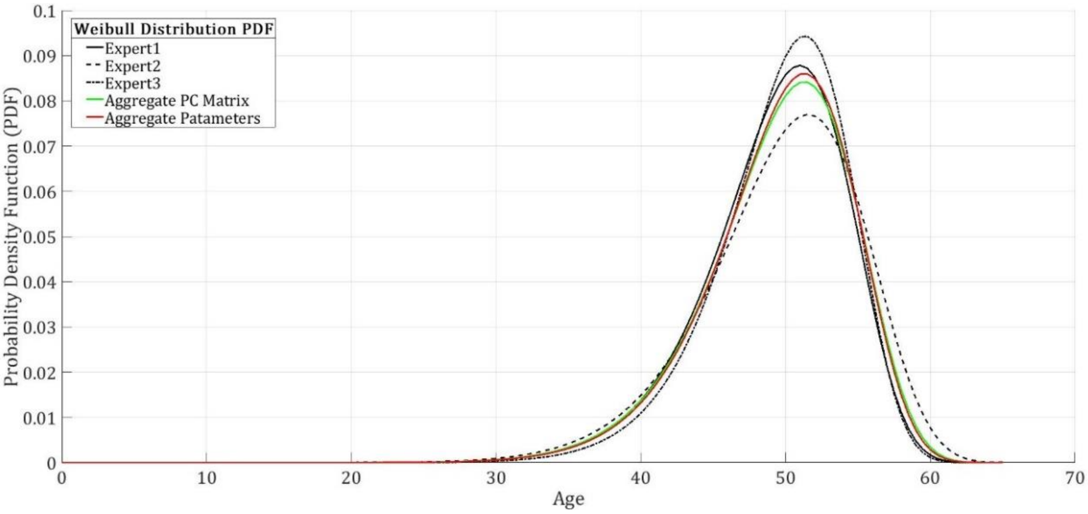


Figure 28: Synthesised PDF

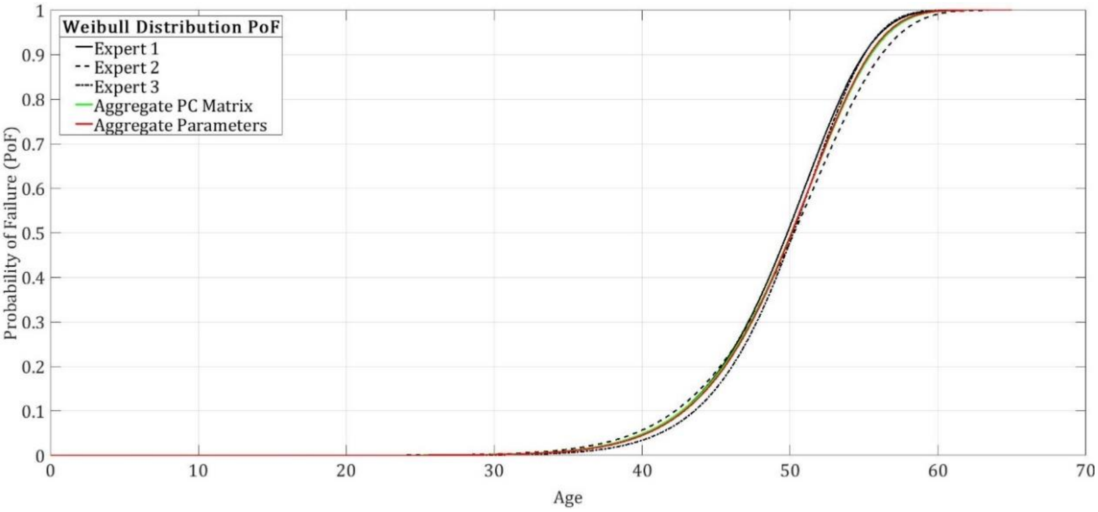


Figure 29: Synthesised PoF

In the case of the HV Wood Poles health assessment with three experts involved, both approaches almost provide the same synthesised results of the generation of PoF distribution. References

5 THE COMPARISON OF AHP AND SW

5.1 Using AHP to Ascertain Expert Judgment on the Relative Contribution Made by Defects to Asset Condition

5.1.1 Delphi Method Iterations for Deriving Initial Ranking of Defects

It is necessary to derive an initial ranking of defects in terms of the experts' perception of defects on the health of HV Wood Poles, before the PC process can commence. In order to derive the initial ranking of the nine defects, the Delphi Method is applied using a questionnaire that asks experts:

Which is the most severe defect that in your experience is likely to have the most adverse effect on pole condition?

The most severe defect is ranked first, and the same question is asked to select a defect and ranked the first from the rest eight defects, so on and so forth until all the nine defects are in the initial ranking. The total number of question iterations to derive the initial ranking of defects with experts is five (for nine defects) and the results of the questionnaire showed that experts did not reach a complete agreement with the initial ranking of defects after five iterations. The rankings from three experts before and after Delphi Method are in Table 34 and Figure 30.

Table 34: Defects Rankings Before and After Delphi Method

Criteria	Ranking (before Delphi Method)			Ranking (after Delphi Method)		
	E1	E2	E3	E1	E2	E3
C_1 - Broken/rusty rod	3	2	3	3	2	3
C_2 - Broken/rusty wire	4	3	4	4	3	4
C_3 - Foundation Eroded	6	**6**	1	6	**4**	1
C_4 - Animals Rubbing	**5**	**4**	8	**8**	**6**	8
C_5 - Damaged permali insulator	**7**	8	**7**	**5**	8	**6**
C_6 - Slack Stay	**9**	5	9	**7**	5	9
C_7 - Broken porcelain stay insulator	**1**	9	5	**2**	9	5
C_8 - Pole Off Plumb	**8**	7	**6**	**9**	7	**7**
C_9 - Pole Top Rot	**2**	1	2	**1**	1	2

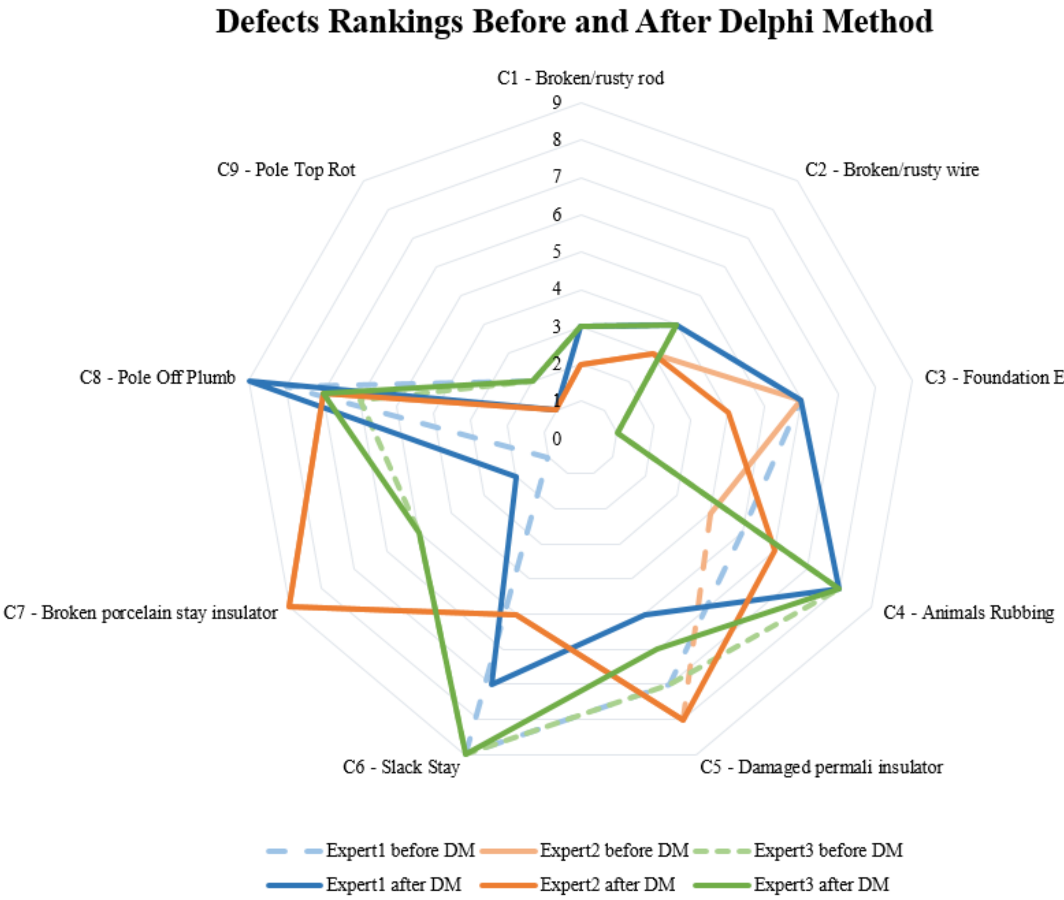


Figure 30: Defects Rankings Before and After Delphi Method

The changes of rankings during the use of the Delphi Method are highlighted with **bold** and underline in Table 34. Rankings before Delphi Method are presented in dashed line and rankings after Delphi Method are presented in solid line as shown in Figure 30. From three experts, it can be seen that Expert 1 alters his judgments most and makes six changes to his judgments on the ranking of these defects after four Delphi Method iterations. And the defect with the least agreement from three experts is the ‘Broken porcelain stay insulator’ since experts experienced a ‘different level’ of broken porcelain stay insulator which affect HV Wood Pole condition to a different extent. There may still be differences between rankings after Delphi Method, in such cases, the opinion of the more experienced experts can contribute more to the aggregated priorities even though the approach considers all experts to have equal weighting. Another method called COOKE method [66] can be used to calibrate expert’s judgments in terms of their experience, such that experts with more experience with certain defects can have a greater ‘relative weighting’ (and influence) attached to their judgments in that specific area. The COOKE method surveys experts to capture expertise. Since the same group of experts is not available, COOKE method which has been researched but not be able to apply in this thesis, it is recommended to do further work in the future.

5.1.2 Derivation of Defects PC-Matrix with Improved AHP

While it has been proved that there is significant agreement among rankings, the Defects PC-Matrix can then be generated for each expert individually.

In the first place, the PC Scale Definition Table for comparing defects is required and developed in Table 35.

Table 35: PC Scale Definition Table for Condition

Scale	Pairwise Comparison Definition
1	same condition as
3	slightly poorer condition than
5	poorer condition than
7	much poorer condition than
9	absolutely poorer condition than
2,4,6,8	are intermediate values

The following considers the ranking after the application of the Delphi Method of Expert 1 in Table 34 for the derivation of the PC-Matrix (shown in Table 36). The question is presented as shown to experts to derive the associated defect PC-Matrix:

The condition of a pole with defect ‘Pole Top Rot’ is considered to be <insert ‘Table 35 Pairwise Comparison Definition for Condition’> a pole with defect ‘Foundation Eroded’ ?

The defect ‘Pole Top Rot’, which ranked the most severe defect affecting asset condition, is compared with the other eight defects respectively and this forms Set 1 of the PC. Elements on the first row in the upper triangular matrix of Table 36 is filled with expert PC judgments. The same process is repeated for the other defects to form Set 2 (seven pairwise comparisons) to Set 8 (one pairwise comparison), and so complete the upper triangular matrix – a total of 36 pairwise comparisons. The lower triangular matrix is then filled with reciprocal value with diagonal axisymmetric.

Table 36: Empty PC-Matrix for Defects – Expert 1

Defects	Pole Top Rot	Bkn porc'ln stay insulator	Broken/rusty rod	Broken/rusty wire	Damaged permali insul	Foundation Eroded	Slack Stay	Animals Rubbing	Pole Off Plumb
Pole Top Rot	1								
Bkn porc'ln stay insulator		1							
Broken/rusty rod			1						
Broken/rusty wire				1					
Damaged permali insul					1				
Foundation Eroded						1			
Slack Stay							1		
Animals Rubbing								1	
Pole Off Plumb									1

While applying the PC as normally for AHP, there are four main shortcomings one can experience, as described in the following:

1. Experts' judgments can be influenced by preceding judgments;
2. Whenever the consistency ratio is calculated at the end of the PC process, and indicates an inconsistency exists with an expert judgment somewhere during the PC process, it is necessary to repeat the entire PC process as it is not possible to determine which comparisons are inconsistent. Since the number of pairwise comparisons is equal to $n * (n-1)/2$ (where n is the number of defects), there can be an excessively large number of comparisons when n is large, which can prove time-consuming and and cumbersome, and become more prone to inconsistency in the clicitation of expert judgments; particularly when it is necessary to repeat due to an identified inconsistency;
3. In practice during the process, experts pointed out that since defects are not numeric criteria, and due to a large number of comparisons, it is difficult for experts to make the comparisons with confidence that no contradictions or conflicts exist amongst them. In addition, to avoid these conflicts, experts will tend to reflect on previous judgments, rather than rely solely on their 'instinctive' response to the specific pairwise comparison under consideration,

which could result in experts manipulating (in some cases almost unconsciously) their judgments and so potentially undermining the veracity and authenticity of the true expert judgments captured;

4. While the capability of identifying inconsistencies is an advantage of the current AHP approach, its inability to identify where the inconsistency lies remains one of the greatest limitations of AHP.

This thesis presents an enhancement of the PC process within the application of AHP, by seeking to locate where and when inconsistencies arise during the pairwise comparison process and so avoid the need for prolonged PC and improve the prospects of eliciting consistent expert judgments. This enhancement works to encourage experts to base their judgments on their ‘instinctive’ or ‘gut’ reaction to the PC questions, by making it more difficult to manipulate their comparisons in order to avoid conflict. This enhancement also provides an opportunity for experts to resolve conflicts without the need to repeat all pairwise comparison again. The associated flow chart is in Figure 31.

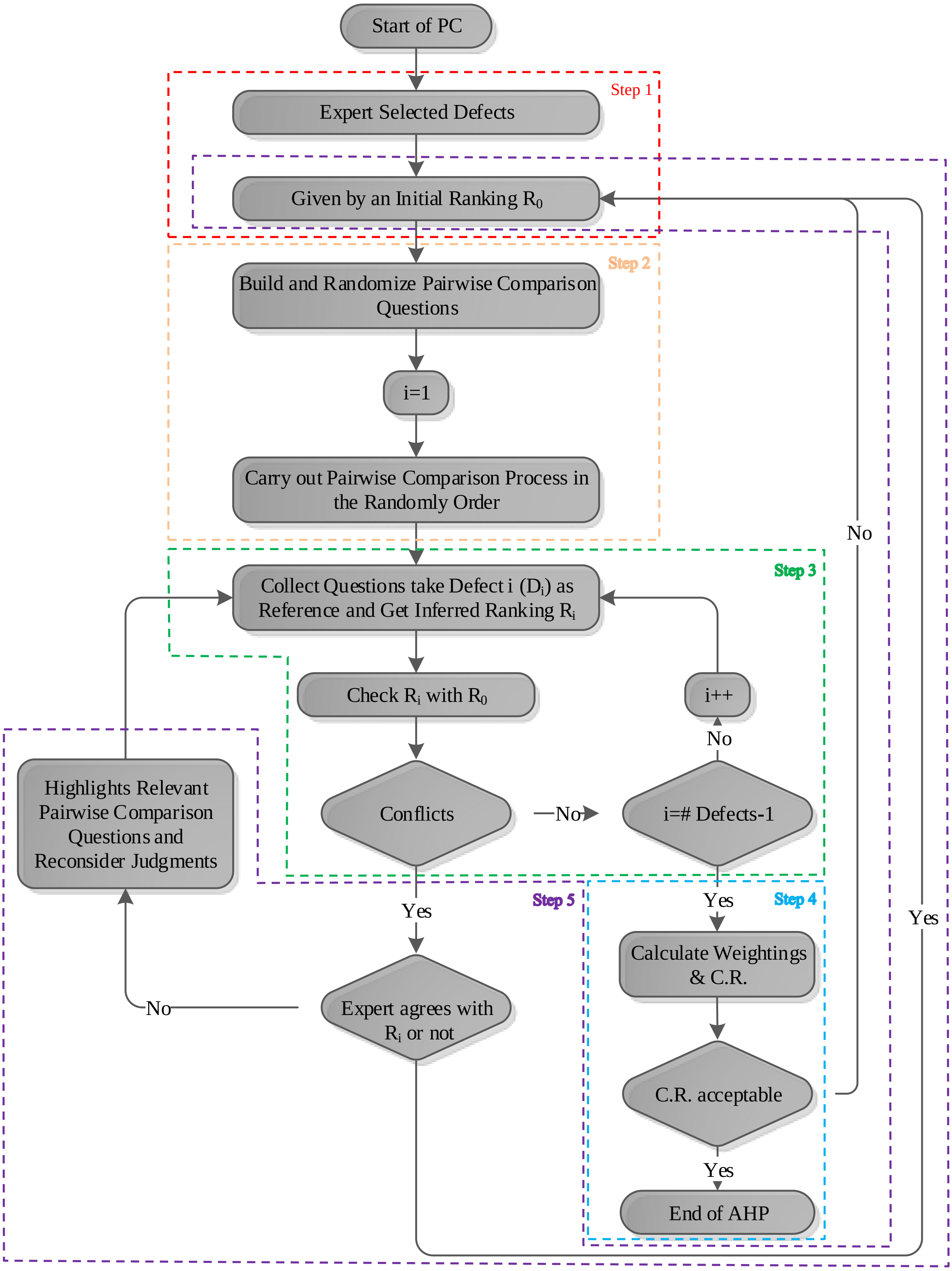


Figure 31: Flow Chart of the Improved PC Process

The steps of the flowchart are described as follows:

Step 1. An initial ranking of the defects is made in descending order from the ‘defect that makes the greatest contribution to the asset health assessment’ to the ‘defect that makes the least contribution to the asset health assessment’. This ranking can be changed later if necessary. The initial ranking is denoted as R_0. For defects representing the highest contribution, the subscript $i=1$. As the contribution of defects decreases, their subscript i increases are D_i, $i=1, 2, ..., n$; where for 9 defects as is the case here, $n=9$;

Step 2. Build the set of Pairwise Comparison questions (36 questions for 9 defects) by comparing defects D_1 to D_i, *where* $i=2, 3...9$, comprising the first set of pairwise comparisons; and then D_2 to D_i, *where* $i=3, 4...9$, *Set 2*, comprising the second set of pairwise comparisons; which continues until the final (8th) set of pairwise comparisons consists of comparing only defects D_8 and D_9; giving a total of 8 sets of pairwise comparisons consisting of a total number of 36 pairwise comparisons for 9 defects. It is important to note that the order in which these pairwise comparisons are presented to the expert for their judgment is random, to ensure they remain unbiased by previous comparisons; encouraging experts to respond instinctively;

Step 3. After each set of pairwise comparisons has been completed by the expert, a new ranked order of defects (i.e., ranked in order of contribution to condition assessment) is generated. The newly ranked order R_i is compared to the previously ranked order R_{i-1}, where i represents the set of pairwise comparisons on which the defects have been ordered. If no difference exists between the two rankings, then the ranking check is moved to the next set of pairwise comparisons;

Step 4. If a conflict or inconsistency exists an indicator will warn the expert to reconsider the most recent set of comparison, where the pairwise comparisons causing the inconsistency are highlighted for reconsideration. The process repeats until no conflicts remain;

Step 5. Once R_{0-8} are identical, priorities and C.R. are calculated, if the C.R. <=0.1, i.e., acceptable, it is appropriate to the end of PC process; however, with the C.R. is unacceptable, the process has to return to the beginning and restart.

The improved PC process is encoded in two excel spreadsheets.

Figure 32 shows Step 1 of the beginning of the improved AHP process using the developed tool spreadsheet. The ‘Reset’ button clears all the previous inputs and provides a clean sheet ready to start from the beginning; the ‘Start’ button asks an expert to provide an initial ranking of these defects.

Please give an initial ranking of these defects

1st Worst	0
2nd	0
3rd	0
4th	0
5th	0
6th	0
7th	0
8th	0
9th	0

(a)

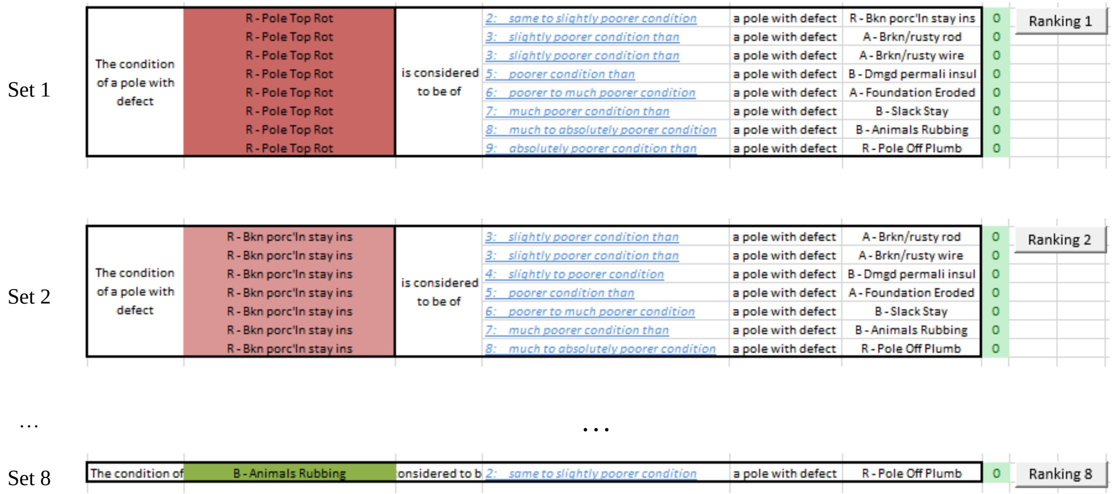
Please give an initial ranking of these defects

1st Worst	R - Pole Top Rot
2nd	R - Bkn porc'ln stay ins
3rd	A - Brkn/rusty rod
4th	A - Brkn/rusty wire
5th	B - Dmgd permali insul
6th	
7th	
8th	
9th	

(b)

Figure 32: PC Process Spreadsheet Screenshot 1

After an initial ranking is provided, Figure 33 shows the sets of pairwise comparison question constructs filled in automatically. In the example, the first two sets are provided, and for the first set, defect ‘Pole Top Rot’ is ranked as the ‘1st (worst)’, i.e., defect that makes greatest contribution to asset condition degradation?, compare with the other eight defects listed on the right-hand side of the figure; and for the second set defect ‘Broken porc’ln stay insulator’ which ranked second next to ‘Pole Top Rot’, compare with the other seven defects listed on the right-hand side of the figure. The other six sets are generated following this process. Note that, in this step, comparison pairs in each set are in descending order.



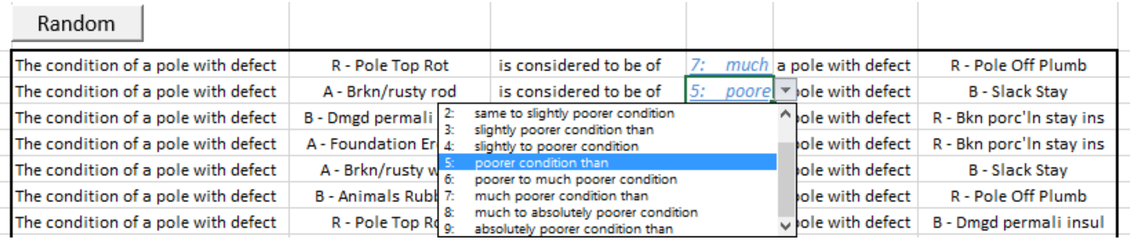
The condition of a pole with defect	R - Pole Top Rot	is considered to be of	2: same to slightly poorer condition	a pole with defect	R - Bkn porc'ln stay ins	0
	R - Pole Top Rot		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty rod	0
	R - Pole Top Rot		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty wire	0
	R - Pole Top Rot		5: poorer condition than	a pole with defect	B - Dmgd permali insul	0
	R - Pole Top Rot		6: poorer to much poorer condition	a pole with defect	A - Foundation Eroded	0
	R - Pole Top Rot		7: much poorer condition than	a pole with defect	B - Slack Stay	0
	R - Pole Top Rot		8: much to absolutely poorer condition	a pole with defect	B - Animals Rubbing	0
	R - Pole Top Rot		9: absolutely poorer condition than	a pole with defect	R - Pole Off Plumb	0

The condition of a pole with defect	R - Bkn porc'ln stay ins	is considered to be of	3: slightly poorer condition than	a pole with defect	A - Brkn/rusty rod	0
	R - Bkn porc'ln stay ins		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty wire	0
	R - Bkn porc'ln stay ins		4: slightly to poorer condition	a pole with defect	B - Dmgd permali insul	0
	R - Bkn porc'ln stay ins		5: poorer condition than	a pole with defect	A - Foundation Eroded	0
	R - Bkn porc'ln stay ins		6: poorer to much poorer condition	a pole with defect	B - Slack Stay	0
	R - Bkn porc'ln stay ins		7: much poorer condition than	a pole with defect	B - Animals Rubbing	0
	R - Bkn porc'ln stay ins		8: much to absolutely poorer condition	a pole with defect	R - Pole Off Plumb	0

The condition of	B - Animals Rubbing	onsidered to b	2: same to slightly poorer condition	a pole with defect	R - Pole Off Plumb	0

Figure 33: PC Process Spreadsheet Screenshot 2

The randomised order can be changed as many times as request by clicking the ‘Random’ button. This randomization is to ensure the expert remain unbiased by previous comparisons judgments. Figure 34 and the 1-9 scale drop list which expert makes judgments by selecting one of the qualitative descriptions of the PC scale.



The condition of a pole with defect	R - Pole Top Rot	is considered to be of	7: much	a pole with defect	R - Pole Off Plumb
The condition of a pole with defect	A - Brkn/rusty rod	is considered to be of	5: poore	ole with defect	B - Slack Stay
The condition of a pole with defect	B - Dmgd permali			ole with defect	R - Bkn porc'ln stay ins
The condition of a pole with defect	A - Foundation Er			ole with defect	R - Bkn porc'ln stay ins
The condition of a pole with defect	A - Brkn/rusty w			ole with defect	B - Slack Stay
The condition of a pole with defect	B - Animals Rubl			ole with defect	R - Pole Off Plumb
The condition of a pole with defect	R - Pole Top R			ole with defect	B - Dmgd permali insul

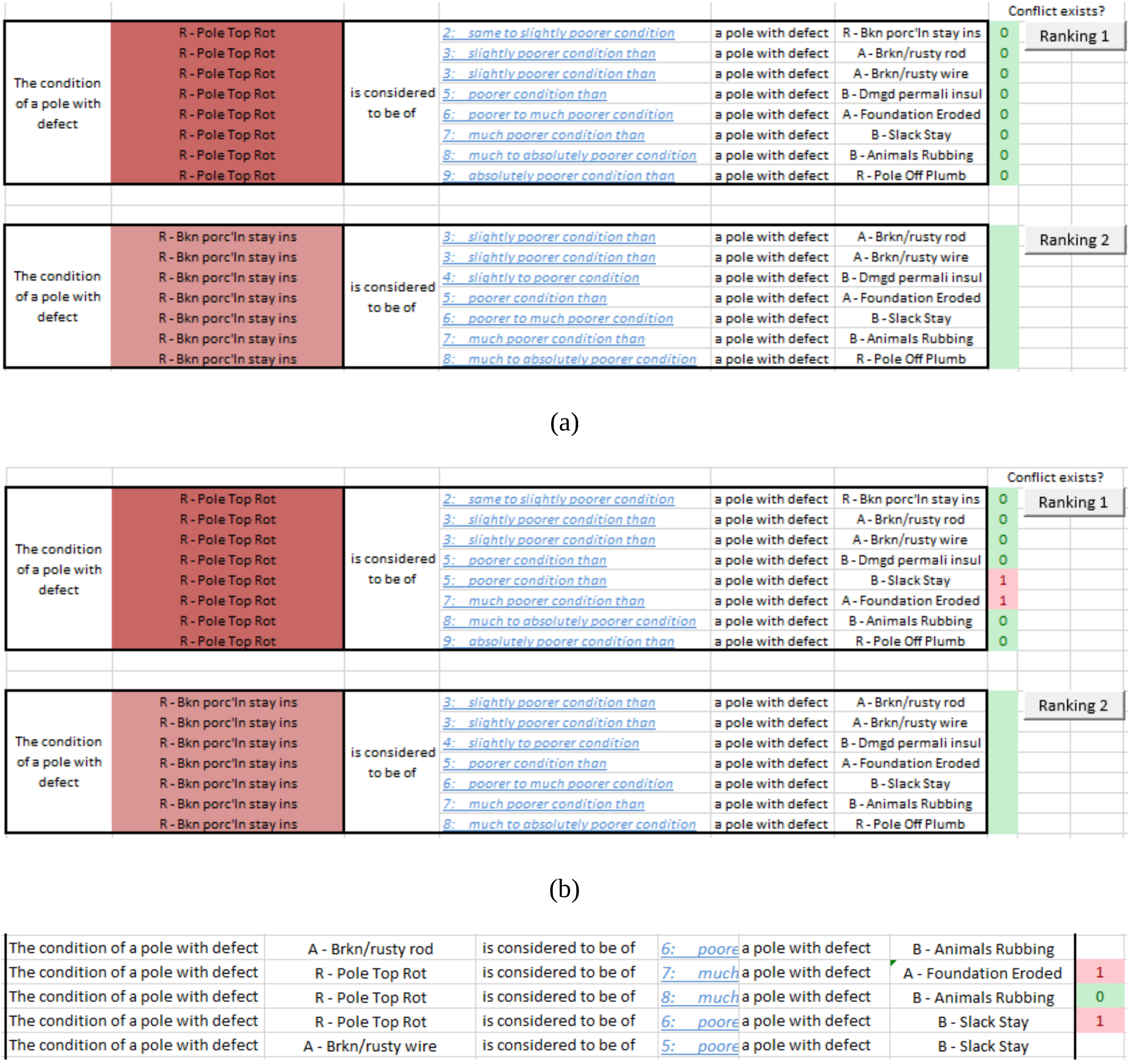
Figure 34: PC Process Spreadsheet Screenshot 3

Following the randomised PC, it is necessary to compare the new ranking with the initial/previous ranking and revise any judgment that cause conflicts if required. There are three steps described below:

1. From Figure 33, it can be seen that a 'Ranking *i*' (where *i* =1, 2,…,8) button is on the right-hand side. By clicking the 'Ranking 1' for the first set, the expert judgment area and Ranking 1, i.e., R_1, will be generated according to the randomised PC, and R_1 will be compared with the initial ranking, R_0. The '0s' indicators represent the accordance between R_1 and R_0 as shown in Figure 35 (a); while '1s' are indicators represent the conflicts between R_1 and R_0, as shown in Figure 35 (b), the order of 'Foundation Eroded' and 'Slack Stay' in R_1 is different from R_0;
2. In order to eliminate the conflicts, it is necessary to either to revise the initial ranking R_0 or revise the expert judgments identified by the indicator '1'. If R_0 remains the same, then the expert is asked to go to the latest PC to reconsider the judgments highlighted by indicator '1' (i.e., conflict exists) as shown in Figure

35 (c); otherwise, the PC process has to be terminated and start again with the new ‘initial ranking R_0’ ;

3. Repeat Step 1 and Step 2 for each set until no conflicts exist as shown in Figure 36, and the resulting PC-Matrix is shown in Table 37 where the calculated C.R. of 0.084 is within the acceptable range.



						Conflict exists?	
The condition of a pole with defect	R - Pole Top Rot	is considered to be of	2: same to slightly poorer condition	a pole with defect	R - Bkn porc'In stay ins	0	Ranking 1
	R - Pole Top Rot		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty rod	0	
	R - Pole Top Rot		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty wire	0	
	R - Pole Top Rot		5: poorer condition than	a pole with defect	B - Dmgd permali insul	0	
	R - Pole Top Rot		6: poorer to much poorer condition	a pole with defect	A - Foundation Eroded	0	
	R - Pole Top Rot		7: much poorer condition than	a pole with defect	B - Slack Stay	0	
	R - Pole Top Rot		8: much to absolutely poorer condition	a pole with defect	B - Animals Rubbing	0	
	R - Pole Top Rot		9: absolutely poorer condition than	a pole with defect	R - Pole Off Plumb	0	

The condition of a pole with defect	R - Bkn porc'In stay ins	is considered to be of	3: slightly poorer condition than	a pole with defect	A - Brkn/rusty rod		Ranking 2
	R - Bkn porc'In stay ins		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty wire		
	R - Bkn porc'In stay ins		4: slightly to poorer condition	a pole with defect	B - Dmgd permali insul		
	R - Bkn porc'In stay ins		5: poorer condition than	a pole with defect	A - Foundation Eroded		
	R - Bkn porc'In stay ins		6: poorer to much poorer condition	a pole with defect	B - Slack Stay		
	R - Bkn porc'In stay ins		7: much poorer condition than	a pole with defect	B - Animals Rubbing		
	R - Bkn porc'In stay ins		8: much to absolutely poorer condition	a pole with defect	R - Pole Off Plumb		

(a)

						Conflict exists?	
The condition of a pole with defect	R - Pole Top Rot	is considered to be of	2: same to slightly poorer condition	a pole with defect	R - Bkn porc'In stay ins	0	Ranking 1
	R - Pole Top Rot		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty rod	0	
	R - Pole Top Rot		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty wire	0	
	R - Pole Top Rot		5: poorer condition than	a pole with defect	B - Dmgd permali insul	0	
	R - Pole Top Rot		5: poorer condition than	a pole with defect	B - Slack Stay	1	
	R - Pole Top Rot		7: much poorer condition than	a pole with defect	A - Foundation Eroded	1	
	R - Pole Top Rot		8: much to absolutely poorer condition	a pole with defect	B - Animals Rubbing	0	
	R - Pole Top Rot		9: absolutely poorer condition than	a pole with defect	R - Pole Off Plumb	0	

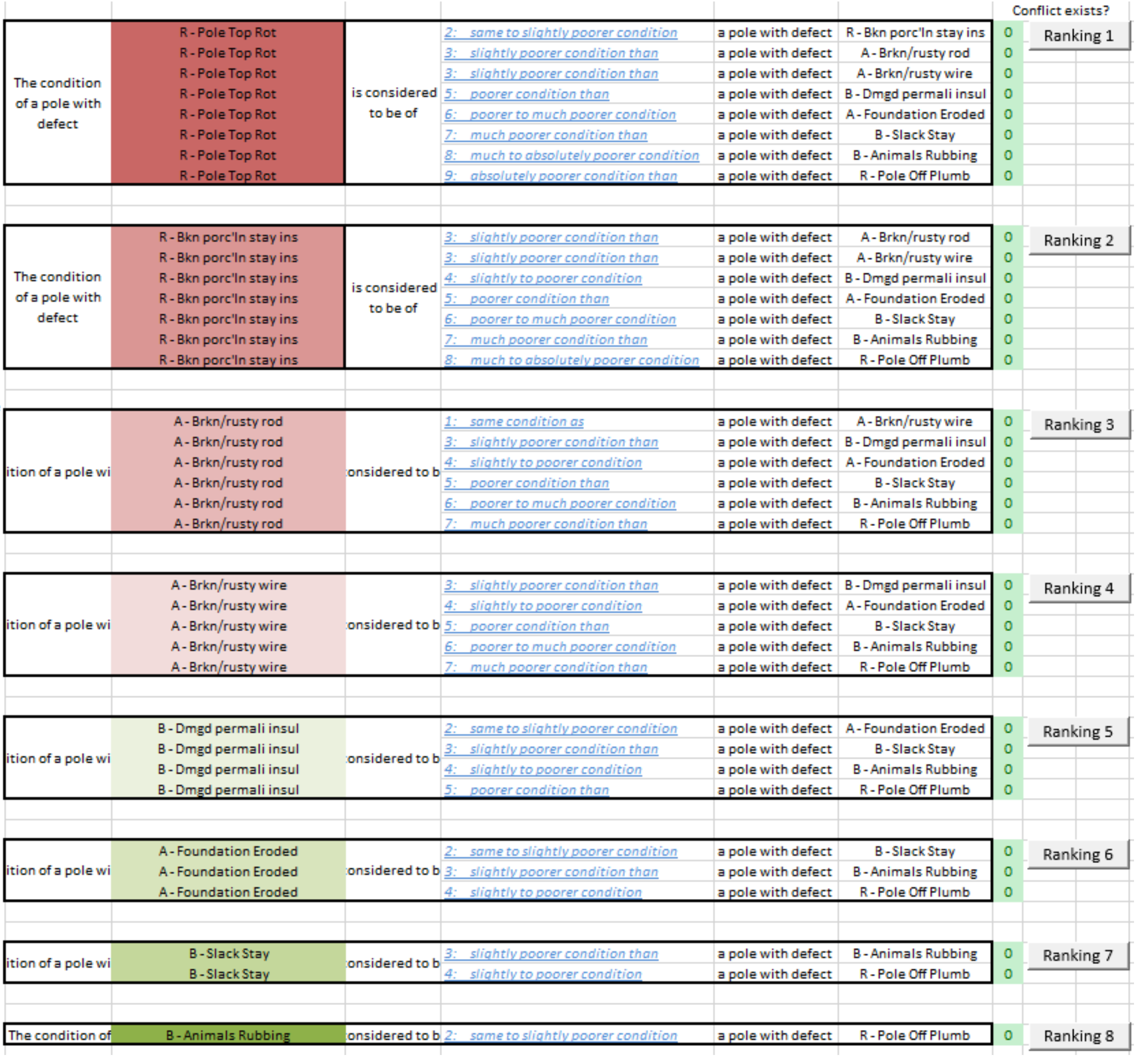
The condition of a pole with defect	R - Bkn porc'In stay ins	is considered to be of	3: slightly poorer condition than	a pole with defect	A - Brkn/rusty rod		Ranking 2
	R - Bkn porc'In stay ins		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty wire		
	R - Bkn porc'In stay ins		4: slightly to poorer condition	a pole with defect	B - Dmgd permali insul		
	R - Bkn porc'In stay ins		5: poorer condition than	a pole with defect	A - Foundation Eroded		
	R - Bkn porc'In stay ins		6: poorer to much poorer condition	a pole with defect	B - Slack Stay		
	R - Bkn porc'In stay ins		7: much poorer condition than	a pole with defect	B - Animals Rubbing		
	R - Bkn porc'In stay ins		8: much to absolutely poorer condition	a pole with defect	R - Pole Off Plumb		

(b)

The condition of a pole with defect	A - Brkn/rusty rod	is considered to be of	6: poore	a pole with defect	B - Animals Rubbing	
The condition of a pole with defect	R - Pole Top Rot	is considered to be of	7: much	a pole with defect	A - Foundation Eroded	1
The condition of a pole with defect	R - Pole Top Rot	is considered to be of	8: much	a pole with defect	B - Animals Rubbing	0
The condition of a pole with defect	R - Pole Top Rot	is considered to be of	6: poore	a pole with defect	B - Slack Stay	1
The condition of a pole with defect	A - Brkn/rusty wire	is considered to be of	5: poore	a pole with defect	B - Slack Stay	

(c)

Figure 35: PC Process Spreadsheet Screenshot 4



						Conflict exists?	
The condition of a pole with defect	R - Pole Top Rot	is considered to be of	2: same to slightly poorer condition	a pole with defect	R - Bkn porc'ln stay ins	0	Ranking 1
	R - Pole Top Rot		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty rod	0	
	R - Pole Top Rot		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty wire	0	
	R - Pole Top Rot		5: poorer condition than	a pole with defect	B - Dmgd permali insul	0	
	R - Pole Top Rot		6: poorer to much poorer condition	a pole with defect	A - Foundation Eroded	0	
	R - Pole Top Rot		7: much poorer condition than	a pole with defect	B - Slack Stay	0	
	R - Pole Top Rot		8: much to absolutely poorer condition	a pole with defect	B - Animals Rubbing	0	
	R - Pole Top Rot		9: absolutely poorer condition than	a pole with defect	R - Pole Off Plumb	0	
The condition of a pole with defect	R - Bkn porc'ln stay ins	is considered to be of	3: slightly poorer condition than	a pole with defect	A - Brkn/rusty rod	0	Ranking 2
	R - Bkn porc'ln stay ins		3: slightly poorer condition than	a pole with defect	A - Brkn/rusty wire	0	
	R - Bkn porc'ln stay ins		4: slightly to poorer condition	a pole with defect	B - Dmgd permali insul	0	
	R - Bkn porc'ln stay ins		5: poorer condition than	a pole with defect	A - Foundation Eroded	0	
	R - Bkn porc'ln stay ins		6: poorer to much poorer condition	a pole with defect	B - Slack Stay	0	
	R - Bkn porc'ln stay ins		7: much poorer condition than	a pole with defect	B - Animals Rubbing	0	
	R - Bkn porc'ln stay ins		8: much to absolutely poorer condition	a pole with defect	R - Pole Off Plumb	0	
ition of a pole wi	A - Brkn/rusty rod	onsidered to b	1: same condition as	a pole with defect	A - Brkn/rusty wire	0	Ranking 3
	A - Brkn/rusty rod		3: slightly poorer condition than	a pole with defect	B - Dmgd permali insul	0	
	A - Brkn/rusty rod		4: slightly to poorer condition	a pole with defect	A - Foundation Eroded	0	
	A - Brkn/rusty rod		5: poorer condition than	a pole with defect	B - Slack Stay	0	
	A - Brkn/rusty rod		6: poorer to much poorer condition	a pole with defect	B - Animals Rubbing	0	
	A - Brkn/rusty rod		7: much poorer condition than	a pole with defect	R - Pole Off Plumb	0	
ition of a pole wi	A - Brkn/rusty wire	onsidered to b	3: slightly poorer condition than	a pole with defect	B - Dmgd permali insul	0	Ranking 4
	A - Brkn/rusty wire		4: slightly to poorer condition	a pole with defect	A - Foundation Eroded	0	
	A - Brkn/rusty wire		5: poorer condition than	a pole with defect	B - Slack Stay	0	
	A - Brkn/rusty wire		6: poorer to much poorer condition	a pole with defect	B - Animals Rubbing	0	
	A - Brkn/rusty wire		7: much poorer condition than	a pole with defect	R - Pole Off Plumb	0	
ition of a pole wi	B - Dmgd permali insul	onsidered to b	2: same to slightly poorer condition	a pole with defect	A - Foundation Eroded	0	Ranking 5
	B - Dmgd permali insul		3: slightly poorer condition than	a pole with defect	B - Slack Stay	0	
	B - Dmgd permali insul		4: slightly to poorer condition	a pole with defect	B - Animals Rubbing	0	
	B - Dmgd permali insul		5: poorer condition than	a pole with defect	R - Pole Off Plumb	0	
ition of a pole wi	A - Foundation Eroded	onsidered to b	2: same to slightly poorer condition	a pole with defect	B - Slack Stay	0	Ranking 6
	A - Foundation Eroded		3: slightly poorer condition than	a pole with defect	B - Animals Rubbing	0	
	A - Foundation Eroded		4: slightly to poorer condition	a pole with defect	R - Pole Off Plumb	0	
ition of a pole wi	B - Slack Stay	onsidered to b	3: slightly poorer condition than	a pole with defect	B - Animals Rubbing	0	Ranking 7
	B - Slack Stay		4: slightly to poorer condition	a pole with defect	R - Pole Off Plumb	0	
The condition of	B - Animals Rubbing	onsidered to b	2: same to slightly poorer condition	a pole with defect	R - Pole Off Plumb	0	Ranking 8

Figure 36: PC Process without Any Conflicts Showing Completed

With the improved AHP process, the PC-Matrix from Expert 1 is shown in Table 37 as an example. As presented in Section 4.3.2.3, all four priority scaling methods (AM, EM, GM and LS) are applied here to derive the priorities and corresponding parameters, i.e., C.R. and E.I., associated with individual expert judgments and shown in Table 38. Table 39 is a summary of the priorities and parameters of the four scaling methods involving all the experts.

Table 37: PC-Matrix for Defects – Expert 1

Defects	Pole Top Rot	Foundation Eroded	Broken/rusty rod	Broken/rusty wire	Damaged permali insul	Bkn porc'ln stay insulator	Slack Stay	Animals Rubbing	Pole Off Plumb
Pole Top Rot	1	2	3	3	5	6	7	8	9
Foundation Eroded	1/2	1	3	3	4	5	6	7	8
Broken/rusty rod	1/3	1/3	1	1	3	4	5	6	7
Broken/rusty wire	1/3	1/3	1	1	3	4	5	6	7
Damaged permali insul	1/5	1/4	1/3	1/3	1	2	3	4	5
Bkn porc'ln stay insulator	1/6	1/5	1/4	1/4	1/2	1	2	3	4
Slack Stay	1/7	1/6	1/5	1/5	1/3	1/2	1	3	4
Animals Rubbing	1/8	1/7	1/6	1/6	1/4	1/3	1/3	1	2
Pole Off Plumb	1/9	1/8	1/7	1/7	1/5	1/4	1/4	1/2	1

Table 38: Priorities and Parameters of Four Scaling Methods of Expert 1

		AM	EM	GM	LS
Priorities	Broken/rusty rod	0.136	0.136	0.138	0.118
	Broken/rusty wire	0.136	0.136	0.138	0.118
	Foundation Eroded	0.051	0.048	0.049	0.046
	Animals Rubbing	0.024	0.023	0.023	0.029
	Damaged permali insulator	0.073	0.070	0.070	0.062
	Slack Stay	0.041	0.038	0.037	0.037
	Bkn porcelain stay insulator	0.228	0.235	0.232	0.234
	Pole Off Plumb	0.018	0.017	0.017	0.024
	Pole Top Rot	0.292	0.296	0.296	0.332
λ_{max}		9.561	9.548	9.547	9.982
C.R.		0.048	0.047	0.047	0.071
E.I.		84.451	109.659	117.033	52.237

Table 39: A Summary of the Priorities and Parameters of All Experts

Priority Scaling Method	AM	EM	GM	LS
Expert 1				
λ_{max}	9.561	9.548	9.547	9.982
Consistency Ratio (C.R.)	0.048	0.047	0.047	0.071
Error Index (E.I.)	84.451	109.659	117.033	52.237
Expert 2				
λ_{max}	9.510	9.505	9.501	9.788
Consistency Ratio (C.R.)	0.044	0.044	0.043	0.068
Error Index (E.I.)	102.974	139.492	120.967	72.938
Expert 3				
λ_{max}	9.533	9.523	9.859	10.083
Consistency Ratio (C.R.)	0.046	0.045	0.076	0.093
Error Index (E.I.)	50.937	66.327	40.867	57.474

It can be seen that all the C.R. values are under 0.1, i.e., acceptable, with LS showing the smallest E.I. among the four scaling methods. As before, it is necessary to find the priorities and parameters associated with the four scaling methods after the aggregation of multiple experts' judgments. As introduced in Section 3.3.4, LogPM is the method chosen to synthesise multiple experts' judgments. Therefore, the calculated priorities and parameters of the four scaling methods from the aggregated PC-Matrix combining the expert judgments of all experts by using LogPM are listed in Table 40.

Table 40: Synthesised Priorities and Parameters

		AM	EM	GM	LS
Priorities	Broken/rusty rod	0.158	0.157	0.159	0.139
	Broken/rusty wire	0.159	0.159	0.160	0.140
	Foundation Eroded	0.119	0.118	0.121	0.121
	Animals Rubbing	0.034	0.033	0.033	0.037
	Damaged permali insulator	0.052	0.051	0.051	0.051
	Slack Stay	0.039	0.038	0.039	0.040
	Bkn porcelain stay insulator	0.078	0.078	0.079	0.082
	Pole Off Plumb	0.029	0.029	0.029	0.034
	Pole Top Rot	0.332	0.337	0.330	0.356
λ_{max}		9.182	9.182	9.181	9.259
C.R.		0.016	0.016	0.016	0.022
E.I.		28.834	34.595	30.906	22.783

A histogram of Error Index (E.I.) (from individual expert and synthesisation) is shown in Figure 37.

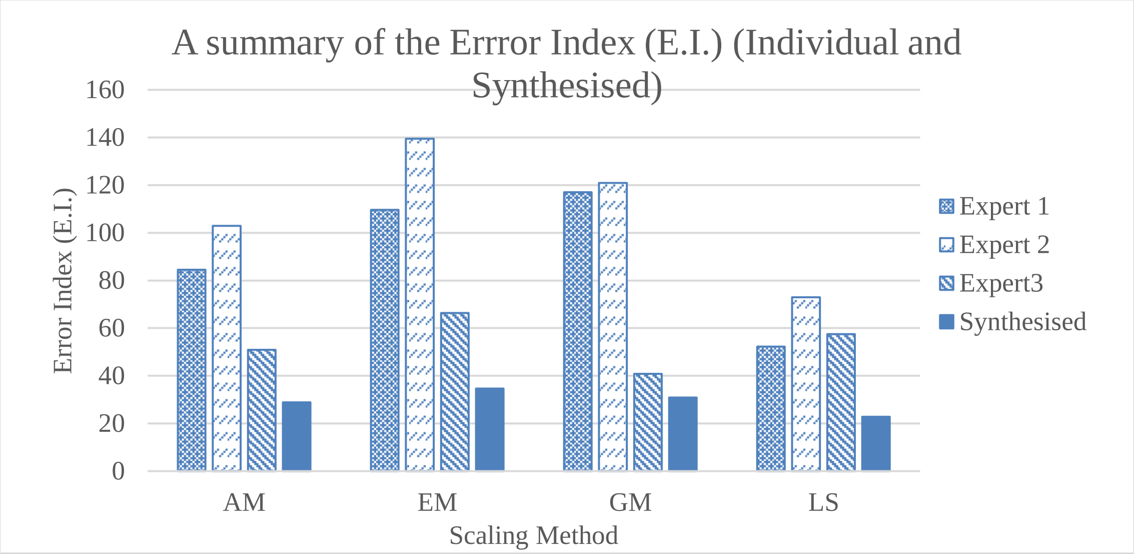


Figure 37: A Summary of the Error Index (E.I.) (Individual and Synthesised

The result shows that all the C.R. values are acceptable, and LS shows the smallest E.I., therefore, this thesis uses the priorities generated by LS as the evaluated result of the condition of the HV Wood Poles as part of the health assessment.

5.2 Using AHP to Ascertain Expert Judgment of the Alternatives

After experts' judgments are collected for all the criteria levels, the next step is to compare alternatives in pairs by criteria on the bottom criteria level, i.e., the Criteria Level 2 in the HV Wood Poles case. According to the hierarchical structure of HV Wood Poles, presented again in Figure 38.

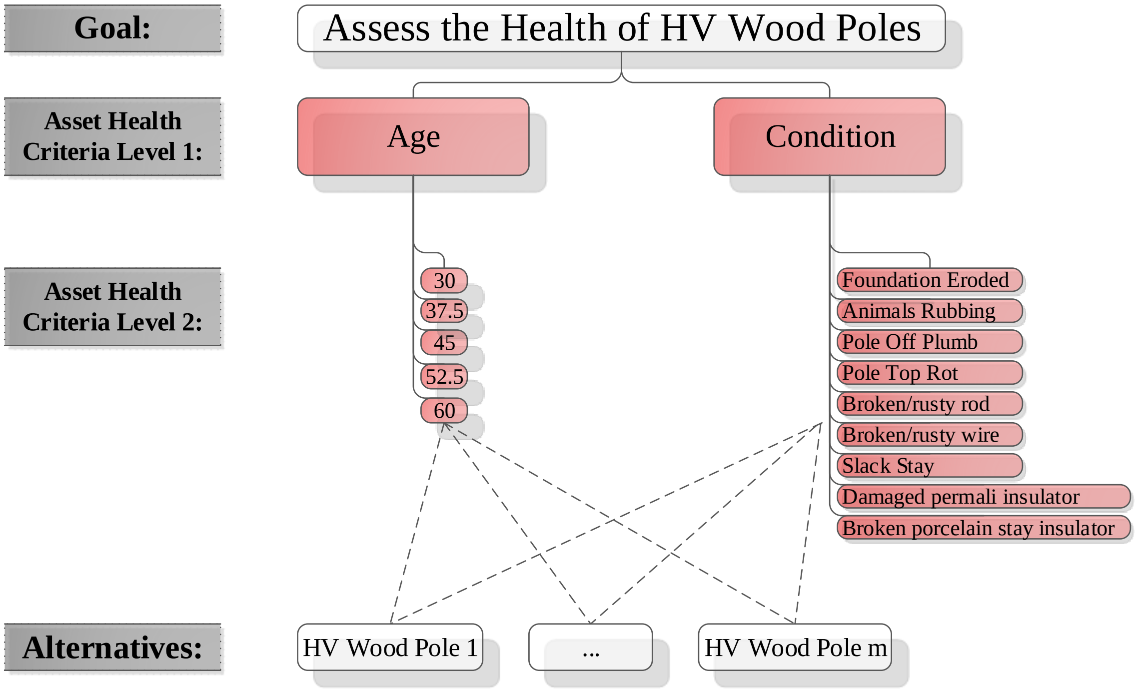


Figure 38: Hierarchical Structure of HV Wood Poles with Identified Age Points

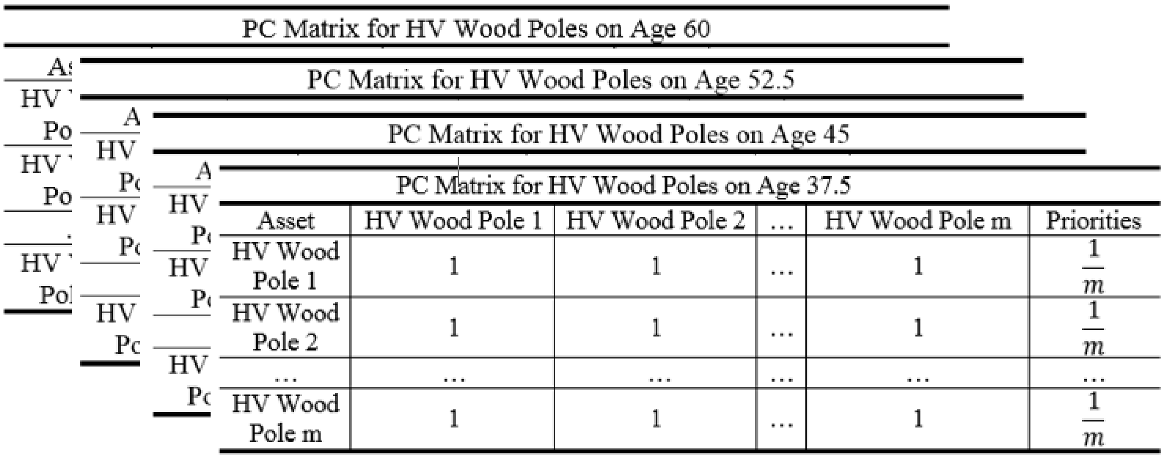
In total, there are five subordinate criteria for age and nine subordinate criteria for the condition, therefore, 14 PC-Matrices in total. The PC-Matrix for HV Wood Poles with respect to Age 30 as an example is in Table 41.

Table 41: PC-Matrix for HV Wood Poles on Age 30

PC-Matrix for HV Wood Poles on Age 30				
Asset	HV Wood Pole 1	HV Wood Pole 2	…	HV Wood Pole m
HV Wood Pole 1	a_{11}	a_{12}	…	a_{1m}
HV Wood Pole 2	a_{21}	a_{22}	…	a_{2m}
…	…	…	…	…
HV Wood Pole m	a_{m1}	a_{m2}	…	a_{mm}

The HV Wood Poles are assumed to be made of the same wood specious and have been manufactured in the same way. Therefore, all the HV Wood Poles have equal likelihood of failure at Age 30, i.e., one can expect $a_{11} = a_{12} = ... = a_{1m} = a_{21} = \cdots = a_{m1} = a_{mm} = 1$ in Table 41. The average weighting for every single HV Wood Pole is the same. In that case, the average weighting will not affect the overall assessment, therefore the priority can be expressed as $\frac{1}{m}$ for every single HV Wood Pole after normalisation, m denotes the number of poles.

It is the same case for the other three criteria of age and nine criteria of the condition. The PC-Matrices are shown in Figure 39 and Figure 40 respectively.



PC Matrix for HV Wood Poles on Age 60

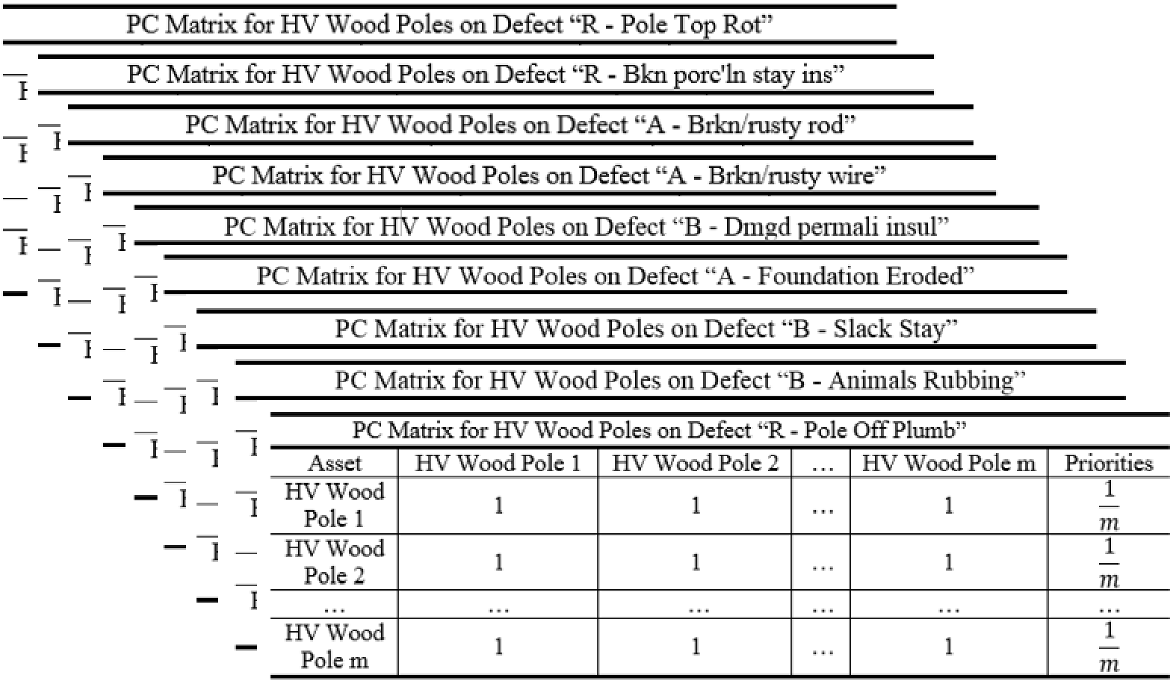
PC Matrix for HV Wood Poles on Age 52.5

PC Matrix for HV Wood Poles on Age 45

PC Matrix for HV Wood Poles on Age 37.5

Asset	HV Wood Pole 1	HV Wood Pole 2	…	HV Wood Pole m	Priorities
HV Wood Pole 1	1	1	…	1	$\frac{1}{m}$
HV Wood Pole 2	1	1	…	1	$\frac{1}{m}$
…	…	…	…	…	…
HV Wood Pole m	1	1	…	1	$\frac{1}{m}$

Figure 39: PC-Matrix for HV Wood Poles on Age



PC Matrix for HV Wood Poles on Defect “R - Pole Top Rot”

PC Matrix for HV Wood Poles on Defect “R - Bkn porc'ln stay ins”

PC Matrix for HV Wood Poles on Defect “A - Brkn/rusty rod”

PC Matrix for HV Wood Poles on Defect “A - Brkn/rusty wire”

PC Matrix for HV Wood Poles on Defect “B - Dmgd permali insul”

PC Matrix for HV Wood Poles on Defect “A - Foundation Eroded”

PC Matrix for HV Wood Poles on Defect “B - Slack Stay”

PC Matrix for HV Wood Poles on Defect “B - Animals Rubbing”

PC Matrix for HV Wood Poles on Defect “R - Pole Off Plumb”

Asset	HV Wood Pole 1	HV Wood Pole 2	…	HV Wood Pole m	Priorities
HV Wood Pole 1	1	1	…	1	$\frac{1}{m}$
HV Wood Pole 2	1	1	…	1	$\frac{1}{m}$
…	…	…	…	…	…
HV Wood Pole m	1	1	…	1	$\frac{1}{m}$

Figure 40: PC-Matrix for HV Wood Poles on Condition

With the derived PoF in Equation (6 - 7) and priorities in Table 40, Figure 39, and Figure 40, the Hierarchical Structure of HV Wood Poles can then be illustrated in Figure 41:

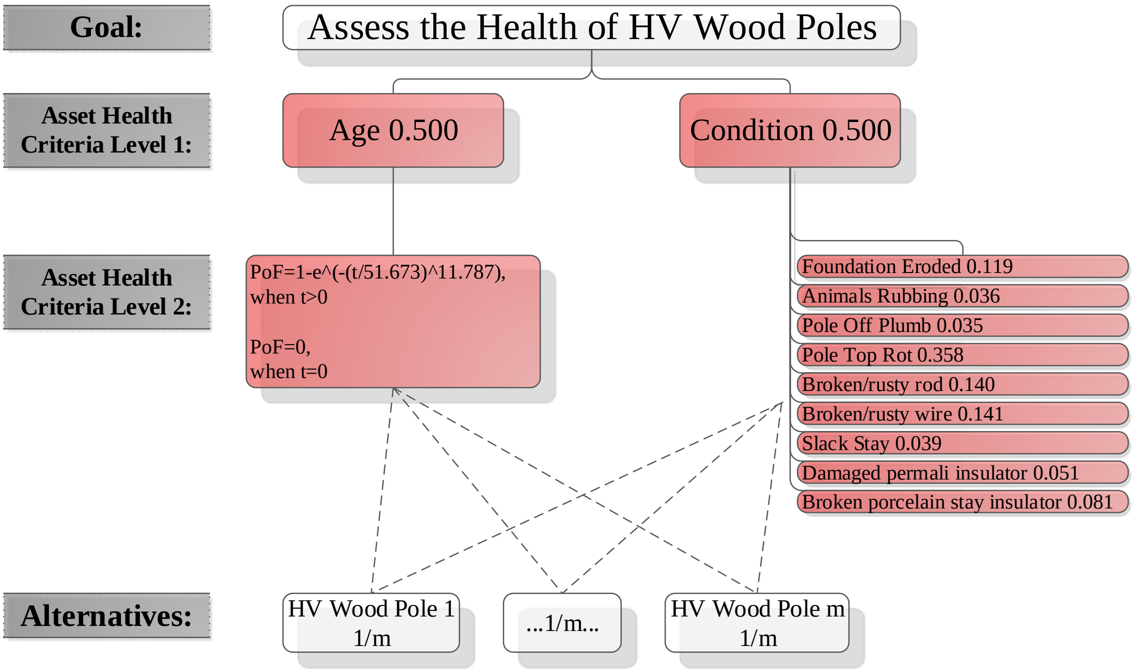


Figure 41: Hierarchical Structure of HV Wood Poles with Derived Priorities

5.3 Overall Asset Health by Using AHP

The above sections use AHP to ascertain expert judgments as follows:

1. Of the relative contribution made by age and condition to asset health;
2. In the derivation of an asset PoF versus age curve;
3. Of the relative contribution made by defects to asset condition with improved AHP process;
4. Of the alternatives.

The synthesised weightings for the above four parts from multiple experts are calculated. The hierarchical structure of HV Wood Poles in Figure 12 (Section 4.3.2) is comprised of above four parts. The overall health score of individual HV Wood Pole can be calculated as follows:

$$Overall\ risk\ of\ health\ of\ individual\ HV\ Wood\ Pole =$$

$$\frac{1}{m} \times PoF(derived\ with\ given\ age) \times age\ priority$$

$$+$$

$$\frac{1}{m} \times condition(priorities\ sum\ of\ the\ defects\ of\ each\ wood\ pole\ from\ AHP) \times condition\ priority$$

This results in a unitless relative and normalised score within a scale of 0-1 or 0 - 100, (as requested by the company). In addition, since $\frac{1}{m}$ is the common factor which can be eliminated, and with the results in Table 19 (Section 4.3.1), i.e age weights 0.5, Equation (6 - 7), and Table 40, the expression then becomes to Equation (6 - 8):

$$Overall\ risk\ of\ health\ of\ individual\ HV\ Wood\ Pole =$$

$$100 \times [(1 - e^{-\left(\frac{t}{51.673}\right)^{11.787}}) \times 0.500 \tag{6 - 8}$$

$$+$$

$$condition(priorities\ sum\ of\ the\ defects\ of\ each\ wood\ pole\ from\ AHP) \times 0.500]$$

A wood pole case study example is used to demonstrate the application of the weightings/scores to provide a quantitative indication of asset health:

Consider one HV Wood Pole among *m* HV Wood Poles is 44 years old with defects *'Broken rusty rod'* and *'Foundation eroded'*, another HV Wood Pole among *m* HV Wood Poles has the age of 18 with defect *'Animal rubbing'*.

Therefore, the overall health of the former (44-year-old) wood pole is:

$$100 \times [\left(1 - e^{-\left(\frac{44}{51.673}\right)^{11.787}}\right) \times 0.500 + (0.140 + 0.119) \times 0.500]$$

$$= 100 \times (0.140 \times 0.500 + 0.259 \times 0.500) = 19.9$$

The overall health of the latter (18-year-old) wood pole is:

$$100 \times [\left(1 - e^{-\left(\frac{18}{51.673}\right)^{11.787}}\right) \times 0.500 + 0.036 \times 0.500] = 1.8$$

From the calculation, the overall health of the two HV Wood Poles are 19.9 and 1.8 respectively. Note that, the smaller the result, the healthier the HV Wood Pole is, i.e., *'0'* indicates a complete healthy pole without further refurbishment and *'100'* suggests an immediately replacement. There is one exception as mentioned in Section 4.2.2 to derive the overall health of the HV Wood Poles, they are defect *'Seriously Damaged'* . Experts decided that assets with either one of these two defects should have an overall health score of 100, i.e., be replaced regardless of the age and existence of other defects.

Above all, the AHP method is introduced and analysed in detail. In Section 5.4, another method, Swing Weights is proposed. This method uses the hierarchical structure developed by AHP, but instead of Pairwise Comparison, Swing Weights compares the criteria with the ‘swing’ of each defect of asset condition. The results comparisons between AHP and SW are described in the following section.

5.4 Using SW to Ascertain the Expert Judgment of the Relative Contribution Made by Defects to Asset Condition

As described in Section 3.1.3.2, AHP is widely applied because of its use in the area decision-making and support introduced by Saaty [16] in 1980. AHP also maps intuitive statements (e.g., ‘same as’ or ‘more likely’) to quantitative scores/measures (i.e., scale 1 to 9) to facilitate the quantification of expert judgments when conducting pairwise comparisons as a means of deriving the ‘relative weightings’ that exists between decision-making criteria. There is no doubt that AHP provides a well-structured and explicit way to a decision-making problem, either quantitative or qualitative alternatives can be compared to derive a solution, and at the same time, the consistency of expert judgments has been monitored which makes the result more trustful. However, despite the advantages and popular application of AHP, as described in 3.1.3, there are three specific shortcomings of AHP in its application to the power system HV Wood Poles case study, which are summarised below:

1. Defects are not in themselves quantitative measures with a numeric scale like temperature, vibration, structural strength, therefore there exists a pre-processing stage for the ‘quantification’ of defects using expert judgment. Although AHP allows qualitative alternatives to be compared and play a role in the whole process, nine defects in this power system HV Wood Poles case study is a large number of non-quantitative alternatives, this increases the workload of pairwise comparisons, and which can potentially result in different outputs of pre-processing of the same defects every comparison.
2. Nine defects indicate 8+7+6+5+4+3+2+1=36 pairwise comparisons; this increases the scope for inconsistency across an expert’s complete set of pairwise comparisons, which requires repeating of the PC process.
3. The inconsistency cannot be eliminated entirely though with the improved AHP process.

The shortcomings outlined above can also have the effect of making this a time-consuming and onerous process for experts to engage with. This can frustrate experts causing them to disengage and so potentially compromise the accuracy of the expert judgments captured. As evidenced here, as the number of criteria subjects to examination and comparison increases, this approach may become increasingly cumbersome.

Therefore, inspired by Keeney [45], Belton([15]135-139)and Parnell [46] ([47] 334-336) ([48] 222-254), an alternative MCDA technique known as the Swing Weights method (SW), was also applied to assess the health of HV Wood Pole. A general flow chart describing how SW is applied is shown in in Figure 42. Compared with the general flow chart of AHP in Figure 11 (Section 4.3), the first three steps are the same for the two methods, i.e., data collection, selection and criteria identification, and hierarchical structure development. The following steps of SW substitute the third branch in Figure 11 of AHP, i.e., the PC process in the derivation of relative contribution made by defects to asset condition. Prior to perform the remaining steps of SW, it is essential that the concept of ‘*swing*’ is carefully explained to the participating experts. SW measures both the ‘*value*’ of ‘*sensitivity*’ and ‘*variation*’. However, the meaning of ‘*importance*’ and ‘*variation*’ vary for different case studies with different criteria. Therefore, details of the meanings of ‘*sensitivity*’ and ‘*variation*’ should be explained carefully for every individual application respectively.

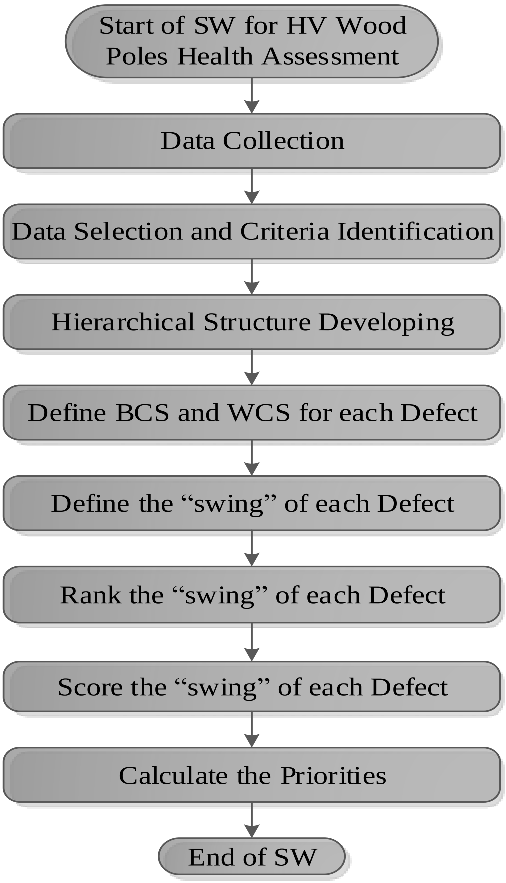
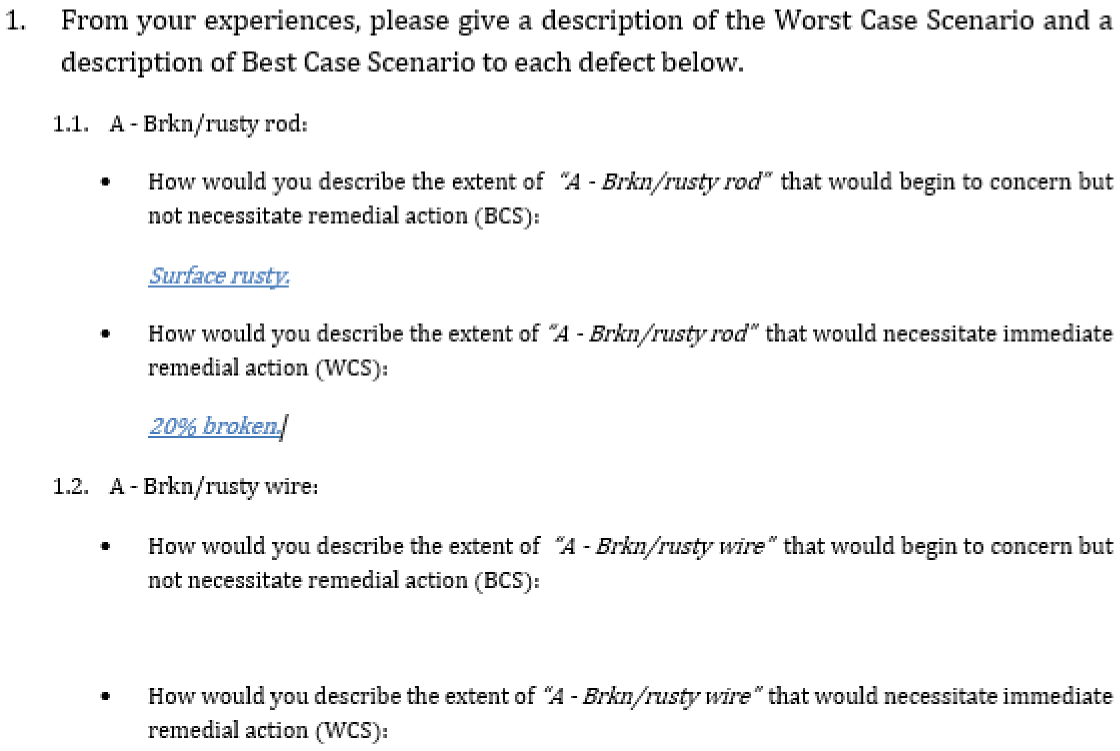


Figure 42: General Flow Chart of SW

Since the first three steps of the flowchart of SW are the same as that of AHP, SW shares the same hierarchical structure but then follows different procedures from AHP to ascertain the expert judgments of the relative contribution made by defects to asset condition. As introduced before, SW requires fewer comparisons than AHP, which is clearly an advantage when a large number of criteria is involved. In addition, the setting of reference points is to some extent a process of quantification for criteria which are not numeric measurements. In that case, SW compares the *‘swing’* between criteria, where the *‘swing’* represents the change from the two reference points, i.e., Best-Case Scenario (BCS) and Worst-Case Scenario (WCS). It is important for the experts to have an accurate and consistent understanding of BCSs and WCSs and provide a clear description of this for each criterion. It is then necessary to complete an SW questionnaire which records the description of BCS and WCS for each defect, as defined by group consensus from multiple experts. This can be used for future reference to ensure an expert’s comparisons are based on the pre-defined *‘swing’*.

With the help of the example in Section 3.1.4, expert accepted and understood the concept of ‘swing’, which is the difference between BCS and WCS, the SW questionnaire then moves to the HV Wood Poles case study. The same as AHP, nine defects are required to be evaluated, each defect is asked to provide the BCS and WCS by an expert. Figure 43 represents a section of the questionnaire where the ‘surface rusty’ has been identified by one expert as the BCS of defect ‘A – Broken/rusty rod’, and ‘Broken’ is the WCS. With the completion of the questionnaire, the BCS and WCS are recorded for each defect.



1. From your experiences, please give a description of the Worst Case Scenario and a description of Best Case Scenario to each defect below.

1.1. A - Brkn/rusty rod:

- How would you describe the extent of *"A - Brkn/rusty rod"* that would begin to concern but not necessitate remedial action (BCS):

  Surface rusty.

- How would you describe the extent of *"A - Brkn/rusty rod"* that would necessitate immediate remedial action (WCS):

  20% broken.

1.2. A - Brkn/rusty wire:

- How would you describe the extent of *"A - Brkn/rusty wire"* that would begin to concern but not necessitate remedial action (BCS):

- How would you describe the extent of *"A - Brkn/rusty wire"* that would necessitate immediate remedial action (WCS):

Figure 43: SW Questionnaire

The BCS and WCS for nine defects of one expert are summarised in Table 42.

Table 42: The Summary of BCS and WCS for Defects of Expert 1

Defects	BCS (description)	WCS (description)
Broken/rusty rod	Surface rusty	20% broken
Broken/rusty wire	Surface rusty	20% broken
Foundation Eroded	20% erosion	80% erosion
Animals Rubbing	Shiny on the pole	34% reduction of the pole diameter
Damaged permali insulator	Slightly chipped	Broken
Slack Stay	Slight slack, could adjust	No tension
Bkn porcelain stay insulator	Slightly chipped	Insulator gone
Pole Off Plumb	No reduction in stat ground clearance	Reduction in stat ground clearance
Pole Top Rot	Moss grown	Pole diameter reduced

After identifying BCS and WCS for each defect, a ranking of the *'swing'* is required. In order to apply the SW method on HV wood pole defects, it is necessary to establish the relative sensitivity of the overall pole condition to any change in the individual defect. In order to obtain this, it is required to determine the change in which defect has the most significant effect on the overall condition from an expert; in other words, which defect's *'swing'* between BCS and WCS has the most significant effect on the overall asset condition. The steps of SW are:

1. Define the *'swing'* between BCS and WCS for each criterion. Taking defect *'A – Broken/rusty rod'* as an example, the *'swing'* is from *'surface rusty'* to *'broken'*;
2. Having defined the swing range, it is necessary to effectively 'score' the swing by considering how sensitive the overall asset condition is to any variation between BCS and WCS for each criterion;
3. Rank the sensitivities in descending order;
4. Set the sensitivity to any variation of each defect between its worst case and best case descriptions on a normalised range of *1-100*. Assign the *1st* ranked defect, i.e., most *'sensitive'* defect with a score of *'100'*, denote as S_1, keep the others with a score of *'0'*;

5. Compare the sensitivity of the *2nd* defect to the 1st with score *'100'*, and assign the *2nd* defect with a score from *1-100*, denote as S_2, *'100'* indicate equal sensitivity;
6. Suppose the score of the *2nd* defect is the maximum level (*100*), compare the sensitivity of the *3rd* defect to the *2nd* and assign the *3rd* defect with a score from *1-100,* denote as S_3, *'100'* indicate equal sensitivity;
7. Repeat Step 6 until all the defects are being scored;

Once the above steps have been completed by an expert, to derive the priorities, i.e., the relative contribution made by defects to asset condition, a normalisation is required. The normalisation consists of two processes: modify the original assigned SW sensitivity scores S_i into w_i with Equation (4 -36); derive priorities p_i from w_i using Equation (4 -37) and have a summation of unity. The derivation of priorities is much more straight forward for SW than it is with AHP.

$$w_i = \begin{cases} 100 & i = 1 \\ \dfrac{S_i \times w_{i-1}}{100} & i = 2, \dots, n \end{cases} \tag{4 -36}$$

$$p_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{4 -37}$$

$$\sum_{i=1}^{n} p_i = 1$$

Where

S_i: $the\ original\ score\ for\ i^{th}\ defect, n = 1, \dots, 9\ in\ the\ defect\ case$;

w_i: $the\ modified\ score\ for\ i^{th}\ defect, n = 1, \dots, 9\ in\ the\ defect\ case$;

p_i: $the\ normalized\ priority\ for\ i^{th}\ defect, n = 1, \dots, 9\ in\ the\ defect\ case$;

Table 43 shows the ranking of the sensitivity of the *'swing'* with scores and calculated priorities by Expert 1.

Table 43: Ranking and Scores of Defects for SW of Expert 1

Ranking of 'swing'	Defects	Original Scores	Modified Scores	Priorities
1st	Pole Top Rot	100	100.000	0.190
2nd	Bkn porcelain stay insulator	95	95.000	0.180
3rd	Broken/rusty rod	90	85.500	0.162
4th	Broken/rusty wire	100	85.500	0.162
5th	Damaged permali insulator	70	59.850	0.114
6th	Foundation Eroded	90	53.865	0.102
7th	Slack Stay	50	26.933	0.051
8th	Animals Rubbing	50	13.466	0.026
9th	Pole Off Plumb	50	6.733	0.013

Figure 44 compares the calculated priorities of AHP and SW. It can be seen that there is a large decrease of the relative weightings occupied by defect *'Pole Top Rot'* from AHP to SW. This is the same case for Expert 2 and Expert 3 in Figure 45 and Figure 46. One of the reasons for this phenomenon is that the measurements being compared in SW and AHP are different. For example, Expert 1 defines the BCS to be *'moss grown'* and WCS to be *'severe rot, little hole'*, indicating that the severity of a wood pole with defect *'Pole Top Rot'* varies from *'moss grown'* to *'severe rot, little hole'*; while when using AHP no *'swing'* is involved and *'loss of balance of the pole'* is being compared with, which is the WCS in theory. So consequently *'Pole Top Rot'* results in a larger defect weighting following the use of AHP than is obtained using SW.

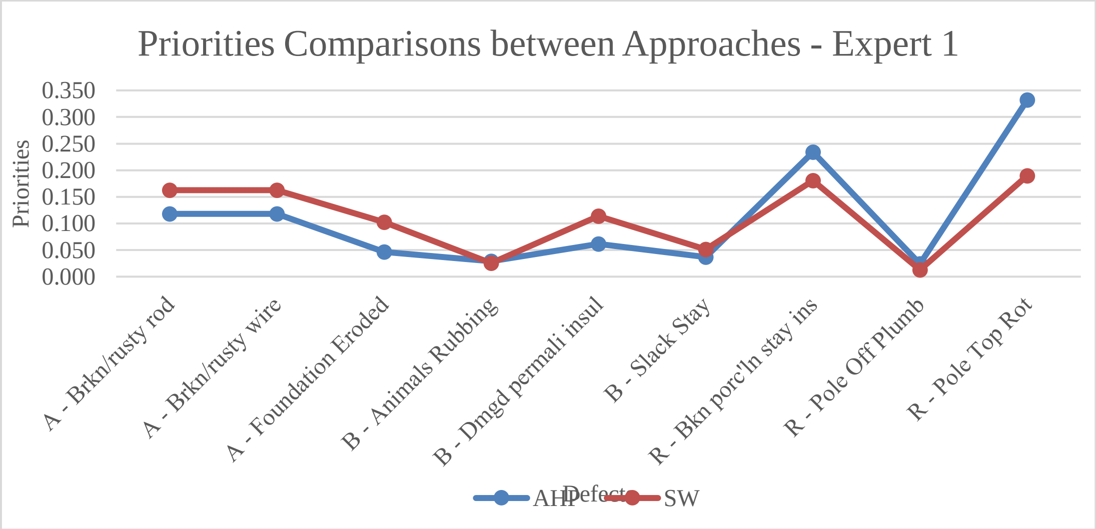


Figure 44: Priorities Comparisons between Approaches - Expert 1

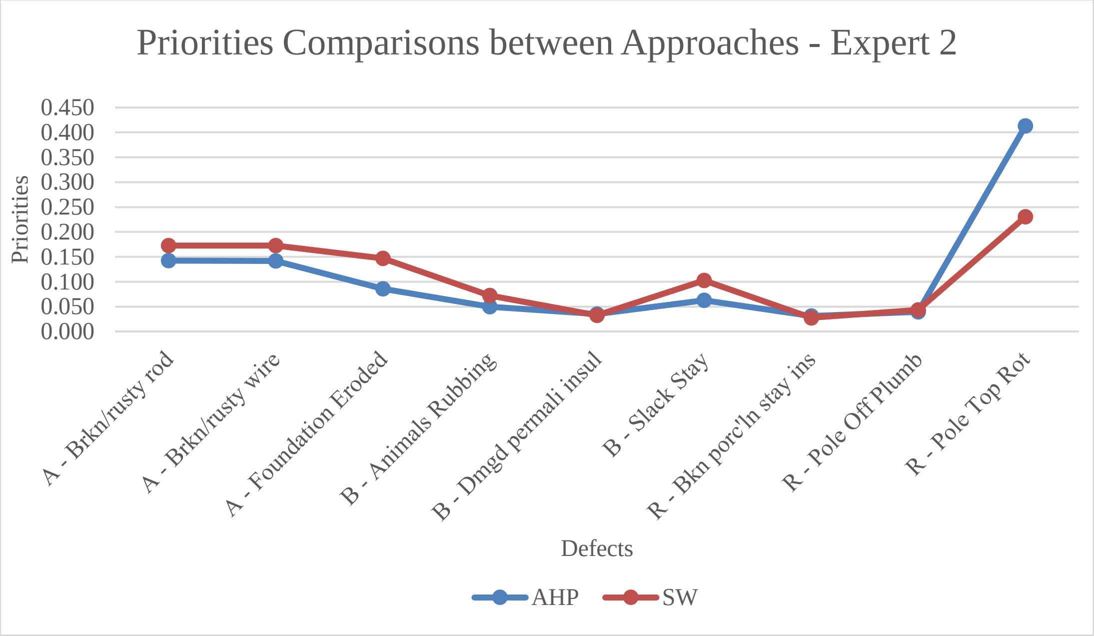


Figure 45: Priorities Comparisons between Approaches - Expert 2

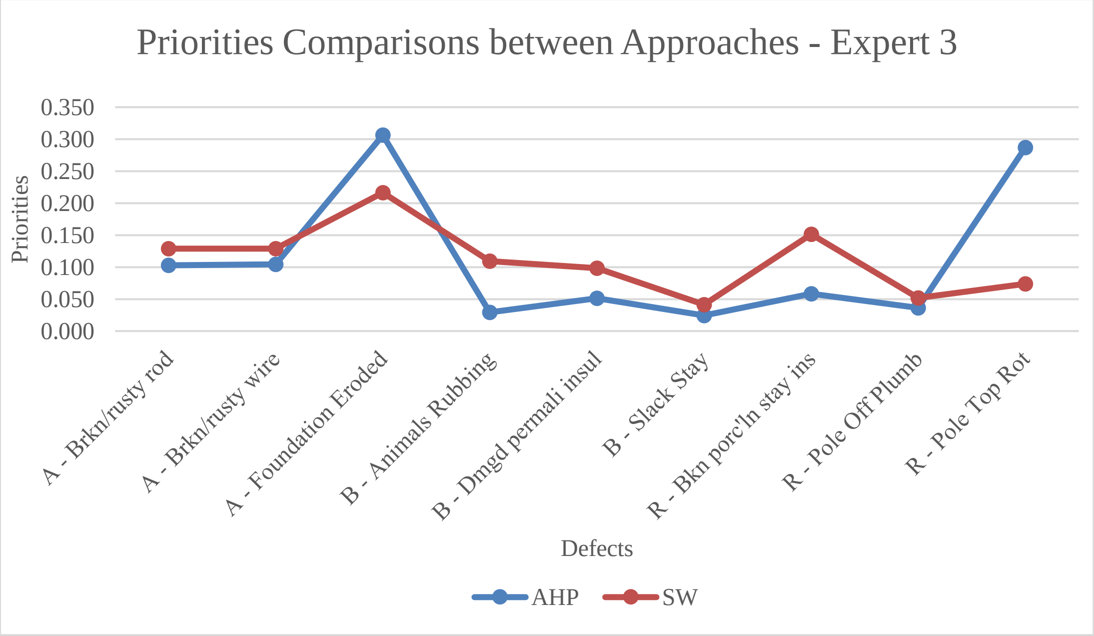


Figure 46: Priorities Comparisons between Approaches - Expert 3

For multiple experts, MEJA is applied to do the synthesisation of the priorities from SW. The geometric mean is calculated from the three sets of priorities of three experts. Figure 47 shows the illustration of the synthesised priorities of AHP and SW respectively. There is a small degree of disagreement between the two approaches, the largest is *'Pole Top*

Rot', then followed by *'Bkn porcelain stay insulator'* and *'Foundation Eroded'*. The priorities of each defect derived from two approaches are listed in Table 44.

Table 44: Priorities Comparisons between Approaches – Synthesised

	Different Approaches		
	AHP	SW	Difference(abs)
A - Brkn/rusty rod	0.139	0.153	0.014
A - Brkn/rusty wire	0.140	0.153	0.013
A - Foundation Eroded	0.121	0.182	0.061
B - Animals Rubbing	0.037	0.062	0.025
B - Dmgd permali insul	0.051	0.083	0.032
B - Slack Stay	0.040	0.043	0.003
R - Bkn porc'ln stay ins	0.082	0.177	0.095
R - Pole Off Plumb	0.034	0.028	0.006
R - Pole Top Rot	0.356	0.119	0.237

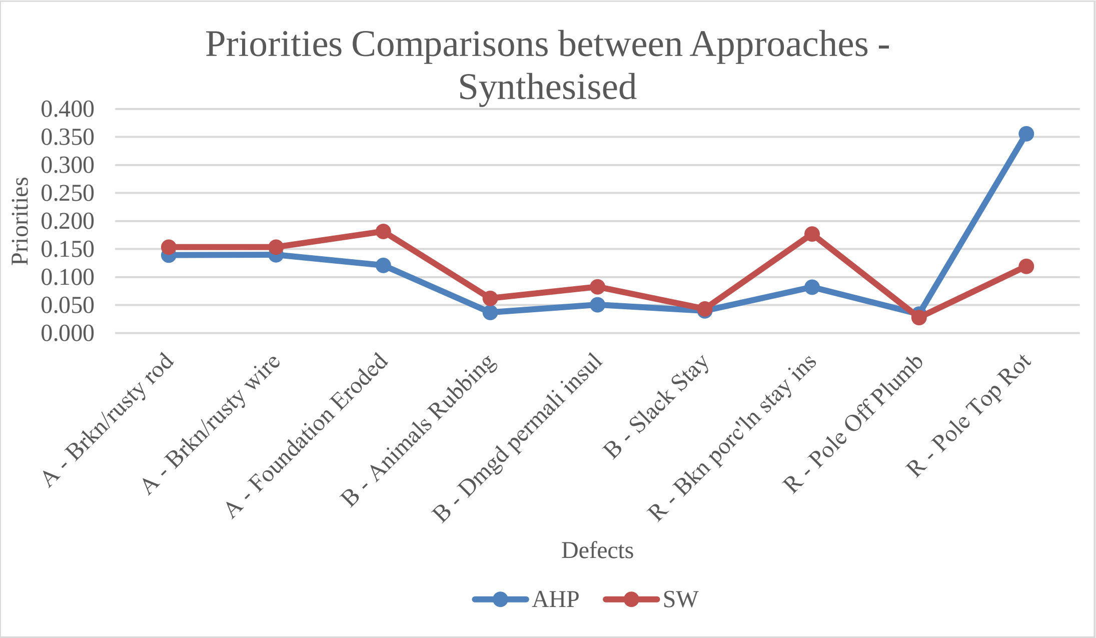


Figure 47: Priorities Comparisons between Approaches – Synthesised

The comparison result after synthetisation shows some degree of correlation between AHP and SW with large value differences between the two approaches of defects such as *'R - Pole Top Rot'* with the largest difference of 0.237, *'A - Foundation Eroded'* and *'R - Bkn porc'ln stay ins'* are the defects with differences of 0.095 and 0.061 respectively. The difference of each defect weighting/scoring between AHP and SW, and in particular with regards to defect *'Pole Top Rot'*, is noticeable with the three experts employed in the thesis. Further research involving more experts (limited to between 15-30 in line with recommendations) could be conducted here to observe the effect this has on different weightings of each defect.

5.5 Overall Asset Health by Using SW

Similar to AHP, the overall asset health assessment is calculated by Equation (6 - 7) while the ‘condition’ in the equation is the priorities sum of the defects of each wood pole from SW in this case, as expressed in Equation (6 - 9):

$$\begin{gathered}
Overall\ risk\ of\ health\ of\ individual\ HV\ Wood\ Pole = \\
100 \times (\frac{1}{m} \times (1 - e^{-\left(\frac{t}{51.673}\right)^{11.787}}) \times 0.500 \\
+ \\
\frac{1}{m} \times condition(priorities\ sum\ of\ the\ defects\ of\ each\ wood\ pole\ from\ AHP) \times 0.500)
\end{gathered} \tag{6 - 9}$$

The same example is used to demonstrate the calculation process: two HV Wood Poles among m HV Wood Poles, one is 44 years old with defects *‘Broken rusty rod’* and *‘Foundation eroded’* and the other HV Wood Pole is at the age of 18 with defect *‘Animal rubbing’*.

Therefore, the overall health of the former one is:

$$100 \times (\frac{1}{m} \times \left(1 - e^{-\left(\frac{44}{51.673}\right)^{11.787}}\right) \times 0.500 + \frac{1}{m} \times (0.153 + 0.182) \times 0.500)$$

$$= 100 \times (\frac{1}{m} \times 0.140 \times 0.500 + \frac{1}{m} \times 0.335 \times 0.500) = 23.75\frac{1}{m}$$

The overall health of the latter one is:

$$100 \times (\frac{1}{m} \times \left(1 - e^{-\left(\frac{18}{51.673}\right)^{11.787}}\right) \times 0.500 + \frac{1}{m} \times 0.062 \times 0.500) = 3.1\frac{1}{m}$$

$\frac{1}{m}$ is to be eliminated and the overall health of the two HV Wood Poles are 23.75 and 3.1 respectively.

5.6 Comparison of Overall Asset Health Results

This section shows the comparison of overall asset health results obtained with no MCDA applied to condition and with improved-AHP and SW applied to condition

This thesis considers 3544 HV Wood Poles with corresponding age and defect profiles derived from routine inspections, which have had their health scored on a range between 0-100 and then assigned into HI 1-5 classifications, where ‘1’ indicates good health and ‘5’ suggests immediate replacement required. The results are listed below.

5.6.1 Wood Pole HI Classifications (Age 0.5, Condition 0.5)

Table 45 is a summary of the number of poles allocated in each HI classification without the application of MCDA, with the application of improved-AHP and SW respectively. The first column represents the HI classifications, the second column indicates the score scales of the corresponding HI classification, defined by expert judgments. For example, poles with score between 0-15 belong to HI 1 and 15-30 belong to HI2, etc. The study found that poles tending to transfer from a higher HI classification to a lower one. Figure 48 shows a more detailed age distribution of each HI classification without the application of MCDA to condition, i.e., the result is purely age-based. Therefore, as expected, as HI classifications are allocated with the increasing age, only poles with age around 60 and above are required to be replaced. A different case is illustrated in Figure 49 (results from improved-AHP) and Figure 50 (results from SW) in which age and condition are equally important according to the experts’ judgments in Section 4.3.1.

Table 45: Wood Pole HI Classifications without and with improved-AHP or SW derived defect/condition-based health assessment (where both Age and Condition weighted equally)

HI Classifications				
Classifications	Score	Without Consideration of Condition (Age 1.0, Condition 0)	With improved-AHP for defect/condition-based (Age 0.5, Condition 0.5)	With SW for defect/condition-based (Age 0.5, Condition 0.5)
1	0-15	2914	2901	2886
2	15-30	34	349	356
3	30-45	260	184	190
4	45-80	275	52	54
5	80-100	61	58	58
Sum (number of poles)		3544	3544	3544

Figure 48 - Figure 50 show the HI classifications of wood poles across a population of age ranging from 1 to 65 years. In Figure 48, the HI classifications are based on using the improved-AHP derived failure distribution for age-based HI classifications (described previously in Section 2.5), but with no consideration given to any defects affecting pole condition (i.e. Age is weighted as 1, as the only contributor to overall health assessment, and Condition is weighted as 0, with no contribution).

From Figure 49 and Figure 50 can be seen that the HI classifications are based on using the improved-AHP derived failure distribution for age-based HI classifications (as before), but now with consideration given to the defects affecting pole condition (i.e. Age is weighted as 0.5, and Condition is also weighted as 0.5, as equal contributors to overall health assessment). The main difference between Figure 49 and Figure 50 is in the application of improved-AHP or SW for defect/condition-based HI classifications, i.e. shown in Figure 49 and Figure 50 respectively.

Comparing the distributions shown in Figure 48 and Figure 49 shows how after the application of any MCDA techniques (i.e. improved-AHP and SW), and with equal influence of age and condition on health assessment, most of the oldest population (between age 55 to age 65) of poles classified as HI 5 (ready for replacement) in Figure 48 are re-classified as HI 4.

There are also more than 50 younger poles (in age range up to 53 years) which are classified as HI 5 in Figure 49 and Figure 50. There are 58 poles in total are classified in HI 5 among the whole population and these account for poles that have been judged to be

‘*Seriously Damaged*’ by experts (i.e., this is their recorded defect classifications), and so are immediately classified as HI 5 – in need of immediate replacement, irrespective of any further condition assessment using any MCDA techniques. These poles are effectively filtered out and immediately classified as being in need of replacement, before any further health assessment across the population is conducted. Generally, it can be seen that the age range of poles in each health index classification has increased after the application of MCDA specifically for condition assessment. This, in conjunction with the 58 poles considered seriously damaged, indicates that older poles can generally be considered in better health that was initially the case when their health assessment was based exclusively on age, with no consideration of condition and no use of MCDA.

When comparing Figure 49 and Figure 50 and the application of improved-AHP compared to SW, the general observation to be made here is that the classifications are largely the same here, with only a slight difference to be seen in how the poles are classified across the health indices where only slightly more younger poles are classified as HI 2 by the SW method.

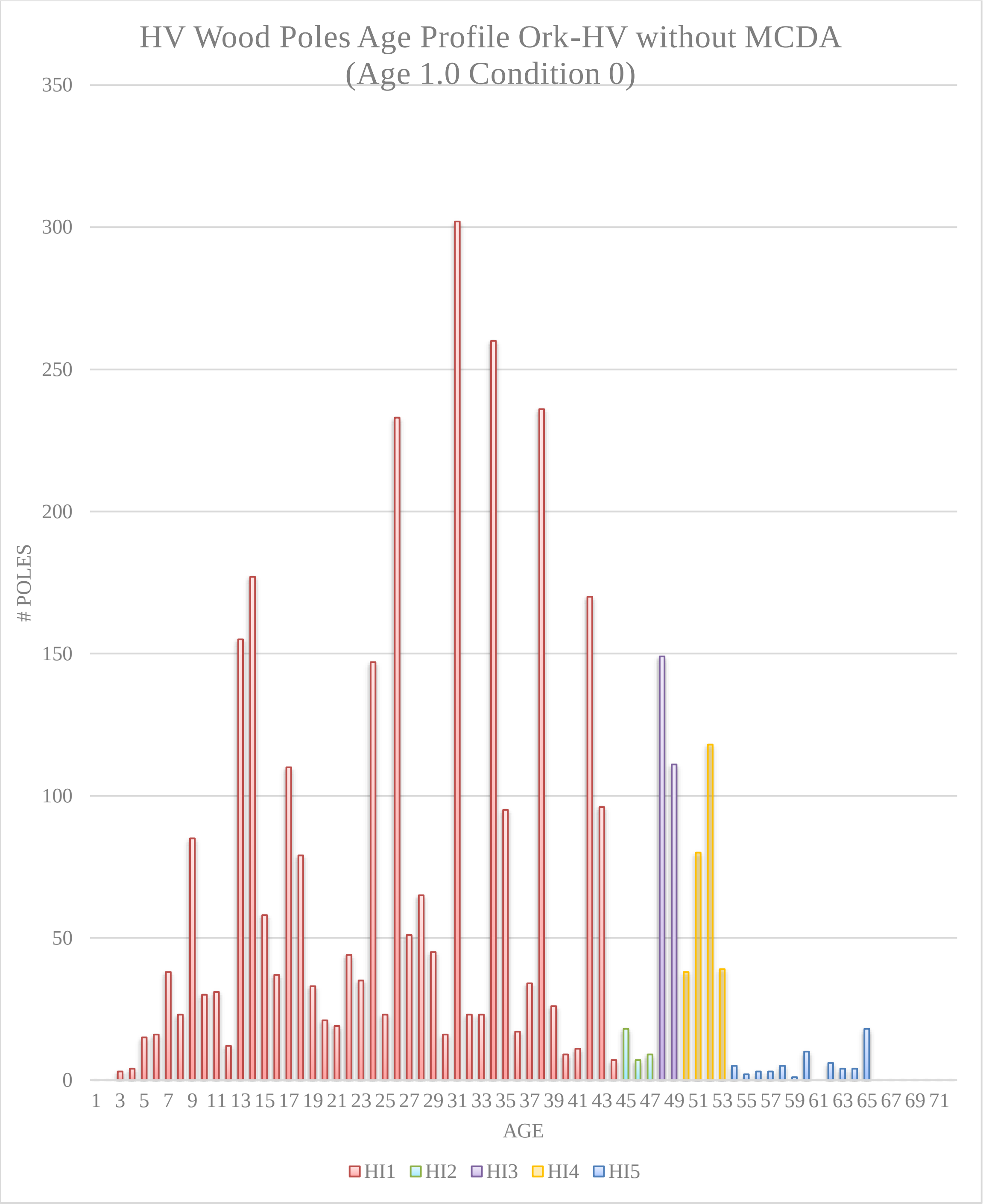


Figure 48: Wood Pole HI Classifications using improved-AHP derived failure distribution for age-based HI classifications, but no consideration of defects affecting pole condition (Age: Condition weighting = 1: 0)

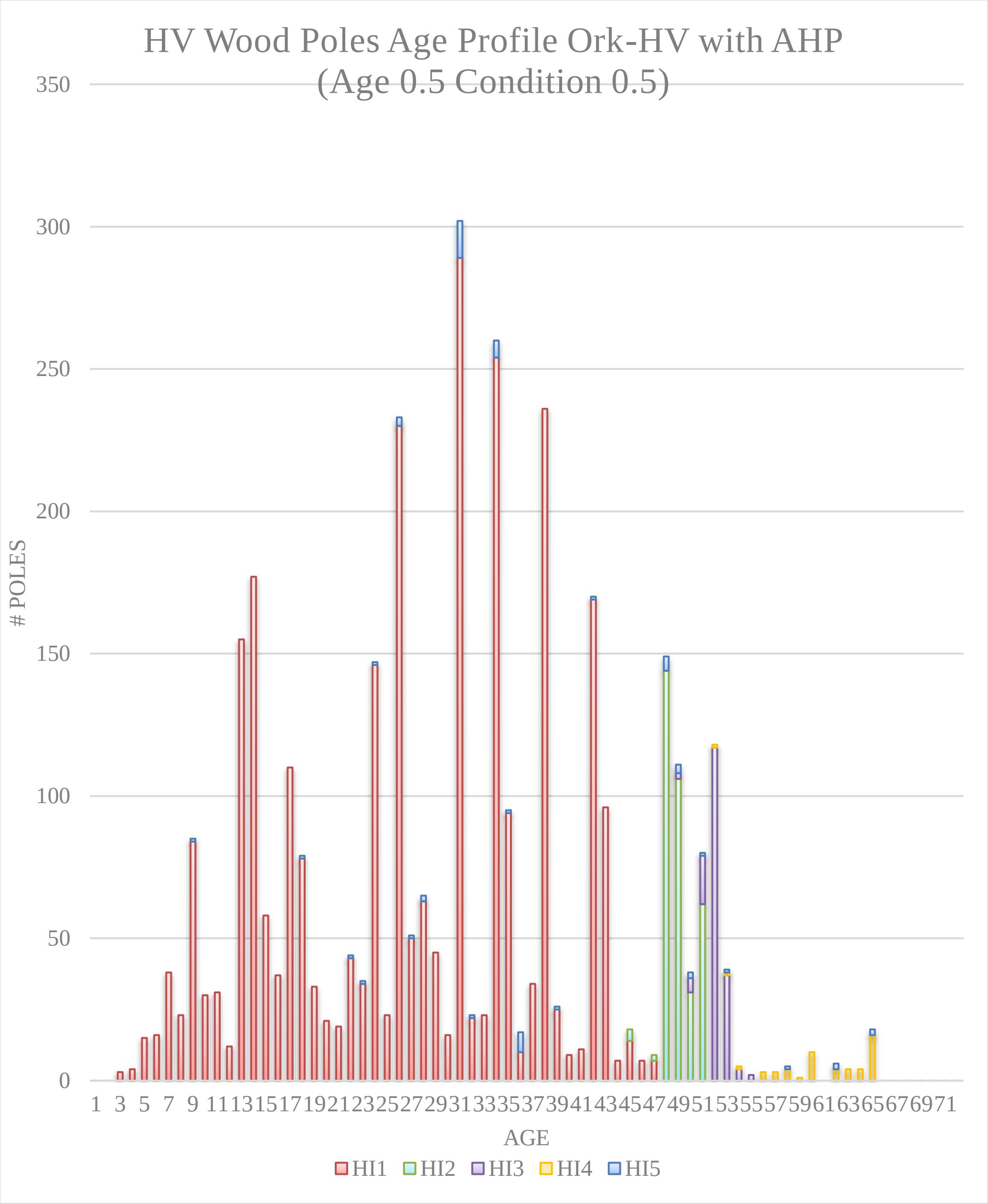


Figure 49: Wood Pole HI Classifications using improved-AHP derived failure distribution for age-based HI classifications, and improved-AHP for defect/condition-based HI classifications (where both Age and Condition weighted equally – same contribution to overall health assessment; Age: Condition weighting = 0.5:0.5)

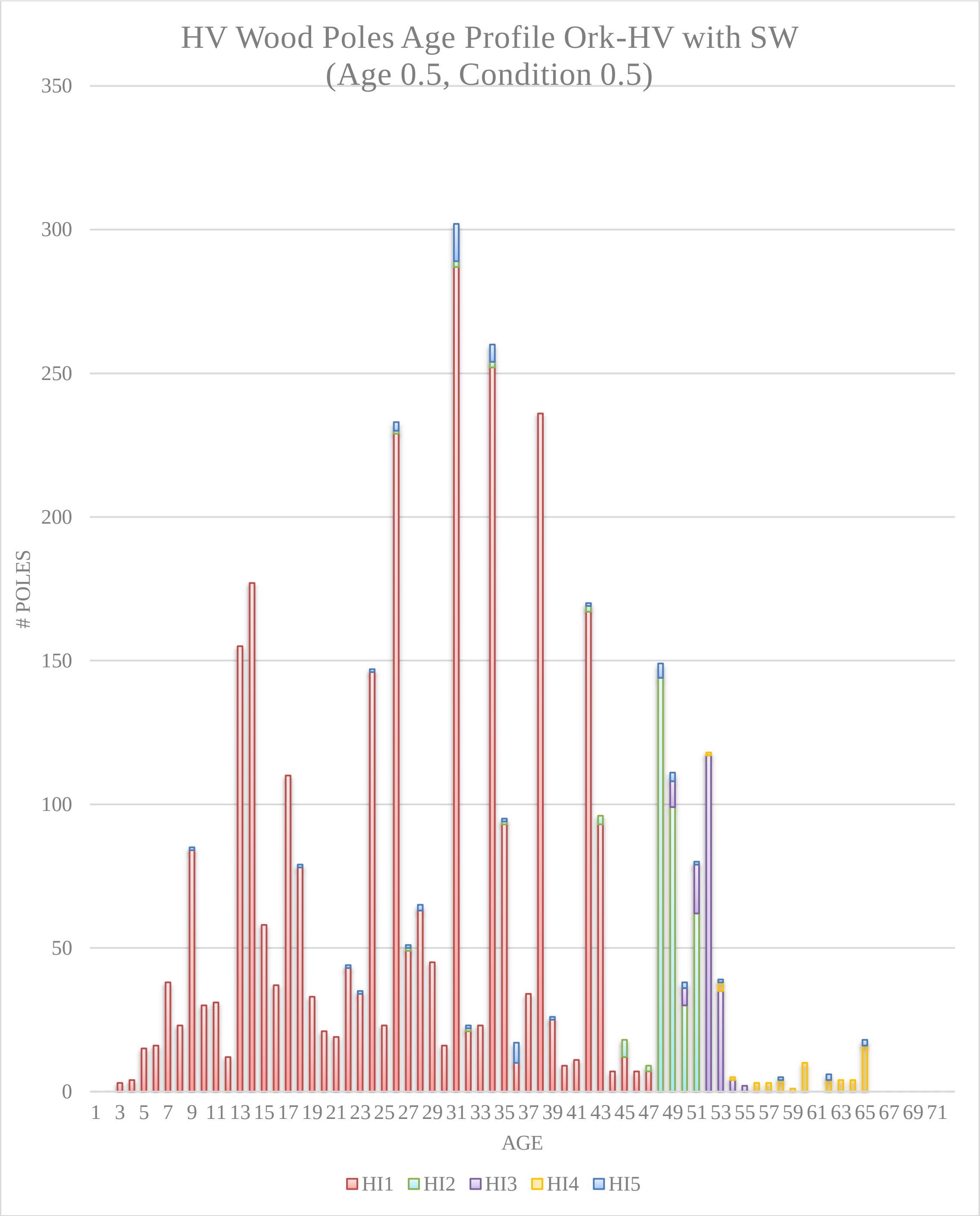


Figure 50: Wood Pole HI Classifications using improved-AHP derived failure distribution for age-based HI classifications, and SW for defect/condition-based HI classifications (where both Age and Condition weighted equally – same contribution to overall health assessment; Age: Condition weighting = 0.5:0.5)

From Table 45 it can be seen that 61 poles (out of a total number of 3544 poles) are classified as HI 5 when condition has a weighting of zero (and so only considering age), while 58 poles classified as HI 5 when there is an equal weighting between age and condition (i.e., 0.5 and 0.5). The figures seem almost the same, however, there are some notable differences here.

Five poles are aged and have the most serious defect '*Seriously Damaged'*, therefore, in either of the age-based health assessment or combined age and condition-based assessment cases, these 5 poles remain classified as HI 5 as one would expect, and so require emergency replacement in both cases.

The remaining 56 poles where no consideration is given to condition (health assessment is age-based only), are 're-classified' from HI 5 to HI 3 (6) and HI 4 (50); effectively after the introduction of MCDA weighting of condition. This indicates that most of the oldest poles are not actually in such poor health as to require immediate replacement. And so, if an age-based approach were adopted this would result in the replacement of 56 poles significantly in advance of their end of life. Conversely, other poles are re-classified from the 'better' health index classifications of HI 1 (41 in no.), HI 3 (8), and HI 4 (4) to the 'poorest' health index classification of HI 5 after the inclusion (weighting) of condition. It should be noted that these re-classified poles had the defect *'Seriously Damaged'* and so there is the possibility that they may be replaced between routine replacements; but as part of a wider asset replacement strategy, based on consideration of age only, these relatively 'new' but *'Seriously Damaged'* poles would not generally be earmarked for replacement as their HI classification would range from 1-4.

Therefore, it can be seen that only when considering age and condition and using MCDA to apply weightings and scores to the health assessment of assets on this basis, are those assets most reliably in need of replacement identified as such, i.e., ensuring the replacement of relatively 'new' or 'young' poles in relatively 'poor' condition, and avoiding the replacement of relatively 'old' poles in relatively 'good' condition. The re-classification of poles' HI after the introduction of 'condition' (in addition to age) as a health criterion can be seen in Table 46 and Table 47.

The transitions among HI classification are similar in the case where improved-AHP derived age and condition-based health assessment is applied (Table 46), and similarly for improved-AHP derived age and SW derived condition-based health assessment (Table 47). Therefore, the introduction of MCDA derived condition-based health assessment has the effect of effectively moving poles from a higher HI classification from which they were placed in using the age-based only approach. However, a transfer from lower-level HI to a higher-level HI is expected and acceptable where poles may have one or more than one defect that combine to provide a weighted health score that is larger than the age-based health assessment score. In Table 47, representing the number of poles transferred between HI classifications using improved-AHP derived failure distribution for age-based HI classifications, and SW for defect/condition-based HI classifications (Age: Condition weighting = 0.5:0.5), it is noticeable that a small number of poles transferred from HI 1 to HI 2 in SW. For the same case, further investigation shows that the 13 poles transferred from HI 1 to HI 2 in SW are around 40 years old, which can be seen to have a low probability of failure from the improved-AHP derived failure distribution Figure 29 in Section 4.3.2. However, the 13 poles all have two different defects which increase the score when using SW. This is also true where improved-AHP is applied to condition. The reason why there is a greater HI transfer (or number of poles reclassified) from HI1 to HI2 using SW compared with those transferred from HI1 to HI2 when using improved-AHP to score condition, is that the SW method resulted in a higher weighting of defects *'A - Brkn/rusty rod', 'A - Brkn/rusty wire'* and *'A - Foundation Eroded'* for the 13 poles with these defects. This ultimately led to a higher score for condition using the SW method, indicating a greater contribution of the condition to the overall pole health assessment, than that derived using AHP.

Table 46: # of Poles Transferred between HI classifications using improved-AHP derived failure distribution for age-based HI classifications, and improved-AHP for defect/condition-based HI classifications (where both Age and Condition weighted equally – same contribution to overall health assessment; Age: Condition weighting = 0.5:0.5)

	HI Classifications				
	From HI1	From HI2	From HI3	From HI4	From HI5
to HI1	0	28	0	0	0
to HI2	0	0	250	93	0
to HI3	0	0	0	176	6
to HI4	0	0	0	0	50
to HI5	41	0	8	4	0

Table 47: # of Poles Transferred between HI classifications using improved-AHP derived failure distribution for age-based HI classifications, and SW for defect/condition-based HI classifications (where both Age and Condition weighted equally – same contribution to overall health assessment; Age: Condition weighting = 0.5:0.5)

	HI Classifications				
	From HI1	From HI2	From HI3	From HI4	From HI5
to HI1	0	26	0	0	0
to HI2	13	0	243	92	0
to HI3	0	0	0	175	6
to HI4	0	0	0	0	50
to HI5	41	0	8	4	0

In order to study the sensitivity of the overall health assessment classification of the pole population to adjustments in the relative weighting of age and condition, a similar study was conducted; this time with age weighted 0.1 and condition weighted 0.9 is described in the next section.

5.6.2 Wood Pole HI Classifications (Age 0.1, Condition 0.9)

This section now considers the effect of altering the weighting of the condition from 0.5 to 0.9 (and so consequently, the weighting of age changes to 1-0.9=0.1).

Table 48 shows the HI classifications in different scenarios, i.e., age- based only using the improved-AHP derived failure distribution (i.e., Age 1.0, Condition 0), using the improved-AHP derived failure distribution with **improved-AHP derived condition** (as dominant contributing health criterion) (Age 0.1, Condition 0.9), and using the improved-AHP derived failure distribution with **SW derived condition condition** (as dominant contributing health criterion) (Age 0.1, Condition 0.9). It can be seen from Figure 51 and Figure 52, that as before, the 58 poles with defect *'Seriously Damaged'* remained in HI 5, and most of the poles are re-classified from HI 1 to HI 2, but in this instance only a couple of poles are re-classified as HI 3 and no poles as HI 4. This suggests that while condition is the dominant criterion in the overall health assessment (weighted at 0.9 here), most of the poles tends to be re-classified into 'better' HIs than that when an age-based only approach is applied. For the oldest poles with age of 65, 14 out of 18 poles are in HI

1. 2 out of 18 poles are in HI 2, with only 2 out of 18 poles are in HI 5 because of defect *'Seriously Damaged'*.

When comparing Figure 51 and Figure 52 and the application of the improved-AHP derived condition-based health assessment, compared with the SW derived condition-based approach, the general observation to be made here is that the HI classifications are largely the same, with only a small difference to be seen in how the poles are distributed across are across the health indices; where there is a few more poles classified as HI 2 by the SW method than the improved-AHP method, i.e. less poles are classified as HI 1 by the SW method than improved-AHP method.

From the observation, it suggests that using MCDA derived condition-based health assessment provides a more representative appraisal of the overall asset health across the pole population. Comparison of the number of poles transferred between HIs when using the improved-AHP derived failure distribution only, to that using improved-AHP derived condition-based or with SW derived condition-based can be found in Table 48.

Table 48: Wood Pole HI Classifications without and with improved-AHP or SW derived defect/condition-based health assessment (where Age: Condition weighting = 0.1:0.9)

HI Classifications				
Classifications	Score	Without Consideration of Condition (Age 1.0, Condition 0)	With improved-AHP for defect/condition-based (Age 0.1, Condition 0.9)	With SW for defect/condition-based (Age 0.1, Condition 0.9)
1	0-15	2914	3402	3309
2	15-30	34	82	173
3	30-45	260	2	4
4	45-80	275	0	0
5	80-100	61	58	58
Sum (number of poles)		3544	3544	3544

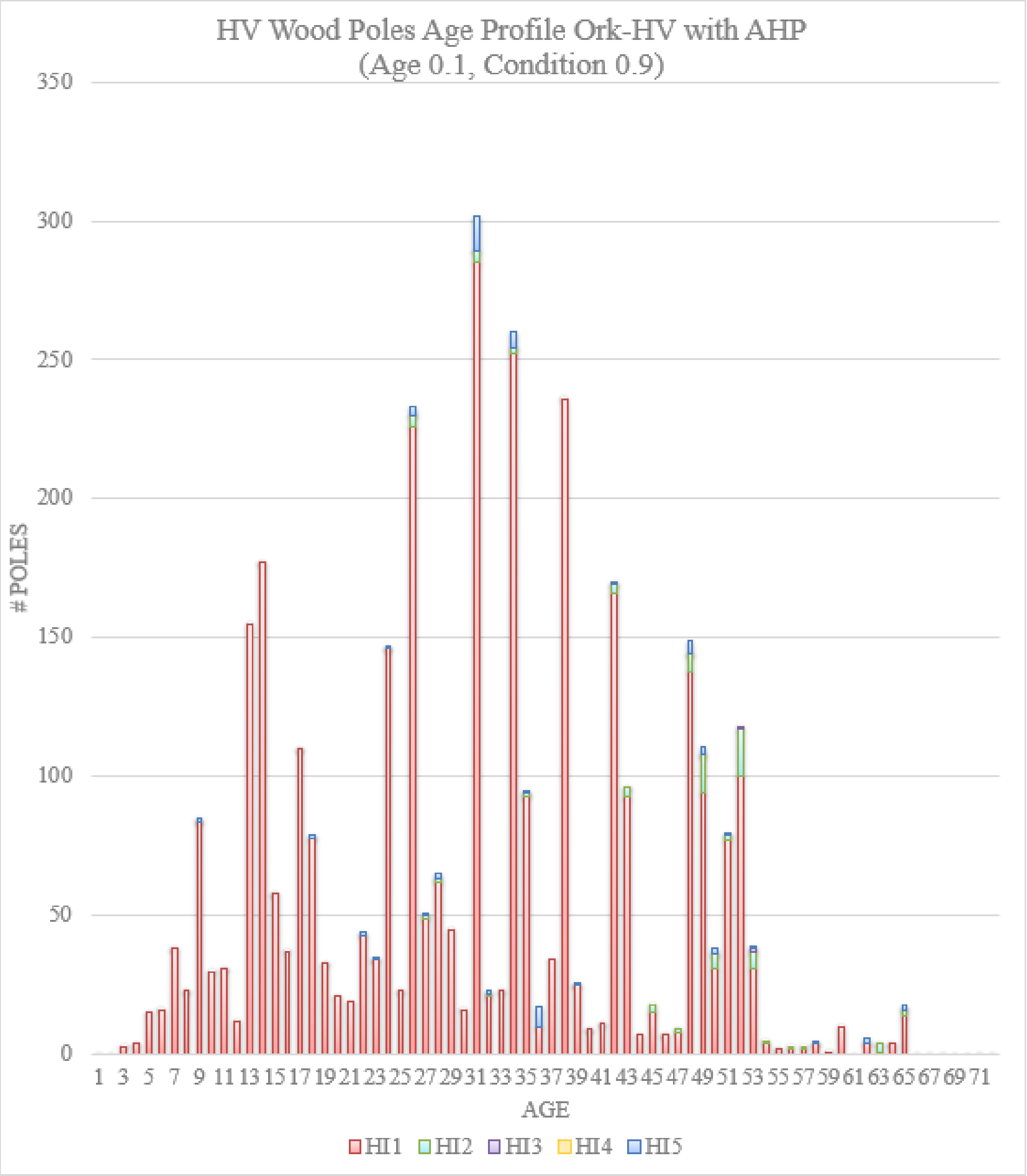


Figure 51: Wood Pole HI Classifications using improved-AHP derived failure distribution for age-based HI classifications, and improved-AHP for defect/condition-based HI classifications (where Age: Condition weighting = 0.1:0.9)

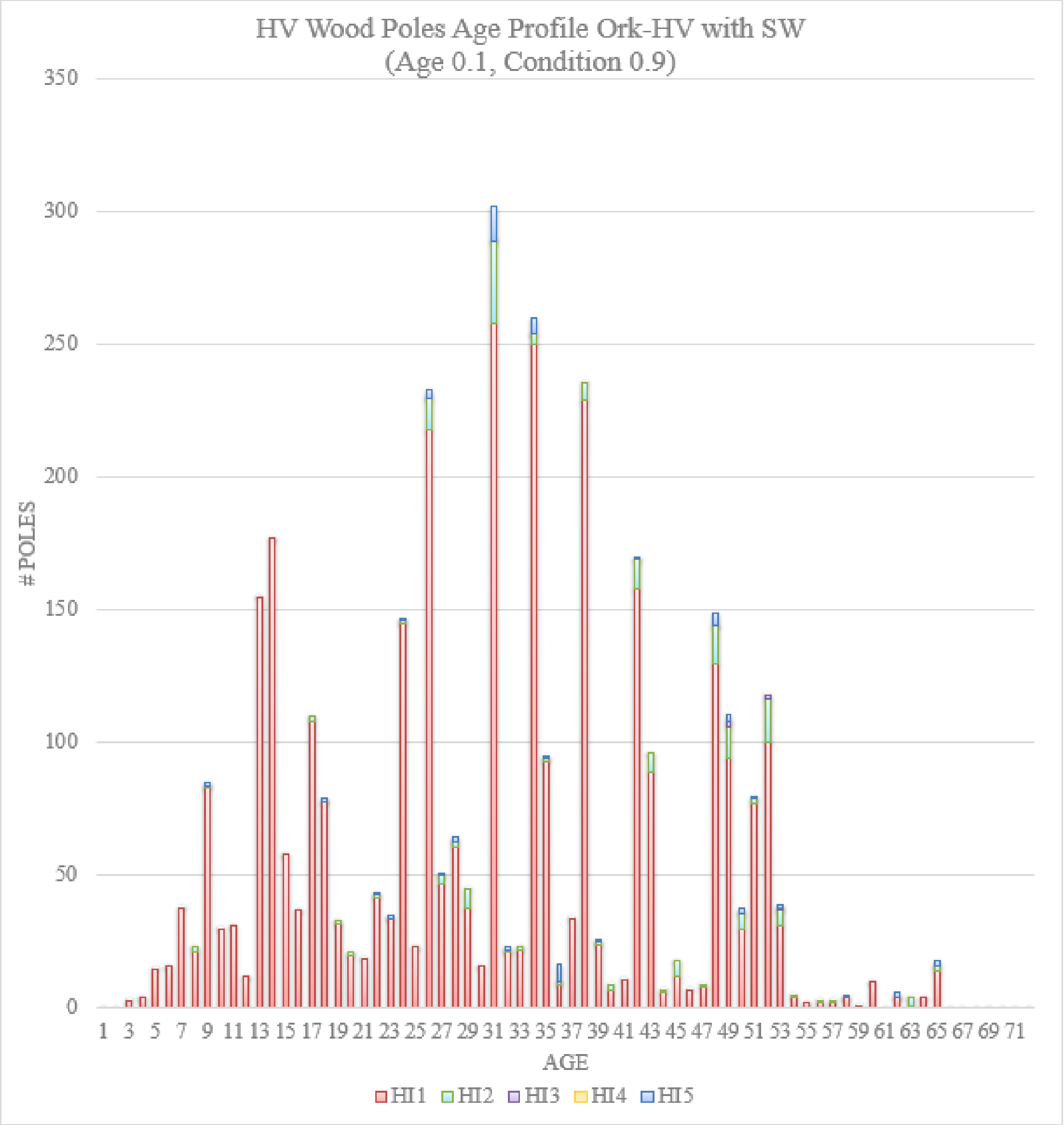


Figure 52: Wood Pole HI Classifications using improved-AHP derived failure distribution for age-based HI classifications, and SW for defect/condition-based HI classifications (where Age: Condition weighting = 0.1:0.9)

Table 49 and Table 50 shows the number of poles transferred between HI classifications using improved-AHP derived failure distribution for age-based HI classifications, and improved-AHP (Table 49) / SW (Table 50) for defect/condition-based HI classifications. Comparing the application of improved-AHP compared to SW, a general observation is that apart from poles transferred from HI 1 to HI 2, the results is mostly the same here. From SW method, a much larger number of poles transferred from HI 1 to HI 2 than improved-AHP method. This is because some of the defects associated with these poles are again weighted higher by SW method than improved-AHP method, therefore and the overall scores of the health assessment of those wood poles breach the threshold between HI 1 and HI 2, i.e., 15, and are classified as HI 2 instead HI 1 as shown.

Table 49: # of Poles Transferred between HI classifications using improved-AHP derived failure distribution for age-based HI classifications, and improved-AHP for defect/condition-based HI classifications (where Age: Condition weighting = 0.1:0.9)

	HI Classifications				
	From HI1	From HI2	From HI3	From HI4	From HI5
to HI1	0	30	232	239	48
to HI2	20	0	20	30	8
to HI3	0	0	0	2	0
to HI4	0	0	0	0	0
to HI5	41	0	8	4	0

Table 50: # of Poles Transferred between HI classifications using improved-AHP derived failure distribution for age-based HI classifications, and SW for defect/condition-based HI classifications (where Age: Condition weighting = 0.1:0.9)

	HI Classifications				
	From HI1	From HI2	From HI3	From HI4	From HI5
to HI1	0	27	224	238	48
to HI2	101	0	26	31	8
to HI3	0	0	0	2	0
to HI4	0	0	0	0	0
to HI5	41	0	8	4	0

5.7 Conclusion

This chapter shows a framework to quantify and assess the health of power system HV Wood Poles using the SW method and an improved-AHP method using the DM involving multiple experts. The asset data used includes the inspection records of each pole containing information such as age and related visually observable defects.

The application of MCDA requires adequate preparation before involving experts. In general, AHP (even with improved-AHP) requires more time and effort than SW because the pairwise comparison process involves a large number of comparisons which could be prone to inconsistency or duplicated comparisons if the metrics, language and terms used to formulate these comparisons is irrelevant or ambiguous. The process is also generally repeated until the degree of consistency is acceptable, as discussed previously Section 3.1.3. In addition, for quantitative, numeric criteria (e.g., distance, age, or time) with clear references, both methods are suitable. For comparison of more qualitative criteria (e.g. defect type), SW is a more appropriate method and arguably a more intuitive approach than AHP because there is a quantification process involved in SW that is not involved in AHP which can transfer a qualitative criteria to a quantitative criteria as described in Section 3.1.4, where SW compares the 'swing' representing the change from the two reference points (i.e., the best-case scenario (BCS) and worst-case scenario (WCS)). Here, it was shown how the SW method requires fewer comparisons than AHP, which is clearly an advantage when a large number of criteria are involved. In addition, the setting of reference points is a process of quantification for criteria, which are not numeric measurements – or quantitative - but qualitative. It is important for experts to have an accurate and consistent understanding of BCSs and WCSs and provide a clear description of this for each criterion. Both improved-AHP and SW can co-operate with MEJA while multiple experts are involved. The results show that both approaches altered the removal and replacement of poles with an age above 45 years, especially those in HI 5 with age over 54 years. Instead, poles in HI 5 spread from as young as age 9 to as old as 65 years, because of the having defect '*Seriously Damaged*', which is dramatically different from age-based approach where all and only the old poles were classified as HI5 and therefore require immediately replacement. To meet the ISO 55000 and RIIO-ED1 requirements, it is important to avoid unnecessary removal and replacement of assets, as well as ensuring appropriate removal and replacement when legitimately required and justifiable based on age AND condition.

5.8 References

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6 CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK

6.1 Conclusion

This thesis develops a robust expert-based MCDA health assessment methodology. This methodology is designed to inform and support industry decision-makers and asset managers in the prioritisation of non-load-related, high volume, low cost (HVLC) asset replacement such as wood poles. The methodology is designed for asset health assessment where historical condition and maintenance data required for probabilistic/stochastic asset degradation modelling are not available. Different expert knowledge aggregation techniques have been applied to power system asset health assessment, along with mathematical and behavioural approaches. The utilization of MCDA and MEJA techniques allow the assessment of asset health based on multiple health criteria, and manage the subjectivity and conflict associated with individual and joint expert judgment. At the same time, a generic process and tool for the development of a scoring mechanisms for power system assets' health assessment has been developed which identifies and manages inconsistency in expert judgements using MCDA techniques. Furthermore, an improved process has been developed to reduce the repetition in the MDCA process especially for a large number of criteria, making the process shorter and more manageable without necessarily compromising accuracy.

The health of assets which are classified as HVLC assets has been assessed in this thesis, using more qualitative expert judgment where on-line condition-monitoring systems may not be cost-effective. The thesis has also applied and compared the improved AHP method and SW method along with other techniques such as the Delphi Method, LogPM, etc., and demonstrated the use of these techniques to include condition assessment based on multiple expert judgments to provide a more representative overall health assessment of the wood pole assets considered in this thesis. In the case considered, this resulted in a significant population of assets being 're- classified' as being in better overall health, and therefore further from replacement, than was initially the case when the de-facto age-based approach was considered.

6.2 Future Work

6.2.1 Apply the Approach within A Larger Size of Expert Group

In this thesis, three experts were available to participate in the MDCA process, however, future work would consider the effect of involving more experts in both the accuracy of the synthesised weightings and scores, how well the process deals with disagreement and inconsistencies and generally how easy the process is to administer with an increase in the size of expert group. In the case of more than three experts, can provide an improvement regarding to the objectivity of the overall judgment. This requires effort to make the expert understand the operation of the approach, what kind of knowledge is required and captured by the questionnaire, and how objective the expert judgments are. However, for more than 20 experts this may approach may become too intractable. Therefore, it is vital to guide the experts in a right direction in the first place in order to improve the accuracy of the result of the approach.

6.2.2 Cooke Method

Future work could also consider other techniques that may improve the accuracy of multi-expert judgment such as the Cooke Method, which is a classical and performance-based method used to aggregate expert judgements [66].

As described in Chapter 3.3, Cooke Method or Cooke’s Classical Model (CCM) is a performance-based method that depends on experts’ judgement. To apply CCM, seed variables need to be prepared and provided by the decision-maker. The seed variables are actual answers to questions/a question known or will be known by the decision-maker with some analysis but not to the experts. Based on the HV Wood Pole Project, one example of seed variables will be chosen as the answers to question ‘What is the age distribution of HV Wood Poles within a certain area? Can you specify the 5%, 50%, 95% quantiles please?’ The subjective assessments of 5%, 50%, 95% quantile reflect the experts’ belief based on their expertise. However, sometimes it is unfamiliar and difficult for experts to express their expertise in terms of quantile, an expert training is required to help experts familiar with the process and quantify their expertise in terms of quantile more accurate. At the same time, a dry run or trial exercise is recommended among another panel of experts who will do the trial exercise only. The purpose of a trial exercise is to find out: if the questions are clearly asked, if the complexity of the case adequate, and if the relevant information can be well received. The quantiles are then used to produce a calibration component and an information component based on K-L distance [68-71]. It will be helpful to examine how much experts agree with each other through a range graph as shown in Figure 53.

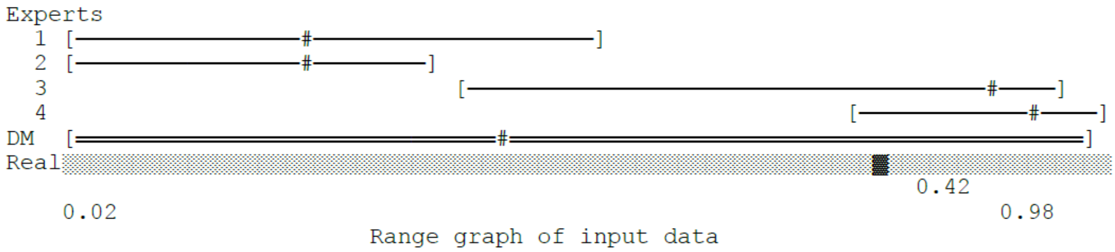

Figure 53: Range graph of input data [67]

The range graph shows the judgments from 4 experts and the synthesised equal weighted result (DM), where ‘[’ denotes the 5% quantiles, ‘]’ denotes the 95% quantiles, and ‘#’ denotes the medians, along with the real data shown with a black rectangle ▓. A general observation shows that the degree of agreement among experts is poor in this situation, Expert 1 and Expert 2 provides a similar judgment like a group as Expert 3 and Expert 4 does, with little overlap between the two groups. Comparing with the real data, Expert 3 and Expert 4 provides a better estimation as the judgments cover the real data within their range and the medians are closer that than Expert 1 and Expert 2. This is then used to derive the performance-based weightings, where if expert who provided a poorly calibrated estimation or too wide that gives little information, then the judgment of that expert will be weighted less i.e., a lower performance-based weighting. The performance-based weighting is then combined with expert’s individual judgments to derive the decision-maker’s assessment of that variable. A guide for the implementation of CCM to synthesise experts’ judgments can be found in [67].

Currently, because of the unavailability of experts, CCM has not been applied in this thesis. It is recommended to investigate the classical model with experts for readily available.

6.3 Application of Methodology to Other HVLC Assets

The approach is developed to assess the health of power system HVLC assets, where the capture and storage of quantitative on-line condition monitoring data for this purpose is not available and generally considered not cost-effective, to form an adequate remove/replace plans based on age and condition derived from a group of experts. Therefore, apart from HV Wood Poles, the approach can also apply on other HVLC distribution assets like distribution switches, underground cables etc. To apply the approach, on switches for example, one need the historical inspection data and a group of experts who maintain the asset with a good knowledge. Apply improved AHP or SW to derive expert judgement individually then combine multiple experts' judgment by using MEJA along with equal weighting as applied in the thesis or performance-based weighting from CCM. Here, it would be interesting to see how performance-based weighting affect the final health assessment of the asset.

6.4 References

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7 APPENDIX

7.1 Experts Judgments of AHP

7.1.1 PC-Matrix of Three Experts of Asset Health

Table 51: PC-Matrix for Age and Condition

Pairwise Comparison Matrix			
	Age	Condition	Priorities
Age	1	1	0.5000
Condition	1	1	0.5000

7.1.2 PC-Matrix of Three Experts of Asset Age

Table 52: Expert Judgments on Age Points A, B, C, D and E

Point	Age
A	30
B	37.5
C	45
D	52.5
E	60

Table 53: PC-Matrix of Age from Expert 1 with Calculated Priorities

Expert 1									
	30	37.5	45	52.5	60	AM	EM	GM	LS
30	1	1/2	1/4	1/9	1/9	0.035	0.034	0.034	0.043
37.5	2	1	1/3	1/8	1/8	0.052	0.050	0.050	0.050
45	4	3	1	1/5	1/5	0.111	0.109	0.108	0.086
52.5	9	8	5	1	1	0.401	0.403	0.404	0.411
60	9	8	5	1	1	0.401	0.403	0.404	0.411
Sum						1.000	1.000	1.000	1.000
λ_{max}						5.119	5.117	5.117	5.228
C.R.						0.027	0.026	0.026	0.051

Table 54: PC-Matrix of Age from Expert 2 with Calculated Priorities

Expert 2									
	30	37.5	45	52.5	60	AM	EM	GM	LS
30	1	1/2	1/4	1/9	1/9	0.036	0.035	0.035	0.043
37.5	2	1	1/3	1/8	1/8	0.052	0.051	0.051	0.050
45	4	3	1	1/4	1/5	0.117	0.115	0.114	0.093
52.5	9	8	4	1	1	0.388	0.388	0.392	0.400
60	9	8	5	1	1	0.407	0.411	0.409	0.414
Sum						1.000	1.000	1.000	1.000
λ_{max}						5.099	5.096	5.097	5.186
C.R.						0.022	0.022	0.022	0.042

Table 55: PC-Matrix of Age from Expert 3 with Calculated Priorities

Expert 3									
	30	37.5	45	52.5	60	AM	EM	GM	LS
30	1	1/2	1/4	1/9	1/9	0.036	0.035	0.035	0.042
37.5	2	1	1/3	1/8	1/8	0.053	0.052	0.051	0.050
45	4	3	1	1/4	1/4	0.122	0.121	0.121	0.104
52.5	9	8	4	1	1	0.394	0.396	0.397	0.402
60	9	8	4	1	1	0.394	0.396	0.397	0.402
Sum						1.000	1.000	1.000	1.000
λ_{max}						5.074	5.073	5.073	5.135
C.R.						0.017	0.016	0.016	0.030

7.1.3 PC-Matrix of Three Experts of Asset Condition

Table 56: PC-Matrix of Expert 1

	R - Pole Top Rot	R - Bkn porc'ln stay ins	A - Brkn/rusty rod	A - Brkn/rusty wire	B - Dmgd permali insul	A - Foundation Eroded	B - Slack Stay	B - Animals Rubbing	R - Pole Off Plumb
R - Pole Top Rot	1	2	3	3	5	6	7	8	9
R - Bkn porc'ln stay ins	1/2	1	3	3	4	5	6	7	8
A - Brkn/rusty rod	1/3	1/3	1	1	3	4	5	6	7
A - Brkn/rusty wire	1/3	1/3	1	1	3	4	5	6	7
B - Dmgd permali insul	1/5	1/4	1/3	1/3	1	2	3	4	5
A - Foundation Eroded	1/6	1/5	1/4	1/4	1/2	1	2	3	4
B - Slack Stay	1/7	1/6	1/5	1/5	1/3	1/2	1	3	4
B - Animals Rubbing	1/8	1/7	1/6	1/6	1/4	1/3	1/3	1	2
R - Pole Off Plumb	1/9	1/8	1/7	1/7	1/5	1/4	1/4	1/2	1

Table 57: PC-Matrix of Expert 2

	R - Pole Top Rot	A - Brkn/rusty rod	A - Brkn/rusty wire	A - Foundation Eroded	B - Slack Stay	B - Animals Rubbing	R - Pole Off Plumb	B - Dmgd permali insul	R - Bkn porc'ln stay ins
R - Pole Top Rot	1	4	4	5	6	7	7	7	8
A - Brkn/rusty rod	1/4	1	1	2	4	4	6	6	6
A - Brkn/rusty wire	1/4	1	1	3	3	4	5	6	6
A - Foundation Eroded	1/5	1/2	1/3	1	1	3	4	5	6
B - Slack Stay	1/6	1/4	1/3	1	1	2	2	2	3
B - Animals Rubbing	1/7	1/4	1/4	1/3	1/2	1	2	2	3
R - Pole Off Plumb	1/7	1/6	1/5	1/4	1/2	1/2	1	2	3
B - Dmgd permali insul	1/7	1/6	1/6	1/5	1/2	1/2	1/2	1	1
R - Bkn porc'ln stay ins	1/8	1/6	1/6	1/6	1/3	1/3	1/3	1	1

Table 58: PC-Matrix of Expert 3

	A - Foundation Eroded	R - Pole Top Rot	A - Brkn/rusty rod	A - Brkn/rusty wire	R - Bkn porc'ln stay ins	B - Dmgd permali insul	R - Pole Off Plumb	B - Animals Rubbing	B - Slack Stay
A - Foundation Eroded	1	1	4	4	5	5	6	7	9
R - Pole Top Rot	1	1	3	3	5	5	6	7	9
A - Brkn/rusty rod	1/4	1/3	1	1	3	3	5	6	7
A - Brkn/rusty wire	1/4	1/3	1	1	3	4	5	6	7
R - Bkn porc'ln stay ins	1/5	1/5	1/3	1/3	1	2	3	5	5
B - Dmgd permali insul	1/5	1/5	1/3	1/4	1/2	1	3	3	4
R - Pole Off Plumb	1/6	1/6	1/5	1/5	1/3	1/3	1	1	2
B - Animals Rubbing	1/7	1/7	1/6	1/6	1/5	1/3	1	1	2
B - Slack Stay	1/9	1/9	1/7	1/7	1/5	1/4	1/2	1/2	1

Table 59: Priorities and Parameters of Four Scaling Methods of Expert 1

		AM	EM	GM	LS
Priorities	Broken/rusty rod	0.136	0.136	0.138	0.118
	Broken/rusty wire	0.136	0.136	0.138	0.118
	Foundation Eroded	0.051	0.048	0.049	0.046
	Animals Rubbing	0.024	0.023	0.023	0.029
	Damaged permali insulator	0.073	0.070	0.070	0.062
	Slack Stay	0.041	0.038	0.037	0.037
	Bkn porcelain stay insulator	0.228	0.235	0.232	0.234
	Pole Off Plumb	0.018	0.017	0.017	0.024
	Pole Top Rot	0.292	0.296	0.296	0.332
λ_{max}		9.561	9.548	9.547	9.982
C.R.		0.048	0.047	0.047	0.071
E.I.		84.451	109.659	117.033	52.237

Table 60: Priorities and Parameters of Four Scaling Methods of Expert 2

		AM	EM	GM	LS
Priorities	Broken/rusty rod	0.167	0.167	0.172	0.142
	Broken/rusty wire	0.165	0.166	0.170	0.142
	Foundation Eroded	0.103	0.098	0.099	0.086
	Animals Rubbing	0.049	0.047	0.048	0.050
	Damaged permali insulator	0.027	0.026	0.027	0.035
	Slack Stay	0.065	0.064	0.066	0.063
	Bkn porcelain stay insulator	0.024	0.023	0.023	0.031
	Pole Off Plumb	0.040	0.037	0.037	0.040
	Pole Top Rot	0.358	0.372	0.359	0.413
λ_{max}		9.510	9.505	9.501	9.788
C.R.		0.044	0.044	0.043	0.068
E.I.		102.974	139.492	120.967	72.938

Table 61: Priorities and Parameters of Four Scaling Methods of Expert 3

		AM	EM	GM	LS
Priorities	Broken/rusty rod	0.129	0.127	0.130	0.103
	Broken/rusty wire	0.134	0.133	0.134	0.104
	Foundation Eroded	0.275	0.285	0.278	0.306
	Animals Rubbing	0.027	0.026	0.026	0.029
	Damaged permali insulator	0.058	0.053	0.054	0.051
	Slack Stay	0.019	0.018	0.018	0.024
	Bkn porcelain stay insulator	0.075	0.071	0.071	0.058
	Pole Off Plumb	0.031	0.029	0.029	0.036
	Pole Top Rot	0.253	0.258	0.261	0.287
λ_{max}		9.533	9.523	9.522	9.859
C.R.		0.046	0.045	0.045	0.074
E.I.		50.937	66.327	66.460	40.867

7.1.4 MATLAB Code

```
# Code for AM
[M,N]=size(A);
B=zeros(M,N);
w=ones(M,1);
Aw=ones(M,1);

for i=1:N
  B(:,i)=A(:,i)./(sum(A(:,i)));
end

for j=1:M
   w(j,1)=sum(B(j,:))/M;
end
EW=w*M;

for i=1:M
   for j=1:N
      A(i,j)=A(i,j)*w(j,1);
   end
   Aw(i,1)=sum(A(i,:));
end
Aw=Aw./w;

lambda=sum(Aw)/M;

ci=(lambda-M)/(M-1);
RI=[0 0 0.58 0.90 1.12 1.24 1.32 1.41 1.45];
ri=RI(M);
cr=ci/ri;


# Code for EM

N=size(A);
n=N(1);
[x,y]=eig(A);
eigenvalue=diag(y);
lambda=eigenvalue(1);
EW=x(:,1);
b=x(:,1)/sum(x(:,1));
ci=(lambda-n)/(n-1);
RI=[0 0 0.58 0.90 1.12 1.24 1.32 1.41 1.45];
ri=RI(n);
cr=ci/ri;
```

```
# Code for GM
[M,N]=size(A);
B=ones(M,1);
w=ones(M,1);
Aw=ones(M,1);

for i=1:M
   for j=1:N
      B(i,1)=B(i,1)*A(i,j);
   end
   EW(i,1)=B(i,1)^(1/M);
end

for j=1:M
   w(j,1)=EW(j,:)/sum(EW);
end

for i=1:M
   for j=1:N
      A(i,j)=A(i,j)*w(j,1);
   end
   Aw(i,1)=sum(A(i,:));
end
Aw=Aw./w;

lambda=sum(Aw)/M;

ci=(lambda-M)/(M-1);
RI=[0 0 0.58 0.90 1.12 1.24 1.32 1.41 1.45];
ri=RI(M);
cr=ci/ri;
```

```
# Code for LS
N=size(A);
n=N(1);

tempMatrix = -(A + A.');

aMatrix = [tempMatrix,-ones(size(tempMatrix,1),1)];

bMatrix = [aMatrix; ones(1, size(tempMatrix, 1)+1)];

cVector = sum(A .* A, 1) + size(tempMatrix, 1) -2;
for i = 1 : size(tempMatrix, 1)
   bMatrix(i , i) = cVector(i);
end
```

```
bMatrix(end,end) = 0;
c=[zeros(1, size(A ,1)),1];
Results = bMatrix\c.';
weightsResults = Results(1:end-1);
EW=weightsResults;

Aw = zeros(size(weightsResults));
for i=1:size(A,1)
   for j=1:size(A,2)
      A(i,j)=A(i,j)*weightsResults(j,1);
   end
   Aw(i,1)=sum(A(i,:));
end
Aw=Aw./weightsResults;

lambda = sum(Aw)/size(A,1);
ci=(lambda-n)/(n-1);
RI=[0 0 0.58 0.90 1.12 1.24 1.32 1.41 1.45];
ri=RI(n);
cr=ci/ri;
```

7.1.5 AHP Results

Table 62: Wood Pole HI Classifications with AHP applied to condition

HI Classifications			
Classifications	Score	#-Before	#-After
1	0-15	2914	2901
2	15-30	34	349
3	30-45	260	184
4	45-80	275	52
5	80-100	61	58
Sum (number of poles)		3544	3544

Table 63: HI Classifications Transition without and with AHP applied to condition

HI Classifications Transition without and with AHP applied to condition		
From	to HI1	HI1 to
HI2	28	0
HI3	0	0
HI4	0	0
HI5	0	-41
From	to HI2	HI2 to
HI1	0	-28
HI3	250	0
HI4	93	0
HI5	0	0
From	to HI3	HI3 to

HI1	0	0
HI2	0	-250
HI4	176	0
HI5	6	-8
From	to HI4	HI4 to
HI1	0	0
HI2	0	-93
HI3	0	-176
HI5	50	-4
From	to HI5	HI5 to
HI1	41	0
HI2	0	0
HI3	8	-6
HI4	4	-50

Table 64: HV Wood Poles Age Profile with AHP

Age	# of poles in HI1	Age	# of poles in HI2	Age	# of poles in HI3	Age	# of poles in HI4	Age	# of poles in HI5
3	3	45	4	49	2	52	1	9	1
4	4	47	2	50	5	53	1	18	1
5	15	48	144	51	17	54	1	22	1
6	16	49	106	52	117	56	3	23	1
7	38	50	31	53	37	57	3	24	1
8	23	51	62	54	4	58	4	26	3
9	84			55	2	59	1	27	1
10	30					60	10	28	2
11	31					62	4	31	13
12	12					63	4	32	1
13	155					64	4	34	6
14	177					65	16	35	1
15	58							36	7
16	37							39	1
17	110							42	1
18	78							48	5
19	33							49	3
20	21							50	2
21	19							51	1
22	43							53	1
23	34							58	1
24	146							62	2
25	23							65	2
26	230								
27	50								
28	63								
29	45								

30	16								
31	289								
32	22								
33	23								
34	254								
35	94								
36	10								
37	34								
38	236								
39	25								
40	9								
41	11								
42	169								
43	96								
44	7								
45	14								
46	7								
47	7								

7.2 Experts Judgments of SW

7.2.1 SW Questionnaire Table

Table 65: Ranking and Scores of Defects for SW of Expert 1

Ranking of ‘swing’	Defects	Original Scores	Modified Scores	Priorities
1st	R - Pole Top Rot	100	100.000	0.190
2nd	R - Bkn porc'ln stay ins	95	95.000	0.180
3rd	A - Brkn/rusty rod	90	85.500	0.162
4th	A - Brkn/rusty wire	100	85.500	0.162
5th	B - Dmgd permali insul	70	59.850	0.114
6th	A - Foundation Eroded	90	53.865	0.102
7th	B - Slack Stay	50	26.933	0.051
8th	B - Animals Rubbing	50	13.466	0.026
9th	R - Pole Off Plumb	50	6.733	0.013

Table 66: Ranking and Scores of Defects for SW of Expert 2

Ranking of ‘swing’	Defects	Original Scores	Modified Scores	Priorities
1st	R - Pole Top Rot	100	100.000	0.230
2nd	A - Brkn/rusty rod	75	75.000	0.173
3rd	A - Brkn/rusty wire	100	75.000	0.173
4th	A - Foundation Eroded	85	63.750	0.147
5th	B - Slack Stay	70	44.625	0.103
6th	B - Animals Rubbing	70	31.238	0.072
7th	R - Pole Off Plumb	60	18.743	0.043
8th	B - Dmgd permali insul	75	14.057	0.032
9th	R - Bkn porc'ln stay ins	85	11.948	0.028

Table 67: Ranking and Scores of Defects for SW of Expert 3

Ranking of ‘swing’	Defects	Original Scores	Modified Scores	Priorities
1st	A - Foundation Eroded	100	100.000	0.216
2nd	R - Bkn porc'ln stay ins	70	70.000	0.151
3rd	A - Brkn/rusty rod	85	59.500	0.129
4th	A - Brkn/rusty wire	100	59.500	0.129
5th	B - Animals Rubbing	85	50.575	0.109
6th	B - Dmgd permali insul	90	45.518	0.098
7th	R - Pole Top Rot	75	34.138	0.074
8th	R - Pole Off Plumb	70	23.897	0.052
9th	B - Slack Stay	80	19.117	0.041

7.2.2 SW Results

Table 68: Wood Pole HI Classifications with SW applied to condition

HI Classifications			
Classifications	Score	#-Before	#-After
1	0-15	2914	2886
2	15-30	34	356
3	30-45	260	190
4	45-80	275	54
5	80-100	61	58
Sum (number of poles)		3544	3544

Table 69: HI Classifications Transition without and with SW applied to condition

HI Classifications Transition without and with SW applied to condition		
From	to HI1	HI1 to
HI2	26	-13
HI3	0	0
HI4	0	0
HI5	0	-41
From	to HI2	HI2 to
HI1	13	-26
HI3	243	0
HI4	92	0
HI5	0	0
From	to HI3	HI3 to
HI1	0	0
HI2	0	-243
HI4	175	0
HI5	6	-8
From	to HI4	HI4 to
HI1	0	0
HI2	0	-92
HI3	0	-175
HI5	50	-4
From	to HI5	HI5 to
HI1	41	0
HI2	0	0
HI3	8	-6
HI4	4	-50

Table 70: HV Wood Poles Age Profile with SW

Age	# of poles in HI1	Age	# of poles in HI2	Age	# of poles in HI3	Age	# of poles in HI4	Age	# of poles in HI5
3	3	26	1	49	9	52	1	9	1
4	4	27	1	50	6	53	3	18	1
5	15	31	2	51	17	54	1	22	1
6	16	32	1	52	117	56	3	23	1
7	38	34	2	53	35	57	3	24	1
8	23	35	1	54	4	58	4	26	3
9	84	42	2	55	2	59	1	27	1
10	30	43	3			60	10	28	2
11	31	45	6			62	4	31	13
12	12	47	2			63	4	32	1
13	155	48	144			64	4	34	6
14	177	49	99			65	16	35	1
15	58	50	30					36	7
16	37	51	62					39	1

17	110							42	1
18	78							48	5
19	33							49	3
20	21							50	2
21	19							51	1
22	43							53	1
23	34							58	1
24	146							62	2
25	23							65	2
26	229								
27	49								
28	63								
29	45								
30	16								
31	287								
32	21								
33	23								
34	252								
35	93								
36	10								
37	34								
38	236								
39	25								
40	9								
41	11								
42	167								
43	93								
44	7								
45	12								
46	7								
47	7								

7.3 Without MCDA Applied to Condition

Table 71: HV Wood Poles Age Profile without MCDA Applied to Condition

Age	# of poles in HI1	Age	# of poles in HI2	Age	# of poles in HI3	Age	# of poles in HI4	Age	# of poles in HI5
3	3	45	18	48	149	50	38	54	5

4	4	46	7	49	111	51	80	55	2
5	15	47	9			52	118	56	3
6	16					53	39	57	3
7	38							58	5
8	23							59	1
9	85							60	10
10	30							62	6
11	31							63	4
12	12							64	4
13	155							65	18
14	177								
15	58								
16	37								
17	110								
18	79								
19	33								
20	21								
21	19								
22	44								
23	35								
24	147								
25	23								
26	233								
27	51								
28	65								
29	45								
30	16								
31	302								
32	23								
33	23								
34	260								
35	95								
36	17								
37	34								
38	236								
39	26								
40	9								
41	11								
42	170								
43	96								
44	7								

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