TOWARDS THE DEVELOPMENT OF TRANSITION PROBABILITY MATRICES IN THE MARKOVIAN MODEL FOR THE PREDICTED SERVICE LIFE OF BUILDINGS

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THESIS SUMMARY

TOWARDS THE DEVELOPMENT OF TRANSITION PROBABILITY MATRICES IN THE MARKOVIAN MODEL FOR THE PREDICTED SERVICE LIFE OF BUILDINGS

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Supervisor: Professor Doctor E Horak
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The global importance of and need for sustainable development demand an informed decision-making process from the built environment to ensure optimum service life, which depends on the ability to quantify changes in condition of building materials over time. The objective of this thesis is to develop a model, which translates expert knowledge and reasoning into probability values through the application of Fuzzy Logic Artificial Intelligence to supplement limited historical performance data on degradation of building materials for the development of Markov Chain transitional probability matrices to predict service life, condition changes over time, and consequences of maintenance levels on service life of buildings. The Markov Chain methodology, a stochastic approach used for simulating the transition from one condition to another over time, has been identified as the preferred method for service life prediction by a number of studies. Limited availability of historic performance data on degradation and durability of building materials, required to populate the Markovian transition probability matrices, however restricts the application of the Markov Chain methodology.

The durability and degradation factors, defined as design and maintenance levels, material and workmanship quality, external and internal climate, and operational environment, similar to the factors identified in the state-of-the–art ‘Factor Method’ for service life prediction, and current condition are rated on a uniform colour-coded five-point rating system and used to develop "IF-THEN" rules based on expert knowledge and reasoning. Fuzzy logic artificial intelligence is then used to translate these rules into crisp probability values to populate the Markovian transitional probability matrices.

Historic performance data from previous condition assessments of six academic hospitals are used to calibrate and test the model. There is good correlation between the transitional probability matrices developed for the proposed model and other Markov applications in concrete bridge deck deterioration and roof maintenance models, based on historic performance data collected over extended periods, which makes the correlation more significant.

Proof is presented that the Markov Chain can be used to calculate the estimated service life of a building or component, quantify changes in condition over time and determine the effect of maintenance levels on service life. It is also illustrated that the limited availability of historic performance data on degradation of building materials can be supplemented with expert knowledge, translated into probability values through the application of Fuzzy Logic Artificial Intelligence, to develop transition probability matrices for the Markov Chain. The proposed model can also be used to determine the estimated loss of or gain in service life of a building or component for various levels of maintenance.

Key words: building maintenance, condition changes, fuzzy logic, Markov Chain, service life prediction, transitional probability matrices.

ABSTRACT

Title: Towards the Development of Transition Probability Matrices in the Markovian Model for the Predicted Service Life of Buildings

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1. INTRODUCTION

1.1. Background

Since the UN Conference on Environment and Development (UNCED) that was held in Rio de Janeiro, Brazil in 1992 and resulted in an agenda for global sustainable development, Agenda 21, *"there has been an ever-increasing focus on the needs to determine durability and service life of materials, components, installations, structures and buildings based on the following two important aspects:*

- *Environmental issues – scarcity of material and energy resources and the building and construction sector as a big consumer of these resources, and the environmental impact caused by buildings*

- *Economic issues – the total value of the built environment on a national level and the value of each specific unit (buildings, structures, roads, bridges, quays, etc.) for the owners (government, private sector or individuals). The conditions of the built environment, the annual costs of management and maintenance and the life cycle costs are of major importance be it for the economy of a country, or maintaining competitiveness within an industry or corporation."* (Hövde and Moser, 2004, p.11).

Sustainable development is defined as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland Report, 1987, cited by International Council for Research and Innovation in Building and Construction 1999, p.17). In the quest for sustainable buildings, the prediction of service life for building materials and components is dependant on the quantification of durability and degradation. This has lead to the establishment of the joint CIB W080/RILEM 175-SLM 'Service Life Methodologies' working committee on 'Prediction of service life of building materials and components' by the International Council for Research and Innovation in Building and Construction (CIB) in partnership with a Technical Committee of the International Association for Building Materials and Structures (RILEM). In March 2004, CIB W080/RILEM 175-SLM published State of the Art Reports on Methods for Service Life Prediction, CIB Report Publication 294 (Hövde and Moser, 2004), where two methods for service life prediction are proposed, the Factor Method and the Engineering Design Method. In the evaluation of the Factor Method, which is the recommended method, Hövde and Moser (2004, p.40) cites Rudbeck (1999), who made an extensive discussion of the Factor Method for service life prediction and concluded that the Markovian model would be the recommended method for service life prediction of building components if the Markov transition probability matrices can be developed and validated.

The thesis deals with the application of Artificial Intelligence (AI) to develop of transition probability matrices for the Markov Chain for service life prediction. Factors influencing degradation and durability are discussed in broad outline, followed by the application of fuzzy logic AI to develop Markov Chain transition probability matrices. The proposed methodology is tested against historical performance data from a set of academic hospitals, followed by some applications of the model.

It is based on research over a period of more than 20 years in the field of structural engineering and maintenance management. Since 1997 project work in close collaboration with the Division Building and Construction Technology of the Council for Scientific and Industrial Research (CSIR), focussed on the development of a building maintenance management system for the provincial government sector in South Africa that culminated in a software system calculating maintenance budget requirements based on condition assessments.

In general, buildings represent substantial investments and building performance over time is of utmost importance, not only to the building owner, but also to the occupants and the community at large. As Lee (1981, p.1) pointed out, *"dilapidated and unhealthy buildings in a decaying environment depress the quality of life and contribute in some measure to antisocial behaviour."*

Developing countries are in a race against time to eradicate poverty and famine, and provide shelter. If drastic steps are not taken sooner than later, existing building stocks in many countries will not be able to provide the required support for sustainable growth and development. Rehabilitation and replacement of buildings and loss of service life due to neglect are unnecessary expenditures depriving a developing economy from scarce resources for progress. Considering that buildings form such a substantial part of the wealth of countries, service life prediction is a powerful and essential management tool, which should be developed and refined to ensure extended service life and properly maintained building infrastructure.

The building owner's objective should be to optimise the return on the investment by extending the service life of the building, which is determined by a minimum performance level. Building performance can be expressed in many ways, the most common being condition.

A building is a complicated three-dimensional configuration of a diverse range of fabrics, materials or components, each with its own characteristics, which interacts differently to the environment, could be old or new, raw or processed, come in different forms, shapes, sizes and finishes, and its applications could vary considerably. Condition changes over time as the environment impacts on the building or component. Hypothetically, this change in condition of a building or component over time can be illustrated by the curve in Figure 1-1 below.

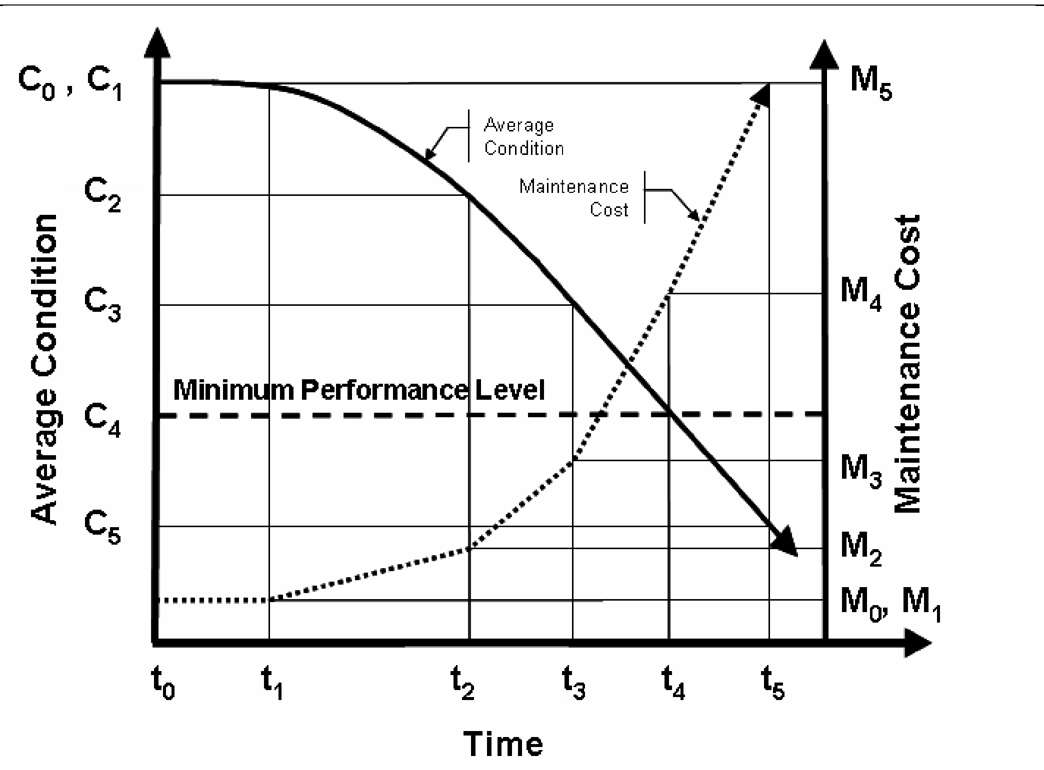

Figure 1-1: Hypothetical curve illustrating relationship between average condition and maintenance cost over time

Assuming normal degradation over time, no maintenance or rehabilitation and no premature failure, the condition profile of the component, that is the percentage of the component in various condition categories, will change or deteriorate. In other words, different portions of a component could be in different conditions at the same point in time. Likewise, the extent of required maintenance actions would range from preventative maintenance to condition-based maintenance, repairs, rehabilitation and eventually replacement, increasing in severity and cost, as illustrated in Figure 1-1 above.

If the minimum performance level for a particular building is an average condition of say C_4, the service life of the building will be t_4 - t_0. The higher the required or desired performance level, the shorter the service life and the lower the maintenance cost, and vice versa.

1.2. Problem Statement

The global importance of and need for sustainable socio-economic development demand an informed decision-making process from the built environment. Resources and non-renewable resources in particular, should be used as responsible and best possible to ensure optimum service life and life cycle costs. Optimum service life and life cycle costs depend on the ability to quantify (calculate) the changes in condition of building fabric and components over time in any given physical and operational environment.

If the change in condition over time can be defined mathematically, it will be possible to calculate the service life and remaining service life of buildings and components, and the consequences and risks of maintenance budget allocations and decisions to defer maintenance. The ability to predict changes in the condition profile of buildings or components is essential for cost-effective maintenance and rehabilitation decisions.

The prediction of the service life of a building or component requires a thorough understanding of the degradation process and the changes in condition over time. A simulation model for the degradation process should be based on actual performance data and provide for all the variables influencing the degradation process. In South Africa, reliable, continuous and consistent data on the historical performance of building materials and components are almost nonexistent. It is only since the mid 1990's that the need for condition assessments was recognised, unfortunately by far too few decision-makers, who still do not appreciate the value of regular and consistent condition assessments, while data remains scarce and inconsistent.

This scarcity of data does not mean that a model to simulate degradation cannot be developed and successfully implemented. The Factor Method (ISO 15686-1:2000), the current state of the art for building service life prediction, provides an empirical estimation of service life by applying seven factors to a reference service life. Although it is a simple technique, the valuation of these factors requires a thorough understanding of the variability and impact of individual and combined factors (e.g. 0.8 negative, 1.0 neutral and 1.2 positive). Calibration of these factor values with assessed performance over time is not clearly defined. The Factor Method calculates the estimated service life and does not provide information on the degradation process, change in condition or condition profile.

A number of studies (Coombes *et al*, 2002; Lounis *et al,* 1998a, p.1; Madanat *et al,* 1995, p.120; Morcous *et al,* 2003, p.353; Rudbeck, 1999 cited by Hövde, 2004, p.40) identified the Markov Chain, a stochastic approach used for simulating the transition from one state (condition) to another over time, as the preferred method for predicting service life and calculating changes in condition. The population of the Markov transitional probability matrix is a problem due to the lack of reliable and consistent historical performance data on the actual degradation rate of materials and components. According to Madanat *et al* (1995, p.120) *"existing approaches used to estimate these transition probabilities from inspection data are mostly ad hoc and suffer from important methodological limitations."*

The development of a reliable and consistent database through regular field assessments is however a very slow process. In general, the best available source of information on degradation is the knowledge and reasoning of experts on material degradation in the built environment. However, as Negnevisky (2002, p.15) stated, "*A major drawback is that human experts cannot always express their knowledge in terms of rules or explain the line of their reasoning. ... experts do not usually think in probability values, but in terms as often, generally, sometimes, occasionally and rarely."* On the interim, a system is needed to translate the verbally expressed knowledge and reasoning of experts into probability values, while using the assessment database as it grows to calibrate, learn and improve the system's reliability and ability to simulate the degradation process, providing for various combinations of the factors effecting degradation.

Problem Statement No. 1:

The 'state-of-the-art' Factor Method for service life prediction only calculates the estimated service life of a building or component, and cannot quantify changes in condition over time or determine the effect of maintenance level on service life.

Problem Statement No. 2:

The application of the Markov Chain to predict service life, quantify changes in condition over time and determine the effect of maintenance levels on service life, is restricted by the limited availability of historic performance data on degradation of building materials to develop transition probability matrices for the Markov Chain.

Problem Statement No. 3:

Experts do not usually think in probability values and cannot always express their knowledge or explain their reasoning in terms of rules. This expert knowledge and reasoning need to be translated into probability values to develop transitional probability matrices for the Markov Chain to predict the change in condition or performance over time and service life of a building or component.

Problem Statement No. 4:

Many buildings are under-maintained because decision-makers are ignorant of the consequences of reduced service life due to inappropriate maintenance levels, deferred maintenance and maintenance budgets cuts.

1.3. Hypotheses

Hypothesis No. 1:

The Markov Chain can be used to calculate the estimated service life of a building or component, quantify changes in condition over time and determine the effect of maintenance levels on service life.

Hypothesis No. 2:

The limited availability of historic performance data on degradation of building materials can be supplemented with expert knowledge and reasoning, to develop transition probability matrices for the Markov Chain.

Hypothesis No. 3:

Expert knowledge and reasoning can be expressed in terms of 'IF-THEN' rules, and translated into probability values for the transitional probability matrices of the Markov Chain through the application of Fuzzy Logic Artificial Intelligence.

Hypothesis No. 4:

The reduction in service life due to inappropriate maintenance levels, deferred maintenance and maintenance budgets cuts can be quantified through the application of the proposed Markov Chain model.

1.4. Objective of the Thesis

The objective of this thesis is to develop a model, which translates expert knowledge and reasoning into probability values through the application of Fuzzy Logic Artificial Intelligence to supplement limited historical performance data on degradation of building materials for the development of Markov Chain transitional probability matrices to predict service life, condition changes over time, and consequences of maintenance levels on service life of buildings.

1.5. Scope of the Thesis

This thesis covers the following areas:

- Identification of durability factors and degradation agents influencing the degradation process.
- The use of fuzzy logic AI applications to translate expert knowledge and reasoning into probability values to populate the transition probability matrix of the Markov Chain.
- The application of the Markov Chain to predict the change in condition of a building or component.
- The application of the Markov Chain to predict the service life of a building or component.
- The application of the Markov Chain to predict the effect of maintenance levels on the service life of a building or component.

The following issues are not covered in this thesis:

- Although degradation agents and factors are identified, these agents are not discussed in detail.
- The philosophy and appropriateness of the Factor Method, which is accepted as the current international "State of the Art", or the Engineering Method for service life prediction.
- The theory of the Markov Chain and other statistical methodologies.
- Although a neuro-fuzzy system was used for the development of the Markov Chain transitional probability matrix values, the learning ability of the system's neural network component has not been activated for the purpose of this thesis, because available historical performance data required for learning purposes is still too limited and inconsistent.
- The theory of neural networks and other artificial intelligence applications.

1.6. Methodology

During the development of a method to calculate a condition-based maintenance budget for buildings and quantify the consequences of deferred maintenance, the need to quantify the change in condition over time was identified.. The search for potential solutions involved literature surveys (both internet and libraries), attendance of international conferences and interfacing with domain experts, which made the exploration of the existing knowledge base possible to gain a better understanding of the problem and identify potential solutions such as the Markov Chain and Factor Method.

Although the 'state of the art' Factor Method, which calculates an empirical estimated service life, does not provide information on the change in condition over time, it provided a better understanding of the degradation and durability factors that influence changes in condition.

Available South African historic performance data on degradation and durability of building components, required to populate the Markovian transition probability matrices, was however too limited and inconsistent to develop a reliable model. The only alternative potential source of transitional probabilities was expert knowledge and reasoning, but needed to be translated into probability values, which led to the exploration of Artificial Intelligence applications and identification of the Neuro-Fuzzy application. Other AI applications, such as expert systems, fuzzy logic systems, artificial neural networks and genetic algorithms were also explored and dismissed. The Neuro-Fuzzy application was selected as the most appropriate system because it can deal with linguistic variables and fuzzy IF-THEN rules of the expert thought process (fuzzy logic) and is capable of learning (artificial neural networks) at the same time.

The fuzzy logic AI application however comprises of a large number of rules and requires the use of a software system. Demo versions of a number of software systems, available as free downloads on the internet, were identified and tested. The FuzzyTECH 5.55c professional edition system, developed by Inform GmbH of Germany was selected as the most suitable of the systems tested and a licence was obtained for the use of the software.

The various degradation and durability factors, similar to the Factor Method, were identified and defined in linguistic terms based on a five point rating system similar to a system used for condition assessments. This was followed by the development of a structure for the fuzzy logic system and IF-THEN rules and degrees of support based on the expert thought process and knowledge providing for all possible combinations and levels of the degradation and durability factors and the current condition, allowing the user to simulate any possible scenario. A three-dimensional plot of condition, maintenance level and degradation rate is produced and expert knowledge is used to adjust the degrees of support of the IF-THEN rules in the Neuro-Fuzzy model to provide realistic degradation rates. The Neuro-Fuzzy model's revised output, expressed as degradation rate, is fed into the Markovian transitional probability matrix to simulate the change in condition over time.

The output of the Markovian model provides the percentages of the building or component in each condition category, at any point in time, also referred to as condition profile. From this condition profile, the average condition of the building or component is calculated and plot against time to provide typical curves for different maintenance levels. By selecting an appropriate performance level expressed as minimum desirable condition the predicted service life of the building or component for different maintenance levels can be obtained.

The model was tested and calibrated on a set of six South African academic hospitals. The selection of these six hospitals was based on the following criteria:

- The proposed model should be able to deal with any building, and the first criterion was to find a building representative of the population of buildings.
- The next criterion was to find a representative sample of buildings that had to be similar in construction (structure, materials and finishes), type (hospital), usage (academic), utilisation, management regime, size and age to allow valid comparisons.
- The third criterion was the existence of reliable historic performance data - the condition of the buildings had to be assessed more than once using the same assessment ratings and process.

The only buildings in South Africa complying with all these criteria are the major academic hospitals, because field assessment data was available for more than one assessment, the hospitals are of similar age and construction, have similar operational environments and internal climates, no major structural changes have been undertaken since construction and an academic hospital offers a good representation of the built environment as they contain most types and usages of buildings (e.g. healthcare, accommodation, offices, teaching & lecturing, workshops, laundries, kitchens, storage, commercial, recreational facilities, M&E plant and installations, and ICT systems, etc.).

During 1995, the National Department of Health commissioned the CSIR to do a National Health Facilities Audit of all the public hospitals in South Africa, which was subsequently followed by a number of similar audits by Provincial Health Departments in collaboration with the CSIR. According to the Health Systems Trust, a South African organisation specialising in health statistics, there are currently 396 public hospitals in South Africa, which vary in construction, type, usage, utilisation, size, location (urban and rural) and age. Eleven of these hospitals are academic hospitals (where doctors are trained), two of which are brand new (no condition assessments have been done to date) while three are old hospitals with a wide range of building and construction types, sizes, and ages. The remaining six hospitals comply with the criteria and were therefore selected as representative samples of the population of buildings. These six hospitals will remain unidentified for the purpose of this thesis due to the political sensitivity around the condition of public health care facilities in South Africa.

Hospital A, a large academic hospital (240,000 m^2 and 2,000 beds) and subject of a current investigation towards redevelopment options, was selected as pilot site, while the other five hospitals were used as control sites. The average assessed conditions of Hospital A, obtained from two field assessments 20 and 30 years after construction, were plotted on the performance over time graph. Based on the current investigation, which included interviews with key role-players in the maintenance and management of the hospital, the maintenance level has been rated as low. With minor adjustments to the model, the low maintenance level curve correlated with the assessed performance of Hospital A. The assessed average conditions of the five control hospitals were then transferred to the graph as control.

There is a good correlation between the transitional probability matrices developed for the proposed model and other Markov applications in concrete bridge deck deterioration and roof maintenance models, where the transition probabilities were based on assessment data collected over extended periods, which makes the correlation more significant.

The proposed model, based on the Markov Chain approach, translates expert knowledge and reasoning into probability values through the application of Fuzzy Logic Artificial Intelligence to supplement limited historical performance data on degradation of building materials for the development of Markov Chain transitional probability matrices to predict service life, condition changes over time, and consequences of maintenance levels on service life of buildings. Degradation and durability factors similar to those identified in the state-of-the–art 'Factor Method' for service life prediction are taken into consideration.

The model also brings the current condition into the equation, which gives it an added dimension, especially when dealing with existing buildings where the remaining service life could be a crucial factor in investment decisions. The ability to predict changes in condition profiles and average condition makes scenario analysis and quantification of the consequences of maintenance levels and deferred maintenance possible leading to an informed decision-making process.

1.7. Terminology and Abbreviations

1.7.1. Terminology

"Degradation	*Reduction over time in performance of a building or a building part*
Durability	*Capability of a building or a building part to perform its required function over a specified period of time under the influence of the agents anticipated in service*
Life cycle	*Successive periods of a building component, starting with the design, the construction, the use, the maintenance, the demolition and reuse*
Maintenance	*Combination of all technical and associated administrative activities during the service period that are meant to retain an item in a state in which it can perform its required function*
Performance (in use)	*Ability of a building or a building part to fulfil its functions under the intended use conditions*
Predicted service life	*Service life predicted from recorded performance over time as obtained, for instance, in ageing tests*
Preservation	*Activities that are meant to maintain the present capacity of a building component (conservation, protection)*
Preventive maintenance	*Maintenance activities performed to avoid failure*
Reference service life	*Service life for a building or a building part for use as a basis for estimating service life*
Service life	*the period after installation during which a building or its parts meet or exceeds the performance requirements*

Service life prediction	*A generic methodology which, for a certain or any reasonable performance requirement, facilitates a prediction on the service life distribution of a building or its parts for the use in a certain or in any reasonable environment"* (Jernberg *et al*, 2004, p.6-10)

1.7.2. Abbreviations

AI	Artificial Intelligence
BELCAM	Building Envelope Life Cycle Asset Management Project (NRCC)
BS	British Standard
CIB	International Council for Research and Innovation in Building and Construction
CS	Canadian Standard
CSIR	Council for Scientific and Industrial Research (South Africa)
ESL	Estimated Service Life
ESLC	Estimated Service Life of a Component
ISO	International Organisation for Standardisation
NRCC	National Research Council Canada
RILEM	International Association for Building Materials and Structures
RSL	Reference Service Life
SLP	Service Life Prediction
TRH4	Technical Recommendations for Highways (CSIR)

1.8. Organisation of the Thesis

This thesis is organised in the following way:

In Chapter 1, the background to the research, problem statement, hypothesis, objective and scope of the thesis, and the methodology are discussed.

Chapter 2 covers the literature review, which covers sustainable development, service life and durability issues, degradation, the Factor Method, Markov Chain, and artificial intelligence applications.

Chapter 3 deals with the research methodology and covers degradation and durability factors, condition, and degradation rate, assessment requirements, the application of artificial intelligence to simulate the degradation process, and the development of the Markov Chain transitional probability matrix for service life prediction.

The results are discussed in Chapter 4, followed by conclusions and recommendations in Chapter 5.

This is followed by the references used in the preparation of the thesis and appendices.

2. LITERATURE REVIEW

2.1. Introduction

The literature review, based on material obtained from libraries, conference proceedings and internet searches, covers sustainable development in the built environment, service life and durability of building materials, degradation agents influencing degradation of building materials, the application of the Markov model to predict changes in condition and the use of artificial intelligence applications in combination with the Markov model.

2.2. Sustainable Development

Since the formulation of Agenda 21 for global sustainable development at the UN Conference on Environment and Development held in Rio de Janeiro, Brazil, in 1992, the international focus on research in the built environment has shifted to durability and sustainability issues, particularly Service Life Prediction (SLP). The Brundtland Report (1987) cited by CIB (1999, p.17) defined sustainable development as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

> *The pursuit of sustainable development throws the built environment and the construction industry into sharp relief. This sector of society is of such vital innate importance that most other industrial areas of the world society simply fade in comparison. Proper housing and the necessary infrastructure for transport, communication, water supply and sanitation, energy, commercial and industrial activities to meet the needs of the growing world population pose the major challenge. The Habitat II Agenda lays stress on the fact that the construction industry is a major contributor to socio-economic development in every country. The construction industry and the built environment must be counted as two of the key areas if we are to attain a sustainable development in our societies.* (CIB, 1999, p.17).

Haagenrud (Jernberg, Lacasse, Haagenrud, and Sjöström, 2004, p.2-1) noted that more than 50% of developed countries' real capital is represented by building stock and infrastructure. The current deteriorating state of the built environment after the *"build and let decay"* age during the past 30 years, has created *"an enormous economic, cultural and environmental problem"* resulting in the demand for reliable service life data becoming a driving force to continued research in this area.

Hövde (Hövde and Moser, 2004, p.9) points out that internationally the built environment is responsible for vast consumption of material and energy, many non-renewable, and waste to landfill deposits, and *"... even a limited reduction in the values for material and energy consumption, or waste, nonetheless represents significant values that have potential for greatly affecting the sustainability of building and construction activities."* This view is supported by Haagenrud (Jernberg *et al.*, 2004, p.2-1) who stated that the *"wasteful consumption of energy and materials linked to the degrading built environment makes this a major environmental problem in the context of sustainable development."*

According to Hövde (Hövde and Moser, 2004, p.9) the need to determine durability and service life is based on the following two aspects:

- **Environmental issues –** scarcity of material and energy resources and the building and construction sector as a big consumer of these resources, and the environmental impact caused by buildings
- **Economic issues** – the total value of the built environment on a national level and the value of each specific unit (buildings, structures, roads, bridges, quays, etc.) for the owners (government, private sector or individuals). The conditions of the built environment, the annual costs of management and maintenance and the life cycle costs are of major importance be it for the economy of a country, or maintaining competitiveness within an industry or corporation.
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He concludes that *"an ability to understand what influences durability and service life of materials, components and structures, to develop more durable materials and components and to establish reliable methods for testing of durability and for prediction of the service life"* could contribute towards addressing environmental problems in the context of sustainable development.

According to Jernberg *et al* (2004, p.3) the development of service life prediction methodologies has now reached the point where *"the possibility of standardising methodologies and incorporating predictions of the service lives of materials and components into the design process for whole buildings is being given serious attention."*

During 1982, the International Council for Research and Innovation in Building and Construction (CIB) and the International Association for Building Materials and Structures (RILEM) established a joint activity on the Prediction of Service Life of Building Materials and Components, denoted W080 and 71-PSL (Prediction of Service Life) within CIB and RILEM, respectively. Between 1982 and 1986, the focus was on describing the state of the art of the research area, and proposed a generic methodology for the prediction of service life. During the period 1987 to 1990 the work centred on developing methodologies for generating data from long-term ageing studies of materials and components in actual, 'in-use', conditions. The focus then shifted to prediction of service life of building materials and components during the third period between 1991 and 1996, followed by additional information subsequently provided in the period between 1997 and 2002. The work of the present committee will continue to refine existing prediction and service life techniques, tools and methods. *"However, the new committee will make efforts towards further development of service life prediction methods in the context of emerging information technologies (IT)."* (Jernberg *et al*, 2004, p.4)

Several initiatives and activities at both the international and national level that illustrate the importance of these issues are listed by Hövde (Hövde and Moser, 2004, p.11-13) and include the following:

- Agenda 21 for a global sustainable development initiated at the UN Conference on Environment and Development (UNCED), Rio de Janeiro, Brazil, in 1992.
- International research and development activities within CIB, in partnership with RILEM.
- RILEM's publication of a Recommendation for prediction of service life of building materials and components which was the basis for the development of standards for service life prediction within the International Organization for Standardization (ISO).
- International Standardization Organisation's (ISO) publication of ISO 6241, a standard describing the principles for preparation of performance standards in buildings and factors that must be considered, ISO 15686-1:2000, Buildings and Constructed Assets – Service Life Planning – Part 1: General Principles, and ISO 15686-2:2001, Buildings and Constructed Assets – Service Life Planning – Part 2: Service Life Prediction Procedures.
- The Construction Products Directive (CPD) (Directive 89/106/EEC adopted by the Commission of the European Union in 1988.
- Development of European Standards within the European Committee for Standardization (CEN).
- The establishment of the European Organization for Technical Approvals (EOTA) under the provisions of the EU Council Directive 89/106/EEC (Construction Products Directive) and publication of a document that describes how to assess the working life of products related to durability.
- The publication of a Guidance Paper regarding durability and the Construction Products Directive in 1999 by the EU Commission.

- Work that has been carried out for decades in Japan on how to deal with methods to predict the durability and service life of materials and buildings both in the planning and the management phase of a building.
- Results of a national study regarding needs for research and development to upgrade the civil infrastructure published in 1993 in the U.S.
- Initiatives in countries such as New Zealand (Building Code published in 1992, introducing quantitative requirements for the service life of building components), the United Kingdom (a national standard for prediction of durability and service life of buildings and building elements, products and components published in 1992), and similar standards in Canada (1995) and Norway (1994 and 1995).

The immense importance of service life prediction towards the development of a sustainable built environment is quite evident from the above-mentioned international initiatives. However, service life prediction goes far beyond a mere prediction of service life, it forms the backbone of sustainable development.

According to Kirkham *et al* (2004a) and Kirkham *et al* (2004b) the emergence of Private Finance Initiative (PFI) and Public Private Partnerships (PPP) *"procurement routes in particular have focused clients and designers to think 'whole life cycle' rather than on a short-term basis."* This paradigm shift *"has placed a heavy emphasis upon the need to manage projects effectively based upon sound risk management and quantification techniques as well as robust and articulate methods of appraising the long-term cost effectiveness of design decisions."*

> *This shift of emphasis within the UK has been lead in part by a government commitment to challenge the way organisations deliver services, and has placed on them a duty to continuously improve in order to provide the services that people require economically, efficiently and effectively. This concept of "best value" has dominated public sector capital investment policy in the UK since the 1990s. This has been the case particularly in large buildings and civil infrastructure projects such as hospitals, prisons and highways. As a result of the fundamental revisions in public procurement policy that have subsequently taken place, interest and demand for the use of Whole Life Cycle Costing (WLCC) techniques has risen to unprecedented levels.* (Kirkham *et al,* 2004a)

In the South African context the implementation of PFI's and PPP's is a slow process linked to the political processes peculiar to South Africa. There is however a move towards a performance based or outcomes based contract. Routine road maintenance has gone a long way down this route and there is a very strong social motive for human capital development and development of SMME's.

Unfortunately this process has not moved fully to outcomes based contracting or PPP's and only hybrids are in place. The biggest problem is sustainability of budgets. At local authority level problems are even bigger due to insufficient and incompetent human resources and funding, which is unique to the South African environment. In the South African context this is a study field on its own and it will be difficult to address this within the scope of this thesis.

2.3. Service Life and Durability of Building Materials and Components

Service Life is defined by ISO 15686-1:2000 as the *"period of time after installation during which a building or its parts meet or exceeds the performance requirements"* which is the *"minimum acceptable level of a critical property"* or *"inherent or acquired attribute of a building or a part of a building that has an acceptable value if its required function is to be fulfilled."* Moser (Hövde and Moser, 2004, p.60) defines service life as *"the point in time, when the foreseen function is no longer fulfilled."*

The objective of service life planning, as stated by ISO 15686-1 (2000, p.7) *"is to assure, as far as possible, that the estimated service life of the building or component will be at least as long as its design life."* Service life prediction is defined as *"A generic methodology which, for a certain or any reasonable performance requirement, facilitates a prediction on the service life distribution of a building or its parts for the use in a certain or in any reasonable environment"* (Jernberg *et al*, 2004, p.10).

According to Jernberg *et al* (2004, p.1-1) the objective of service life analysis is to establish and explain the performance-over-time functions, which *"describe how the measured values of some chosen performance characteristics are expected to vary with time. Performance characteristics are measurable, physical quantities corresponding to the critical properties identified for the component in its application. With performance-over-time functions established for the range of in-use conditions considered and agreed performance criteria, all essentials are known to make a service life prediction."*

They used Figure 2-1 below to show some hypothetical performance-over-time functions for a component in a certain service environment, which describes statistical distributions of performance characteristics. The use of a performance criterion suggests a minimum acceptable performance standard, which means that although the building or component might still be functional or operational below this value, the performance might no longer be acceptable for the intended function.

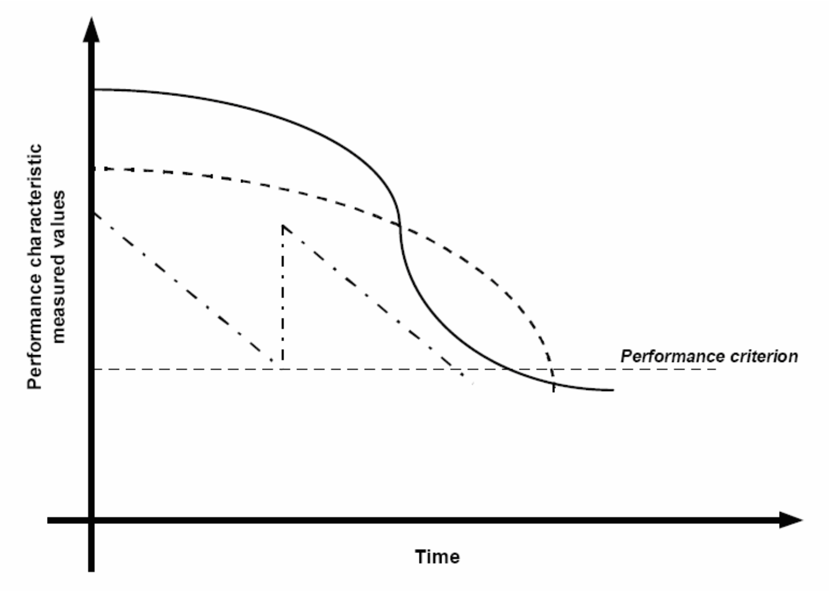


Figure 2-1: Hypothetical performance over time functions (Jernberg *et al*, 2004, p.1-1)

The design life of hospitals varies between 50 to 60 years, according to the Capital Investment Manual: Business Case Guide (1995, p.37) and the Design Brief Working Group (2002). Aikivuori (1999), cited by Moser (Hövde and Moser, 2004, p.59), claimed that the limiting factor for service life is in most cases not durability. This is especially true in the case of health care facilities, where development and innovation in modern medical and health care technology often render buildings or components obsolete before it has reached the end of its service life.

There appears to be a similarity between the approach used to determine design periods and strategies for roads and service life prediction for buildings. In Figure 2-2 below, the CSIR (1985, p.6) produced generalised performance over time curves for roads in South Africa, clearly showing the effect of maintenance and rehabilitation on the performance of the road, in this case riding quality.

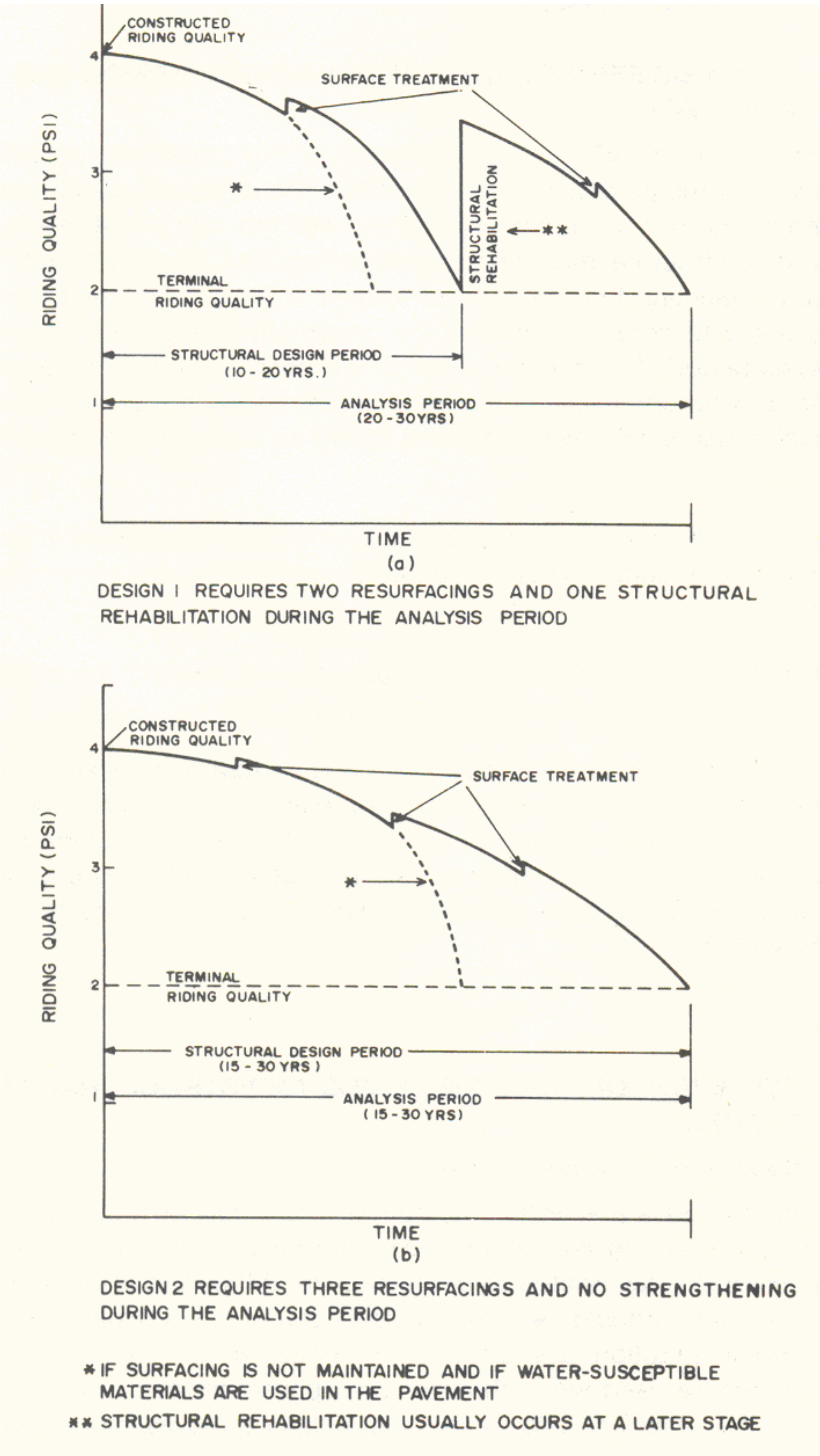


Figure 2-2: Typical performance over time curves for roads (CSIR, 1985, p.6)

The minimum performance level is defined as terminal riding quality, which corresponds to the performance criterion in Figure 2-1 above by Jernberg *et al* (2004). The riding quality unit is present serviceability index (PSI), measured on a scale from 5 to 0, with the terminal riding quality varying between 2.5 and 1.5 PSI. It is interesting to note the use of two periods: the structural design period and the analysis period. Structural design period is defined as *"the period during which it is predicted with a high degree of confidence that no structural maintenance will be required"*, while the analysis period is *"a convenient planning period during which full reconstruction of the pavement is undesirable."*

Haagenrud in Jernberg *et al* (2004, p.2-6) states that chemical or physical deterioration or corrosion in most cases cause materials degradation and loss of characteristic properties, as described by performance over time functions.

Hövde (Hövde and Moser, 2004) devotes a whole chapter to the need for service life prediction tools. Some of the specific requirements for service life prediction in Europe, New Zeeland, Canada, EU, ISO and EOTA are presented. Typical design service life categories for buildings from the Canadian, European, ISO and EOTA codes and guidelines are shown. He concludes, *"Life Cycle Assessment (LCA) can be an important tool that is typically used for establishing more sustainable construction activities and achieving sustainable buildings. (....) The introduction of LCA into the building and construction sector will therefore increase the need for service life prediction of construction products."*

Durability is defined as the *"capability of a building or its parts to perform its required function over a specified period of time under the influence of the agents anticipated"* (ISO 15686-1:2000). According to Hövde (Hövde and Moser, 2004, p.9) sustainability, service life, cost of repair and refurbishment, and environmental impact are influenced by durability.

Moser (Hövde and Moser, 2004, p.59) cites Aikivuori (1999), who pointed out *"that service life limited by durability is seldom reached, as components are refurbished earlier due to other reasons. In most cases the limiting factor for service life is not durability."*

2.4. Degradation

The Oxford Dictionary defines degradation as a term used to describe the process to *"break down or deteriorate chemically,"* and according to ISO 15686-1:2000(E) it is *"changes over time in the composition, microstructure and properties of a component or material which reduce its performance"*. According to Jernberg *et al* (2004, p.7) it is the reduction in the ability of a building or component over time to fulfil its functions under the intended use conditions.

Degradation is, according to Hövde and Moser (2004, p.62), and Mishalani and Madanat (2002, p.139), regarded as a stochastic process. Jernberg *et al* (2004, p.1-12) states that a performance-over-time function *"is a complicated, non-linear, multivariate function of time as well as of agent intensities or combinations of such agent intensities."*

2.4.1. Degradation Agents

According to Jernberg *et al* (2004, p.1-18) the origin of external degradation agents is either the atmosphere or ground, which *"mostly involves complicated chemical and/or physical processes governed by a great number of degradation agents"* while occupancy, design and installations are the main sources of internal degradation agents. It is also possible that a design consequence could result in an agent acting externally, while 'external' agents could influence internal degradation.

The nature and class of degradation agents affecting the service life of building materials and components are identified by Jernberg *et al* (2004, p.1-5) in Table 2-1 below.

Nature	Class
Mechanical agents	Gravitation, forces and imposed or restrained deformations, kinetic energy, vibrations and noises
Electromagnetic agents	Radiation, electricity, magnetism
Thermal agents	Extreme levels or fast alterations of temperature
Chemical agents	Water and solvents, oxidising and reducing agents, acids, bases, salts, chemically neutral
Biological agents	Vegetable, microbial and animal

Table 2-1: Degradation agents affecting the service life of building materials and components (Jernberg *et al,* 2004, p.1-5)

Jernberg *et al* (2004, p.1-6) also states that although limitations of the knowledge available will always exist, identification of all reasonable possible degradation mechanisms and effects by which the identified degradation agents are known or believed to induce changes in the properties and performance of the component should be identified. An important consideration highlighted by Jernberg *et al* (2004, p.1-19) is combined degradation agents and combination of degradation agents:

> *Some agents are combined by more than one co-existing factor, e.g. an imposed force such as freeze-thaw stress is due to cycling temperature and to the presence of water. At the same time, water solely is a chemical agent. Temperature itself is the thermal agent, while for many chemical reactions the temperature is decisive for the reaction rate. Other agents of the same or different nature can give rise to significant synergistic effects, e.g. sulphur dioxide together with nitric oxides, and UV radiation together with oxygen (photo oxidation).*

Chemical and physical incompatibility between dissimilar components is another important issue that should be considered. *"Incompatibility includes, for example, corrosion caused by contact between dissimilar metals or stress caused by different thermal expansion coefficients of rigidly connected dissimilar components."* (Jernberg *et al*, 2004, p.1-20)

2.4.2. Climate

According to Eurin *et al* (1985) cited by Jernberg *et al* (2004, p.1-18) *"every attempt in practice to measure and describe the degradation environment is an approximation and simplification."*

Haagenrud from the Norwegian Institute for Air Research (NILU) in Jernberg *et al* (2004, p.2-9 and 2-19 to 2-46) elaborates on the characterisation of key environmental degradation factors and discusses climatic ranges in detail. In Figure 2-3 below, he illustrates the different levels of climatic classification based on macro, meso and microclimate. *"This division means a definition of different scales describing the variations in the meteorological variables. There exist no common and exact definitions of the different scales."*

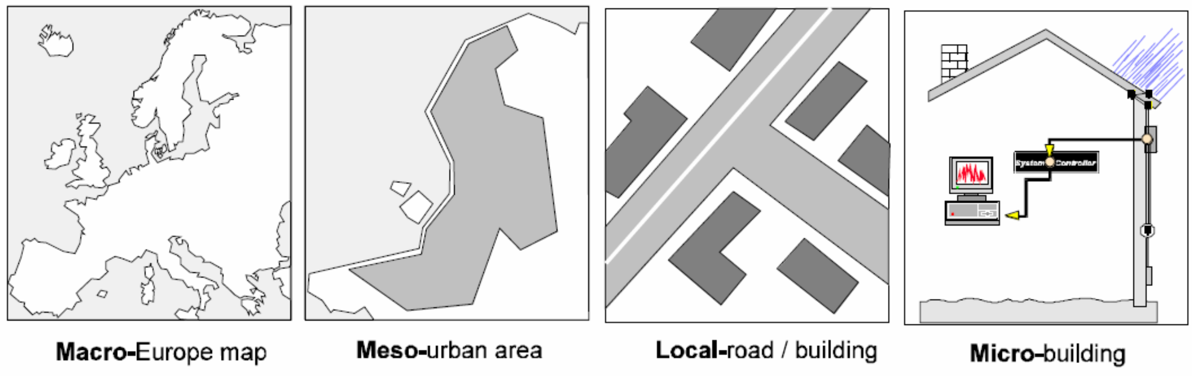


Figure 2-3: Exposure environment on different geographical scales (Source: Jernberg *et al*, 2004, p.2-9)

The macroclimate describes the gross meteorological conditions *"in terms like polar climate, subtropical climate and tropical climate. The descriptions are based on measurement of meteorological agents such as air temperature, precipitation etc."* The meso climate takes "the effects of the terrain and of the built environment" into account, while *"the climatological description is still based on the standard meteorological measurements."* The local scale describes, *"The local conditions in the building proximity, such as for example in the streets around the building."* The meteorological variables in the absolute proximity of a material surface are described by the microclimate, which *"is crucial to understanding and estimating material degradation. The most important variables describing microclimate include relative humidity, surface moisture, surface temperature, irradiation and deposition of air pollutants. ... The actual in-use condition relevant to materials degradation is the microclimate, i.e. the prevailing environmental condition in a layer adjacent to a component surface. ... As weather does not repeat itself — i.e. every year is not a standard year — one has to be cautious in drawing conclusions from one exposure period to another."* (Jernberg *et al*, 2004, p.2-9)

Haagenrud (Jernberg *et al*, 2004, p.2-8) states that the choice of degradation indicators and establishment of performance requirements are limited due to the currently available dose-response functions.

> *Another major barrier to reliable predictions of service life and/or maintenance intervals is insufficient knowledge of the relevant exposure environment. However, substantial knowledge and data exist on the environmental exposure conditions on the macro and meso level. It is a serious problem that these tend to be in a generalised form such as a contour map of average data, for example mean temperature, humidity etc., while researchers and designers need to consider the specific form, for instance time of*

wetness .... and also the local- and micro-environmental conditions of the building. A third barrier is just this adaptation of data and knowledge to the local and micro environmental conditions. The complexities of a structure can result in very different climatic and environmental conditions on a single structure and greatly affecting damage rates.

According to Durango and Madanat (2002, p.765) there exists an uncertainty in generating a set of parameters for a deterioration model, reflecting the effect of deterioration (degradation) factors, which can be attributed to:

a.) Exogenous factors: Uncertainty in predicting the environmental and level of utilisation factors produces uncertainty in the parameters of the deterioration model.
b.) Endogenous factors: Unknown variability in facility design and materials can make similar facilities respond differently to the same exogenous conditions.
c.) Statistical factors: Limited size and variability of data used to generate deterioration models are often complemented by experience (expert opinion).

On the impact of the climate on road materials in South Africa Weinert (1980, p.19) states the influence of the environment on the life and performance of a road is often greater than realized. Observed variations in the performance of weathered dolerite used in road construction in different parts of the South Africa eventually culminated into the development of Weinert's climatic N-value, which is expressed by the following formula:

$$\mathbf{N} = \frac{12E_J}{P_a}$$

where E_J is the computed evaporation from a shallow free water surface during January (warmest month), and P_a is the total annual precipitation

There was a marked difference in the performance of dolerite when used in road pavements to the east and west of an imaginary north-south line running from Port Elizabeth through Bloemfontein to Mafikeng. This line has an N-value of 5 as shown in Figure 2-4 below. To the east of this line where N < 5 the performance was unsatisfactory, while to the west where N > 5 the performance was satisfactory.

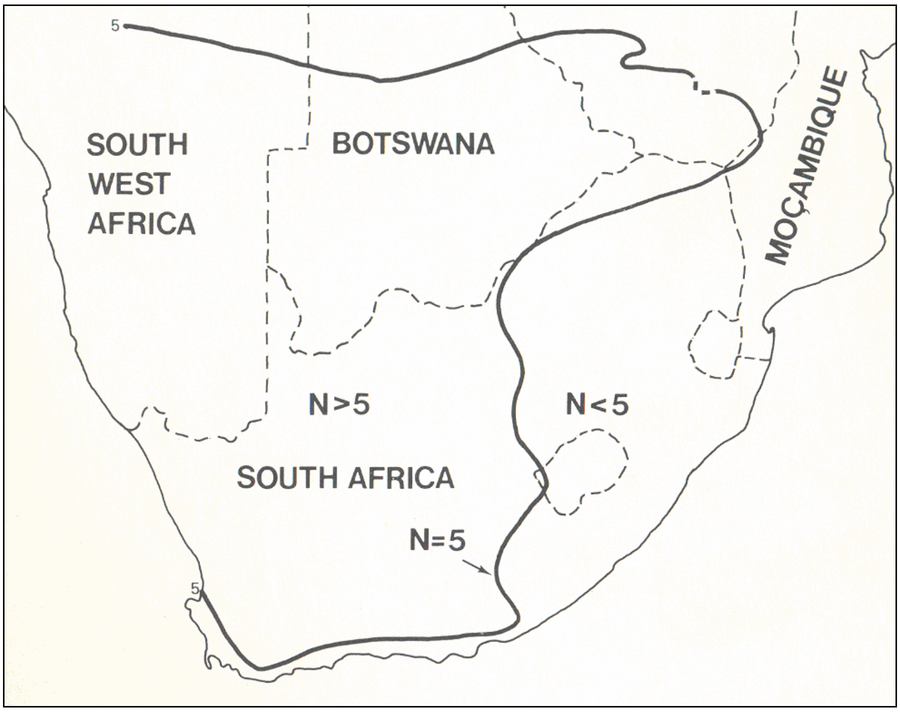


Figure 2-4: Weinert's Climatic N-values (Source: Brink, 1978, p.31)

Brink (1978, p.30) also refers to Weinert who *"has demonstrated that mechanical disintegration is the predominant mode of rock weathering in areas where his climatic N-value is greater than 5, whereas chemical decomposition predominates where the N-value is less than 5."*

On climatic regions and the design of road pavements the CSIR (1985, p.26) states that the environment under which a road functions is defined by the climatic conditions (moisture and temperature) and must be taken into account in the structural design of the pavement. The influence of the climate on the equilibrium moisture content and the weathering, durability and stability of natural road building materials is discussed. The climatic conditions should always be considered and the use of excessively water-susceptible or temperature-sensitive materials in adverse conditions should be avoided.

In Figure 2-5 below the three macroclimatic regions of Southern Africa is shown. In the western region, which has a dry climate with N > 5, mechanical degradation is dominant. The southern and central region is smaller and a transitional zone with a moderate climate, where both mechanical and chemical degradation take place. The eastern region has a wet climate with an N-value < 5, where chemical degradation is dominant. This demarcation is based on the weathering of natural road materials such as dolerite, which is a natural rock occurring throughout South Africa. Some of the materials used in the built environment are also natural materials and these three macroclimates could therefore also apply to these natural materials.

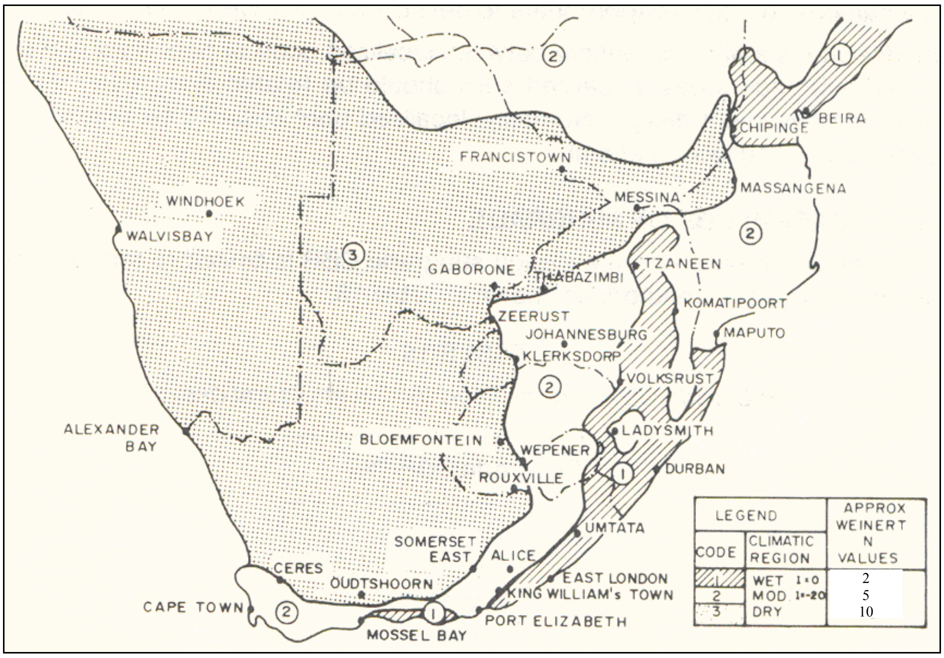


Figure 2-5: Macroclimatic Regions of Southern Africa (Source: CSIR, 1985, p.27)

The mean annual rainfall, evaporation and temperatures for South Africa are shown in Figures 2-6 to 2-8 below. It is interesting to note the correlation with the three macroclimatic zones shown in Figure 2-5 above.

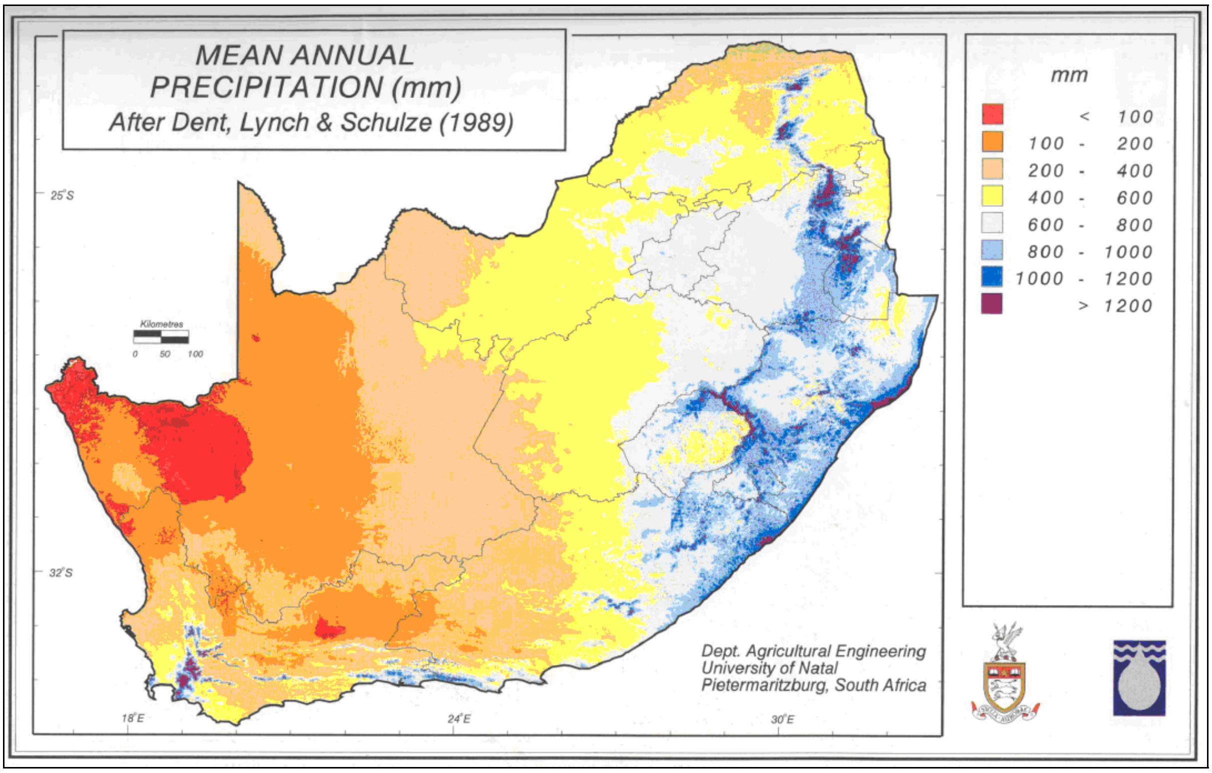


Figure 2-6: Mean Annual Precipitation for South Africa (source: University of Natal)

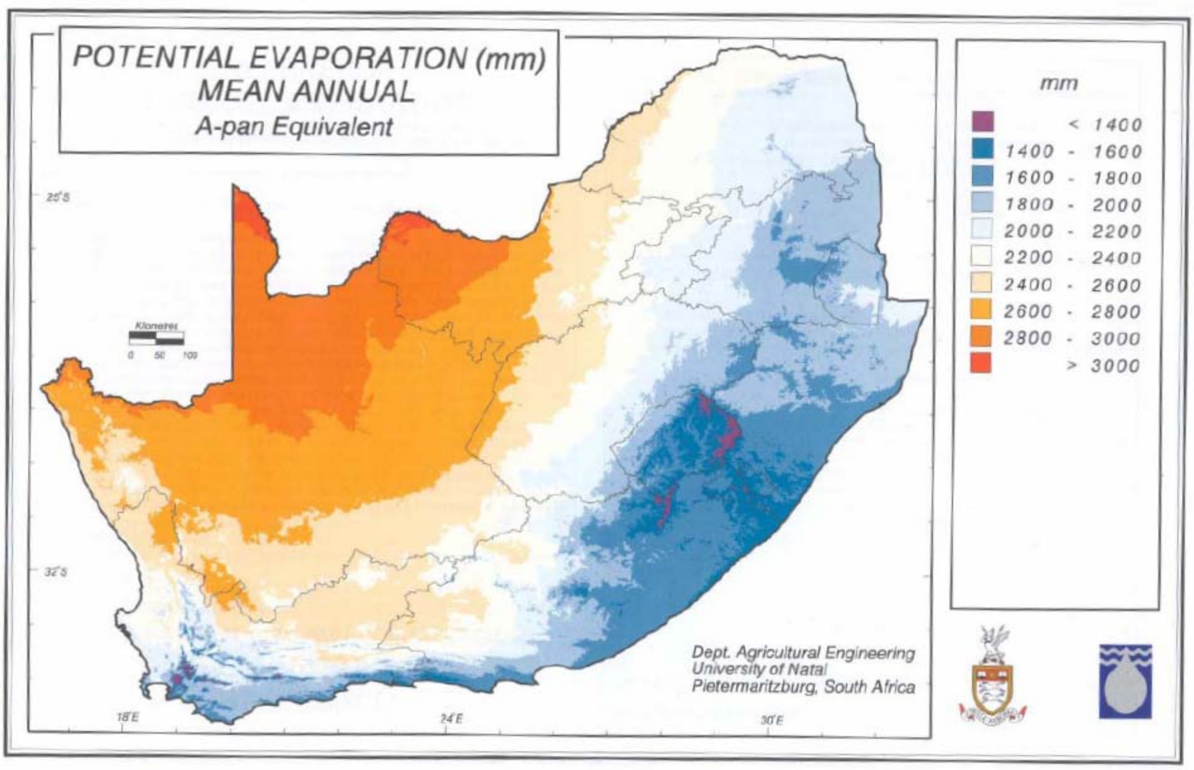


Figure 2-7: Mean Annual Potential Evaporation for South Africa (source: University of Natal)

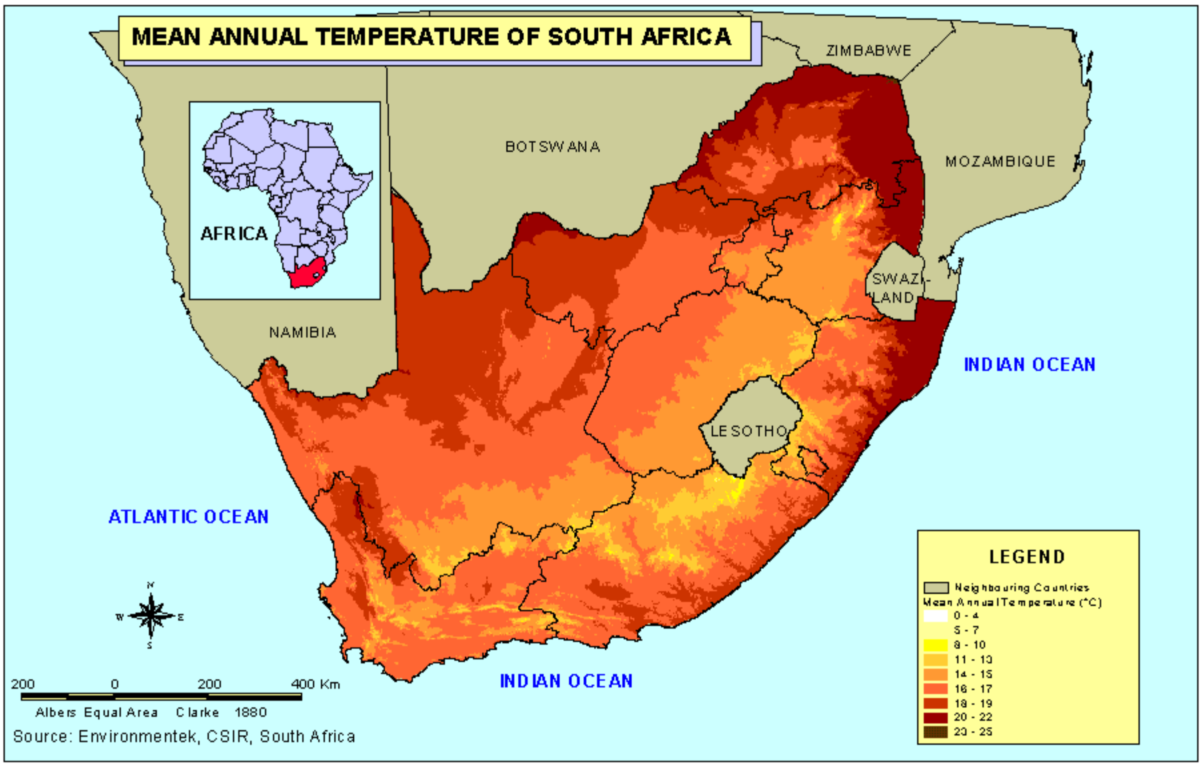
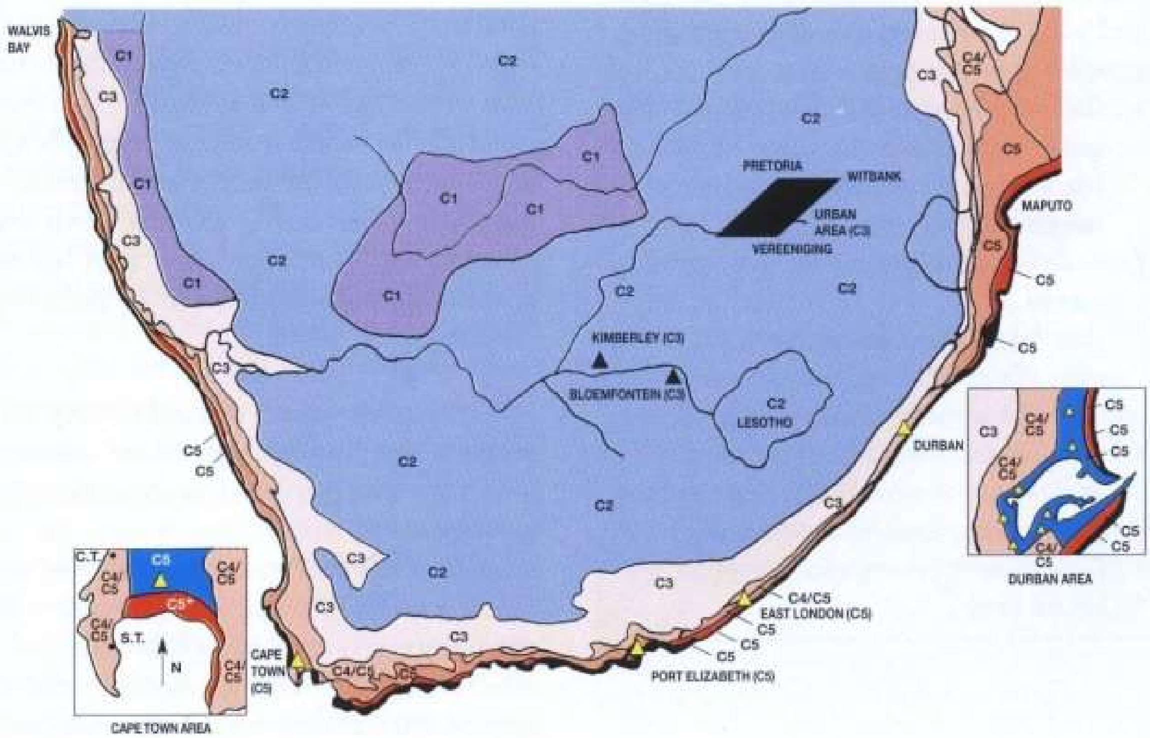


Figure 2-8: Mean Annual Temperatures (Source: CSIR)

In Figure 2-9 below a map indicating the atmospheric corrosion of zinc is shown as an example of the influence of the environment on the degradation of metals. The corrosion rate of uncoated mild steel is also given.

ATMOSPHERIC CORROSION OF ZINC



CATEGORY	DESCRIPTION	LEGEND	SEVERITY OF CORROSION	CORROSION RATE UNCOATED MILD STEEL	ZINC COATING LOSS
C5+	USUALLY LESS THAN 50m FROM H.W.M.	(black line)	SEVERE MARINE	+300μm/ YEAR	> 30μm/ YEAR
C5	USUALLY 50m TO 1km FROM H.W.M.	(red)	MARINE	200 - 300 μm/YEAR	15 - 30 μm/ YEAR
C4/C5	1km TO 40km FROM SEA	(salmon)	AVERAGE MARINE	20 - 200 μm/YEAR	2 - 15 μm/ YEAR
C3	40km TO 100km FROM SEA	(light pink)	MILDLY MARINE	10 - 20 μm/YEAR	1 - 2 μm/ YEAR
C2	INLAND	(blue)	RURAL	LESS THAN 10μm/YEAR	< 0.8 μm/ YEAR
C1	INLAND	(purple)	DESERT	LESS THAN 5μm/YEAR	< 0.5 μm/ YEAR
C3	URBAN INLAND	(black triangle)	INDUSTRIAL	10 - 30 μm/YEAR	1 - 3 μm/ YEAR
C5	URBAN COASTAL	(blue with yellow triangles)	MARINE INDUSTRIAL	50 - 150 μm/YEAR	5 - 15 μm/ YEAR
	H.W.M - HIGH WATER MARK				

Figure 2-9: Atmospheric corrosion of zinc

(Source: [web page], http://www.ckit.co.za/Secure/Conveyor/Troughed/corrosion%20protection/Steel%20Protection/Steel%20Protection%20-%2013%20Corrosion%20Resistance.htm. Date accessed: 18 November 2005)

2.4.3. Evaluation of degradation

Hövde (Hövde and Moser, 2004, p.23) cites BS 7543:1992, Guide to Durability of Buildings and Building Elements, Products and Components, which states that:

> *Prediction of durability is subject to many variables and cannot be an exact science. Accelerated testing of components by itself can seldom be used to give an accurate basis for predicting service life. …*
>
> *Whatever method is used to assess it, the predicted service life is unlikely to be a precise figure because the effect of an action in any building is not likely to be accurately predictable. More reliable predictions can be made when there is a correlation between the results of different assessments.*
>
> *The interpretation of data from tests requires skill and experience and knowledge of building maintenance. It is often necessary to rely on an informed opinion for service life prediction.*

Hövde (Hövde and Moser, 2004, p.25) also cites Canadian Standard CS 478-95, which states, *"the predicted service life of any building component, including repaired as well as new components, is approximate based on the assumed environmental conditions and on installation, operating and maintenance procedures."*

Change in condition over time seems to be a common accepted method to evaluate degradation (Mishalani and Madanat (2002, p.139); Coombes *et al* (2002); Morcous *et al* (2003, p.353)). Jernberg *et al* (2004, p.1-30) states that the purpose of the investigation determines the information required, which usually includes the change in material properties over time, the cause of failure and the effect thereof. The following example of evaluation levels for condition is presented:

- Condition 0: Intact, no changes
- Condition 1: Minor damages, some maintenance is suggested
- Condition 2: Malfunction, maintenance needed as soon as possible
- Condition 3: Out of order, replace or repair immediately

Another example of degradation evaluation used for the BELCAM project by the NRCC is presented by Lounis *et al* (1998a, p. 9) in Table 2-2 below.

Condition rating	Condition/state description	Damage (%)
7	Excellent : No noticeable distresses/anomalies.	0-10
6	Very Good: Minor anomalies (e.g. small blisters)	11-25
5	Good: Presence of some distresses (ridges).	26-40
4	Fair: Moderate deterioration; Water tightness is still adequate.	41-55
3	Poor: Major deterioration; Potential loss of water tightness	56-70
2	Very Poor: Extensive deterioration; Localized water leakage	71-85
1	Failed: Extensive water leakage.	>85

Table 2-2: Condition Assessment of Built-up Roofing Membranes (BELCAM Project)

Morcous *et al* (2003, p.354) cites Lipkus (1994) and Thompson *et al* (1998) for a 1 to 5 rating system used for bridge decks, where state 1 represents the condition of a new undamaged element, state 5 represents a severely deteriorated element, and states 2, 3, and 4 represent intermediate levels of damage. A 1 to 6 system used by the Ministe´re des Transports du Que´bec (MTQ) is also presented.

Madanat *et al* (1995) and Madanat *et al* (1997) present examples of road pavement (1 to 8) and bridge deck (0 to 9) condition ratings.

During 1995 and 1996 the CSIR was commissioned by the National Department of Health to undertake the National Health Facilities Audit (NHFA). For this project, which looked at the condition, suitability and other characteristics of health facilities in South Africa, the CSIR used a five-point rating system to assess the condition and suitability. The original ratings have since been adjusted and redefined, see Table 2-3 below, and used with great success in subsequent audits of health and other government facilities. The objective was to define the ratings in such a way as to ensure common interpretation by assessment staff and users of the information generated by the process. The introduction of colour coding attached to the ratings ensured maximum user friendliness, especially to people without a built environment background (such as medical, education, financial, etc.) and improved communication, which was identified by Mc Duling (2003) as one of the major problems in the built environment.

CONDITION RATING	Condition	Action Required	Description
5	Very Good	Planned Preventative Maintenance	The component or building is either new or has recently been maintained, does not exhibit any signs of deterioration
4	Good	Condition-based Maintenance	The component or building exhibits superficial wear and tear, minor defects, minor signs of deterioration to surface finishes and requires maintenance/servicing. It can be reinstated with routine scheduled or unscheduled maintenance/servicing.
3	Fair	Repairs Required	Significant sections or component require repair, usually by a specialist. The component or building has been subjected to abnormal use or abuse, and its poor state of repair is beginning to affect surrounding elements. Backlog maintenance work exists.
2	Bad	Rehabilitation Required	Substantial sections or component have deteriorated badly,suffered structual damage or require renovations. There is a serious risk of imminent failure. The state of repair has a substantial impact on surrounding elements or creates a potential health or safety risk.
1	Very Bad	Replacement Required	The component or building has failed, is not operational or deteriorated to the extent that does not justify repairs, but should rather be replaced. The condition of the element actively contributes to the degradation of surrounding elements or creates a safety, health or life risk.

Table 2-3: Condition Ratings (Abbott & Mc Duling, 2004)

2.5. The Factor Method

Hövde (Hövde and Moser, 2004, p.29) refers to the Japanese Principal Guide for service life planning of buildings, based on decades of development and published in 1989, followed in 1993 by a shorter version in English (AIJ 1993), which promoted the use of the Factor Method for service life prediction. The Guide identifies the following classification concerning the deterioration factors:

a) Items relating to the inherent (durability) characteristics of performance over time:

1) Performance of materials

2) Quality of designing

3) Quality of construction work

4) Quality of maintenance and management

b) Items relating to the environmental deterioration factor:

1) Site and environmental conditions

2) Condition of building

The starting point of the factor method is the reference service life, which is defined as *"a documented period in years that the component or assembly can be expected to last in a reference case under certain service conditions."* (Jernberg *et al*, 2004, p.1-15). According to Hövde (Hövde and Moser, 2004) there are three different types of service life prediction methods: research or probabilistic methods, deterministic methods and engineering methods. The Factor Method for the calculation of the Estimated Service Life of a Component (ESLC), as defined in ISO 15686–1:2000, is based on the deterministic approach and given by the following formula:

ESLC = RSLC x factor A x factor B x factor C x factor D x factor E x factor F x factor G.

- factor A: quality of components
- factor B: design level
- factor C: work execution level
- factor D: indoor environment
- factor E: outdoor environment
- factor F: in-use conditions
- factor G: maintenance level,

where RSLC is the Reference Service Life of the Component.

Factor A: Quality of components: It is a measure of the quality of the design, the materials used, the manufacturing and assembly of the component as supplied to site.

Factor B: Design level: It is a measure of the level of protection and shelter or exposure to degradation agents offered to the component by the design in terms of installation.

Factor C: Work execution level: This factor is determined by the quality of workmanship and control of the site work based on the likelihood of achieving the manufacturers' recommendations and the specified level of workmanship, *"including issues such as storage, protection during installation, ease of installation, number of trades required for each activity, site applied coatings etc."* and the level of control on site.

Factor D: Indoor environment: This factor is a measure of the exposure to and severity of internal degradation agents, based on the use of the building or space providing for locations subject to wetting, steam and temperature, such as kitchens, bathrooms and cold rooms.

Factor E: Outdoor environment: This factor is a measure of the exposure to and severity of external environment degradation agents, and although an assessment at meso level may be adequate, the impact of the macro- and microclimates should also be taken into consideration.

Factor F: Maintenance level: The assessment of this factor is based on the planned or actual level of maintenance and the likelihood of that being achieved for the type of building under consideration. Accessibility and requirement for special equipment for access, and the expertise of cleaning should also be taken into account. (Jernberg *et al*, 2004, p.1-16)

The quality of the fabric, material and workmanship in the initial construction and subsequent maintenance also has a major affect on the resistance of the building to the environment. It is interesting to note that according to Seeley (1987, p.6 - 7) hospitals built in Britain during the 1960's and 1970's can cost up to three or four times as much to maintain as older hospitals because of the experimental methods by which many were constructed. He also points out that the appalling state of repair of many of Britain's school buildings is *"rooted in the educational building boom of the 1960's when decades of common sense in materials and detailing were discarded in favour of non-durable and inadequately researched materials, poor and sometimes 'unbuildable' detailing, and lax supervision of construction."*

Human processes are a very important influence on degradation of public buildings. According to Lee (1981, p.1):

> *The built environment expresses in physical form the complex social and economic factors which give structure and life to a community. The condition and quality of buildings reflect public pride or indifference, the level of prosperity in the area, social values and behaviour and all the many influences both past and present, which combine to give a community its unique character. There can be little doubt that dilapidated and unhealthy buildings in a decaying environment depress the quality of life and contribute in some measure to antisocial behaviour.*

This also applies to South Africa, where cultural differences and perceptions are prominent. There is a general lack of understanding of the need for maintenance, aggravated by a culture of vandalism stemming from the apartheids era when vandalism of public buildings (houses, schools and hospitals in particular) was part of the freedom struggle.

The factor method considers each of the variables that are likely to affect service life, but provides only an empirical estimate of the service life based on what information is available. Hövde (Hövde and Moser, 2004, p.38) refers to Aarseth and Hövde (1999) who applied a *"step-by-step"* principle, which *"enables a stochastic handling of the modifying factors in the ISO factor method by performing a triple estimate for each factor. After the statistical calculation the estimated service life is expressed as three figures: the expected value plus/minus one standard deviation."*

Moser (Hövde and Moser, 2004, p.81) has also carried out an evaluation and improvement of the factor method by use of statistical methods. He applied an individual statistical treatment of each factor and employs variables with density-functions instead of plain figures.

> *The variables are based on data given by the manufacturer, by tests, by experience, by expert opinion, and others. Reliable data from expert opinion can be derived by application of the so-called recursive Delphi method. Experts are required to estimate the minimum (say 5%), the average (50%) and the maximum (say 95%) fractals of the variable considered. These estimates are fitted into density distributions of any kind such as: standard, symmetric, asymmetric, custom-defined, or others (or even deterministic, here for design level).*

Hövde (Hövde and Moser, 2004, p.39) cites Rudbeck (1999) who states that *"From a statistical point of view"* Moser's statistical approach *"seems to be the most reliable."* According to Hövde (Hövde and Moser, 2004, p.41) the lack of knowledge of the Factor method among practitioners has limited *"widespread practical application of the method."* Moser (Hövde and Moser, 2004, p.62) summarised the main shortcomings of the Factor Method as follows:

- The plain multiplication of factors, which in reality might have a different weight,
- The result being a single figure instead of a result to reflect variance of reality,
- The data still to be accumulated,
- The lack of a direct relation to data gathered e.g. on environment, climate, installation quality, in use conditions, etc. The factors are usually set basing directly on the behaviour of the component in a given set of conditions, rather than basing on the influence of individual parameters such as regimes of rainfall, temperature, wetting time, type of use, etc.
- Considering the efforts in gathering input data, the simple figure result of the factor method, when executed as set out in ISO 15686, seems not to be adequate.

2.6. The Markov Chain

"The Markov Chain is used in the analysis of time dependent systems." (Van As, 2001, p.17-1). A number of studies (Morcous *et al,* 2003, p.353; Lounis *et al,* 1998a, p.1; Rudbeck, 1999 cited by Hövde and Moser, 2004, p.40; Madanat *et al,* 1995, p.120) identified the Markov Chain, a stochastic approach used for simulating the transition from one state (condition) to another over time, as the preferred method to predict service life. According to Kyle *et al* (2002a) *"Markov Chain models are one of the most promising technologies to determine the remaining service life."* Populating the Markov transition probability matrix however remains a challenge (Morcous *et al,* 2003, p.354; Zhang *et al,* 2005).

> *In many processes, significant dependence exists between successive trails or steps that can be identified in a physical process. The state of such systems invariably depends on some parameter, for example time or space. The transition from one state to another, or its corresponding transitional probability, may generally depend on the prior states. If, however, the transitional probability depends only on the current state, the process of change is said to be memoryless and may be modelled by the Markov process.* (Van As, 2001, p.17-1)

2.6.1. Transitional Probability

According to Van As (2000), the transitional probability that a system with *m* possible states will change from state *i* at time t_m to state *j* at time t_n is:

$P_{mn}(ij) = P[X_n = j / X_m = i]$ *for* $n > m$, where *X* donates the state of the system

If $P_{mn}(ij)$ depends only on the difference in times $k = t_n - t_m$, the Markov Chain is said to be homogeneous and the *k*-step transition probability is then given by:

$P_k(ij) = P[X_k = j / X_o = i]$ *for* $k > 0$

"This step represents the conditional probability that a homogeneous Markov Chain will change state from state i to state j in k time steps. The one-step transitional probabilities, P(ij), can be summarized in a matrix of m states, called the transitional probability matrix (in which the probabilities in each row add up to 1):"

		[1]	[2]	…..	[m]	
	(1)	P(11)	P(12)	…..	P(1m)	∑P(1j) = 1
P =	(2)	P(21)	P(22)	…..	P(2m)	∑P(2j) = 1
	…	…	…	…..	…	…
	(m)	P(m1)	P(m2)	…..	P(mm)	∑P(mj) = 1

"This matrix represents the probability that a system will change from state i (indicated by round brackets) to state j (indicated by square brackets) in one-step. This process is only homogeneous if the process is independent of the time or the step number."

Van As (2000) states that the probabilities of the initial states of the system are required as additional information for a homogeneous Markov chain:

$P(0) = [P_0(1), P_0(2) \ldots P_0(m)]$

Where $P_0(i)$ is the probability that the system is initially in state *i*. In the special case for which the initial state is known to be *i*, $P_0(i) = 1$ and the other probabilities are 0. After one transition, the probability that the system will move from state *i* to state *j* can be determined by using the following event table:

Time 0 states		Transition	Time 1 states	
State *i*	$P_0(i)$	*P(ij)*	State *j*	$P_1(j)$
1	$P_0(1)$	P(1j)	j	$P_1(j) = P_0(1).\ P(1j)$
2	$P_0(2)$	P(2j)	j	$P_1(j) = P_0(2).\ P(2j)$
…	…	…	…	…
m	$P_0(m)$	P(mj)	j	$P_1(j) = P_0(m).\ P(mj)$

The probability that the system will be in state *j* is then determined as the summation:

$$P_1(j) = \sum_{j=1}^{m} P_0(i).P(ij)$$

In matrix notation, the single stage state probability is a vector of probabilities:

$$\mathbf{P}(1) = \mathbf{P}(0).\mathbf{P}$$

Van As (2000) concludes that by repeating the process, it can be shown that the n-stage probability vector is given by:

$$\begin{aligned}\mathbf{P}(n) &= \mathbf{P}(n-1).\mathbf{P} \\ &= \mathbf{P}(n-2).\mathbf{P}.\mathbf{P} \\ &= \mathbf{P}(0).\mathbf{P}^{n}\end{aligned}$$

2.6.2. Application of the Markov model

According to Davison and Hinkley (1999, p.1) *"The explicit recognition of uncertainty is central to the statistical sciences. Notions such as prior information, probability models, likelihood, standard errors and confidence limits are all intended to formalize uncertainty and thereby make allowance for it. In simple situations, the uncertainty of an estimate may be gauged by analytical calculation based on an assumed probability model for the available data. But in more complicated problems this approach can be tedious and difficult, and its results are potentially misleading if inappropriate assumptions or simplifications have been made."* This is very relevant for building degradation analysis where the opinion of the domain expert and inconsistent field data are often the only source of available data.

Moser (Hövde and Moser, 2004, p.62) stated, *"The Markov model assumes deterioration to be a stochastic process governed by random variables. The structure may be split into a number of components, which deteriorate randomly. The main parameters of the deterioration are established for each component, together with the deterioration variables versus time."*

Moser (Hövde and Moser, 2004, p.66) cited Lounis, Z., Lacasse, M.A., Siemes, A.J.M., and Moser, K. (1998), who stated that:

> *The Markov model considers steadily degrading systems, where for each property, during each time period, a probability of deterioration is defined. This method thus requires sophisticated inputs in the form of probabilities, which are not easily estimated, as they cannot be read directly off the real behaviour of the structure in the field. The Markov model requires an in depth knowledge of the system dealt with or on the other hand has to rely on significant simplifications.*

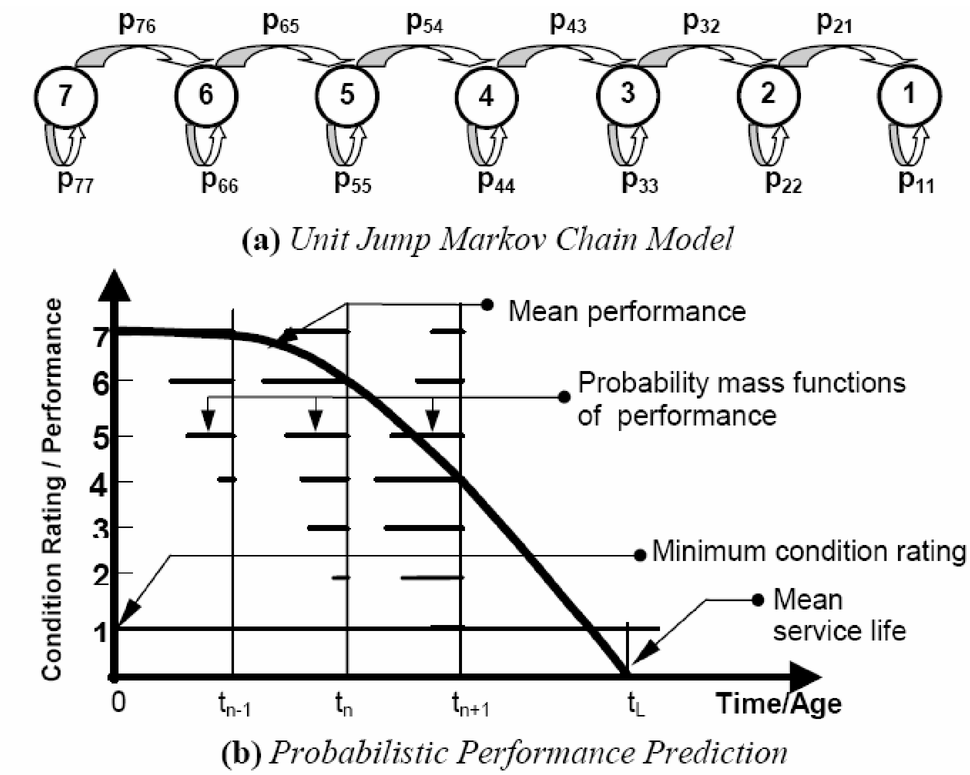


Figure 2-10: Markov deterioration function (Lounis *et al*, 1998, p.5)

In Figure 2-10 above, Lounis *et al* (1998) illustrates the Markov deterioration function. It is assumed that the condition rating can only jump one rating from its current rating to a more deteriorated rating in one time interval or it can stay in its current rating. This implies that the condition can only get worse or stay the same, but cannot improve without deliberate intervention (such as maintenance, repairs, rehabilitation or replacement). In Figure 2-10 (a) p_{77} is the probability that the component under consideration will remain in condition 7 during the interval under consideration, while p_{76} represents the probability that the condition will deteriorate from condition 7 to condition 6 during the same interval.

The following two recent research projects established the Markov Chain as a recognised method for service life prediction:

a.) Service Life Prediction of Roofing Membranes – BELCAM Project

The Building Envelope Life Cycle Asset Management (BELCAM) Project by the NRCC in Canada can be regarded as one of the milestones in the development of service life prediction methods. According to Kyle *et al* (2002a) *"The objectives of the Building Envelope Life Cycle Asset Management (BELCAM) Project were to develop techniques to predict the remaining service life of building envelope components and procedures to optimize their maintenance."* The use of visual inspection techniques to investigate the service life of multi-component systems was a BELCAM first. *"Data were collected on 2800 roof sections from a wide range of systems and climatic regions across Canada"* … *"since the domain of the entire building envelope was too large for the budget of the project."* … *"Markov Chain modelling was used to predict the change in conditions of representative samples; deterioration curves were generated to predict the change in condition, and remaining service life of specific components of the roofing system could be estimated from these data."*

> *Industry will require years if not decades of data collection to have enough data to develop Markov Chain-based service life models in all the important domains. This three-year project barely produced enough data to generate service life curves for the generalized cases for specific types of low slope roofs. In addition, insufficient multi-year data was collected in the term of the project for two principal reasons: (1) there is very little change in the performance in this time frame to warrant annual inspections and (2) inspections are too expensive to carry out annually for every asset type in a large portfolio. In place of multi-year*

> *data, a technique using random sampling of data was used to generate the required deterioration curves.* (Kyle *et al,* 2002a)

Kyle *et al* (2002a) *also* cites Vanier (2001) who recommended *"generalized models for deterioration as temporary substitutes"* should be developed until sufficient data are available.

According to Lounis *et al* (1998b, p.3) *"The performance prediction is based on a probabilistic Markovian model (Ross, 1996) that captures the time-dependence, uncertainty and variability associated with the roof section performance (or condition rating). This model is developed from in-field performance data collected during roofing inspections, considering the system and material types, environmental conditions, age, workmanship quality and maintenance level. "*

Figure 2-10 above illustrates the probabilistic prediction of the performance*, "which indicates the evolution with time of the probability mass function of the roofing performance. Initially, the probability mass is close to condition rating 7. As the roofing component ages and deteriorates, this probability mass shifts from states of high condition ratings to those with lower ratings."*

> *"The transition probability matrix is determined from the historical performance data collected during inspections. The proposed model enables the forecast of future performance of roofing systems throughout their entire service lives. The performance of roofing components and systems is dependent upon several explanatory variables, including age, environmental conditions, material type, quality of work executed and materials used as well as the amount and quality of maintenance. In order to validate the Markov chain model, it is necessary to develop transition probability matrices for roofing components and systems according to their classification with regard to these explanatory variables.*
>
> *The development of the Markovian model requires a relatively limited amount of historical performance data at two or more points in time. If the probability of a roofing component decaying by more than one state in one transition period is assumed negligible, the transition probability matrix is greatly simplified, and the deterioration process may be modelled by the unit-jump Markov chain shown in"* Figure 2-10(a). (Lounis *et al*, 1998b, p.5)

One of the biggest problems in building maintenance is the lack of reliable and consistent historical performance data. If the model does require data at only "two or more points in time", the application of the Markovian model becomes more viable in view of the lack of data.

To ensure negligible probability of decay by more than one state in one transition period, the length of the transition period should be appropriate. Historical performance data under 'normal' conditions, manufacturer or supplier information, and expert opinion could be used to determine suitable transition periods, which could vary from months to any number of years, depending on the component or fabric.

Zhang *et al* (2005) looked at "Uncertainty Analysis in Using Markov Chain Model to Predict Roof Life Cycle Performance" based on earlier work by Van Winden and Dekker (1998) and the BELCAM Project (Lounis *et al*, 1999). It was found that the predictions based on Markov model might be sensitive to deviation caused by parameter variance. The complex and probabilistic nature of the degradation process simulation due to the uncertain environmental factors in the service life duration and the variability of the factors is pointed out. *"Hence it is desirable to simulate and predict this process in the framework of stochastic models. However, the validation and parameter identification of a stochastic model depends on the availability and format of data, coming either from controlled experiments or field tests."* Two very important issues are discussed in some detail. Firstly, the issue of the service life span, accelerated degradation experiments, making *"inference on the real service life through the lab testing results"* and the limited accessibility to field data. Secondly, the consistency and objectivity of the inspection/assessment process are mentioned.

The seven-point condition rating system of the BELCAM project was used. According to Zhang *et al* (2005, p.5) the requirement that *"the observed roofing systems should be of the same kind and expose to similar circumstances, is too restrictive to make it a realistic method. Another difficulty is that inspected data under certain maintenance policy may never reach certain states. ... It is more practical to infer parameters from a service life curve, coming either from lab test or expert opinion. When it comes to expert opinion, intuition is to let experts directly estimate the coefficient in Markov chain model. However, this estimation requires the expert to be familiar with both the assumptions of Markov chain model and the specific transition behavior."*

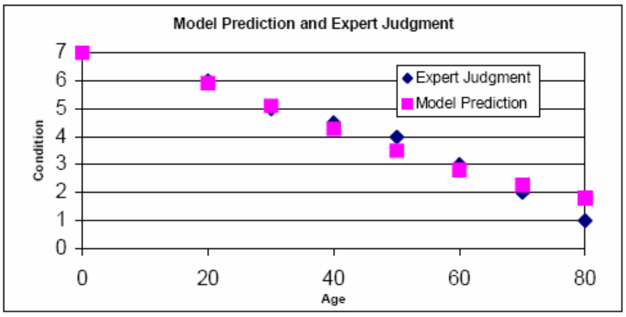


Figure 2-11: Expert Judgment Data and Model Prediction (Zhang *et al*, 2005, p.5)

Figure 2-11 illustrates a comparison between expert judgment on service life condition under natural degradation and model prediction, from which the matrix as shown in Figure 2-12 is derived.

$$P = \begin{pmatrix} 0.95 & 0.05 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.93 & 0.07 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.91 & 0.09 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.88 & 0.12 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Figure 2-12: Markov Chain Transition Probability Matrix (Zhang *et al*, 2005, p.5)

b.) Identification of Environmental Categories for Markovian Deterioration Models of Bridge Decks by Morcous *et al* (2003).

Morcous *et al* (2003, p.353–361) discuss the application of Markovian deterioration models to identify environmental categories for bridge decks in Canada. It was found that *“the categories used to describe the various possible environments for a bridge element are neither accurately defined nor explicitly linked to the external factors affecting the element deterioration.”*

	1	2	3	4	5
1	0.98	0.02	0	0	0
2	0	0.97	0.03	0	0
3	0	0	0.97	0.03	0
4	0	0	0	0.96	0.04
5	0	0	0	0	1

Benign environment

	1	2	3	4	5
1	0.95	0.05	0	0	0
2	0	0.94	0.06	0	0
3	0	0	0.94	0.06	0
4	0	0	0	0.92	0.08
5	0	0	0	0	1

Low environment

	1	2	3	4	5
1	0.93	0.07	0	0	0
2	0	0.92	0.08	0	0
3	0	0	0.91	0.09	0
4	0	0	0	0.90	0.10
5	0	0	0	0	1

Moderate environment

	1	2	3	4	5
1	0.87	0.13	0	0	0
2	0	0.86	0.14	0	0
3	0	0	0.85	0.15	0
4	0	0	0	0.83	0.17
5	0	0	0	0	1

Severe environment

Figure 2-13: Transition probability matrices of concrete bridge decks with asphalt concrete overlay for the four environments (Morcous *et al*, 2004, p.355)

A set of transition probability matrices for various climatic environments, based on data obtained from the Ministére des Transports du Québec, is developed as shown in Figure 2-13 above. Two important principles are displayed in these graphs: first, condition cannot improve ($p_{ij} = 0$ where $i > j$) without rehabilitation, and second: condition changes only one-step per time interval ($p_{ij} = 0$ where $j > i + 1$).

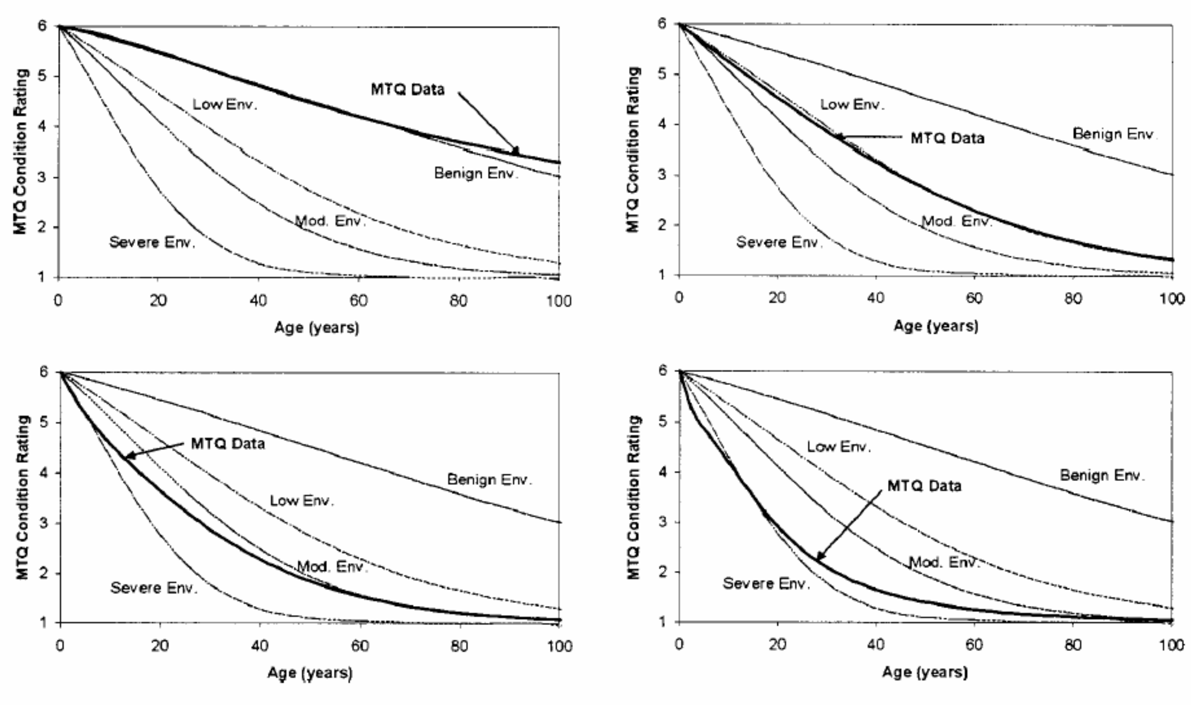


Figure 2-14: Genetic algorithm-generated deterioration curves for the four environmental categories (Morcous *et al*, 2004, p.359)

> Genetic algorithms are used *"to determine the combinations of deterioration parameters that best fit each environmental condition."* Performance over time curves for each of the four environmental categories, showing the change in condition over time, are presented in Figure 2-14 above.

Kirkham and Boussabaine (2004) proposed a stochastic approach to the forecasting of the residual service life of NHS hospital buildings. The results from their proposed model, based upon a combination of weighted average techniques and a Markov property; the minimum of exponentials, were compared with those obtained by means of existing deterministic methods and revealed an average percentage difference of 56.26%. *"This confirms the notion that stochastic approaches in combination with elemental weightings could yield greater accuracy. Whilst the results obtained can be used primarily to determine the overall residual service life of a hospital building, the model also allows the condition state transition probabilities to be calculated at a given time. On the macro level, this information can be used for optimization of maintenance strategies."*

Some other documented examples of Markov applications briefly cited by Moser (Hövde and Moser, 2004, p.63) are listed below:

a.) Development of prediction models for sewer deterioration

Abraham and Wirahadikusumh (1999) explored the probability-based Markovian approach for modelling deterioration of sewer lines. They used expert opinions from engineers for validating the deterioration models, which enabled the comparison of predicted values with actual field observations.

b.) Sewer lines

"A somewhat simplified deterioration model" has been applied to sewer lines by Kaempfer *et al* (2002). They assessed the condition of sewer pipes, using a five-point scale for different damage classes, ranging from very serious to negligible. *"... aging curves were derived from the available inspection data and the construction year for each status class. ... The average residual service life of the sewer section is represented by a vertical line between the real age of the sewer section and the point of intersection with the aging curve of intervention status class. The different intersections on the horizontal line with the aging curves of different status classes indicate the ages at which the section is likely to drop to the next class or, going back in time, came from the previous class."*

c.) Service life of bridge elements

Ansell *et al* (2002) reported a Markov approach in estimating the service life of bridge elements in Sweden. *"Deterioration of bridge elements can be analysed numerically using the Markov chain theory. The deterioration of a particular structural member must be defined by a number of states, in this case given by the assessed condition classes. The numerical method used, is based on an iterative stepwise combination of the matrix elements until the error between a known deterioration average curve and a curve given by the Markov chain is minimised."*

Other documented examples of Markov applications include the following:

a.) Highway pavement management

Puterman (1994, p.5) discusses the development of a pavement management system by the Arizona Department of Transportation *"based on a Markov decision process model to improve allocation of its limited resources while ensuring that the quality of its roadways was preserved"*. A dynamic long-term model was used to *"identify maintenance policies which minimize long-run average costs subject to constraints on road quality."* The model was applied to 7,400 one-mile sections based on *"road type, traffic density, and regional environment."* The model provided for condition, associated maintenance actions, expected yearly deterioration, and costs for each maintenance action.

> *Transition probabilities specify the likelihood of yearly changes in road condition under the various maintenance actions. These were estimated using existing data, under the assumption that each dimension of the state description varied independently. Since in each state only a limited number of subsequent states could occur, most of the transition probabilities (97%) were zero.*

According to Puterman, the saving in the first year of implementation, 1980, was $14 million, *"nearly a third of Arizona's maintenance budget with no decline in road quality."*

b.) Stormwater pipes

Coombes *et al* (2002) looked at deterioration, depreciation and serviceability of stormwater pipe networks in Newcastle, Australia, and presented a Markov model for the structural deterioration of stormwater pipes. Bayesian techniques are used to calibrate the model with structural condition assessment data. It was found that the deterioration process was influenced by *"diameter, construction material, soil type and exposure classification"*. The model is also presented as a *"rational approach to assessing depreciation"* as required by Australian Accounting Standard AAS27.

c.) Bridge decks and infrastructure:

Madanat *et al* (1995) and Madanat *et al* (1997) worked on transition probabilities for bridge decks. It is pointed out that inspection data *"suffer from important methodological limitations."* Inspection ratings are *"discrete ordinal measurements ... instead of continuous condition indices"* and do not account *"for the presence of heterogeneity in the panel data." ... which may lead to biased coefficient estimates."*

Incremental deterioration models, which *"predicts changes in condition that are added to previous condition to estimate the new condition"* have been developed and claimed to be *"more realistic representations of the deterioration process than models which predict condition directly because they take the form of difference equations (or differential equations for the continuous time case) where condition at a point in time is a function of both condition at a previous point in time and other explanatory variables such as age, traffic, weather, and maintenance."*

The "expected-value" method for estimating transitional probabilities for the Markovian model is discussed and pointed out that the deterioration process *"is not explicitly modelled"* and *"the latent nature of infrastructure deterioration"* is not recognised. Corrosion of concrete reinforcement is presented as an example of latent deterioration, which is a very important and often neglected consideration.

In Madanat *et al* (1995, p.124) and Madanat *et al* (1997, p.6) the role of age in the deterioration process is also highlighted. It is agued, quite correctly, that older bridge decks deteriorate faster than new bridge decks, which *"clearly illustrates the nonstationarity of the deterioration process."*

In Madanat *et al* (1997, p.4 - 5) the issue of state dependence is discussed. It is stated that the assumption that deterioration might not be independent of history in the case of *"some types of facilities in which early stress initiation leads to accelerated deterioration in later stages of their lives. ... In the context of deterioration modelling, the Markovian assumption states that the probability that the facility's condition drops to a lower state in a given time period is independent of its deterioration in previous time periods."* Due to the influence of past deterioration, it is argued that the transition process is a *"function of past experience",* which is referred to as *"state dependence"*.

State dependence could be due to historical deterioration, called true state dependence, or differences in *"certain unmeasured characteristics that influence deterioration but are not influenced by history"* or heterogeneity. True state dependence invalidates the Markovian assumption, while *"heterogeneity, if properly accounted for in the model, does not."*

2.7. Artificial Intelligence Applications

2.7.1. Introduction

The fundamental question of artificial intelligence is *"Can machines think?"* Negnevisky (2002, p.2) quotes Boden (2000) who states that *"the goal of Artificial Intelligence (AI) as a science is to make machines do things that would require intelligence if done by humans."*

According to Negnevisky (2002, p.1) *"The first work recognised in the field of artificial intelligence (AI) was presented by Warren McCulloch and Walter Pitts in 1943"*, who *"proposed a model of artificial neural networks in which each neuron was postulated as being in binary state."* Neural networks *"can learn, adapt to changes in a problem's environment, establish patterns in situations where rules are not known, and deal with fuzzy or incomplete information. However, they lack explanation facilities and usually act as a black box."* Negnevisky (2002, p.14)

He also discusses the development of the expert system (1970's to mid 1980's), which goal it is to incorporate the "domain expert's" expertise into a computer program to make it perform at a human expert level. This is of course very relevant to service life prediction, where there are many experts but very little historical performance data available, and the opinion of these experts are very often the only means to compensate for the lack of consistent reliable statistics. *"A major drawback is that human experts cannot always express their knowledge in terms of rules or explain the line of their reasoning."*

Genetic algorithms, evolutionary strategies, and genetic programming, all evolutionary artificial intelligence applications, are *"based on the computational models of natural selection and genetics"*. Negnevisky (2002, p.14) points out that *"an evolutionary strategies approach can be considered as an alternative to the engineer's intuition. Evolutionary strategies use a numerical optimisation procedure, similar to a focused Monte Carlo search."*

> *Another very important technology dealing with vague, imprecise and uncertain knowledge and data is fuzzy logic. Most methods of handling imprecision in classic expert systems are based on the probability concept. ... However, experts do not usually think in probability values, but in terms as often, generally, sometimes, occasionally and rarely. Fuzzy logic is concerned with the use of fuzzy values that capture the meaning of words, human reasoning and decision making. As a method to encode and apply human knowledge in a form that accurately reflects an expert's understanding of difficult, complex problems, fuzzy logic provides the way to break through the computational bottlenecks of traditional expert systems."* (Negnevisky, 2002, p.1-21)

From the above, the following artificial intelligence applications have been identified:

- Rule-based expert systems,
- Fuzzy logic systems,
- Frame-based expert systems,
- Artificial neural networks (ANN),
- Genetic algorithms (evolutionary computation), and
- Hybrid intelligent systems:
  - Neural expert systems,
  - Neuro-fuzzy systems,
  - Adaptive Neuro-fuzzy Inference System (ANFIS),
  - Evolutionary neural networks, and
  - Fuzzy evolutionary systems.

For the purpose of this thesis, only the Fuzzy logic, Artificial Neural Networks (ANN) and Neuro-fuzzy systems will be looked at in brief.

2.7.2. Fuzzy Logic

In a discussion on the differences between stochastic uncertainty and linguistic uncertainty Von Altrock (1995, p.8 - 11) points out that *"Stochastic uncertainty deals with the uncertainty of whether a certain event will take place, and probability theory lets you model this. In contrast, lexical uncertainty deals with the uncertainty of the definition of the event itself. Probability theory cannot be used to model this because the combination of subjective categories in human decision processes does not follow its axioms."*

According to Negnevisky (2002, p.87-90) fuzzy logic is logic that describes fuzziness in contrast to Boolean or conventional logic which uses sharp distinctions. *"Fuzzy logic is the theory of fuzzy sets, sets that calibrate vagueness. Fuzzy logic is based on the idea that all things admit of degrees."* He continues by stating, *"Unlike two-valued Boolean logic, fuzzy logic is multi-valued. It deals with degrees of membership and degrees of truth. Fuzzy logic uses the continuum of logical values between 0 (completely false) and 1 (completely true). Instead of just black and white, it employs the spectrum of colours, accepting that things can be partly true and partly false at the same time. ... The basic idea of the fuzzy set theory is that an element belongs to a fuzzy set with a certain degree of membership."*

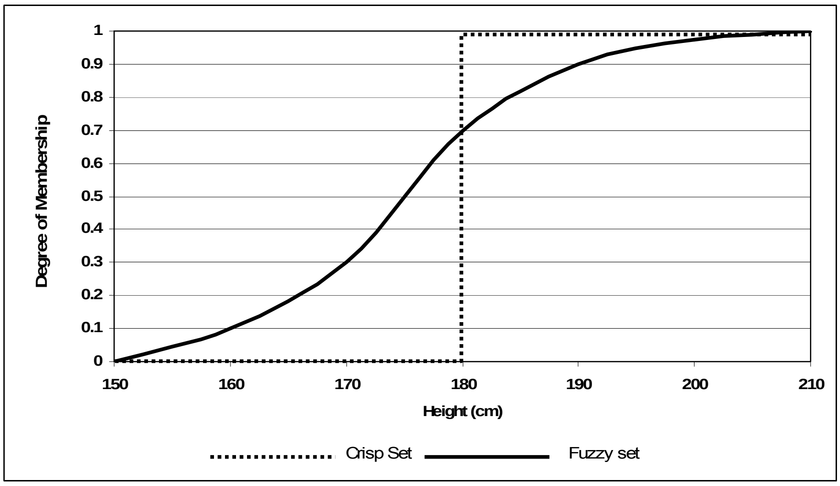


Figure 2-15: Examples of crisp and fuzzy sets (after Negnevisky, 2002)

The horizontal axis represents the universe of discourse (the range of all possible values applicable to a chosen variable), while the vertical axis represents the membership value of the fuzzy set. A fuzzy set is capable of providing a graceful transition across a boundary and *"can be simply defined as a set with fuzzy boundaries."*

In the classical set theory, if X is the universe of discourse and x its elements, then the "crisp set A of X or characteristic function of A is defined as function $f_A(x)$:

$f_A(x)$: X → 0, 1,

where

$$f_A(x) = \begin{cases} 1, & \text{if } x \in A \\ 0, & \text{if } x \notin A \end{cases}$$

This set maps universe X to a set of two elements. For any element x of universe X, characteristic function $f_A(x)$ is equal to 1 if x is an element of set A, and is equal to 0 if x is not an element of A.
In the fuzzy theory, fuzzy set A of universe X is defined by function, $\mu_A(x)$ called the membership function of set A

$\mu_A(x) : X \rightarrow [0,1]$,
where
$\mu_A(x) = 1$ *if x is totally in A;*
$\mu_A(x) = 0$ *if x is not in A;*
$0 < \mu_A(x) < 1$ *if x is partially in A*

This set allows a continuum of possible choices. For any element x of universe X, membership function $\mu_A(x)$ equals the degree to which x is an element of set A. This degree, a value between 0 and 1, represents the degree of membership, also called membership value, of element x in set A." (Negnevisky, 2002, p.92)

According to Negnevisky (2002, p.92) a number of methods learned from knowledge acquisition such as the knowledge of single expert, multiple experts or artificial neural networks can be applied to determine the membership function.

"If X is the reference super set and A is a subset of X, then A is said to be a fuzzy subset of X if, and only if,

$$A = \{(x, \mu_A(x)\} \quad x \in X, \mu_A(x) : X \rightarrow [0,1]$$

Fuzzy subset A of the finite reference super set X can be expressed as,

$$A = \{(x_1, \mu_A(x_1)\},\{(x_2, \mu_A(x_2)\}, \ldots,\{(x_n, \mu_A(x_n)\}$$

However it is more convenient to represent A as,

$$A = \{\mu_A(x_1)/x_1\}, \{\mu_A(x_2)/x_2\}, \ldots ,\{\mu_A(x_n)/x_n\},$$

where the separating symbol / is used to associate the membership value with its coordinate on the horizontal axis." Negnevisky (2002, p.93 - 94)

"A fuzzy rule can be defined as a conditional statement in the form:

IF x is A

THEN y is B

Where x and y are linguistic variables; and A and B are linguistic values determined by fuzzy sets on the universe of discourses X and Y, respectively. ... Fuzzy reasoning includes two distinct parts: evaluating the rule antecedent (the IF part of the rule) and implication or applying the result to the consequent (the THEN part of the rule)." If in fuzzy systems *"the antecedent is true to some degree of membership, then the consequent is also true to that same degree."* (Negnevisky, 2002, p.103-104).

According to Von Altrock (1995) the rule blocks contain the control strategy of a fuzzy logic system. All rules for the same combination of variables are confined in a rule block. The rules' 'IF' part describes the situation, for which the rules are designed. The 'THEN' part describes the response of the fuzzy system in this situation. The degree of support (DoS) is used to weigh each rule according to its importance.

Negnevisky (2002, p.106) defines fuzzy inference *"as a process of mapping from a given input to an output, using the theory of fuzzy sets. ... The most commonly used fuzzy inference technique is the so-called Mamdani method,"* which applies *"a set of fuzzy rules supplied by experienced human operators. ... The Mamdani-style fuzzy inference process is performed in four steps: fuzzification of the input variables, rule evaluation, aggregation of the rule outputs, and finally defuzzification."*

Step 1: Fuzzification

The degree to which the inputs the crisp inputs, x1 and y1, a numerical value limited to the universe of discourse X and Y respectively, belong to each of the appropriate fuzzy sets is firstly determined. *"The ranges of the universe of discourses can be determined by expert judgments. .... While some of the inputs can be measured directly (height; weight, speed, distance, temperature, pressure etc.), some of them can be based only on expert estimate."* The crisp inputs, x1 and y1, are fuzzified against the appropriate linguistic fuzzy sets over all the membership functions used by the fuzzy rules. (Negnevisky, 2002, p.107)

Step 2: Rule evaluation

Next, the fuzzified inputs are applied to the antecedents of the fuzzy rules. The fuzzy operator (AND or OR) is used to obtain a single number (the truth-value) that represents the result of the antecedent evaluation when a given fuzzy rule has multiple antecedents, which is then applied to the consequent membership function. The OR fuzzy operation is used to evaluate the disjunction of the rule antecedents.

This is followed by clipping or scaling of the consequent membership function to the level of the truth-value of the rule antecedent through the application of the result of the antecedent evaluation to the membership function of the consequent. Clipping slices the top of the membership function and loses some information, but *"involves less complex and faster mathematics, and generates an aggregated output surface that is easier to defuzzify."*

"While clipping is a frequently used method, scaling or correlation product offers a better approach for preserving the original shape of the fuzzy set. The original membership function of the rule consequent is adjusted by multiplying all its membership degrees by the truth value of the rule antecedent This method, which generally loses less information, can be very useful in fuzzy expert systems." (Negnevisky, 2002, p.107)

Step 3: Aggregation of the rule outputs

The next step, aggregation, combines all rule consequents previously clipped or scaled into a single fuzzy set. *"Thus, the input of the aggregation process is the list of clipped or scaled consequent membership functions, and the output is one fuzzy set for each output variable."* (Negnevisky, 2002, p.110)

Step 4: Defuzzification

Defuzzification is the retranslation of the fuzzy output into a crisp value through membership functions, and there are several defuzzification methods such as Centre of Maximum (CoM) method, Centre of Area (CoA) or Centre of Gravity (CoG) method, Fast Centre of Area (Fast CoA) method, Mean of Maximum (MoM) method and Hyper Centre of Maximum (Hyper CoM) method (Von Altrock, 1995, p.235-244). According to Negnevisky (2002, p.111) *"probably the most popular one is the centroid technique. It finds the point where a vertical line would slice the aggregate set into two equal masses. Mathematically this centre of gravity (COG) can be expressed as*

$$\mathrm{COG} = \frac{\int_a^b \mu_A(x)x\,dx}{\int_a^b \mu_A(x)\,dx}$$

A centroid defuzzification method finds a point representing the centre of gravity of the fuzzy set, A, on the interval, ab."

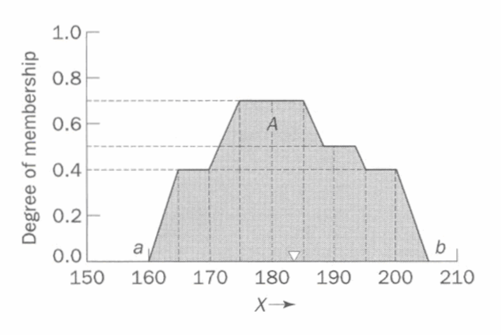


Figure 2-16: The centroid method of defuzzification (Negnevisky, 2002, p.111)

According to Von Altrock (1995, p.225-246) a disadvantage of the Centre-of-Area defuzzification method is its high computational effort and most software development tools and fuzzy logic processors use the so-called fast-CoA, which *"computes the individual areas under the membership functions during compilation to avoid numerical integration during run time. This approach neglects the overlapping of the areas; hence it is only an approximation of the 'real' CoA."* The Centre-of-Maximum (CoM) method *"first determines the most typical value for each term and then computes the best compromise of the fuzzy logic inference result. ... To obtain the best compromising value for the result of the fuzzy logic inference ... as a real number, the inference results are considered 'weights' at the positions of the most typical values of the terms. The best compromise is where the defuzzified (crisp) value balances the weights."* Where the result of the fuzzy logic inference is that no evidence exists, the Centre-of-Maximum defuzzification approach does not work and a compromise between two good solutions can lead to a bad result.

The Mean-of-Maximum Method (MoM) computes a system output only for the term with the highest resulting degree of validity, such as pattern recognition applications. In decision support systems, the choice of defuzzification method depends on the context of the decision. CoM is used for quantitative decisions, such as budget allocation or project prioritization, while MoM is used for qualitative decisions, such as credit card fraud detection or credit worthiness evaluation.

2.7.3. Artificial Neural Networks (ANN)

"A neural network can be defined as a model of reasoning based on the human brain." The human brain consists of a densely interconnected set of nerve cells, called neurons, with synapses or connections between them. A neural network exhibits plasticity, which means that *"connections between neurons leading to the 'right answer' are strengthened while those leading to the' wrong answer' weaken. As a result, neural networks have the ability to learn through experience."*

"An artificial neural network consists of a number of very simple and highly interconnected processors, also called neurons, which are analogous to the biological neurons in the brain." (Negnevisky, 2002, p.164)

A neuron as shown in Figure 2-18 below is an elementary information-processing unit. It can receive several weighted input signals x_1 to x_n and produce a single output Y. The input signals could be raw data or output signals from other neurons and the output Y could be the end result or an input signal to other neurons.

The basic structure of an artificial neural network is shown in Figure 2-19 below. *"The neurons are connected by weighted links passing signals from one neuron to another. Each neuron receives a number of input signals through its connections; however, never produces more than one output signal.… Weights are the basic means of long-term memory in ANN's. They express the strength, or in other words importance, of each neuron input. A neural network 'learns' through repeated adjustments of these weights."* (Negnevisky, 2002, p.165)

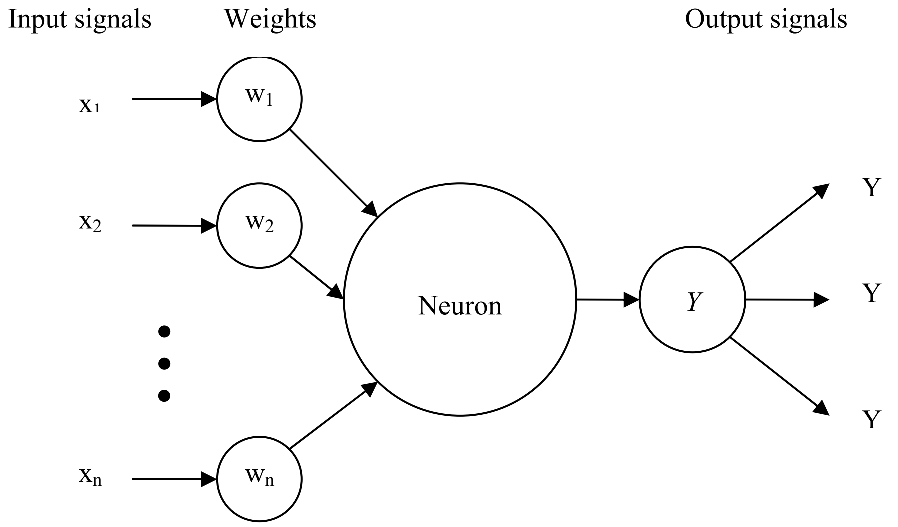


Figure 2-17: Diagram of Neuron (Negnevisky, 2002, p.166)

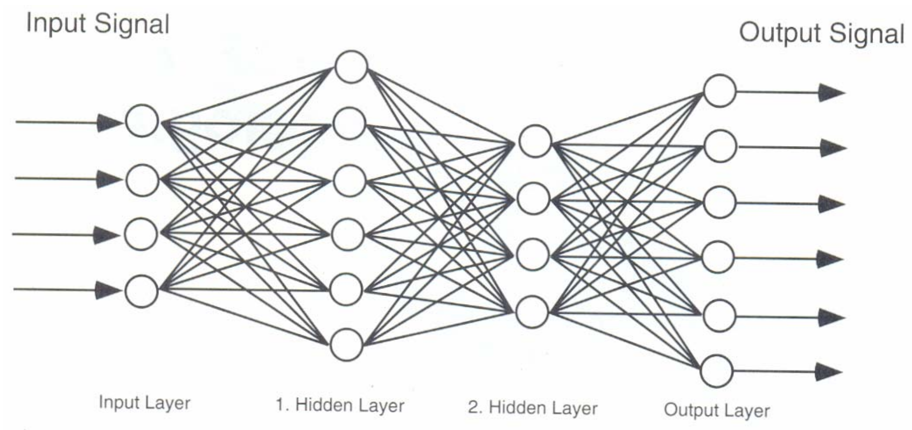


Figure 2-18: Basic structure of an artificial neural network (Von Altrock, 1995, p.64)

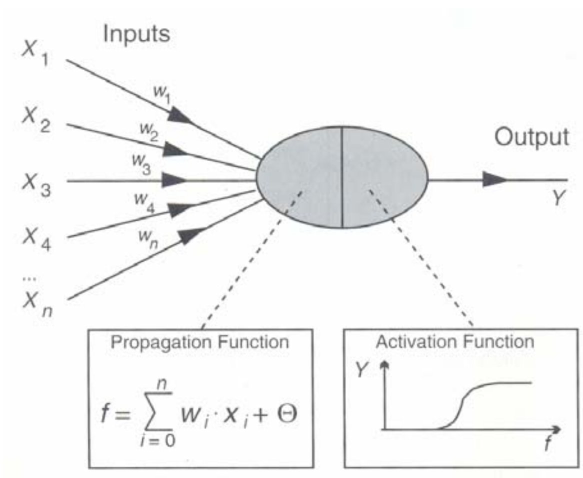


Figure 2-19: Simple mathematical model of a neuron (Von Altrock, 1995, p.66)

According to Negnevisky (2002, p.167) the neuron activation function is given by:

$$X = \sum_{i=1}^{n} x_i w_i \qquad\qquad Y = \begin{cases} +1 & \text{if } X \geq \theta \\ -1 & \text{if } X < \theta \end{cases}$$

"Where X is the net weighted input to the neuron, x_i *is the value of input i,* w_i *is the weight of input i, n is the number of neuron inputs, and Y is the output of the neuron"* and θ is a threshold value. *"This type of activation function is called a sign function. ... and can be represented as:"*

$$Y = sign\left[\sum_{i=1}^{n} x_i w_i - \theta\right]$$

According to Negnevisky (2002, p.169) the perceptron, the simplest form of a neural network and training algorithm introduced by Frank Rosenblatt in 1958, learns *"by making small adjustments in the weights"* of input signals *"to reduce the difference between the actual and desired outputs of the perceptron."*

The learning process comprises of an initially random assignment of weights, which are then adjusted to obtain outputs consistent with training examples or actual data from field assessments, pilot studies or testing (accelerated or long-term).

2.7.4. Neuro-Fuzzy Systems

On Neuro-Fuzzy systems, the combination of fuzzy logic and neural networks, Negnevisky (2002, p.266-267) stated:

> *Fuzzy logic and neural networks are natural complementary tools in building intelligent systems. While neural networks are low-level computational structures that perform well when dealing with raw data, fuzzy logic deals with reasoning on a higher level, using linguistic information acquired from domain experts. However, fuzzy systems lack the ability to learn and cannot adjust themselves to a new environment. On the other hand, although neural networks can learn, they are opaque to the user. The merger of a neural network with a fuzzy system into one integrated system therefore offers a promising approach to building intelligent systems. Integrated neuro-fuzzy systems can combine the parallel computation and learning abilities of neural networks with the human-like knowledge representation and explanation abilities of fuzzy systems. As a result, neural networks become more transparent, while fuzzy systems become capable of learning.*
>
> *A neuro-fuzzy system is, in fact, a neural network that is functionally equivalent to a fuzzy inference model. It can be trained to develop IF-THEN fuzzy rules and determine membership functions for input and output variables of the system. Expert knowledge can be easily incorporated into the structure of the neuro-fuzzy system.*

Neuro-Fuzzy is therefore the ideal application in the situation where system input initially depends mainly on expert knowledge while historical performance data is being collected, which is then used for system 'learning'.

"The structure of a neuro-fuzzy system is similar to a multi-layer neural network. In general, a neuro-fuzzy system has input and output layers, and three hidden layers that represent membership functions and fuzzy rules." (Negnevisky, 2002, p.267). Figure 3-21 shows a Mamdani fuzzy inference model and Figure 3-22 the corresponding Neuro-fuzzy system.

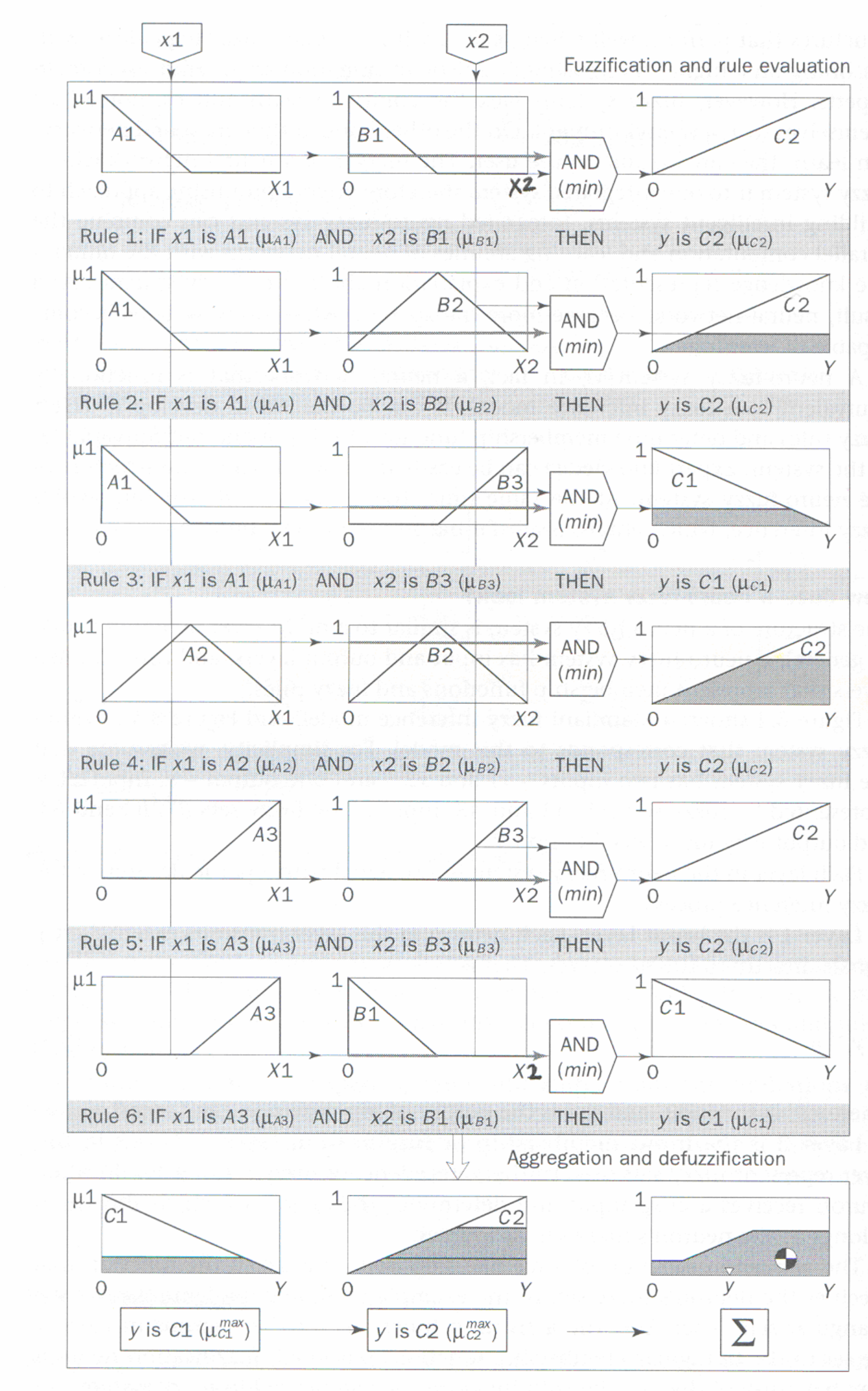


Figure 2-20: Mamdani fuzzy inference system (Negnevisky, 2002, p.268)

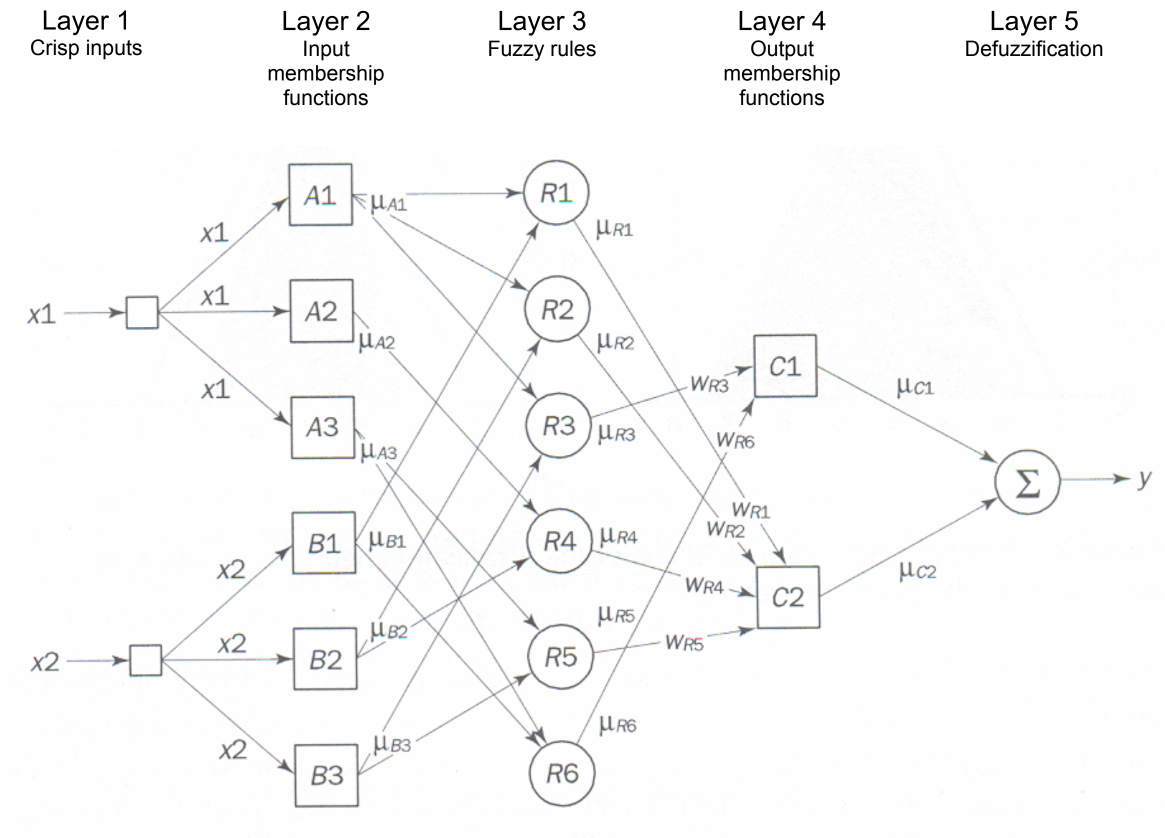


Figure 2-21: Neuro-fuzzy equivalent system (Negnevisky, 2002, p. 269)

According to Negnevisky (2002, p.271-272):

> *A neuro-fuzzy system is essentially a multi-layer neural network, and thus it can apply standard learning algorithms developed for neural networks, ... When a training input-output example is presented to the system, the back-propagation algorithm computes the system output and compares it with the desired output of the training example. The difference (also called the error) is propagated backwards through the network from the output layer to the input layer.*

2.7.5. Examples of relevant Artificial Intelligence Applications

- Assessment of the service life of bridges:

  Liang *et al* (2001, p.133), also cited by Moser (Hövde and Moser, 2004, p.78), developed a multiple layer fuzzy evaluation model for evaluating the damage state of existing reinforced concrete bridges. *"In addition, the evaluated results may also be used as a design reference for service life in future bridge building. The evaluated model may be divided into the degrees of grades I, II, III, IV, and V, which are described as nondamage (sic), light damage, moderate damage, sever (sic) damage, and unfit for service, respectively."*

- Fuzzy logic in building cost models:

  Baguley *et al* (2002) examined *"current cost modelling practices and methods, as well as fuzzy logic as a way of reducing the data in building cost models. ... using principally expert knowledge."*

- Neurofuzzy system for predicting cost and duration of construction projects:

  Boussabaine *et al* (1997) investigated *"the feasibility of developing a neurofuzzy system for predicting cost and duration of construction projects. ... The hypothesis of this study envisages that combining these methodologies would improve and benefit cost and time estimation of construction projects.* It is concluded that: *"Neurofuzzy systems offer several advantages over traditional methods for the prediction of construction projects cost and duration."*

3. RESEARCH METHODOLOGY

3.1. Introduction

The global importance of and need for sustainable socio-economic development demand an informed decision-making process. In the built environment, resources, and non-renewable resources in particular, should be used as responsible and best possible to ensure maximum service life. Central to a sustainable built environment is service life prediction, which depends on the ability to quantify the degradation rate of building fabric and components.

The Factor Method, which is the current state of the art for service life prediction, applies a number of factors to a reference service life and produces a single figure with limited application compared to the wider and more practical applications offered by the Markov Chain methodology, besides service life prediction. A number of studies (Morcous *et al,* 2003, p.353; Lounis *et al,* 1998a, p.1; Rudbeck, 1999 cited by Hövde and Moser, 2004, p.40) identified the Markov Chain, a stochastic approach used for simulating the transition from one state (condition) to another over time, as the preferred method for service life prediction and other maintenance related applications. The population of the Markov transitional probability matrix however remains a problem due to the lack of continuous, reliable and consistent historical performance data on the actual degradation rate of building materials and components.

The primary objective of this thesis is to investigate the application of artificial intelligence applications towards the development of transition probability matrices for the Markovian model based on expert knowledge and limited historical performance data.

The research methodology is based on a process that first looks at the broad principles of the degradation process and the factors affecting the rate of degradation. Next, the simulation of the degradation process through artificial intelligence applications towards the development of transition probability matrices for the Markovian model is investigated. Finally, the proposed model is tested against historical performance data from a set of academic hospitals, followed by some applications of the model.

3.2. The Degradation of Building Materials and Components

3.2.1. Introduction

A building is a complicated three-dimensional human-made configuration of a diverse range of fabrics, materials and components, each with its own characteristics, which interacts differently to the influences of its environment, could be old or brand new, raw or processed, come in different forms, shapes, sizes and finishes, and its applications could vary considerably. The environment acts on a building or component through mechanical, electromagnetic, thermal, chemical and biological agents causing degradation over time.

The vast consumption of material and energy, many non-renewable, and waste to landfill deposits due to degradation and an ever-growing need for shelter are putting the sustainability of natural resources under enormous pressure. According to Hövde (Hövde and Moser, 2004, p.9) *"... even a limited reduction in the values for material and energy consumption, or waste, ... have potential for greatly affecting the sustainability of building and construction activities."* It is therefore of critical importance to understand the degradation process and be able to quantify degradation over time.

3.2.2. The Degradation Process of Building Materials and Components

The degradation process, as illustrated in Figure 3-1 below, is a continuous interaction between durability factors, which counters degradation, and degradation factors, which promotes or cause degradation. These factors are similar to the factors used in the 'Factor Method' (ISO 15686 Part 1, 2000) and the Japanese Principle Guide (AIJ, 1993), as shown in Table 3-1 below.

Japanese Principle Guide (AIJ, 1993)	**'Factor Method' (ISO 15686 Part 1, 2000)**	**Proposed Model (Figure 3-1)**
Performance of materials	Quality of components	Material Quality
Quality of designing	Design level	Design Level
Quality of construction work	Work execution level	Workmanship Quality
Site and environmental conditions	Indoor environment	Internal Climate
	Outdoor environment	External Climate
	In-use conditions	Operational Environment
Quality of maintenance and management	Maintenance level	Maintenance Level
Condition of building		Condition (refer 3.2.5 below)

Table 3-1: Comparison between Japanese Principle Guideline, Factor Method and Proposed Model

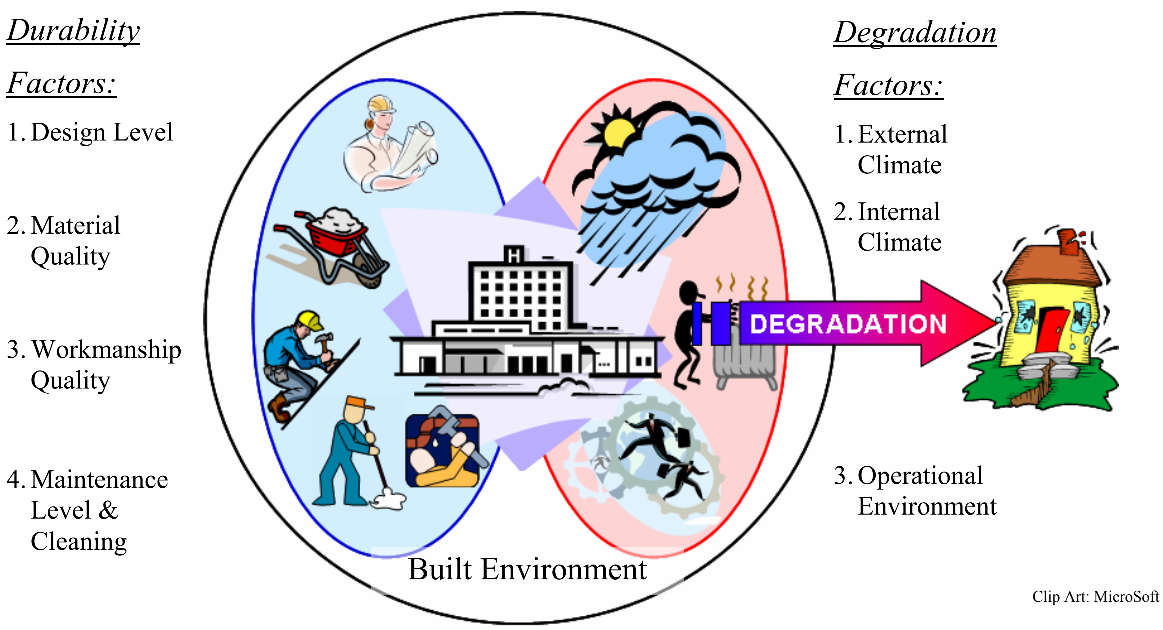


Figure 3-1: Degradation Process

The impact of these factors on the building material or component in combination with others, could improve, reduce, neutralise or aggravate the effect. Some factors, such as design level, material and workmanship quality, is determined during the planning, design and construction phase and do not change much during the service life of the building or component. External climate is a variable difficult to control, while the internal climate and operational environment can be manipulated to some degree. The maintenance level (and cleaning) is the only factor that can be controlled, following the completion of construction, to counter degradation.

In the following sections, the degradation and durability factors, affecting the degradation of building materials and components, will be looked at in broad outline and defined in linguistic terms based on a five point colour-coded rating system similar to a system used for condition assessments during the 1995 the National Health Facilities Audit (NHFA) by the CSIR. For this project, which looked at the condition, suitability and other characteristics of health facilities in South Africa, the CSIR used a five-point rating system to assess the condition and suitability. The original ratings have since been adjusted and redefined by Abbott and Mc Duling, and used with great success in subsequent audits of health and other government facilities. The objective is to define the ratings in such a way as to ensure common interpretation by assessment staff and users of the information generated by the process. (Mc Duling, 2000b).

3.2.3. Durability Factors

Durability is the ability of a building or component to resist the adverse effects of exposure to its environment. The following durability factors determine the resistance of a building or component to the impact of the environmental on the building:

a.) *Design Level*

The design level is a measure of the quality of the design or the appropriateness of the material used in the construction and protection against degradation agents provided by the design. The focus is on the location of the component relative to other components, chemical and physical incompatibility between dissimilar components, and the exposure to the climate (internal, external or both) and operational environment.

Example of chemical and physical incompatibility between dissimilar components:

Steel bolts were used to secure anodised aluminium handrails to the top of a concrete balustrade wall. The incompatibility of the two metals and the presence of moisture resulted in an electro-chemical reaction and corrosion of the bolts and reinforcing steel in the concrete. The designer should have foreseen this when the materials were specified at design stage. An experienced contractor should also pick this up during installation.

Appropriate technology falls under this factor. It is particularly evident in new public hospitals, where inexperienced consultants are appointed to design and specify components and systems in highly specialised areas without proper experience in hospital design, construction and operation. The result is that inappropriate technology, materials, components and systems are specified and installed (often incorrectly), and hospital and maintenance staff are stuck with the problems after the consultants and contractors have left the site. Sometimes this technology is the 'state of the art', but due to the location of the facility, technical support and spare parts may not be readily available or there may not be suitably trained and experienced staff on site to meet its operational requirements, with the result that this 'state of the art' technology becomes a 'state of the art' problem for the users of the facility while the equipment cannot be used.

Design level is categorised as follows:

- 5 – 'Very High': the component is ideal and very suitable for the application and its location in the building provides effective protection against degradation agents, there are suitably trained and experienced maintenance and support staff and spare parts available on site, the component is easily accessible for maintenance, repairs and replacement without damage to the component or surrounding components

- 4 – 'High': the component is suitable for the application and its location in the building provides protection against degradation agents, there are suitably trained and experienced maintenance and support staff and spare parts available at short notice, the component is accessible for maintenance, repairs and replacement without damage to the component or surrounding components

- 3 – 'Medium': the component is acceptable for the application and its location in the building provides some protection against degradation agents, maintenance and support staff or spare parts are available, but not on short notice, the component is accessible for maintenance, repairs and replacement with some damage to the component or surrounding components

- 2 – 'Low': the component is unsuitable for the application and partially exposed to degradation agents, maintenance and support staff or spare parts may be available, but difficult to get hold of, the component is not accessible for maintenance, repairs and replacement without damage to the component or surrounding components

- 1 – 'Very Low': the component is totally unsuitable for the application and completely exposed to degradation agents, there are no maintenance and support staff or spare parts available, the component is not accessible for maintenance, repairs and replacement

b.) *Maintenance Level*

The maintenance level is an extremely important factor throughout the service life of any building or component. When the construction of the building is completed, the other durability factors (design level, material and workmanship quality) are already determined and little can be done to manipulate these factors during the balance of the service life. On the other hand, the maintenance level can be adjusted as required throughout the service life. Maintenance level is determined by the type, appropriateness, frequency, objective and effectiveness of the maintenance actions, control and management.

Maintenance levels can be categorised as follows:

- 5 – 'Very high': Planned preventative maintenance forms the basis of a regular maintenance programme. The objective is to prevent degradation and ensure optimum performance of the component on a continuous basis. Pro-active maintenance.
- 4 – 'High': Planned and unplanned condition-based maintenance, identification of degradation or failures and scheduling of maintenance activities to return the component to a level where its performance will meet requirements
- 3 – 'Normal': Focus is on repairs and 'so-called' day-to-day maintenance, planning focussed on routine tasks,
- 2 – 'Low': Ad hoc repairs or replacements; wait until failure, then repair or replace. Reactive maintenance, no planning involved.
- 1 – 'Very low': No or very little maintenance, only absolutely essential repairs or replacements (often with used parts)

The principles of material and workmanship quality, as discussed below, also applies to maintenance level, because that is when most new materials and components are installed after completion of the initial construction. Cleaning practises should also be taken into consideration. A good example is hospital floors, where the wrong cleaning products are often used unknowingly by ignorant cleaners due to a lack of training and involvement, while expensive floor covering is being destroyed in the process.

c.) *Material Quality*

This factor is a measure of the suitability, durability, resistance to degradation, appearance, dimensional variations, structural soundness and quality of treatment and preparations of the component as supplied to site.

Material Quality ratings are categorised as follows:

- 5 – 'Very High': The material as supplied to site is ideal for the intended application, durable and a high resistance to degradation agents, is aesthetically pleasing, has the correct dimensions and tolerances, a sound structure without flaws, and received the specified treatment and preparation strictly in accordance with manufacturers' recommendations and tightly controlled.

- 4 – 'High': The material as supplied to site is suitable for the intended application, durable and resistant to degradation agents, has the correct dimensions and acceptable tolerances, and a sound structure with acceptable flaws, and received the specified treatment and preparation in accordance with manufacturers' recommendations.

- 3 – 'Medium': The suitability of the material as supplied to site is acceptable for the intended application, durability and resistance to degradation agents are average, the variation in dimensions and tolerances is acceptable, and its structure has acceptable flaws, and the material received the specified treatment and preparation but not in accordance with manufacturers' recommendations.

- 2 – 'Low': The material as supplied to site is not really suitable for the intended application, has a low durability and resistance to degradation agents, is aesthetically not pleasing, has inconsistent dimensions and a structure with flaws, and the material received some treatment or preparation but not in accordance with manufacturers' recommendations.

- 1 – 'Very Low': The material as supplied to site is unsuitable for the intended application and not durable, has almost no resistance to degradation agents, is aesthetically unpleasing, does not have the correct dimensions and its structure is full of flaws, and did not received any treatment or preparation in accordance with manufacturers' recommendations.

d.) Workmanship Quality

There is a saying in the construction industry that 'a good artisan can fix a poor design', in other words, good workmanship on site can, to some extent, compensate for poor design details and materials. Inexperienced and/or ill-equipped construction staff can destroy the best designs, specifications and materials, while the opposite is also true. This also applies to maintenance, where the consequences of poor workmanship by inexperienced maintenance staff can cost a fortune. An example is the replacement of hinges on fire doors in a major public hospital with industrial rising hinges resulted in artisans cutting off the top of the fire doors to prevent them jamming, which destroyed otherwise good fire doors, negated the primary purpose of the door, and totally compromised fire compartmentation, which seriously increased the fire risk to occupants. Tight control on site to ensure the site work is in accordance with manufacturers' recommendations is of utmost importance. The likelihood of achieving the desired level of workmanship, protection during storage, handling and installation should also be assessed.

Workmanship Quality ratings are categorised as follows:

- 5 – 'Very High': The level of skill and control in site work is strictly in accordance with manufacturers' recommendations and tightly controlled by experienced supervisors. The maintenance staff is a professional outfit with all the required trades, properly trained, equipped and experienced to ensure the likelihood of achieving the designed level of workmanship and installation. Proper procedures are in place and closely monitored to ensure protection during storage, handling and installation.

- 4 – 'High': The level of skill and control in site work is in accordance with manufacturers' recommendations and controlled. The maintenance staff is trained, equipped and experienced. There are procedures in place to ensure protection during storage, handling and installation.

- 3 – 'Medium': There is some skill and control in site work. The maintenance staff is trained, equipped and experienced, and may be able to achieve the designed level of workmanship and installation. There is some protection during storage, handling and installation.

- 2 – 'Low': There is very little skill and control in site work. The maintenance staff has some training, equipment and experience but not enough to ensure the likelihood of achieving the designed level of workmanship and installation. There is very little protection during storage, handling and installation.

- 1 – 'Very Low': There is no level of skill or control in site work. The 'maintenance staff' is not trained, equipped or experienced. There are no procedures in place to ensure protection during storage, handling and installation.

3.2.4. Degradation Factors

The environment in and around a building can be divided into a physical and operational environment. The physical environment is determined by the climate in and around the building or component. If the component under consideration is an external component, the external climate should be considered, and likewise the internal climate for an internal component. There are however components where both the external and internal climates should be considered, such as external walls where both climates could affect the degradation process.

a.) External Climate

The macroclimate in the South African context plays a major role in degradation, as can be seen from Weinert (1980), Brink (1978) and CSIR (1985). Weinert's work was based on the weathering of Karoo dolerite, commonly found throughout South Africa and besides road construction, also used as aggregate in concrete. The point is that dolerite is a natural material as most of the materials used in building construction. Some of the materials are used in their natural state while others are processed or combined with other materials. The addition of bonding materials and chemicals during the processing of these materials could change the characteristics of the natural material to some extend (e.g. galvanising of steel, anodising of aluminium), but the base material will remain the same.

Weinert's N-values are based on rainfall and evaporation. Water can only contribute to the degradation process if it is present on the surface of material (the microclimate). The evaporation of surface water is determined by the humidity of the surrounding air and the temperature of the surface and the surrounding air.

In the Namib and Kalahari deserts there are known cases of vehicle wrecks that have been standing in the desert for many years almost without any sign of corrosion of the metal. It is also common knowledge that on the wetter eastern coastline of South Africa (Weinert's N-value < 2) corrosion of metal is a major problem, while in regions with an N-value > 5, corrosion is less problematic. Mould growth is another scourge of the coastal regions, which is almost unknown in the drier regions. In regions with an N-value < 5 special attention should be given to the impact of water on the degradation process.

There is an interesting difference between the eastern coastal areas and the Western Cape, both with an N-value < 5. In KwaZulu Natal, a summer rainfall region, there are lots of moisture (rainfall season) and heat (hot summer months), but because of the high humidity of the air, evaporation is low, resulting in an aggressive environment for buildings. In the Western Cape, a winter rainfall region, the temperatures are low during the rainfall season resulting in low evaporation of surface water; again an aggressive environment in terms of degradation processes less dependent on temperature.

However, water is not the only degradation agent found in the external climate. Electromagnetic processes, especially in the drier and hotter parts of the country (N-value > 5), could in combination with high temperatures have a very negative impact on the degradation patterns of building materials. Ultra-violet radiation is harmful not only to humans, but also to building materials, and its effect should not be underestimated.

The Weinert N-values can be used to categorise the macroclimate in South Africa for the degradation of building materials, but with circumspection. Other degradation factors should also be taken into consideration. In general the classification of the CSIR (1985) as shown in Figure 2-5, could be quite useful, if the applicable degradation processes are taken into consideration. The dry regions (N-value > 5) could in general be classified as 'favourable', the moderate areas (2 < N-value < 5) as 'less favourable', and the wet areas (N-value < 2) as 'slightly aggressive'. Again, this should not be applied blindly as certain materials could be more vulnerable to degradation in dry and hot conditions.

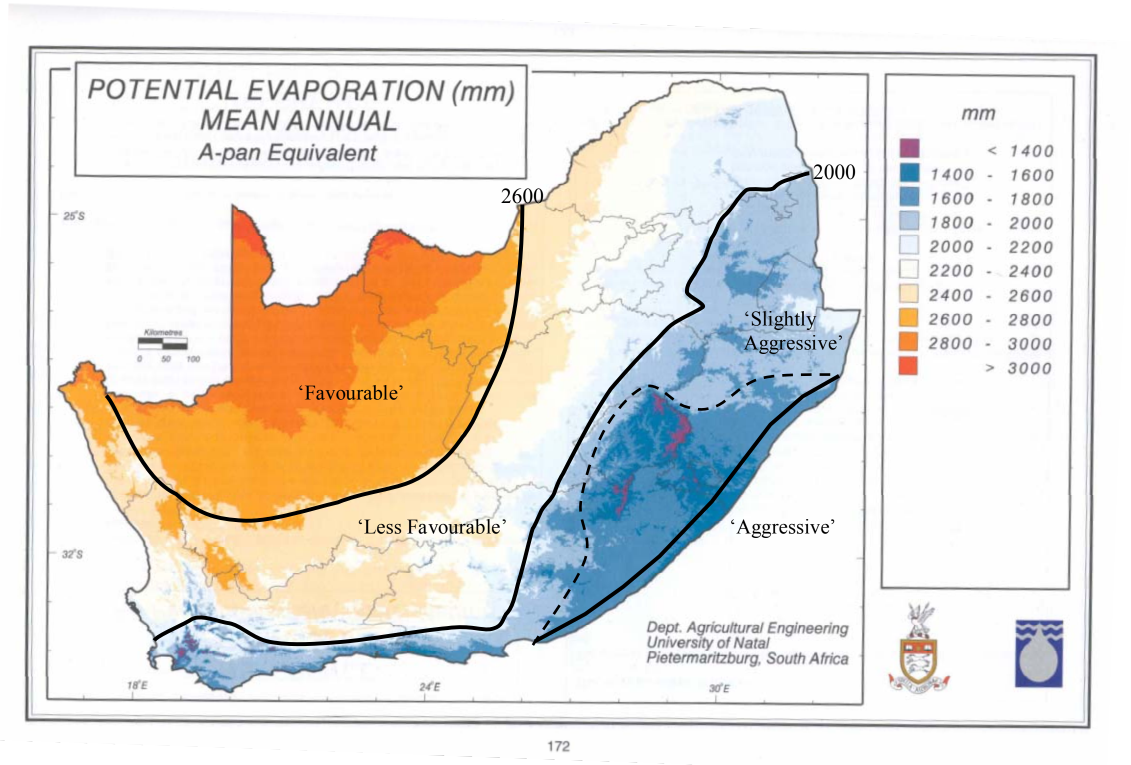


Figure 3-2: Proposed Macroclimate Zone Classification for Chemical and Biological Degradation Agents (Base map: University of Natal)

In Figure 3-2 above the proposed climate zones for chemical and biological degradation agents are shown on a Potential Evaporation map by the Department of Agricultural Engineering, University of Natal. The proposed zones correspond with the TRH4 (CSIR, 1985) zones for roads. There are three macroclimate zones, with a fourth zone along the narrow eastern and southern coastal belt, where corrosion is a problem. This corresponds to the map in Figure 2-9 showing the levels of atmospheric corrosion of zinc. The broken line indicates an area where the macroclimate could be classified as 'aggressive' in the case of biological degradation.

In the western regions mechanical, electromagnetic and thermal degradation agents are more dominant and the classifications are as shown in Figure 3-3 below should apply.

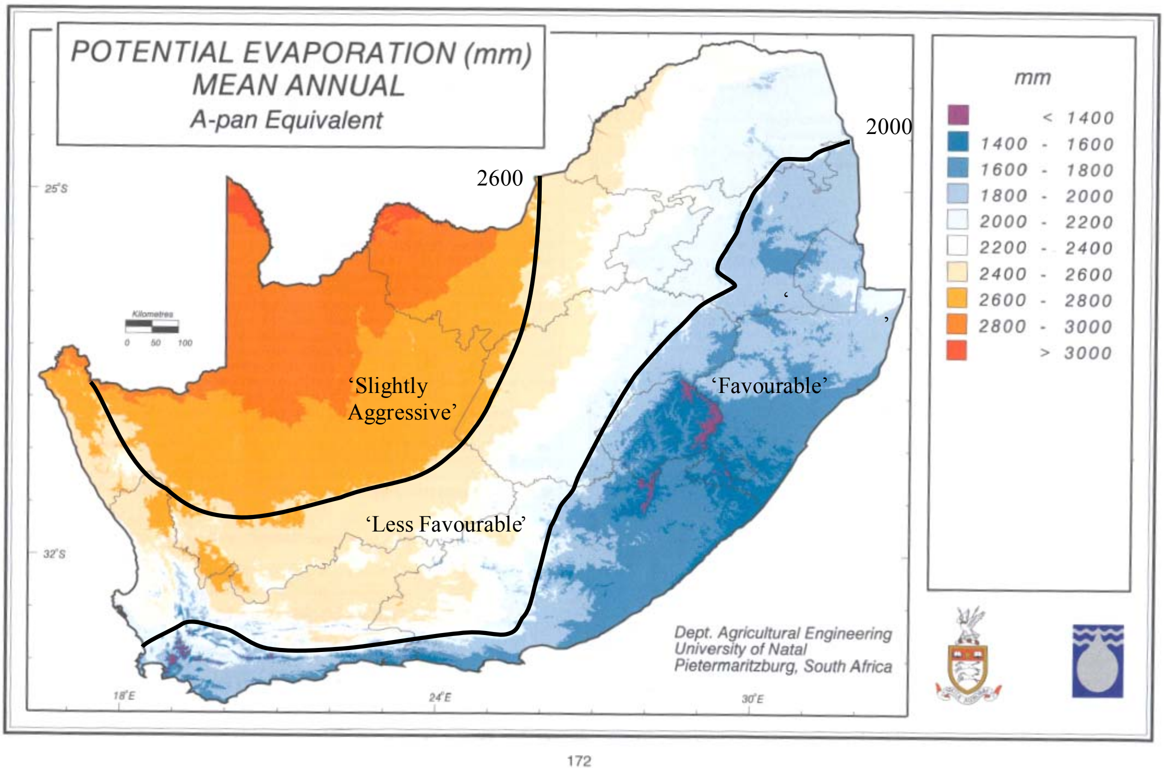


Figure 3-3: Proposed Macroclimate Zone Classification for Mechanical, Electro-magnetic and Thermal Degradation Agents (Base map: University of Natal)

Figures 3-2 and 3-3 are however only indicative of macroclimate zoning and need further investigation, development and refinement. A particular macroclimate might be aggressive towards one component, but favourable for another. An evaluation of the macroclimate should therefore be based on an impact analysis of the prevailing degradation agents applicable to the material (i.e. chemical, biological, mechanical, electromagnetic or thermal) in the region under consideration.

The mesoclimate should also be considered, especially in major industrial and surrounding areas, where air and water pollution could be a problem (e.g. Witbank/Middelburg and Secunda areas in Mpumalanga and Sasolburg/Vanderbijlpark/Vereeniging triangle in Gauteng). Acid rain, caused when fossil fuels are burnt (e.g. coal-fired power stations) and sulphur is released into the air, has a major impact on degradation of building materials and should be taken into consideration where applicable.

The topographical location and orientation of the building could have a major impact. An interesting observation was made at a major health facility in the Western Cape where, after thirty years, the jointing mortar between the face bricks on the northern and western facades were more degraded than the eastern and southern facades. This could be attributed to the difference in the cyclic drying and wetting, and direct exposure to prevailing winds, driving rain and sunlight.

Jointing mortar on the southern facade

Jointing mortar on the northern facade

As a 'rule of thumb', the external climate should be classified as 'aggressive' to 'slightly aggressive' if buildings are in or down-wind from heavily polluted industrial areas'. Should the macroclimate have a classification of 'slightly aggressive' and the mesoclimate is 'aggressive', the external climate could become 'aggressive' to 'very aggressive' depending on the microclimate or space in the absolute proximity of a material surface. Here the design level should also be considered to determine the level of protection offered by the design and installation of the component.

The combined effect of all three external climate levels (macro, meso and micro) should be taken into consideration, with microclimate being the decisive factor.

The external climate factor ratings are categorised as follows:

- 5 – 'Favourable': Degradation agents (individually and/or in combination with others) have very little or no effect on the building or component (e.g. sheet metal roof in the Kalahari region).
- 4 – 'Less Favourable': The building or component is exposed to degradation agents from time to time. The dosages are relatively low and of short duration.
- 3 – 'Slightly Aggressive': The building or component is exposed to degradation agents for longer periods. Areas where large temperature variations, strong winds, heavy driving rain, hail and snow, earth tremors (mining areas) occur.

- 2 – 'Aggressive': The building or component is exposed to high doses of degradation agents (e.g. industrial areas where pollution is problematic), where a combination of degradation agents are present (e.g. moisture and heat) on the surface of the component (microclimate) most of the time.

- 1 – 'Very Aggressive': The building or component is constantly and directly exposed to very aggressive degradation agents (e.g. unprotected steel exposed to salt-spray or within 50 meters from the high water mark on the east coast)

b.) Internal Climate

The internal climate is easier to control and generally has a less negative impact on the degradation process. However, there are spaces in buildings where the internal climate could be extremely aggressive, such as plantrooms, kitchens, laboratories, laundries and bathrooms where the combination of heat, water, steam and chemicals could create hostile environments.
The internal climate factor ratings are categorised as follows:

- 5 – 'Favourable': The component is effectively protected against or not exposed to degradation agents

- 4 – 'Less Favourable': The component may be exposed to dust, dry or humid air, variations in temperature or direct sunlight

- 3 – 'Slightly Aggressive': The component may be exposed to dust, heat, water, steam, chemicals, oil, fuel and/or effluent (sewage, blood, etc.) for short periods of time

- 2 – 'Aggressive': The component is exposed to dust, heat, water, steam, chemicals, oil, fuel and/or effluent (sewage, blood, etc.) most of the time

- 1 – 'Very Aggressive': The component is constantly exposed to a combination of dust, heat, water, steam, chemicals, oil, fuel and/or effluent (sewage, blood, etc.)

c.) Operational Environment:

The operational environment, or human interface, is determined by the level and extent of the utilisation of the building by the occupants. Another way to express this term could be the 'user culture'. The aggressiveness or 'friendliness' of the operational environment is determined by the type, level and intensity of the activities and utilisation. Mechanical processes play a major role in the operational environment. The level of maintenance and cleaning is sometimes also taken into consideration with utilisation to determine the operational environment of a building. In the case of the 'Factor Method' this approach could result in 'double counting', because maintenance level is a factor in its own right.

The operational environment factor ratings are categorised as follows:

- 5 – 'Favourable': Areas where the component is not effected by the activities in or the utilisation of the building or component

- 4 – 'Less Favourable': Areas where the activities in or the utilisation of the building or component does have some effect on the component. This would be the standard operational environment

- 3 – 'Slightly Aggressive': Heavily utilised areas (e.g. entrances to public buildings, passages, lifts)

- 2 – 'Aggressive': Areas where vandalism is normally a problem (e.g. public and school toilets, train and bus stations), or where the activities are aggressive and of mechanical nature (e.g. light industrial workshops, large kitchens and warehouses – use of forklifts), over utilised areas

- 1 – 'Very Aggressive': Areas where the building or component is constantly exposed to intense and rough, 'almost violent', activities causing extensive damage to the building or component (e.g.

factories, heavy industrial plants and workshops were there are mechanical vibrations and impact)

3.2.5. Condition

The "fitness" of a building is determined by the age and current condition of the building. Just like the human body, a building needs to be fit to withstand the onslaught by the environment.

It is interesting to note that age and condition are not identified as factors in the 'Factor Method' or international research papers, except for the Japanese Principle Guideline (AIJ, 1993), which identified condition. This is difficult to understand, because the remaining service life of a building or component depends very much on the current condition, age and maintenance level. An explanation for this could be that the focus is very much on the service life of new buildings and improvement of new components, which is understandable. One of the main objectives of research is to improve our environment and the focus should be strong on the future, but the existing should not be forgotten. The importance of maintenance of existing buildings in developing countries is totally underestimated and the prediction of the remaining service life for existing buildings is essential to persuade decision-makers of the consequences of neglect, and importance and necessity of proper maintenance. Developing countries simply cannot afford the luxury to replace existing buildings while the need for shelter is growing by the day.

The current condition of existing buildings and components should be brought into consideration when calculating the remaining service life. The current condition has a major impact on the degradation rate. The better the current condition, the slower the degradation rate, and vice versa.
The current condition is rated on a five point scale (see Table 3-1 below), based on the type of maintenance work required as a result of the condition. Linguistic terms and colour are used to ensure optimum user friendliness for non-technical persons.

- 5 – 'Very Good': the condition of the component is 'as new' and only planned preventative maintenance is required to maintain the condition

- 4 – 'Good': degradation has set in and planned and/or unplanned condition-based maintenance actions, including minor repairs, are required as a result of the current condition

- 3 – 'Fair': the component is still functional, but major repairs are required to return its condition to a level where it fully complies with the required level of service

- 2 – 'Bad': the component is still functional, but in need of rehabilitation (replacement of sections and extensive repairs) to return its condition to a level where it fully complies with the required level of service

- 1 – 'Very Bad': the component is 'dysfunctional' and needs to be replaced

3.2.6. Degradation Rate

The degradation rate, which is the rate of change in the condition of the building or component over time, is determined by the current condition and durability of the building or component, the level of exposure to its environment and the maintenance level, as illustrated in Figure 4-4 below.

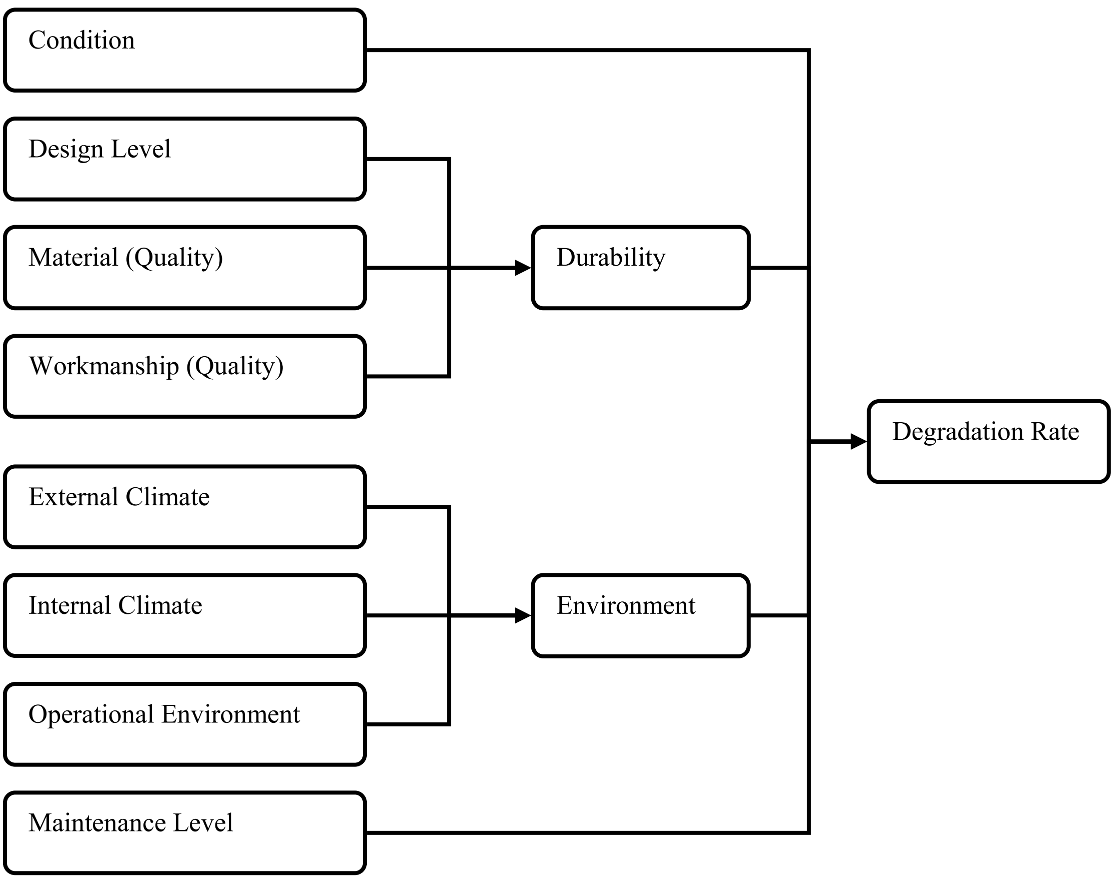


Figure 3-4: Diagram illustration the factors influencing degradation rate

Durability is determined by the design level and the quality of material and workmanship. It is a measure of the resistance to the impact of the mechanical, electromagnetic, thermal, chemical and biological degradation agents present in the environment in and around the building or component. The maintenance level together with the durability and environmental (degradation) factors are similar to the factors of the 'Factor Method'. The 'Factor Method' does however not provide for the current condition of the building or component (refer Table 3-1 above).

If the performance criterion is an acceptable condition, the service life of a building or component is determined by the change in condition over time. Because the durability and environmental factors that influence the change in condition over time are determined during the planning, design and construction phases (see Figure 3-5 below) the objective should be to control this change within limits. Thereafter it becomes difficult to manipulate these factors. Subsequent to construction the degradation rate is determined to a large extend by the level of maintenance.

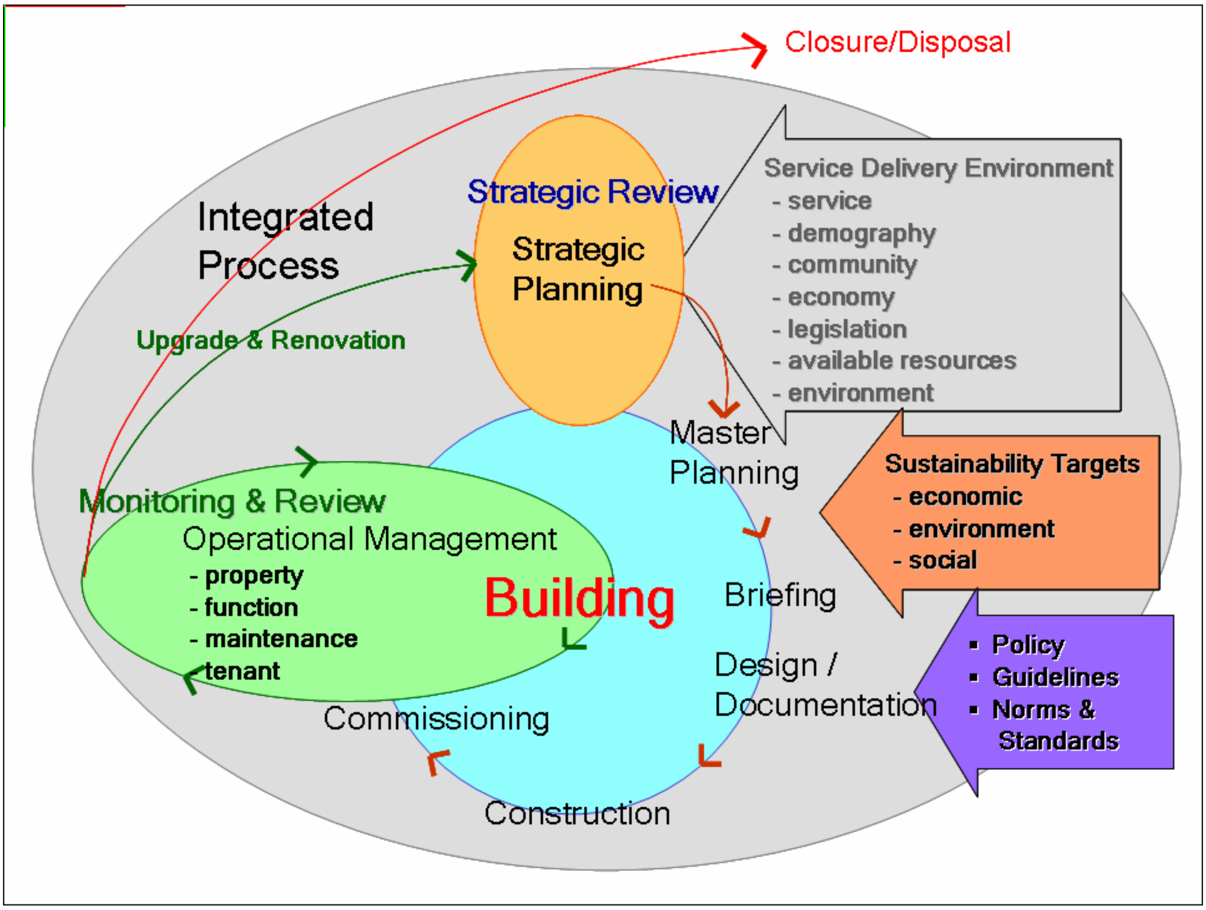


Figure 3-5: Building Life Cycle (Abbott, 2005)

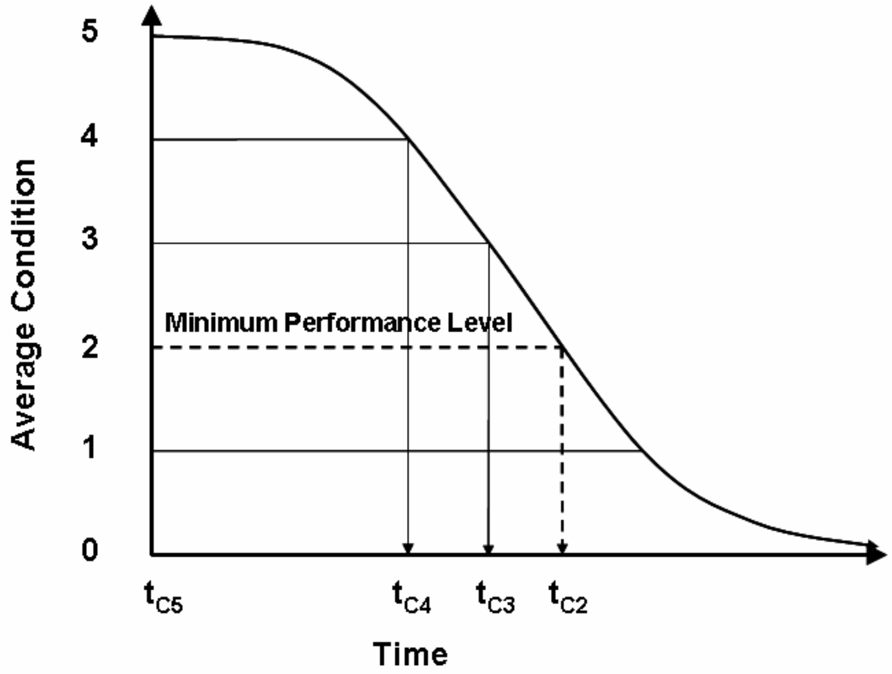


Figure 3-6: Change in condition over time (hypothetical)

The service life of a building or component is the period after construction *"during which all conditions of a building or a building part meet or exceed the performance requirements"* (Jernberg *et al*, 2004). If the minimum performance level is an average condition of 2, as illustrated in Figure 3-6, the service life of the building or component is $t_{c2} - t_{c5}$, where t_{c2} is the point in time when the performance level, average condition in this case, has reached the minimum performance level, and t_{c5} is the point in time when construction is completed and the average condition is equal to 5.

When exactly the degradation process starts will vary from component to component and is debatable. Initially the degradation rate is slow and it may be difficult to detect any degradation because the surface of the component usually appears still 'new', but slowly over time as the degradation processes set in the appearance starts to change and degradation becomes more obvious. However, degradation is not always visible and from the outside the component may appear to be still in a very good condition, while on the inside it could be totally rotten (e.g. wood) or corroded (e.g. reinforcing steel in concrete). Latent defects are one of the reasons why condition assessments should be done by suitably qualified and experienced people or 'forensic experts, who can see beyond the obvious'.

3.2.7. Condition ratings and assessment consistency

During 1995, the National Department of Health commissioned the CSIR to undertake the National Health Facilities Audit (NHFA). For this project, which looked at the condition, suitability and other characteristics of health facilities in South Africa, the CSIR used a five-point rating system to assess the condition and suitability. The original ratings have since been adjusted and redefined by Abbott and Mc Duling, and used with great success in subsequent audits of health and other government facilities. The objective was to define the ratings in such a way as to ensure common interpretation by assessment staff and users of the information generated by the process.

CONDITION RATING	Condition	Action Required	Description
5	Very Good	Planned Preventative Maintenance	The component or building is either new or has recently been maintained, does not exhibit any signs of deterioration
4	Good	Condition-based Maintenance	The component or building exhibits superficial wear and tear, minor defects, minor signs of deterioration to surface finishes and requires maintenance/servicing. It can be reinstated with routine scheduled or unscheduled maintenance/servicing.
3	Fair	Repairs Required	Significant sections or component require repair, usually by a specialist. The component or building has been subjected to abnormal use or abuse, and its poor state of repair is beginning to affect surrounding elements. Backlog maintenance work exists.
2	Bad	Rehabilitation Required	Substantial sections or component have deteriorated badly,suffered structual damage or require renovations. There is a serious risk of imminent failure. The state of repair has a substantial impact on surrounding elements or creates a potential health or safety risk.
1	Very Bad	Replacement Required	The component or building has failed, is not operational or deteriorated to the extent that does not justify repairs, but should rather be replaced. The condition of the element actively contributes to the degradation of surrounding elements or creates a safety, health or life risk.

Table 3-2: Colour-coded Condition Ratings (Abbott & Mc Duling, 2004)

The introduction of colour coding attached to the ratings ensured maximum user friendliness, especially to people without a built environment background (such as medical, education, financial, etc.) and improved communication, which was identified by Mc Duling (2003) as one of the major problems in the built environment.

Condition focuses on the degree to which the materials or components used in the building have deteriorated through either normal wear and tear or exposure and is exacerbated, amongst others, by the level of maintenance and repair work undertaken (or not undertaken), vandalism, poor choice and quality of materials or poor workmanship. Poor condition influences the function or services accommodated and can be so severe as to create situations where safety, health or life could be at risk.

Maintenance and backlogs funding provision is determined by the current condition offset against the current construction cost for a new facility, i.e. the amount required to bring the existing facility up to an 'as new' condition. The maximum provision is current construction cost plus, in the case of replacement, possible disposal or demolition costs.

Parameter rating	Condition 5 (%)	Condition 4 (%)	Condition 3 (%)	Condition 2 (%)	Condition 1 (%)
Component	a	b	c	d	e

a + b + c + d + e = 100%

Table 3-3: Condition rating

Condition rating, as illustrated in Table 3-2 above, is an often-misunderstood concept. An assessment of 2 implies that the whole component is in condition 2. In the event of a small component, this might be true, but in most cases, the condition of the component can be spread over more than one condition category. If 10% of a component is in condition 1 and needs replacement, while 90% is in condition 4 and only requires condition-based maintenance, the single rating approach will result in a condition rating of 4 and the 10% in condition 1 will disappear and most probably remain unattended. The correct way is to rate each condition category as illustrated in Table 3-3 above. A single rating would resulted in an average condition of 4, while the actual average condition is 3.7

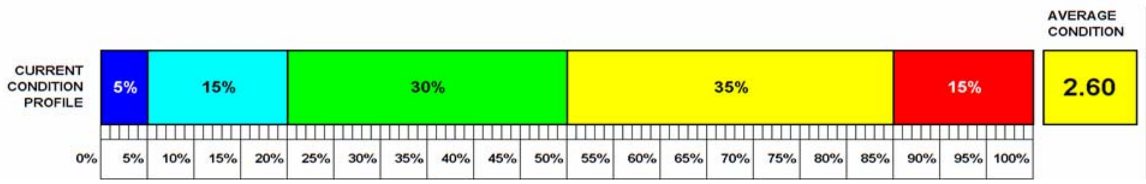


Figure 3-7: Typical Condition Profile

In Figure 3-7 above, where a = 5%, b = 15%, c = 30%, d = 35% and e = 15%, the average condition = 0.05 x 5 + 0.15 x 4 + 0.30 x 3 + 0.35 x 2 + 0.15 x 1 = 2.60

The added advantage of the proposed condition rating is illustrated in Figure 3-7. The condition profile not only gives an insight in the actual condition of the component or building, but it is essential for budget calculations, because as the condition deteriorates the cost of the maintenance action increases. In the above example, illustrated in Figure 3-7, the maintenance of the 50% in conditions 5, 4 and 3 will cost 4 times less than the 50% in conditions 2 and 1.

The importance of consistency of assessments cannot be overemphasized. Assessment staff or inspectors should have a background and appropriate experience in the built environment, and be properly trained and calibrated to ensure common and consistent interpretations and assessments between assessments (time), buildings (location), and individuals (people). The ideal situation would be to send the same person to assess the condition of a specific building or component year after year, but this is seldom possible. It is therefore necessary to calibrate assessment staff to ensure common and consistent interpretations or the rating system. It is also important that the same person do a consistent assessment of different buildings or components to ensure that you compare *"apples with apples"* when the assessment results of these buildings or components are compared. There are known cases where the importance of this has been overlooked by decision-makers resulting in millions 'being wasted' because the results could not be compared on an equitable basis. Data collected during condition assessments is very valuable information for decision-makers, if it is consistent and reliable. Unfortunately there is a general belief that any building professional (architect, engineer or quantity surveyor, etc.) can do condition assessments based on their academic training. The reality is that the tertiary institutions responsible for the training of these professionals, provide very little or no training in maintenance of buildings and components, let alone condition assessments. What is needed is a person that can identify latent defects and see *'beyond the obvious'* – the person must be able to asses what caused the degradation or failure and what course of action is required to treat the cause and rectify the situation. This is only possible with experience and practical training. The other unfortunate rule rather than the exception is the use of inexperienced junior persons (e.g. students) to do these assessments because they cost less than more experienced persons, resulting in questionable quality of information.

The use of consultants must be carefully controlled and monitored. Quality assurance checks should form an integral part of the assessment process to prevent hidden agendas by the consultants who might assess the condition of the building or component lower in the hope of getting an appointment to repair, rehabilitate or replace the building or component. Another problem is executives attending briefing and training sessions, while junior staff, who did not attend the training, does the fieldwork.

The best assessments are done by the so-called works inspectors, commonly found in government departments. These people are normally trained artisans who came through the ranks with years of experience in maintenance work. They have dirtied their hands and ‘can see beyond the obvious’ because they have the experience in doing the maintenance or repairs and are ‘forensic experts’ in their own right. It is however still necessary and important to train them properly in assessment procedures to ensure consistency and reliability of the data.

Another important consideration is the use of well-defined and consistent assessment procedures and rating systems. Needs and experience change with time and create the need for revision of the assessment process and ratings. Caution should however be taken not to introduce changes that could render previous assessment data incompatible with future assessments.

3.3. The Application of Artificial Intelligence to Simulate the Degradation Process

3.3.1. Introduction

Available information on the actual degradation of building materials and components is largely limited to supplier or manufacturer specifications on some materials, scattered and inconsistent field assessments and the opinion of degradation experts. Incompleteness of available information is a major problem with specifications and field assessments, while *“experts cannot always express their knowledge in terms of rules or explain the line of their reasoning. ... experts do not usually think in probability values, but in terms as often, generally, sometimes, occasionally and rarely.”* (Negnevisky, 2002, p.15). Information sources are therefore limited, incomplete, inconsistent or ‘fuzzy’.

Long-term field-testing is an expensive and time-consuming process, while accelerated testing has limitations and cannot guarantee reliable results due to the complexity of the degradation process and the many factors influencing it. Research is also mainly limited to manufacturers and focussed more on the development of new materials and products, while information is often biased and based on accelerated testing.

The proposed solution to this dilemma is based on the use of expert opinion supplemented by available specifications and field assessment data. As more data becomes available through regular and consistent field assessments and the quality of the information constantly improves through experience and calibration of the assessment staff, a more reliable and consistent database will develop. A system is therefore needed to translate the knowledge and reasoning of experts into probability values while using a growing database to calibrate, learn and improve its reliability and ability to simulate the degradation process, providing for various combinations and dosages of the factors effecting degradation.

3.3.2. Selection of an appropriate Artificial Intelligence system

The selection of a suitable system was guided by the need for a system with an ability to accommodate the lack of existing data on the degradation rate by using expert opinion, and use field data as it becomes available to calibrate itself and become more accurate in terms of the actual degradation process. AI applications, such as expert systems, fuzzy logic systems, artificial neural networks and genetic algorithms were explored and the Neuro-Fuzzy artificial intelligence application was selected as the most appropriate system because it can deal with linguistic variables and fuzzy IF-THEN rules of the expert thought process (fuzzy logic) and is capable of learning (artificial neural networks) at the same time.

The fuzzy logic AI application however comprises of a large number of rules and requires the use of a software system. Demo versions of a number of software systems, available as free downloads on the internet, were identified and tested. The FuzzyTECH 5.55c professional edition system, developed by Inform GmbH of Germany was selected as the most suitable of the systems tested and a licence was obtained for the use of the software.

3.3.3. Fuzzy Logic

a.) Structure of the fuzzy logic system

The system structure identifies the fuzzy logic inference flow from the input variables to the output variables. The fuzzification in the input interfaces translates analogue inputs into fuzzy values. The fuzzy inference takes place in IF-THEN rule blocks, which contain the linguistic control rules. The output of these rule blocks is linguistic variables, which are translated into analogue variables through defuzzification in the output interfaces.

Figure 3-8 below shows the structure of the fuzzy system including input interfaces, rule blocks and output interfaces. The connecting lines symbolise the data flow. The input variables are the durability and degradation factors influencing the degradation of the material or component, defined in linguistic or fuzzy terms. These factors are similar to the factors used in the Factor Method, except for the valuation or rating of the factors. A five point colour-coded rating system is used based on the rating system used for condition assessments.

The output variable, degradation rate, is expressed as the percentage of the material or component that changes from one condition to the next worst condition during one time interval. This interval, which could vary from material to material, is determined by the time required for the material to change from one condition to the next worst condition without jumping more than one-step at a time in order to keep the model as simple as possible and dictates the assessment frequency. The degradation rate is the transition probability required for the Markov process.

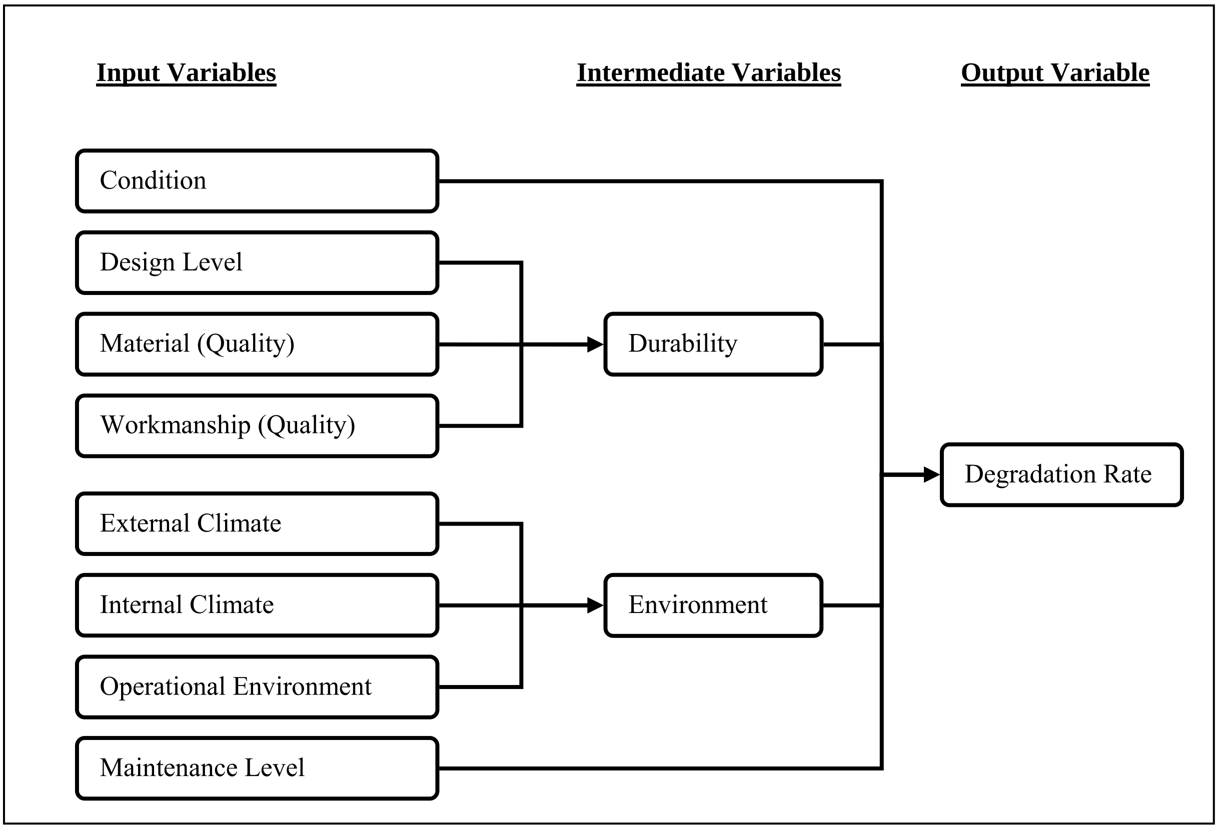


Figure 3-8: Structure of the Fuzzy Logic System

b.) Variables

This section contains the definition of all linguistic variables and of all membership functions. Linguistic variables are used to translate real values into linguistic values. The possible values of a linguistic variable are not numbers but so called ‘linguistic terms’. Linguistic variables have to be defined for all input, output and intermediate variables. The membership functions are defined using a few definition points only. The following tables list all variables of the system as well as the respective fuzzification or defuzzification method.

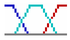
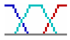
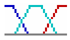
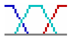
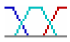
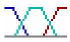
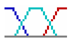
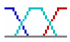
No	Variable Name	Fuzzification method	Unit	Min	Max	Default	Term Names
1	Condition		Units	1	5	4	Very Bad Bad Fair Good Very Good
2	Design Level		Units	1	5	4	Very Low Low Medium High Very High
3	External Climate		Units	0	5	4	Internal Element Very Aggressive Aggressive Slightly Aggressive Less Favourable Favourable
4	Internal Climate		Units	0	5	4	External Element Very Aggressive Aggressive Slightly Aggressive Less Favourable Favourable
5	Maintenance Level		Units	1	5	4	Very Low Low Normal High Very High
6	Material Quality		Units	1	5	4	Very Low Low Medium High Very High
7	Operational Environment		Units	1	5	4	Very Aggressive Aggressive Slightly Aggressive Less Favourable Favourable
8	Workmanship Quality		Units	1	5	4	Very Low Low Medium High Very High

Table 3-4: Input Variables

No	Variable Name	Term Names
9	Durability	Very Low Low Medium High Very High
10	Environment	Very Aggressive Aggressive Slightly Aggressive Less Favourable Favourable

Table 3-5: Intermediate Variables

No	Variable Name	Defuzzification method	Unit	Min	Max	Default	Term Names
11	Degradation Rate	CoM	Percentage	0	100	0	Very Slow Slow Medium Fast Very Fast

Table 3-6: Output Variable

The Centre of Maximum (CoM) (CoM) defuzzification method is used for most fuzzy logic applications, such as quantitative decisions (budget allocation or project prioritization) and computes a crisp output as a weighted mean of the term membership maxima, weighted by the inference results. Other defuzzification methods are:

- CoA (Center of Area) (CoA): demanding computation process
- MoM (Mean of Maximum) (MoM): used for qualitative decisions, such as pattern recognition applications

3.3.4. Fuzzy Sets

The universe of discourse is defined by:

$X = \{x_1, x_2, x_3, x_4, x_5\}$,

where

$x_1 = 1,\ x_2 = 2,\ x_3 = 3,\ x_4 = 4,\ x_5 = 5$

The membership function for fuzzy set A is defined as:

$\mu_A(x) : X \rightarrow [0,1]$,

where

$\mu_A(x) = 1$ if x is totally in A;

$\mu_A(x) = 0$ if x is not in A;

$0 < \mu_A(x) < 1$, if x is partly in A

Fuzzy set A $\quad A = \{(x, \mu_A(x))\}\ \ x \in X,\ \mu_A(x) : X \rightarrow [0,1]$, a.) Current Condition

Fuzzy set A ('Very Bad') $A = \{(1,1), (2,0), (3,0), (4,0), (5,0)\}$

Fuzzy set B ('Bad'): $B = \{(1,0), (2,1), (3,0), (4,0), (5,0)\}$

Fuzzy set C ('Fair'): $C = \{(1,0), (2,0), (3,1), (4,0), (5,0)\}$

Fuzzy set D ('Good'): $D = \{(1,0), (2,0), (3,0), (4,1), (5,0)\}$

Fuzzy set E ('Very Good'): $E = \{(1,0), (2,0), (3,0), (4,0), (5,1)\}$

Term Name	Shape	Definition Points (x, y)				
Very Bad	linear	(1, 1)	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Bad	linear	(1, 0)	(2, 1)	(3, 0)	(4, 0)	(5, 0)
Fair	linear	(1, 0)	(2, 0)	(3, 1)	(4, 0)	(5, 0)
Good	linear	(1, 0)	(2, 0)	(3, 0)	(4, 1)	(5, 0)
Very Good	linear	(1, 0)	(2, 0)	(3, 0)	(4, 0)	(5, 1)

Table 3-7: Definition Points of Fuzzy Sets for Current Condition

Figure 3-9: Fuzzy Sets for Current Condition

b.) Design Level

Fuzzy set A ('Very Low'): $A = \{(1,1), (2,0), (3,0), (4,0), (5,0)\}$

Fuzzy set B ('Low'): $B = \{(1,0), (2,1), (3,0), (4,0), (5,0)\}$

Fuzzy set C ('Medium'): $C = \{(1,0), (2,0), (3,1), (4,0), (5,0)\}$

Fuzzy set D ('High'): $D = \{(1,0), (2,0), (3,0), (4,1), (5,0)\}$

Fuzzy set E ('Very High'): $E = \{(1,0), (2,0), (3,0), (4,0), (5,1)\}$

Term Name	Shape	Definition Points (x, y)				
Very Low	linear	(1, 1)	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Low	linear	(1, 0)	(2, 1)	(3, 0)	(4, 0)	(5, 0)
Medium	linear	(1, 0)	(2, 0)	(3, 1)	(4, 0)	(5, 0)
High	linear	(1, 0)	(2, 0)	(3, 0)	(4, 1)	(5, 0)
Very High	linear	(1, 0)	(2, 0)	(3, 0)	(4, 0)	(5, 1)

Table 3-8: Definition Points of Fuzzy Sets for Design Level

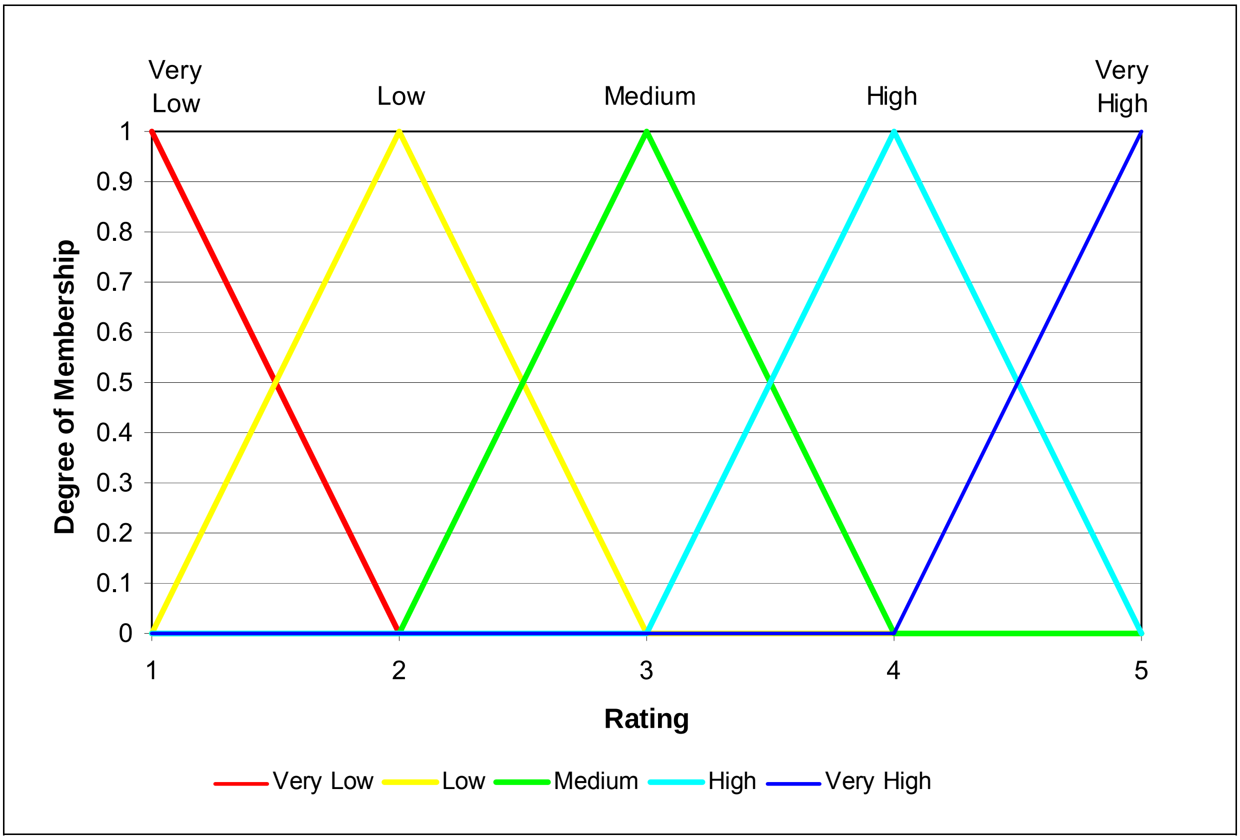


Figure 3-10: Fuzzy Sets for Design Level

c.) Quality of Material

Fuzzy set A ('Very Low'): *A = {(1,1), (2,0), (3,0), (4,0), (5,0)}*

Fuzzy set B ('Low'): *B = {(1,0), (2,1), (3,0), (4,0), (5,0)}*

Fuzzy set C ('Medium'): *C = {(1,0), (2,0), (3,1), (4,0), (5,0)}*

Fuzzy set D ('High'): *D = {(1,0), (2,0), (3,0), (4,1), (5,0)}*

Fuzzy set E ('Very High'): *E = {(1,0), (2,0), (3,0), (4,0), (5,1)}*

Term Name	**Shape**	**Definition Points (x, y)**				
Very Low	linear	(1, 1)	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Low	linear	(1, 0)	(2, 1)	(3, 0)	(4, 0)	(5, 0)
Medium	linear	(1, 0)	(2, 0)	(3, 1)	(4, 0)	(5, 0)
High	linear	(1, 0)	(2, 0)	(3, 0)	(4, 1)	(5, 0)
Very High	linear	(1, 0)	(2, 0)	(3, 0)	(4, 0)	(5, 1)

Table 3-9: Definition Points of Fuzzy Sets for Material Quality

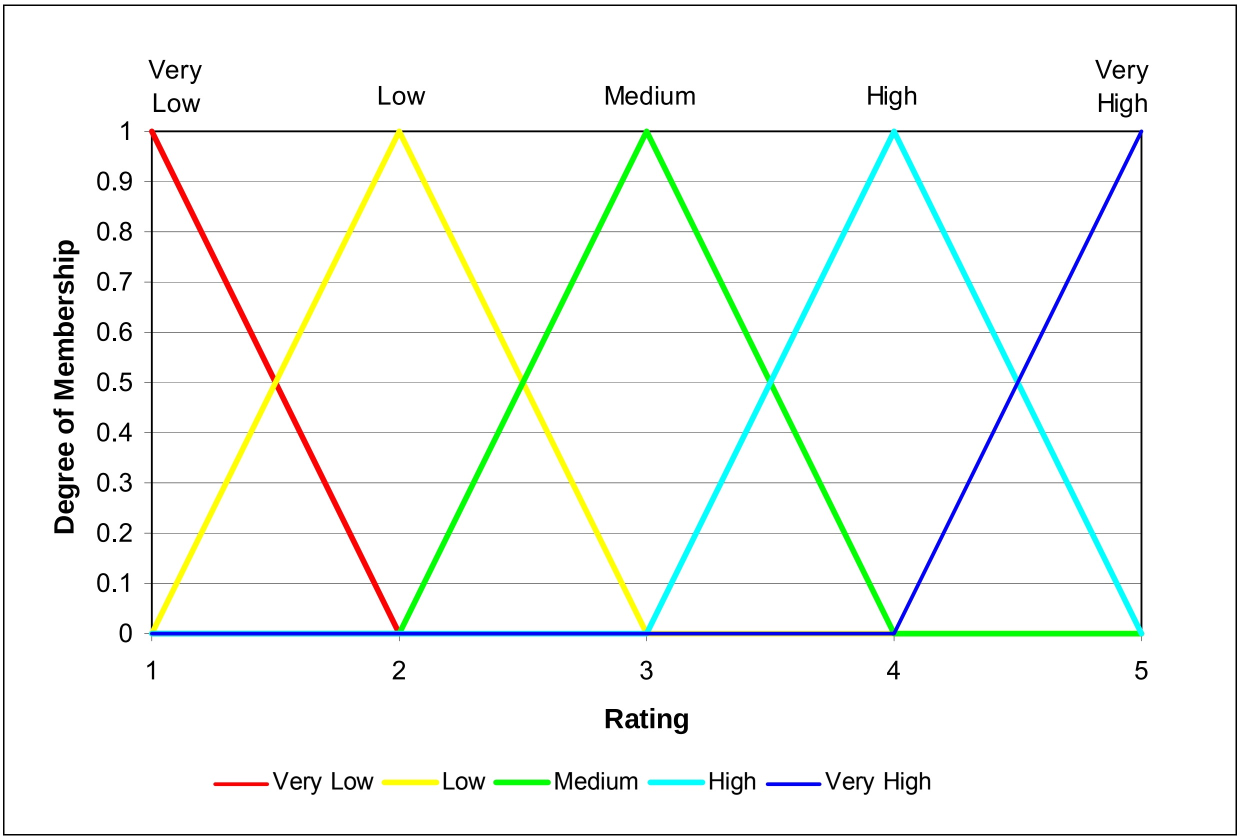


Figure 3-11: Fuzzy Sets for Material Quality

d.) Quality of Workmanship

Fuzzy set A ('Very Low'): *A = {(1,1), (2,0), (3,0), (4,0), (5,0)}*

Fuzzy set B ('Low'): *B = {(1,0), (2,1), (3,0), (4,0), (5,0)}*

Fuzzy set C ('Medium'): *C = {(1,0), (2,0), (3,1), (4,0), (5,0)}*

Fuzzy set D ('High'): *D = {(1,0), (2,0), (3,0), (4,1), (5,0)}*

Fuzzy set E ('Very High'): *E = {(1,0), (2,0), (3,0), (4,0), (5,1)}*

Term Name	Shape	Definition Points (x, y)				
Very Low	linear	(1, 1)	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Low	linear	(1, 0)	(2, 1)	(3, 0)	(4, 0)	(5, 0)
Medium	linear	(1, 0)	(2, 0)	(3, 1)	(4, 0)	(5, 0)
High	linear	(1, 0)	(2, 0)	(3, 0)	(4, 1)	(5, 0)
Very High	linear	(1, 0)	(2, 0)	(3, 0)	(4, 0)	(5, 1)

Table 3-10: Definition Points of Fuzzy Sets for Workmanship Quality

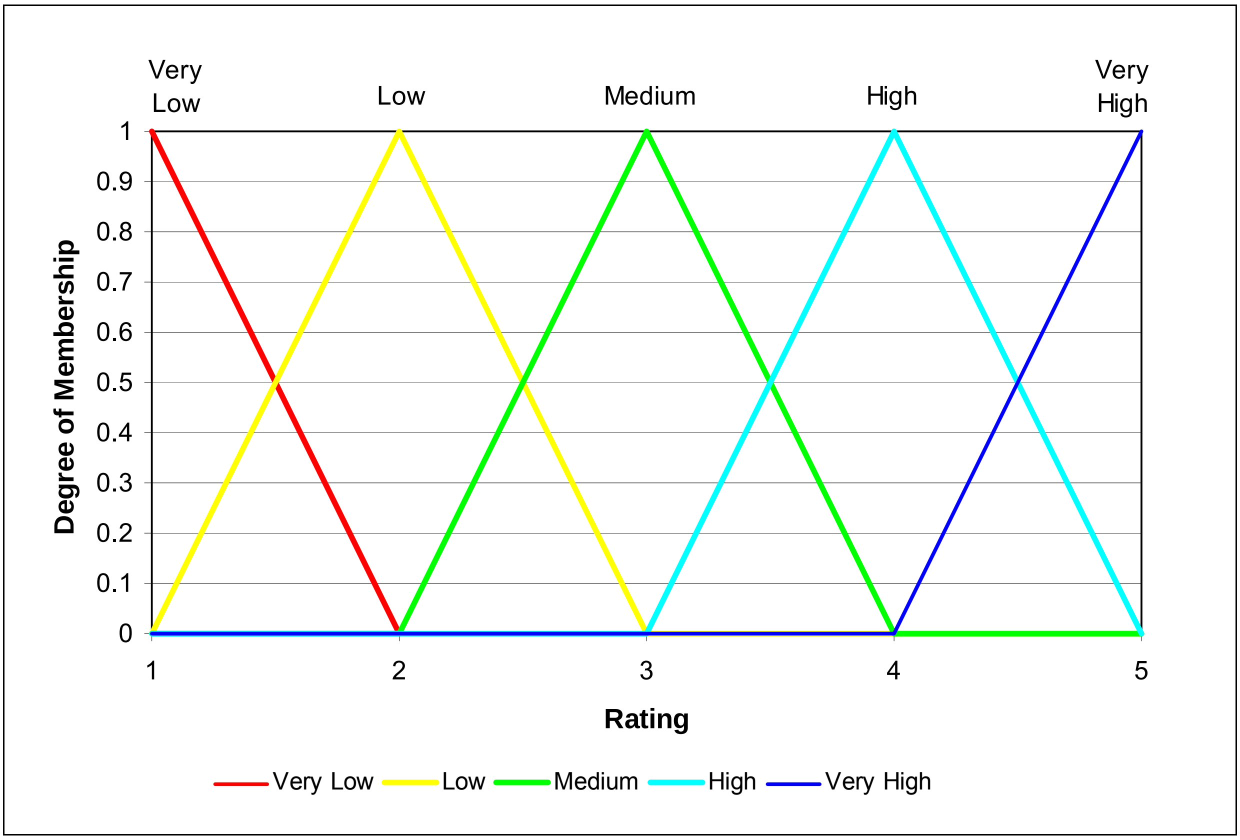


Figure 3-12: Fuzzy Sets for Workmanship Quality

e.) External Climate

Fuzzy set A ('Internal Component'): A = *{(0,0), (1,0), (1,1), (2,0), (3,0), (4,0), (5,0)}*

Fuzzy set B ('Very Aggressive'): *B = {(0,0), (1,1), (2,0), (3,0), (4,0), (5,0)}*

Fuzzy set C ('Aggressive'): *C = {(0,0), (1,0), (2,1), (3,0), (4,0), (5,0)}*

Fuzzy set D ('Slightly Aggressive'): *D = {(0,0), (1,0), (2,0), (3,1), (4,0), (5,0)}*

Fuzzy set E ('Less Favourable'): *E = {(0,0), (1,0), (2,0), (3,0), (4,1), (5,0)}*

Fuzzy set F ('Favourable'): *F = {(0,0), (1,0), (2,0), (3,0), (4,0), (5,1)}*

An additional fuzzy set, A, is introduced to provide for the external climate to have no effect when dealing with an internal component.

Term Name	Shape	Definition Points (x, y)						
Internal Component	linear	(0, 1)	(1, 1)	(1, 0),	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Very Aggressive	linear	(0, 0)	(1, 0)	(1, 1)	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Aggressive	linear	(0, 0)	(1, 0)	(1, 0)	(2, 1)	(3, 0)	(4, 0)	(5, 0)
Slightly Aggressive	linear	(0, 0)	(1, 0)	(1, 0)	(2, 0)	(3, 1)	(4, 0)	(5, 0)
Less Favourable	linear	(0, 0)	(1, 0)	(1, 0)	(2, 0)	(3, 0)	(4, 1)	(5, 0)
Favourable	linear	(0, 0)	(1, 0)	(1, 0)	(2, 0)	(3, 0)	(4, 0)	(5, 1)

Table 3-11: Definition Points of Fuzzy Sets for External Climate

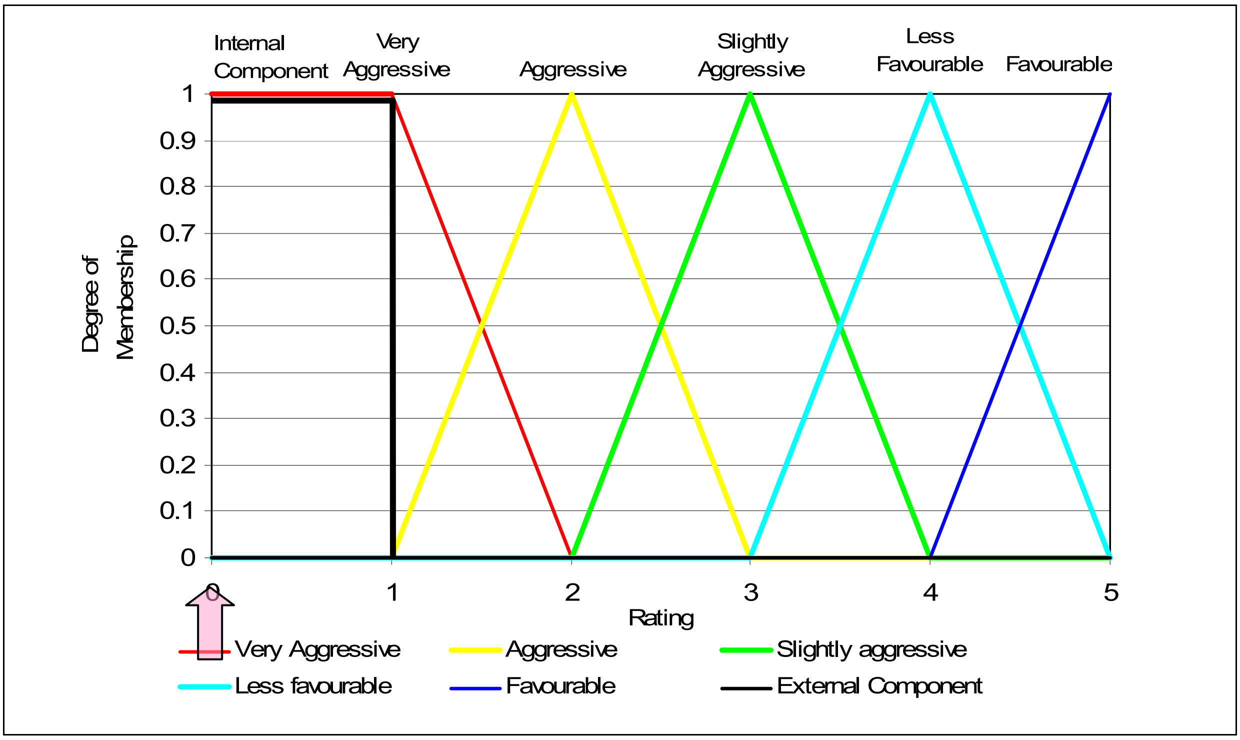


Figure 3-13: Fuzzy Sets for External Climate

The arrow in Figure 3-13 indicates the setting for External Climate if the component under consideration is an internal component and the external climate has no impact or effect on the component.

f.) Internal Climate

Fuzzy set A ('External Component'): A = *{(0,0), (1,0), (1,1), (2,0), (3,0), (4,0), (5,0)}*

Fuzzy set B ('Very Aggressive'): *B = {(0,0), (1,1), (2,0), (3,0), (4,0), (5,0)}*

Fuzzy set C ('Aggressive'): *C = {(0,0), (1,0), (2,1), (3,0), (4,0), (5,0)}*

Fuzzy set D ('Slightly Aggressive'): *D = {(0,0), (1,0), (2,0), (3,1), (4,0), (5,0)}*

Fuzzy set E ('Less Favourable'): *E = {(0,0), (1,0), (2,0), (3,0), (4,1), (5,0)}*

Fuzzy set F ('Favourable'): *F = {(0,0), (1,0), (2,0), (3,0), (4,0), (5,1)}*

An additional fuzzy set, A, is introduced to provide for the internal climate to have no effect when dealing with an external component.

Term Name	Shape	Definition Points (x, y)						
External Component	linear	(0, 1)	(1, 1)	(1, 0),	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Very Aggressive	linear	(0, 0)	(1, 0)	(1, 1)	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Aggressive	linear	(0, 0)	(1, 0)	(1, 0)	(2, 1)	(3, 0)	(4, 0)	(5, 0)
Slightly Aggressive	linear	(0, 0)	(1, 0)	(1, 0)	(2, 0)	(3, 1)	(4, 0)	(5, 0)
Less Favourable	linear	(0, 0)	(1, 0)	(1, 0)	(2, 0)	(3, 0)	(4, 1)	(5, 0)
Favourable	linear	(0, 0)	(1, 0)	(1, 0)	(2, 0)	(3, 0)	(4, 0)	(5, 1)

Table 3-12: Definition Points of Fuzzy Sets for Internal Climate

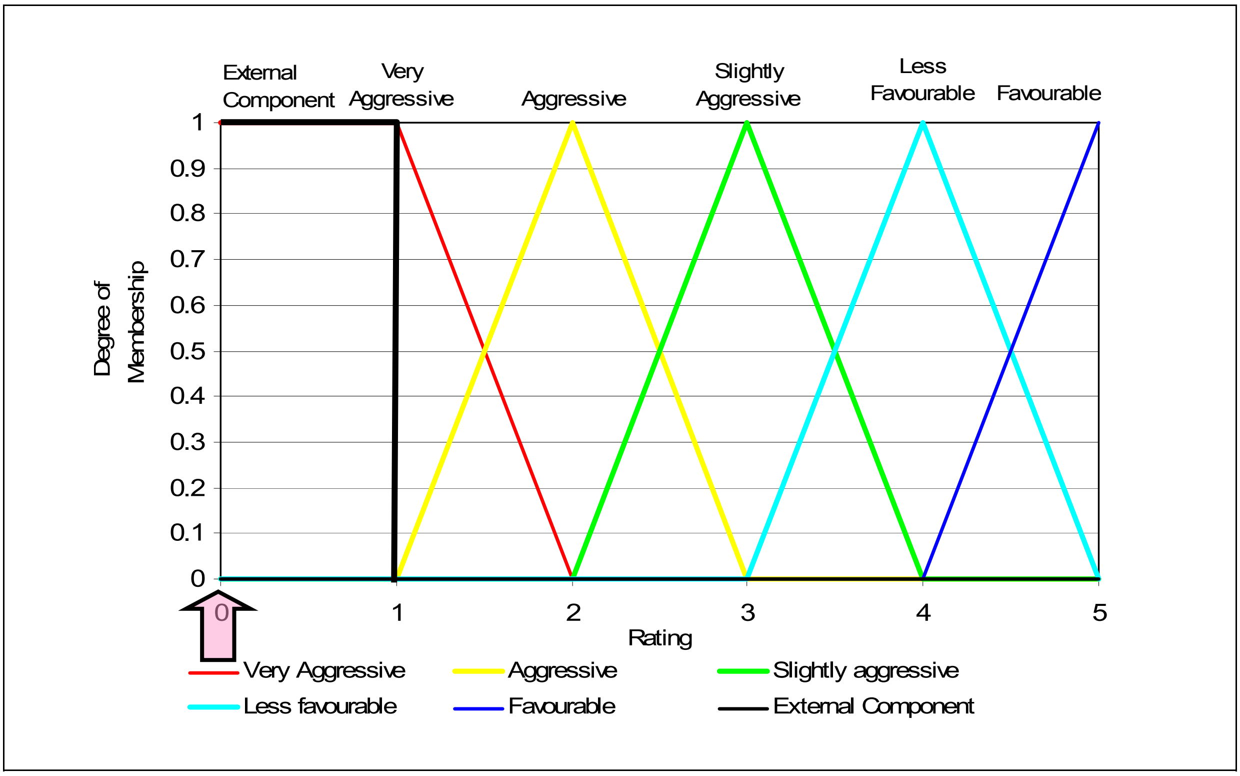


Figure 3-14: Fuzzy Sets for Internal Climate

The arrow in Figure 3-14 indicates the setting for Internal Climate if the component under consideration is an external component and the internal climate has no impact or effect on the component.

g.) Operational Environment

Fuzzy set A ('Very Aggressive'): $A = \{(1,1), (2,0), (3,0), (4,0), (5,0)\}$

Fuzzy set B ('Aggressive'): $B = \{(1,0), (2,1), (3,0), (4,0), (5,0)\}$

Fuzzy set C ('Slightly Aggressive'): $C = \{(1,0), (2,0), (3,1), (4,0), (5,0)\}$

Fuzzy set D ('Less Favourable'): $D = \{(1,0), (2,0), (3,0), (4,1), (5,0)\}$

Fuzzy set E ('Favourable'): $E = \{(1,0), (2,0), (3,0), (4,0), (5,1)\}$

Term Name	Shape	Definition Points (x, y)				
Very Aggressive	linear	(1, 1)	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Aggressive	linear	(1, 0)	(2, 1)	(3, 0)	(4, 0)	(5, 0)
Slightly Aggressive	linear	(1, 0)	(2, 0)	(3, 1)	(4, 0)	(5, 0)
Less Favourable	linear	(1, 0)	(2, 0)	(3, 0)	(4, 1)	(5, 0)
Favourable	linear	(1, 0)	(2, 0)	(3, 0)	(4, 0)	(5, 1)

Table 3-13: Definition Points of Fuzzy Sets for Operational Environment

Figure 3-15: Fuzzy Sets for Operational Environment

h.) Maintenance Level

Fuzzy set A ('Very Low'): $A = \{(1,1), (2,0), (3,0), (4,0), (5,0)\}$

Fuzzy set B ('Low'): $B = \{(1,0), (2,1), (3,0), (4,0), (5,0)\}$

Fuzzy set C ('Medium'): $C = \{(1,0), (2,0), (3,1), (4,0), (5,0)\}$

Fuzzy set D ('High'): $D = \{(1,0), (2,0), (3,0), (4,1), (5,0)\}$

Fuzzy set E ('Very High'): $E = \{(1,0), (2,0), (3,0), (4,0), (5,1)\}$

Term Name	Shape	Definition Points (x, y)				
Very Low	linear	(1, 1)	(2, 0)	(3, 0)	(4, 0)	(5, 0)
Low	linear	(1, 0)	(2, 1)	(3, 0)	(4, 0)	(5, 0)
Medium	linear	(1, 0)	(2, 0)	(3, 1)	(4, 0)	(5, 0)
High	linear	(1, 0)	(2, 0)	(3, 0)	(4, 1)	(5, 0)
Very High	linear	(1, 0)	(2, 0)	(3, 0)	(4, 0)	(5, 1)

Table 3-14: Definition Points of Fuzzy Sets for Maintenance Level

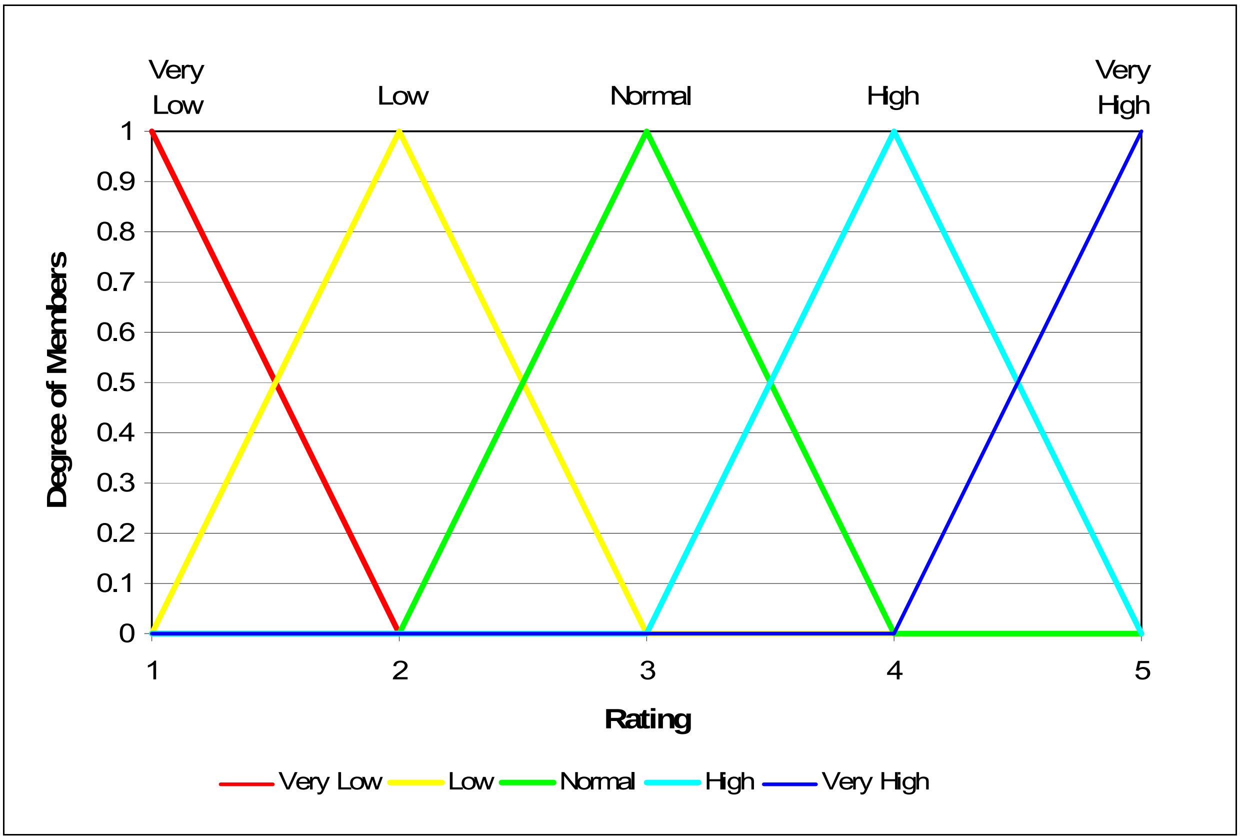


Figure 3-16: Fuzzy Sets for Maintenance Level

i.) Output Variable: Degradation Rate

Fuzzy set A ('Very Slow'): *A = {(1,1), (2,0), (3,0), (4,0), (5,0)}*

Fuzzy set B ('Slow'): *B = {(1,0), (2,1), (3,0), (4,0), (5,0)}*

Fuzzy set C ('Medium'): *C = {(1,0), (2,0), (3,1), (4,0), (5,0)}*

Fuzzy set D ('Fast'): *D = {(1,0), (2,0), (3,0), (4,1), (5,0)}*

Fuzzy set E ('Very Fast'): *E = {(1,0), (2,0), (3,0), (4,0), (5,1)}*

Term Name	Shape	Definition Points (x, y)				
Very Slow	linear	(0, 1)	(25, 0)	(50, 0)	(75, 0)	(100, 0)
Slow	linear	(0, 0)	(25, 1)	(50, 0)	(75, 0)	(100, 0)
Medium	linear	(0, 0)	(25, 0)	(50, 1)	(75, 0)	(100, 0)
Fast	linear	(0, 0)	(25, 0)	(50, 0)	(75, 1)	(100, 0)
Very Fast	linear	(0, 0)	(25, 0)	(50, 0)	(75, 0)	(100, 1)

Table 3-15: Definition Points of Fuzzy Sets for Degradation Rate

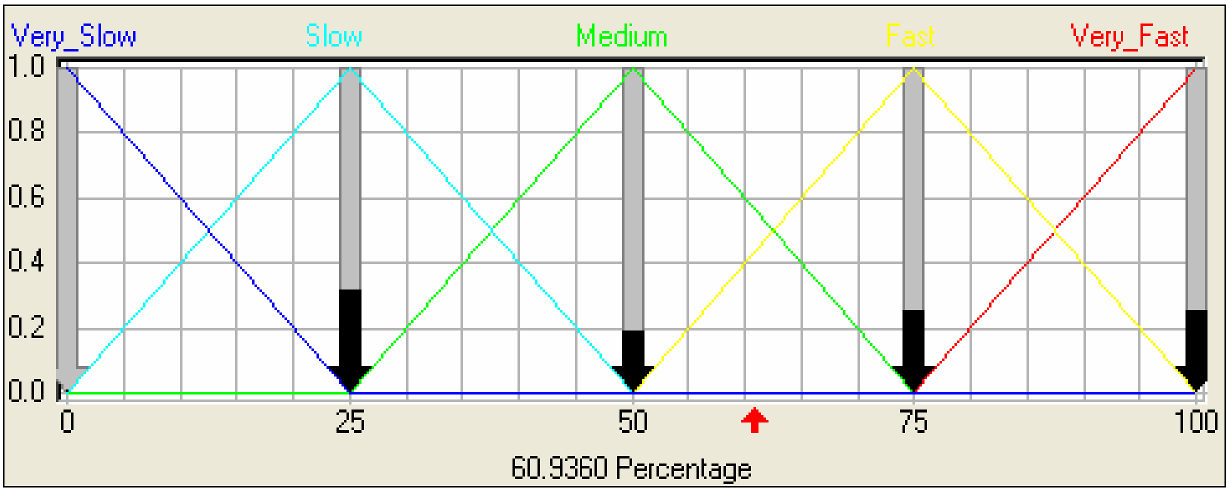


Figure 3-17: Fuzzy Sets for Degradation Rate

3.3.5. Fuzzy Rules

a.) Rule Block 1

Input variables:		Intermediate Variable (Output):
Design Level		
Material Quality	⇒	Durability
Workmanship Quality		

The Fuzzy Associative Memory (FAM) in the form of a matrix for Rule Block 1 is shown in Figure 3-18 below.

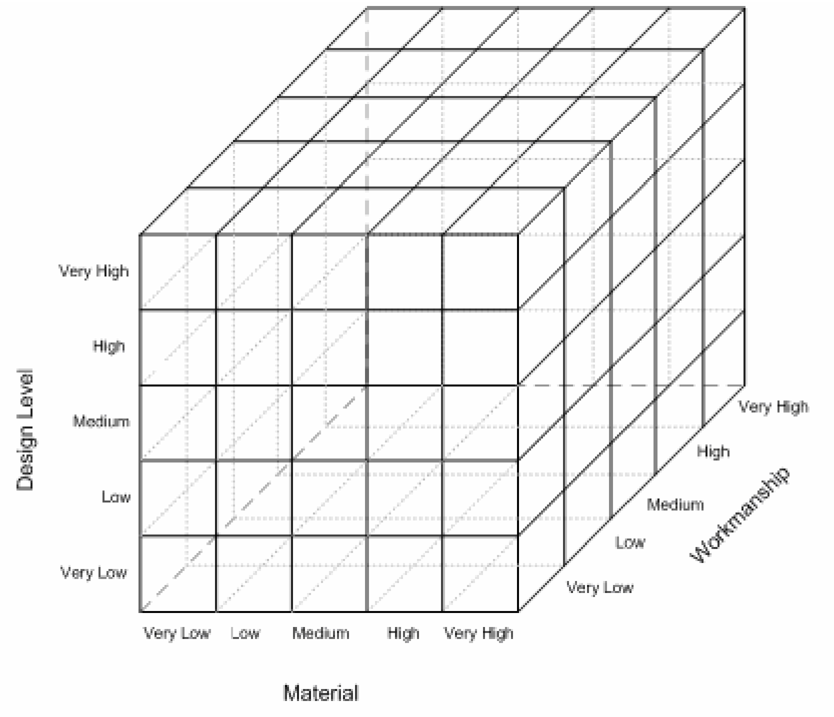


Figure 3-18: Cube Fuzzy Associative Memory (FAM) for Rule Block 1

Aggregation:	GAMMA
Parameter:	0.00
Result Aggregation:	BSUM
Number of Inputs:	3
Number of Outputs:	1
Number of Rules:	305

There are three input variables and for the base-line model it is assumed that each input variable in Rule Block 1 has the same weight or degree of support (DoS), in this case 1/3 = 0.333. For the rule details of Rule Block 1 please refer to Appendix A.

b.) Rule Block 2

Input variables:		Intermediate Variable (Output):
External Climate		
Internal Climate	⇨	Environment
Operational Environment		

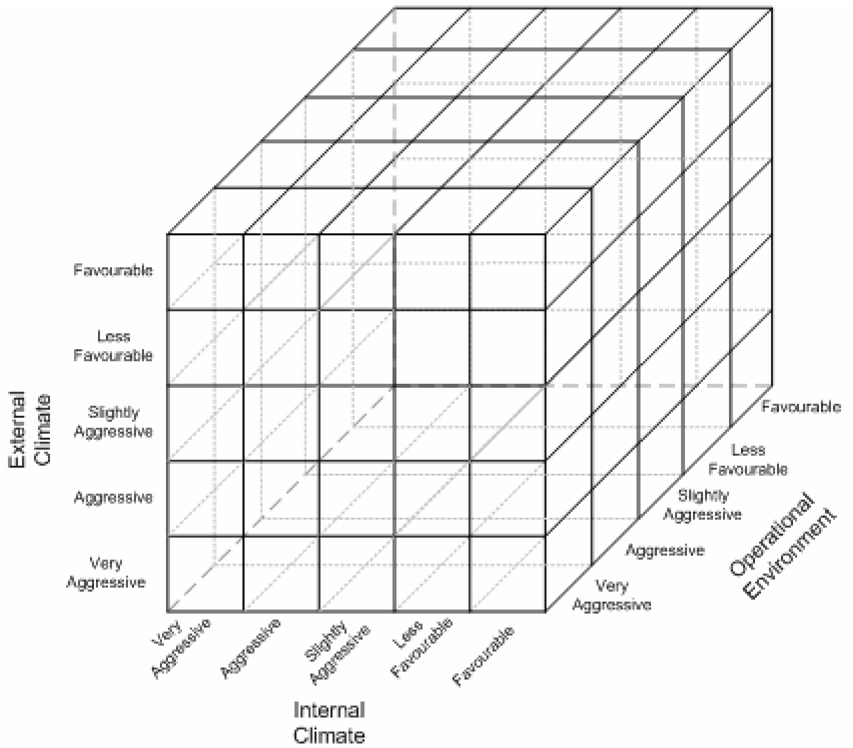


Figure 3-19: Cube Fuzzy Associative Memory (FAM) for Rule Block 2

Aggregation:	GAMMA
Parameter:	0.00
Result Aggregation:	BSUM
Number of Inputs:	3
Number of Outputs:	1
Number of Rules:	395

There are three input variables and for the base-line model it is assumed that each input variable in Rule Block 2 has the same weight or degree of support (DoS), in this case 1/3 = 0.333. For the rule details of Rule Block 2 please refer to Appendix A.

c.) Rule Block 3

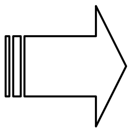
Input variables:

Durability

Environment

Condition

Maintenance Level



Output:

Degradation Rate

Aggregation	GAMMA
Parameter:	0.00
Result Aggregation:	BSUM
Number of Inputs:	4
Number of Outputs:	1
Number of Rules:	3,125

There are four input variables and for the base-line model it is assumed that each input variable in Rule Block 3 has the same weight or degree of support (DoS), in this case 1/4 = 0.25. For the rule details and the Fuzzy Associative Memory (FAM) of Rule Block 3 please refer to Appendix A.

3.4. Development of Transition Probability Matrices for the Markovian Model

3.4.1. Introduction

This section covers the development of a Neuro-fuzzy model to simulate the degradation process and obtain degradation rates for different scenarios. These degradation rates will then be used to populate the transitional probability matrix of the Markov Chain to determine the change in condition over time and eventually the predicted service life.

3.4.2. Neuro-fuzzy model

The Fuzzy Logic structure of the system is shown in Figure 3-20. This structure, together with the fuzzy sets for each variable ('Factor') and the rule blocks ("IF-THEN" rules) developed in §3.3.5 above, are then used to develop a simulation model in the fuzzyTECH 5.55c Professional Edition software, with the NeuroFuzzy add-on Module installed, to generate degradation rates. Figure 3-20 below is a 'screendump' of the model.

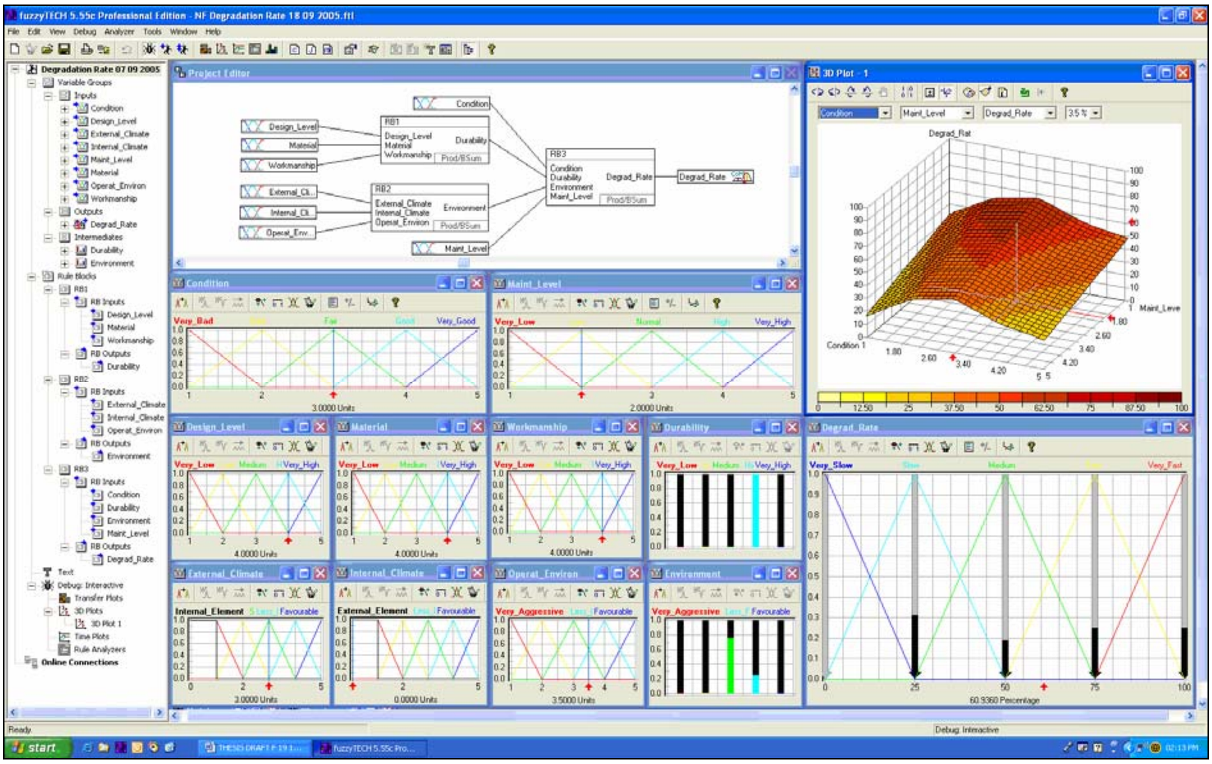


Figure 3-20: Screendump of 'base-line' fuzzyTECH model

The variable ratings shown in Table 3-15 below were kept constant during the simulation, while the maintenance level and condition ratings were adjusted to obtain degradation rates for various scenarios. The motivation for this is that design level, material, workmanship, and external and internal climate are largely predetermined during planning, design and construction, while operational environment could vary slightly but mostly stay relatively constant over the service life of the building or component. Subsequent to completion of construction, the degradation rate is controlled mainly by the maintenance level. There is also an increase in the rate of degradation as the condition deteriorates.

VARIABLES	RATING
Design Level	4 - High
Material	4 - High
Workmanship	4 - High
External Climate	3 - Slightly Aggressive
Internal Climate	0 - External Elements
Operational Environment	3.5 - Less Favourable to Slightly Aggressive

Table 3-16: Ratings of variables for 'base-line' fuzzyTECH model

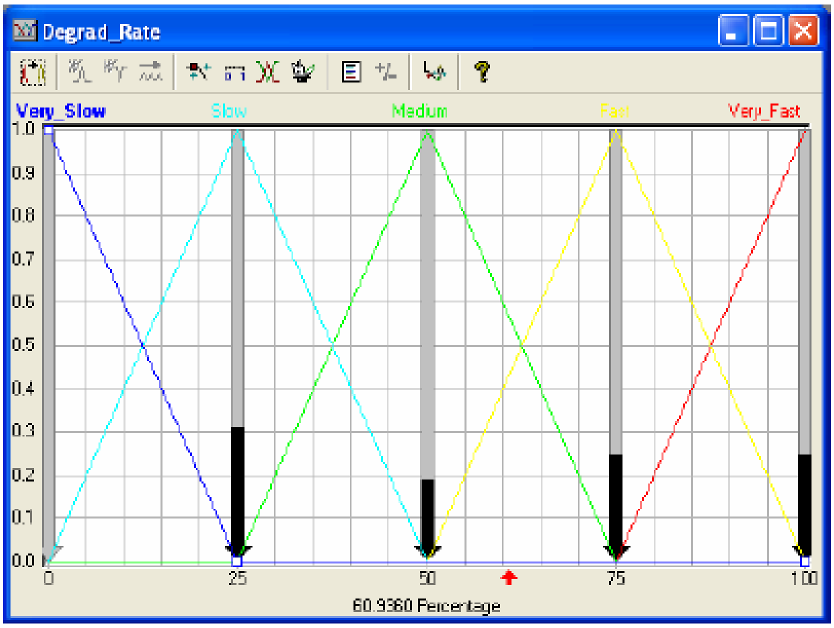


Figure 3-21: Degradation Rate window in 'base-line' fuzzyTECH model

In Figure 3-21 above the Degradation Rate window in ‘base-line’ fuzzyTECH model is shown. The degradation rate for the specific scenario is obtained from this window. The output unit is percentage, in other words the degradation rate is given as the percentage of the building or component that will deteriorate from one condition rating to the next worse condition over a period of one year. If the building or component is in condition 4 and the degradation rate output is 40% it means that over a period of one year 40% of the building or component will deteriorate from condition 4 to condition 3 and 60 % will remain in condition 4.

The three-dimensional plot of condition, maintenance level and degradation rate is shown in Figure 3-22 below. The other variables/factors are predetermined, while condition and maintenance level are adjustable factors or variables, and degradation rate is the output of the model. By adjusting the maintenance level settings, degradation rates are obtained for different conditions ratings.

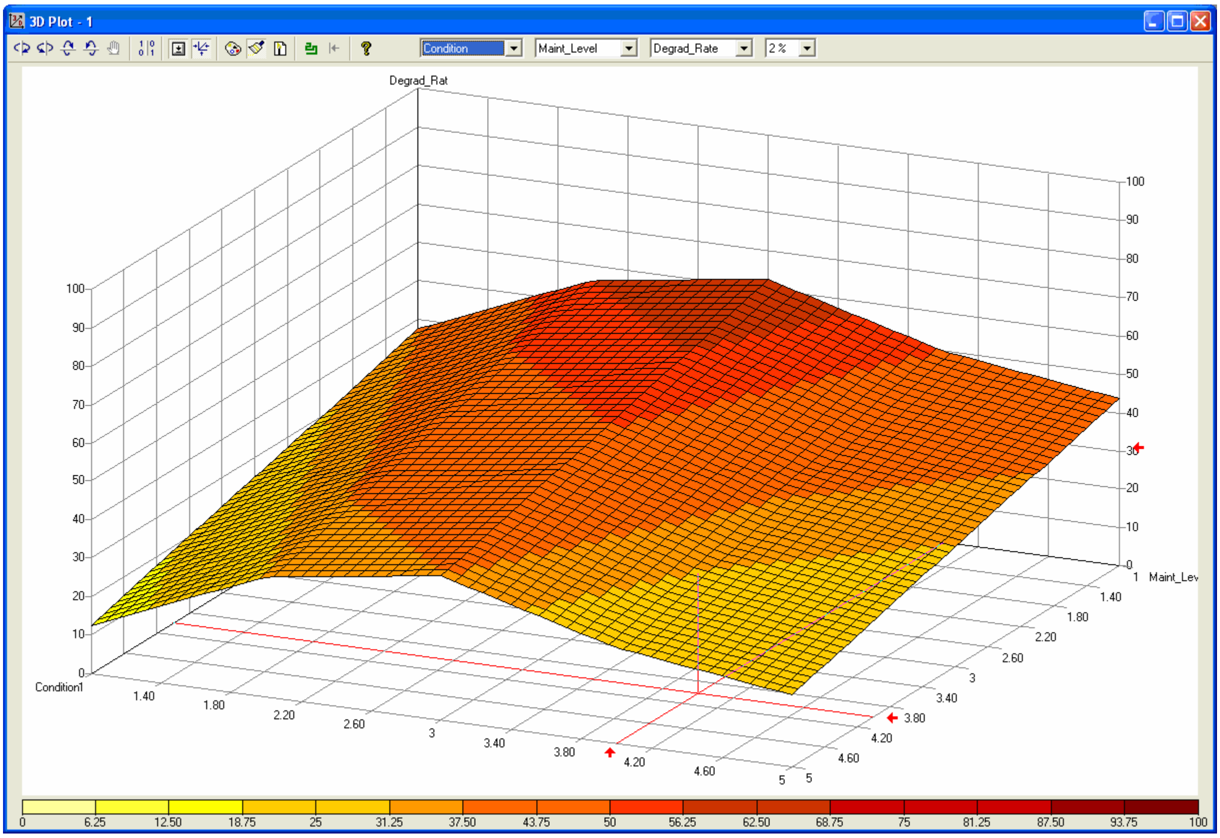


Figure 3-22: A 3-D Plot of the ‘base-line’ fuzzyTECH Model

3.4.3. Transition from Artificial Intelligence to Markov Chain

Degradation rate is defined as that percentage of the building or component that will 'transit' or change to a condition of worse degradation in one time interval. In the case of buildings, this time interval is normally one year, but could be months, weeks or even days, depending on the reference service life of the component under consideration.

Due to the influence of the degradation and durability factors on the building, the transition to a condition of worse degradation is probabilistic with the transitional probabilities depending on the current condition of the building. However, this approach does not take the latent nature of degradation into consideration as discussed by Madanat *et al* (1995, p.120).

Therefore, degradation rate is defined as the transition from condition i to the next worse condition j in one time interval:

$$\therefore \text{ Degradation rate } = \text{ transitional probability } P(ij)$$

For a five-point condition rating system, with Condition 5 the initial ('best' or 'as new') condition, progressively worsening towards Condition 1, where the material or component has failed and needs to be replaced, the transitional probability matrix is defined as:

		[5]	[4]	[3]	[2]	[1]	
	(5)	P(55)	P(54)	P(53)	P(52)	P(51)	∑P(5j) = 1
P =	(4)	P(45)	P(44)	P(43)	P(42)	P(41)	∑P(4j) = 1
	(3)	P(35)	P(34)	P(33)	P(32)	P(31)	∑P(3j) = 1
	(2)	P(25)	P(24)	P(23)	P(22)	P(21)	∑P(2j) = 1
	(1)	P(15)	P(14)	P(13)	P(12)	P(11)	∑P(1j) = 1

It is assumed, that under normal circumstances the condition will only deteriorate and not improve, in other words, it can only change from Condition 5 to Condition 4 to Condition 3 to Condition 2 to Condition 1, and not in the other direction. It is also assumed that the change in condition will only happen one step at a time (refer also to Figure 3-12), in other words, it is assumed that a one year interval is short enough to ensure that the change in condition will not jump more than one condition rating.

This means that P(ij) = 0 when i < j and j < i - 1, and the transitional probability matrix then looks like this:

		[5]	[4]	[3]	[2]	[1]	
P =	(5)	P(55)	P(54)	0	0	0	∑P(5j) = 1
	(4)	0	P(44)	P(43)	0	0	∑P(4j) = 1
	(3)	0	0	P(33)	P(32)	0	∑P(3j) = 1
	(2)	0	0	0	P(22)	P(21)	∑P(2j) = 1
	(1)	0	0	0	0	1	∑P(1j) = 1

∑P(ij) = 1

∴ P(55) + P(54) = 1 → P(55) = 1 - P(54), where P(54) = degradation rate from Condition 5 to Condition 4 in one year,

P(44) + P(43) = 1 → P(44) = 1 - P(43) ...

P(33) + P(32) = 1 → P(33) = 1 - P(32) ...

P(22) + P(21) = 1 → P(22) = 1 - P(21) ...

P(11) + P(10) = 1 → P(11) = 1 ...

The three-dimensional plot in Figure 3-22 above however suggests that P(11) < 1, in other words, the degradation rates at condition 1 for all levels of maintenance are greater that zero (P(10) ≠ 0). In the Markov model, the building or component has reached the end of its life at condition 1, needs to be replaced and theoretically no further degradation can take place. In reality, degradation will however continue at a slower rate until eventually only a ruin will remain (e.g. many of the ruins of ancient buildings from previous civilisations throughout history and all over the world).

The transition probabilities P(54), P(43), P(32), and P(21), shaded in Table 3-19 below, are obtained from the Neuro-fuzzy simulation and used to populate the Markov Transitional Probability Matrix.

Markov Transition Probability Matrix		Condition at time t = 1				
		5	4	3	2	1
Condition at time: t = 0	5	0.578	0.422	0	0	0
	4	0	0.516	0.484	0	0
	3	0	0	0.391	0.609	0
	2	0	0	0	0.453	0.547
	1	0	0	0	0	1

Table 3-17: Markov Transition Probability Matrix for 'base-line' Model

At time t = 0, the initial states, the building's condition profile, is as follows:

Age	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1	Average Condition
0	100.000%	0.000%	0.000%	0.000%	0.000%	**5.00**

The probabilities of the initial states are as follows:

P(0) = [1.00, 0, 0, 0, 0]

After one time interval, one year in this case, the probability that the condition will be in state *j* is then determined by:

$$P_1(j) = \sum_{j=1}^{m} P_0(i).P(ij)$$

$$= P_0(1)\cdot P(1j) + P_0(2)\cdot P(2j) + P_0(3)\cdot P(3j) + P_0(4)\cdot P(4j) + P_0(5)\cdot P(5j)$$

This is used to determine the proportion of the building or component in the various conditions.

P(1) = [(1.00 x 0.578 + 0 x 0 + 0 x 0 + 0 x 0 + 0 x 0),
(1.00 x 0.422 + 0 x 0.516 + 0 x 0 + 0 x 0 + 0 x 0),
(1.00 x 0 + 0 x 0.484 + 0 x 0.391 + 0 x 0 + 0 x 0),
(1.00 x 0 + 0 x 0 + 0 x 0.609 + 0 x 0.453 + 0 x 0),
(1.00 x 0 + 0 x 0 + 0 x 0 + 0 x 0.547 + 0 x 1)]
= [0.578, 0.422, 0, 0, 0]

This process is repeated for a number of times equal to the reference service life plus ten to twenty years to ensure sufficient coverage. The results for the 'base-line' model, with maintenance level = 2 ('Low'), over a period of 60 years are shown in Table 3-17 below. This process is then repeated for each of the five maintenance levels.

Age	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1		Average Condition
0	100.000%	0.000%	0.000%	0.000%	0.000%		**5.00**
1	57.818%	42.182%	0.000%	0.000%	0.000%		**4.58**
2	33.429%	46.140%	20.431%	0.000%	0.000%		**4.13**
3	19.328%	37.892%	30.329%	12.450%	0.000%		**3.64**
4	11.175%	27.692%	30.201%	24.123%	6.809%		**3.12**
5	6.461%	18.993%	25.211%	29.334%	20.001%		**2.63**
6	3.736%	12.519%	19.048%	28.654%	36.043%		**2.19**
7	2.160%	8.031%	13.505%	24.591%	51.714%		**1.84**
8	1.249%	5.052%	9.165%	19.372%	65.162%		**1.58**
9	0.722%	3.132%	6.027%	14.363%	75.756%		**1.39**
10	0.417%	1.920%	3.872%	10.181%	83.611%		**1.25**
11	0.241%	1.166%	2.442%	6.972%	89.178%		**1.16**
12	0.140%	0.703%	1.519%	4.647%	92.991%		**1.10**
13	0.081%	0.421%	0.934%	3.031%	95.533%		**1.06**
14	0.047%	0.251%	0.569%	1.943%	97.191%		**1.04**
15	0.027%	0.149%	0.344%	1.227%	98.253%		**1.02**
16	0.016%	0.088%	0.207%	0.765%	98.924%		**1.02**
17	0.009%	0.052%	0.124%	0.473%	99.343%		**1.01**
18	0.005%	0.031%	0.074%	0.289%	99.601%		**1.01**
19	0.003%	0.018%	0.044%	0.176%	99.759%		**1.00**
20	0.002%	0.011%	0.026%	0.106%	99.856%		**1.00**
21	0.001%	0.006%	0.015%	0.064%	99.914%	*	**1.00**
22	0.001%	0.004%	0.009%	0.038%	99.949%		**1.00**
23	0.000%	0.002%	0.005%	0.023%	99.970%		**1.00**
24	0.000%	0.001%	0.003%	0.013%	99.982%		**1.00**
25	0.000%	0.001%	0.002%	0.008%	99.989%		**1.00**
26	0.000%	0.000%	0.001%	0.005%	99.994%		**1.00**
27	0.000%	0.000%	0.001%	0.003%	99.996%		**1.00**
28	0.000%	0.000%	0.000%	0.002%	99.998%		**1.00**
29	0.000%	0.000%	0.000%	0.001%	99.999%		**1.00**
30	0.000%	0.000%	0.000%	0.001%	99.999%	*	**1.00**
31	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
32	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
33	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
34	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
35	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
36	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
37	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
38	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
39	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
40	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
41	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
42	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
43	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
44	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
45	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
46	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
47	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
48	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
49	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
50	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
51	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
52	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
53	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
54	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
55	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
56	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
57	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
58	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
59	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**
60	0.000%	0.000%	0.000%	0.000%	100.000%		**1.00**

Table 3-18: Results of Markov Chain simulation for ‘base-line’ model

The average condition of each year is calculated and plotted as shown in Figure 3-23 below.

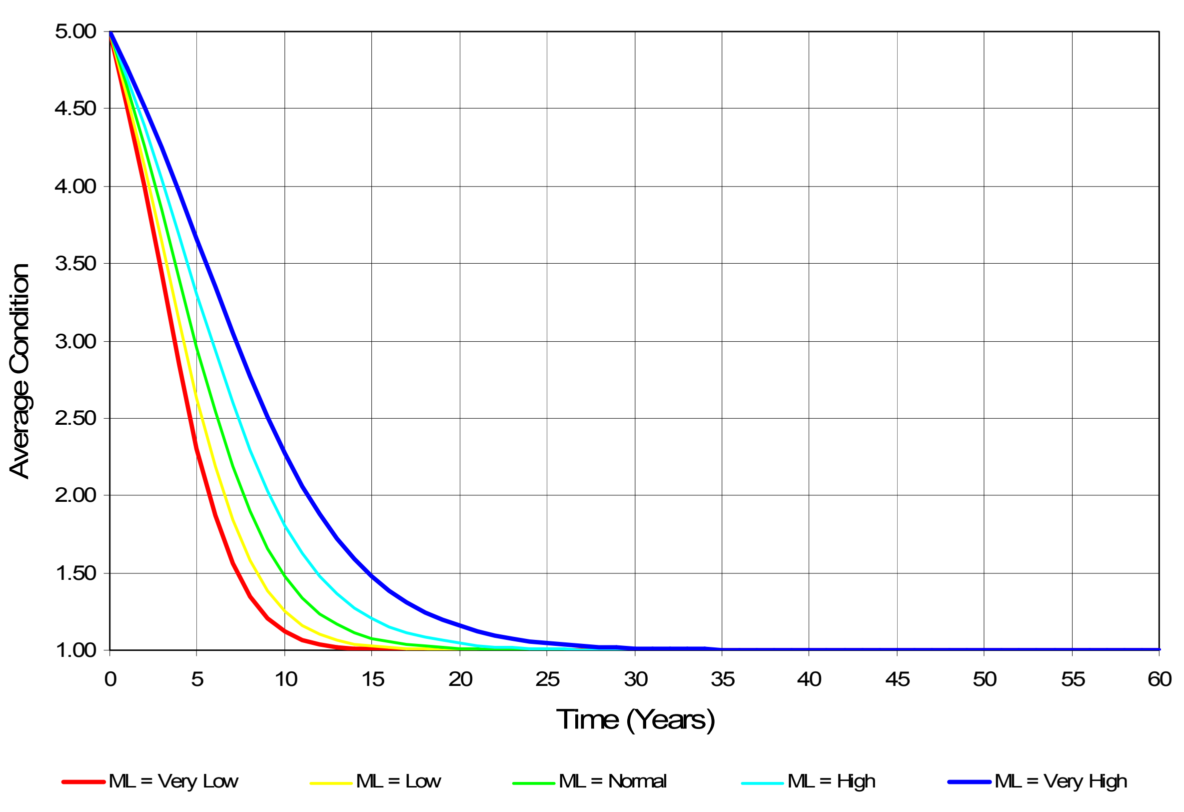


Figure 3-23: Performance over time curves for different levels of maintenance – 'base-line' model

The curves in Figure 3-23 above, imply that the building under consideration will deteriorate from Condition 5, at time t = 0, to Condition 1, where it needs to be replaced, in anything between 15 and 30 years. This is obviously wrong, as the reference service life for an academic hospital with a maintenance level of 4 ('High') should be 50 years (it may however be refurbished or upgraded at an earlier age due to changing needs in modern health care and medicine, rather than the condition of the building or component).

In the 'base-line' Neuro-fuzzy model, it was assumed that the variables in each rule block carried the same weight, and this is the reason why these results are wrong. This illustrates the role of the domain expert, who needs to evaluate the results of the simulation and determine acceptable output values. The curve representing a high maintenance level should cross condition 3, the 'desirable' service or performance level for an academic hospital, at year 50. The 'base-line' model therefore requires adjustments to the weights allocated to the variables in the Neuro-fuzzy rule blocks (IF-THEN rules). Clearly, the degradation rates obtained from the 'base-line' model is far too high and need to be much lower if the high maintenance level curve is to reach Condition 3 at year 50. These weights of the variables are adjusted by a domain expert until the system output yields acceptable results.

3.4.4. Calibration of the neuro-fuzzy model

For the purpose of this thesis, six academic hospitals were chosen as pilot and control sites to base and calibrate the model on. Although there are currently approximately 27 tertiary hospitals and 380 other government hospitals in South Africa, there are several reasons for choosing only six academic hospitals. During the 1995 NHFA, 572 hospitals were assessed, but since then many have either been degraded to community health centres, closed or disposed of. A number of new hospitals have also been added since. The six hospitals are of similar age and were all build within a seven year period during the 1970's, have similar construction types, design, material and workmanship levels and operational environments, and their condition have been assessed at least twice since 1995. Other important considerations are a personal involvement in the assessments of these hospitals and little changes or additions to the main hospital buildings happened since completion of construction, except for Hospital F. None of the hospitals is identified in this thesis and the findings should not be seen as criticism of the respective health departments, hospitals, management or maintenance staff.

Hospital A

Facility Type	Tertiary Hospital (Academic - Government)			
Year construction completed	1975	Age	30 years	(2005)
Total Floor Area	218,603	m^2	Main building only	
No of levels	15			
Structural frame	Reinforced concrete			
External walls	Face brick			
External windows	Aluminium			
Roof	Flat concrete slabs with waterproofing			
Estimated current consruction cost			R 1,882,376,130	
			$289,596,328	± @ R6.50/US$1.00

VARIABLES	**Rating**	
Design Level	4	High
Material	4	High
Workmanship	4	High
External Climate	3	Slightly Aggressive
Internal Climate	0	External Elements
Operational Environment	3.5	Less Favourable to Slightly Aggressive
Maintenance level	**2**	**Low**
Current Average Condition	**3.02**	**Fair**

Table 3-19: General Information of the Pilot Site: Hospital A

The design level, material and workmanship quality of Hospital A, are high and the general appearance from a distance is that of a building in a good condition. During 1996, a condition assessment was done as part of the National Health Facilities Audit (NHFA) by the CSIR. Another assessment was done in 2005 by the author. The average condition (see Figure 4-7) at the time of the 1996 audit, when the hospital was 21 years old, was 3.65. The hospital is now 30 years old and the 'current' average condition as assessed during July 2005 has deteriorated to 3.02. The weights of the variables in the Neuro-fuzzy model's 'IF-THEN' rule blocks therefore need to be adjusted to yield a degradation rate that will result in an average condition of 3.65 at 21 years and 3.02 at 30 years for a 'Low' maintenance level. A further requirement is that the curve representing a 'High' level of maintenance should cross condition 3, the 'desirable' Service Level or performance level for an academic hospital, at year 50.

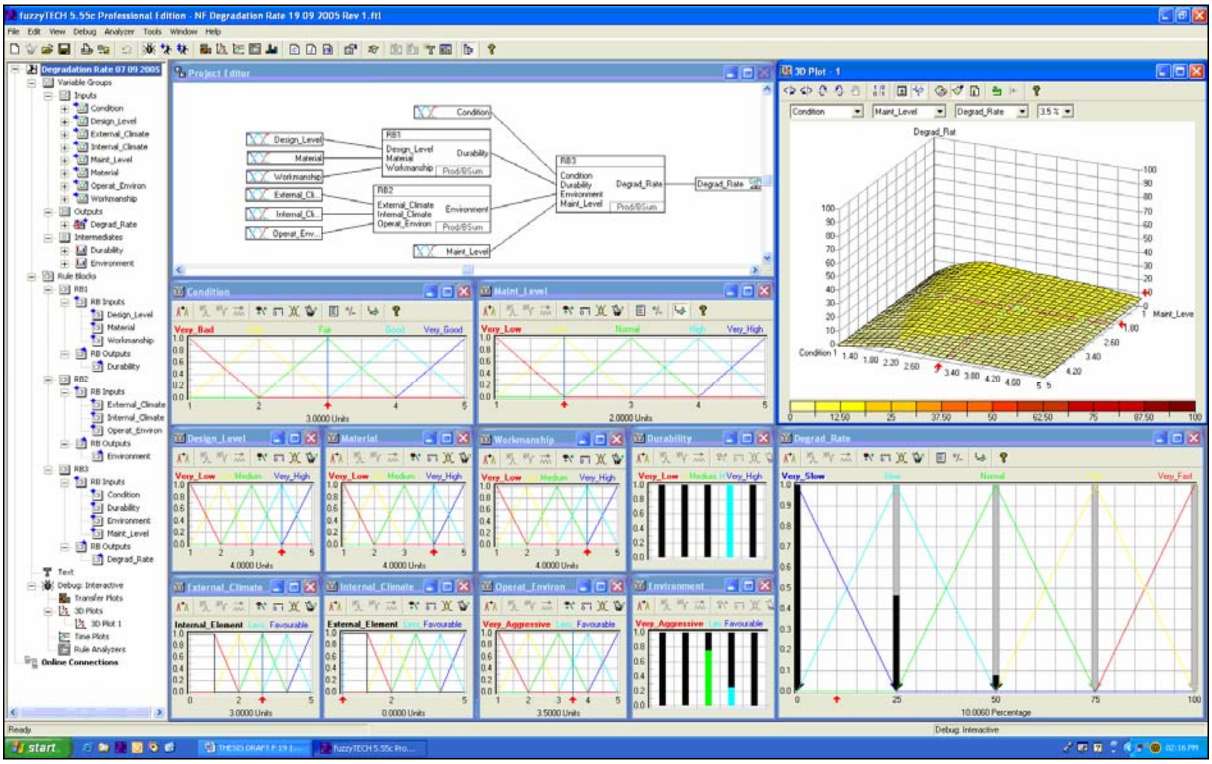


Figure 3-24: Screendump of revised fuzzyTECH model

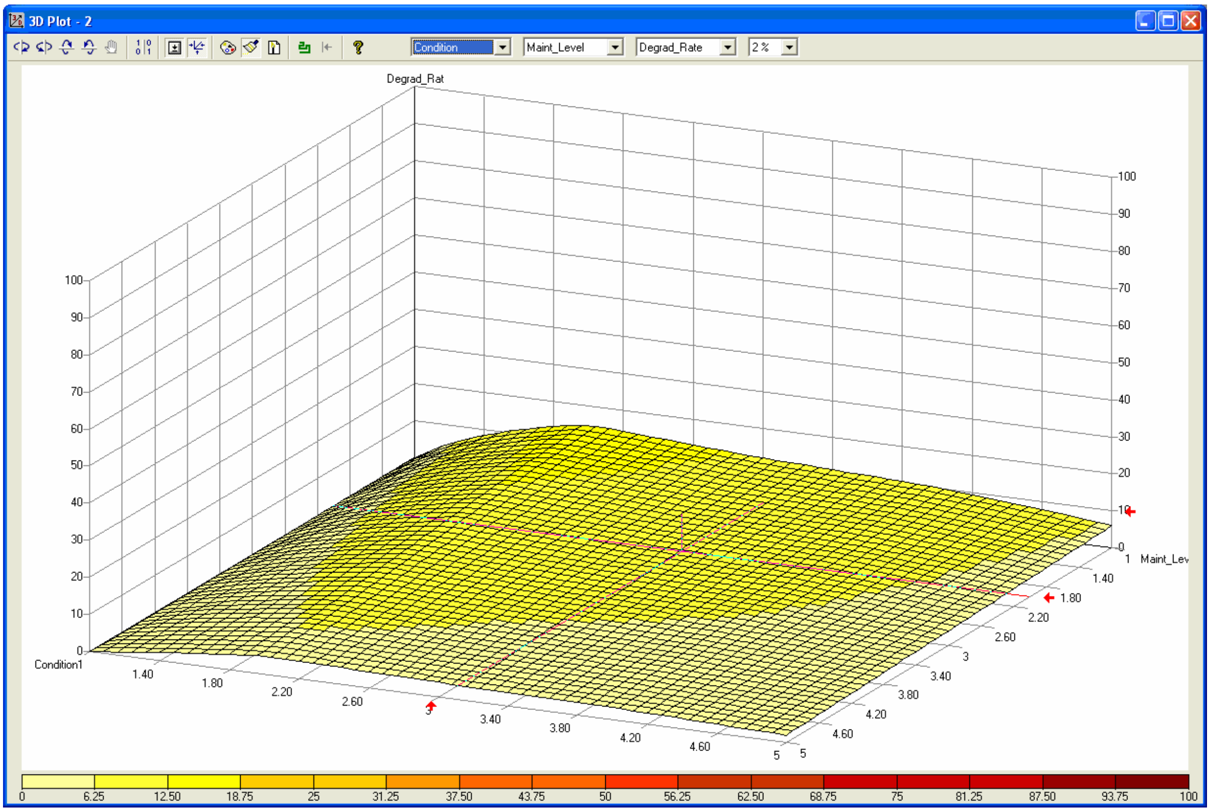


Figure 3-25: A 3-D Plot of the revised fuzzyTECH Model

Figure 3-24 and Figure 3-25 above are a screendump and three-dimensional plot of the calibrated model, after expert opinion was taken into consideration. Note that the condition 1 degradation rate for all five levels of maintenance has changed to zero (compare with Figure 3-22 above), which is in line with the Markov Model.

Markov Transition Probability Matrix		Condition at time t = 1				
		5	4	3	2	1
Condition at time t = 0	5	0.950	0.050	0	0	0
	4	0	0.915	0.085	0	0
	3	0	0	0.900	0.100	0
	2	0	0	0	0.875	0.125
	1	0	0	0	0	1

Table 3-20: Markov Transition Probability Matrix for revised Model

There is a remarkable similarity between the matrix in Table 3-19 and the matrices shown in Figure 2-13, for bridge decks in Canada (Morcous *et al*, 2003, p.355), and Table 2-16, which apparently originated from the Belcam Project on roof systems in Canada (Lounis *et al*, 1998, and Kyle *et al*, 2002).

For details of the transition probability matrices for all levels of maintenance please refer to Appendix C.

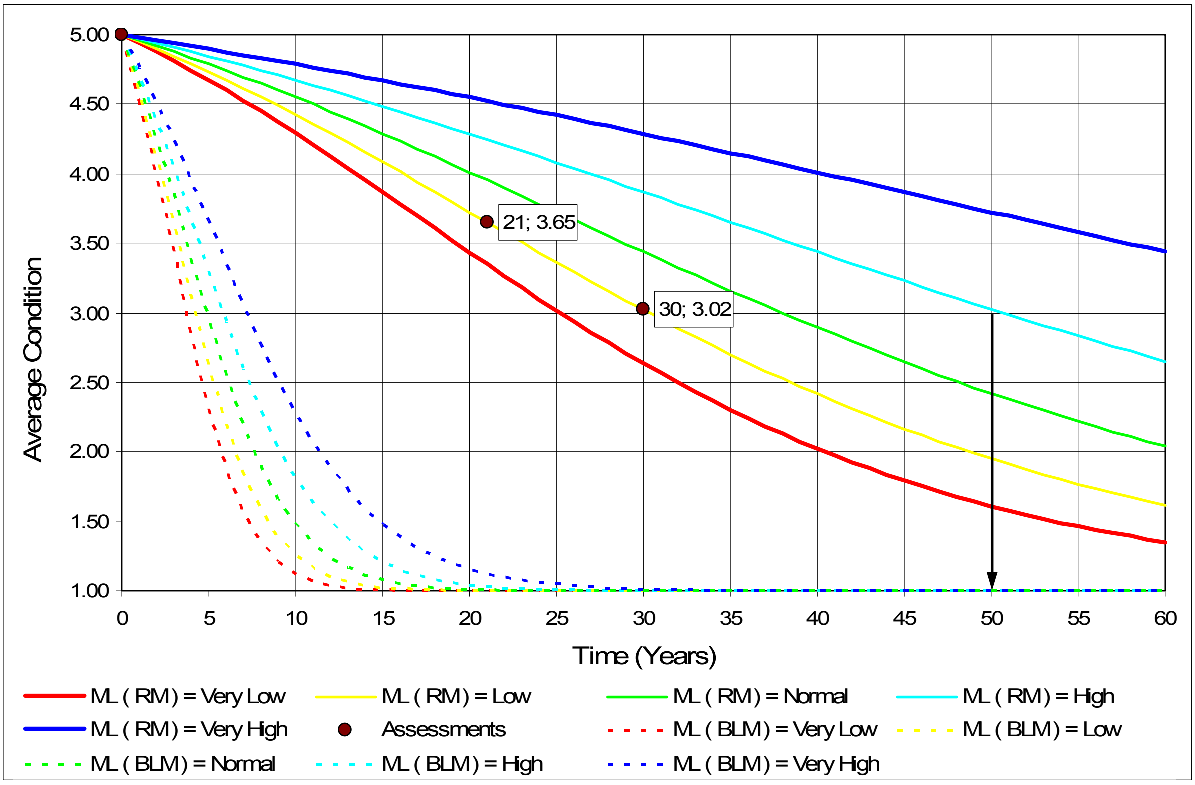


Figure 3-26: Performance over Time curves for different levels of maintenance – Revised Model (RM) vs 'Base-Line' Model (BLM)

In Figure 3-26, the revised model is compared to the 'base-line' model. The 'Low' maintenance level curve yields an average condition of 3.65 at year 21 and 3.02 at year 30, which is in line with the pilot hospital. The 'High' maintenance curve also yields an average condition of 3 ('reference performance standard') at year 50 ('reference service life' for an academic hospital).

The next step is to plot the assessed average conditions of the control sites on the graph. The details and factor ratings of the control sites are shown in Tables 3-23 and 3-24 below:

Site	Construction Area (m²)	No of Levels	Estimated Current Construction Cost (R6.50 = $1.00)	Structural Frame	Wall Type	Roof Type	Construction date	Audit Year and Average Condition							
								1995	1996	1999	2001	2002	2003	2004	2005
Pilot Hospital															
Hospital A	321,300	15	R 2,766,700,000	Concrete	Face brick	Flat concrete slab	1975		3.65						3.02
Control Hospitals															
Hospital B	103,293	7	R 890,000,000	Concrete	Face brick	Sheet metal	1973	4.10		3.71	3.91				
Hospital C	111,038	15	R 956,000,000	Concrete	Precast panels	Flat concrete slab	1980	4.00					3.80		
Hospital D	378,589	12	R 3,260,000,000	Concrete	Concrete	Flat concrete slab	1976	3.73		3.60	3.80				
Hospital E	119,260	3	R 1,027,000,000	Concrete	Face brick	Sheet metal	1973	4.00		3.61	3.89				
Hospital F	101,696	4	R 876,000,000	Concrete	Precast panels	Flat concrete slab	1980	3.89				3.88		3.77	

Table 3-21: General Information on Pilot and Control Sites (Source: CSIR)

FACTOR	Design Level	Material	Workmanship	External Climate	Intenrnal Climate	Operational Environment	Maintenance Level
Pilot Hospital							
Hospital A	4	4	4	3	0	3.5	2
Control Hospitals							
Hospital B	4	4	4	4	0	3.5	3.75
Hospital C	4	4	4	4	0	3.5	3
Hospital D	4	4	4	4	0	3.5	2.5
Hospital E	4	4	4	4	0	3.5	3.5
Hospital F	4	4	4	3	0	3.5	3

Table 3-22: Factor Ratings for Pilot and Control Sites

In Figure 3-27 below the average conditions of the control sites are shown on the curves for a 'slightly aggressive' external climate. In Table 3-21 above the external climate for four of the five control sites is however indicated as 'less favourable'. Figure 3-28 shows the average conditions on the curves for a 'less favourable' external climate. A comparison between the curve for a 'slightly aggressive' external climate and a 'less favourable' external climate shows that the curves have moved slightly upwards for the 'less favourable' external climate, which indicates a slightly longer service life and is in line with the whole philosophy of the model.

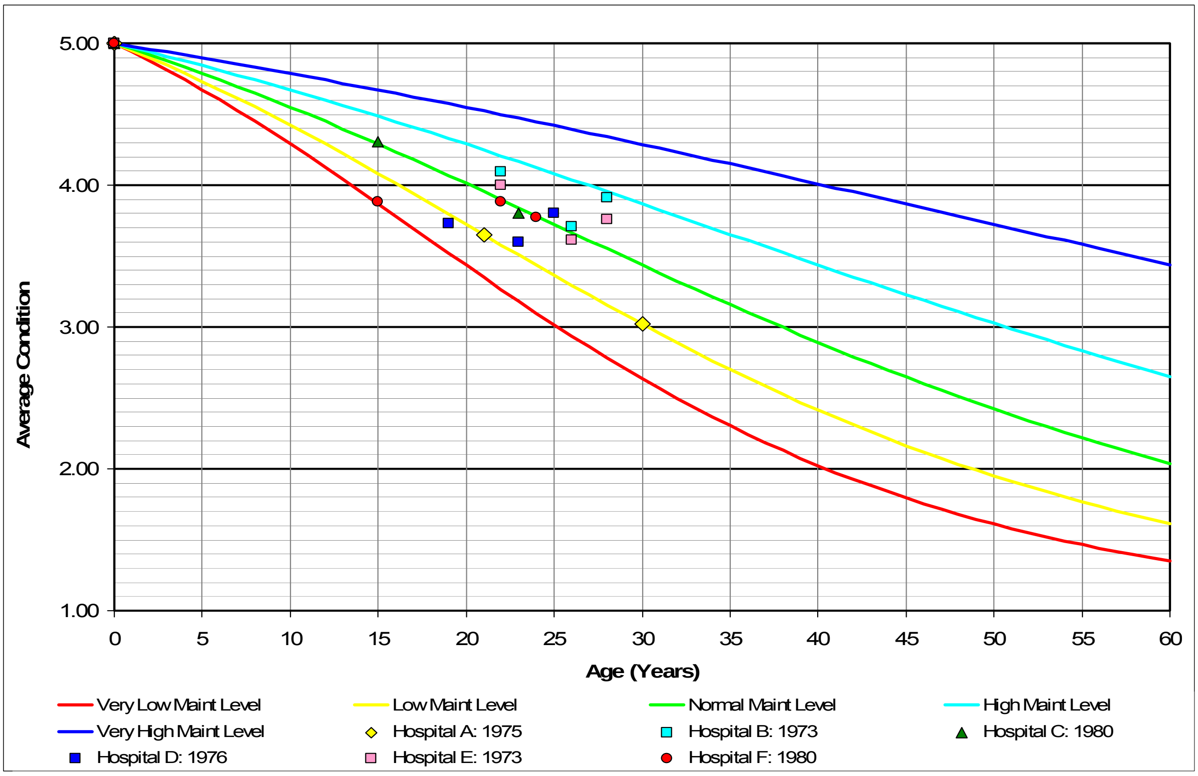


Figure 3-27: Performance over Time Curves for 'Slightly Aggressive' External Climate

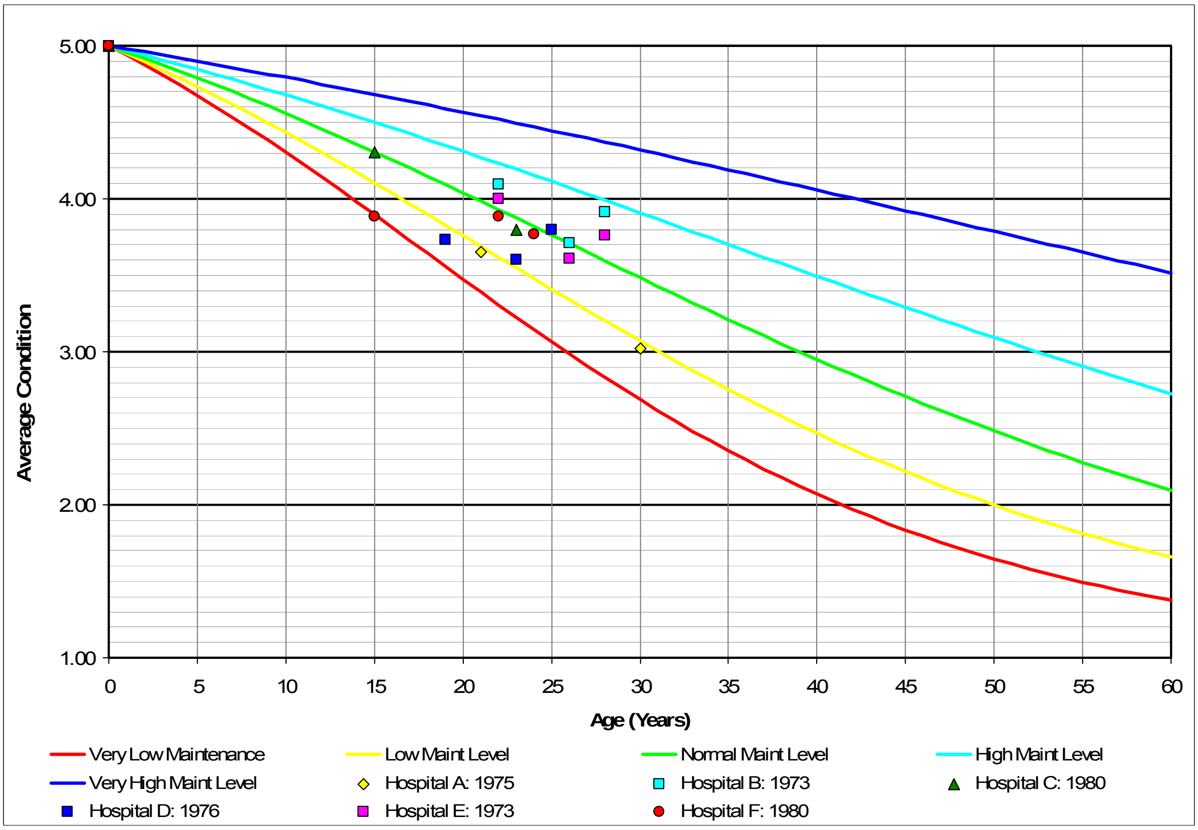


Figure 3-28: Performance over Time Curves for 'Less Favourable' External Climate

3.5. The Prediction of Service Life for Buildings and Components

3.5.1. Introduction

For service life prediction, the condition of a building or component is a relatively easy to assess and ideal to use performance indicator. The minimum performance requirement for academic hospitals should be Condition 3. Below a level 3 the building or component is simply not able to provide an environment supportive of proper health care. There are areas in hospitals where the performance requirements are higher (e.g. operating theatres and intensive care units). For other building types, this performance standard may be different. The performance requirements for buildings and components should be determined by clearly defined and appropriate policies and codes.

3.5.2. Service Life Prediction

In Figure 3-29 and Figure 3-30, the predicted service life for an academic hospital can be read from the graph for various levels of maintenance. In a similar way, curves for other types of buildings or components can be developed for the whole range of durability and degradation factors. By doing regular condition assessments during the service life of the building or component, ‘progress’ can be measured against these curves and the necessary corrective actions can be implemented in time to either ensure that the desired service life is achieved or exceeded.

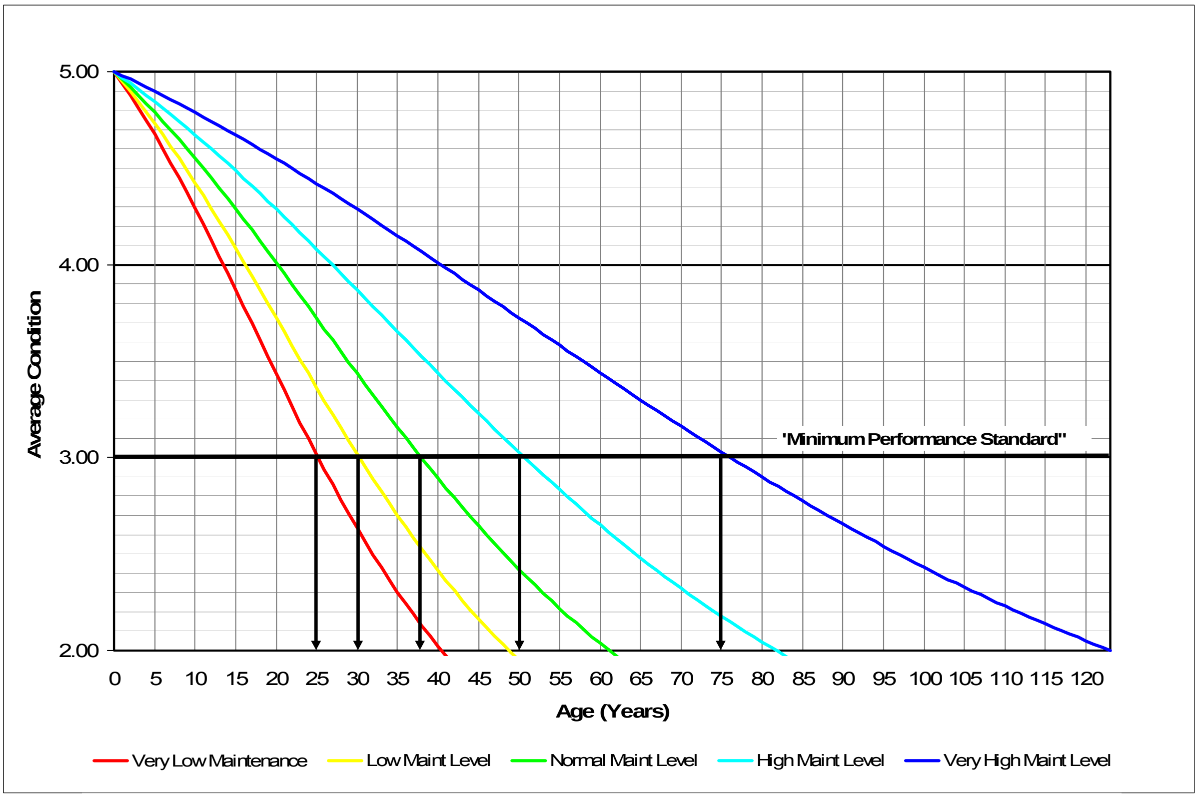


Figure 3-29: Service Life Prediction Graph for Academic Hospitals in South Africa in a 'Slightly Aggressive' External Climate

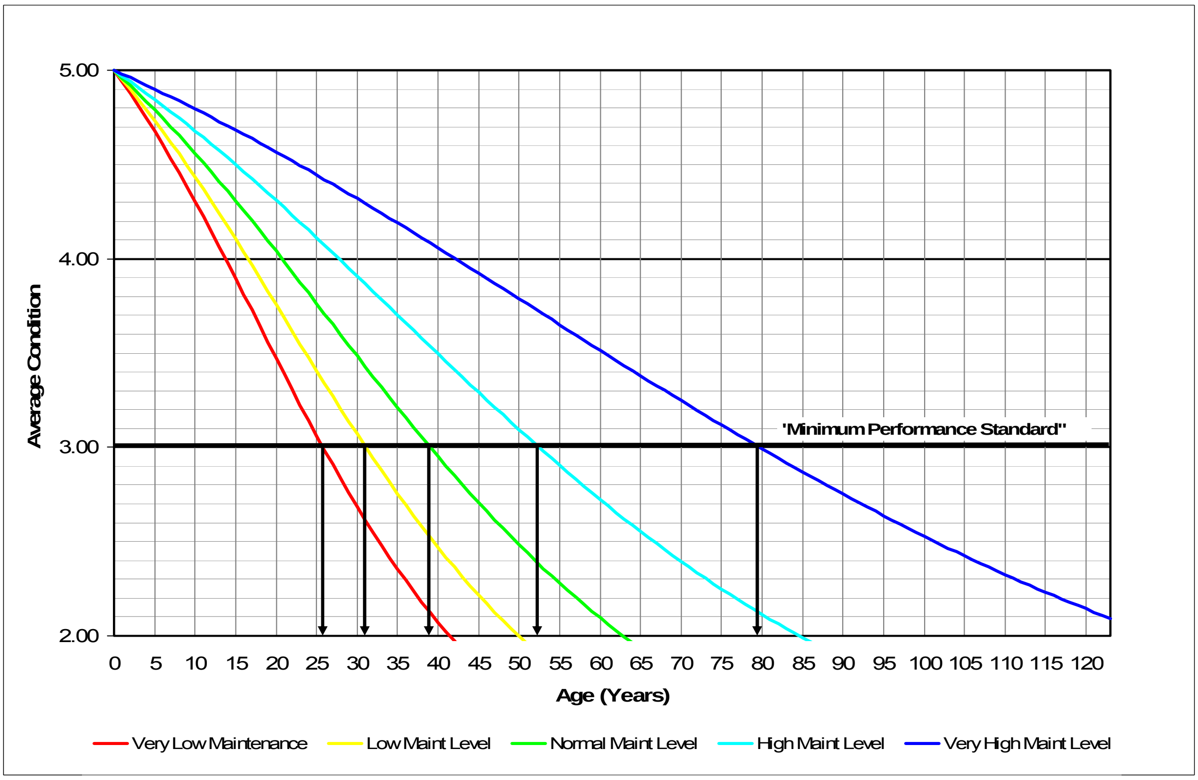


Figure 3-30: Service Life Prediction Graph for Academic Hospitals in South Africa in a 'Less Favourable' External Climate

3.6. Other Applications

The Markov Chain method offers a number of applications in the field of maintenance management, some of which is briefly discussed below.

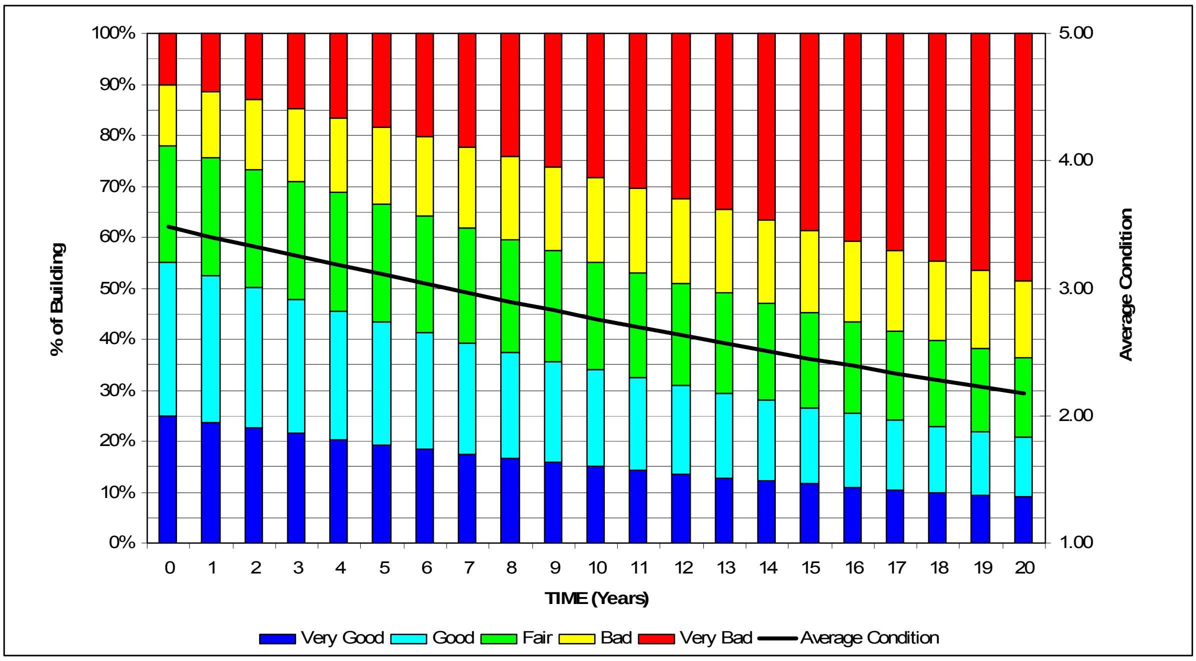


Figure 3-31: Anticipated change in condition profile and average condition over time

In Figure 3-31 above, the column at time 0 represents the current assessed condition profile of a building. The anticipated change in the condition profile and average condition for a specific maintenance regime can be calculated through a Markov Chain simulation. The ability to anticipate the change in condition profile through the application of the Markov model enables the decision-maker to do scenario analysis and quantify the impact of maintenance strategies on the maintenance backlog. This makes it possible to estimate what percentage of the building or component will fall in the different condition categories at any point in time for a specific maintenance regime. With this information and using a classification as shown in Figure 3-32 below, it is possible to determine what type of maintenance will be required, including backlog maintenance.

RATING	CONDITION	ACTION REQUIRED	PRESERVATION PROGRAMME	"MAINTENANCE" TYPE
1	Very Bad	Replacement	Replacement	"Backlog" Maintenance
2	Bad	Rehabilitation	Repairs & Rehabilitation	
3	Fair	Repairs		
4	Good	Condition-based Maintenance	Maintenance	Normal Maintenance
5	Very Good	Preventative Maintenance		

Figure 3-32: Maintenance types vs condition assessment ratings

There is a common misconception that a new building or component does not need maintenance, resulting in no or very little preventative maintenance being done. The intention of 'day-to-day' maintenance is attending to on-going planned preventative maintenance activities and minor repairs and replacements due to unplanned or unforeseen failures or breakages. The planned preventative part however seldom happens. The classification to distinguish between maintenance and backlog maintenance, as shown in Figure 3-32 above, is therefore very important because most of the work done as maintenance actually is repairs, rehabilitation or replacement and not maintenance.

The cost of reparation work increases as the condition deteriorates, and this is the primary reason for the decaying built environment. Because the demand for action is much higher in the case of backlog maintenance, available funds are first allocated to these activities and due to the high cost all the available funds disappear in backlog maintenance activities, with nothing left for planned preventative maintenance. The consequences of this are increased backlog maintenance and reduced service life of existing buildings.

The solution to this problem is the introduction of a preservation programme, as illustrated in Figure 3-33 below. The objective of the preservation programme is to eradicate backlog maintenance and focus on planned preventative maintenance because it is the most cost effective or cheapest form of maintenance.

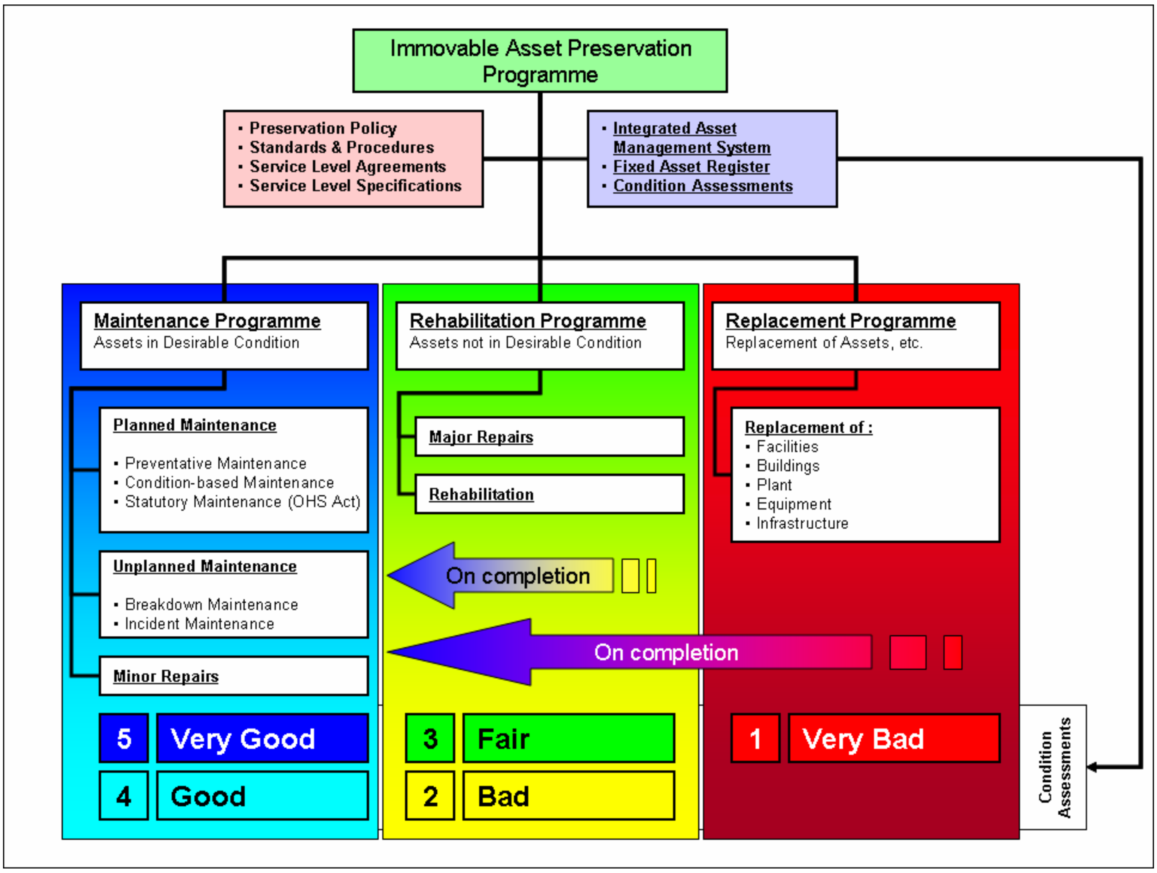


Figure 3-33: Preservation programme diagram

Based on the assessed condition of the building or component, the actions (work) required to reinstate the building or component to the desired condition is identified and the associated costs estimated. Depending on the preservation policy requirements, work will either be classified as capital works (e.g. large capital projects such as replacement or refurbishment of whole buildings or facilities), or preservation programme. Work classified as preservation programme is categorised according to the condition rating, as shown in Figure 3-33 above. Funds are allocated proportionally to each programme (maintenance, repairs and rehabilitation, replacement). When repairs, rehabilitation and replacements have been completed, the building or component returns to the maintenance programme where planned preventative maintenance is done to retain it in a Condition 4 or above for as long as possible. The main objective of the preservation programme is to implement planned preventative maintenance and ensure the allocation funds for planned preventative maintenance.

3.7. Summary of Methodology

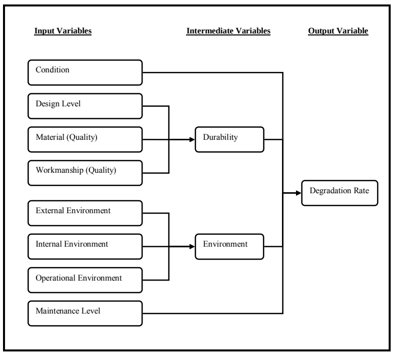
Table 3-22 below provides a graphic summary of the proposed methodology for 'Service Life Prediction' and strategic service life planning applications.

Step ***Process*** ***Action***

1

- Identify type of building or component for Service Life Prediction (e.g. ambulance garage building, or external face brick walls, or aluminium window frames, etc.)

2



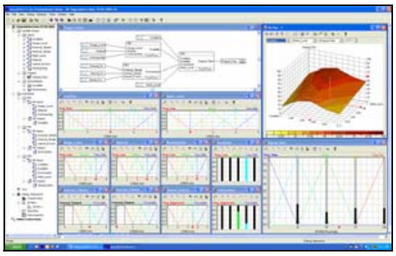
- Define Fuzzy structure
- Analyse degradation and durability factors for building or component under consideration

3

CONDITION RATING	Condition	Action Required	Description
5	Very Good	Planned Preventative Maintenance	The component or building is either new or has recently been maintained, does not exhibit any signs of deterioration.
4	Good	Condition-based Maintenance	The component or building exhibits superficial wear and tear, minor defects, minor signs of deterioration to surface finishes and requires maintenance/servicing. It can be reinstated with routine scheduled or unscheduled maintenance/servicing.
3	Fair	Repairs Required	Significant sections or component require repair, usually by a specialist. The component or building has been subjected to abnormal use or abuse, and its poor state of repair is beginning to affect surrounding elements. Backlog maintenance work exists.
2	Bad	Rehabilitation Required	Substantial sections or component have deteriorated badly, suffered structural damage or require renovations. There is a serious risk of imminent failure. The state of repair has a substantial impact on surrounding elements or creates a potential health or safety risk.
1	Very Bad	Replacement Required	The component or building has failed, is not operational or deteriorated to the extent that does not justify repairs, but should rather be replaced. The condition of the element actively contributes to the degradation of surrounding elements or creates a safety, health or life risk.

- Allocate ratings (5 point scale) to each factor

4



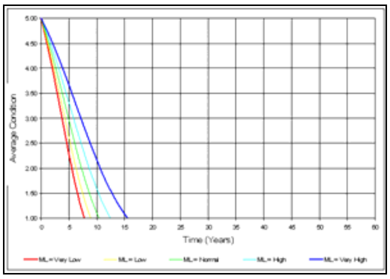
- Develop Fuzzy Sets for variables (factors) – input, intermediate and output
- Develop IF – THEN rules
- Feed into Neuro-fuzzy system
- Adjust ratings for each variable (factor) according to allocations made in Step 2

5

Markov Transition Probability Matrix		Condition at time t = 1				
		5	4	3	2	1
Condition at time t = 0	5	57.818%	42.182%	0.000%	0.000%	0.000%
	4	0.000%	51.564%	48.436%	0.000%	0.000%
	3	0.000%	0.000%	39.064%	60.936%	0.000%
	2	0.000%	0.000%	0.000%	45.312%	54.688%
	1	0.000%	0.000%	0.000%	0.000%	100.000%

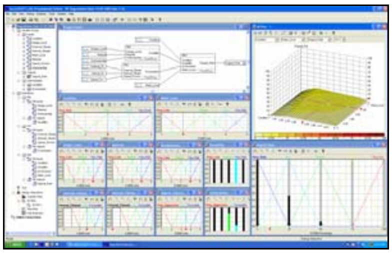
- Feed output from Neuro-fuzzy system into Markov Chain Transition Probability Matrix

6



- Do a Markov Chain simulation of the anticipated condition profile transition over time
- Plot 'base-line' 'Performance over Time' graph
- Evaluate 'base-line' output

7



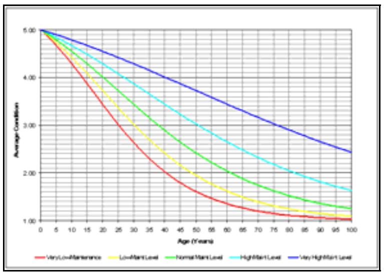
- Return to Neuro-fuzzy system and adjust 'Degree of Support' or weights of variables in Rule Blocks

8

Markov Transition Probability Matrix		Condition at time t = 1				
		5	4	3	2	1
Condition at time t = 0	5	95.000%	5.000%	0.000%	0.000%	0.000%
	4	0.000%	91.500%	8.500%	0.000%	0.000%
	3	0.000%	0.000%	90.000%	10.000%	0.000%
	2	0.000%	0.000%	0.000%	87.500%	12.500%
	1	0.000%	0.000%	0.000%	0.000%	100.000%

- Feed output from Neuro-fuzzy system into Markov Chain Transition Probability Matrix

9



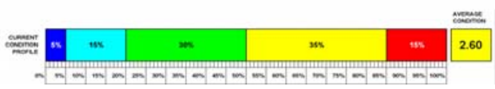
- Do a Markov Chain simulation
- Plot 'Performance over Time' graph
- Evaluate output
- Repeat Steps 7, 8 and 9 till 'realistic' degradation rates are obtained

10

CONDITION RATING	Condition	Action Required	Description
5	Very Good	Planned Preventative Maintenance	The component or building is either new or has recently been maintained, does not exhibit any signs of deterioration
4	Good	Condition-based Maintenance	The component or building exhibits superficial wear and tear, minor defects, minor signs of deterioration to surface finishes and requires maintenance/servicing. It can be reinstated with routine scheduled or unscheduled maintenance/servicing.
3	Fair	Repairs Required	Significant sections or component require repair, usually by a specialist. The component or building has been subjected to abnormal use or abuse, and its poor state of repair is beginning to affect surrounding elements. Backlog maintenance work exists.
2	Bad	Rehabilitation Required	Substantial sections or component have deteriorated badly, suffered structural damage or require renovations. There is a serious risk of imminent failure. The state of repair has a substantial impact on surrounding elements or creates a potential health or safety risk.
1	Very Bad	Replacement Required	The component or building has failed, is not operational or deteriorated to the extent that does not justify repairs, but should rather be replaced. The condition of the element actively contributes to the degradation of surrounding elements or creates a safety, health or life risk.

- Identify suitable pilot buildings or components
- Perform condition assessment of set of pilot buildings or components

11



- Develop condition profiles of pilot buildings or components
- Calculate average conditions

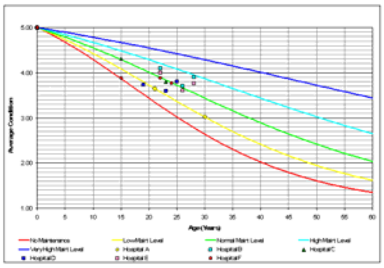
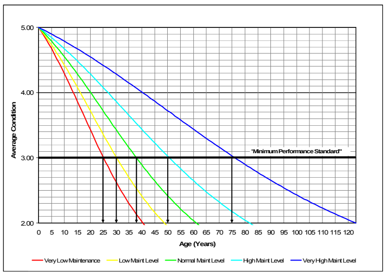
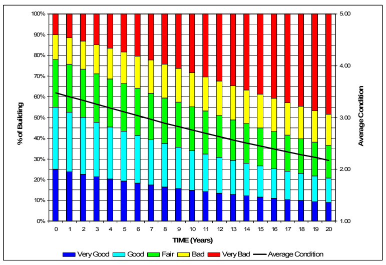
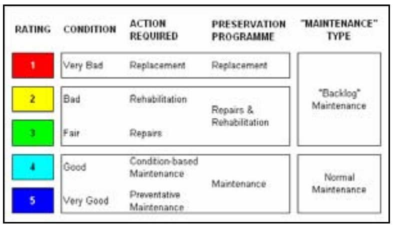
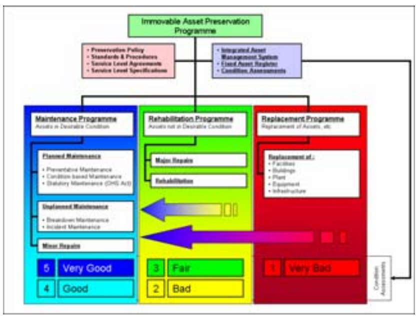
12		• Plot pilot building or component data on 'Performance over Time' graph from Step 9 • Compare plot with 'base-line' graphs • If no or bad correlation between model and assessment data, return to Step 7 and repeat process • If model correlates with assessment data → calibrated system
13		• Determine 'desirable' Service Level – (e.g. for hospital Average Condition > 3 on 5 point rating system) • From calibrated 'Performance over Time' graph obtain predicted 'Service Life' for various levels of maintenance
14		• Run Markov Chain simulation with 'calibrated' Transition Probability Matrix • Plot Anticipated Changes in Condition Profile and Average Condition from Markov simulation
15		• From Graph in Step 14 calculate maintenance budgets • Develop maintenance budget scenarios and strategies • Develop Service Life scenario and cost analysis
16		• Implement Preservation Programme • Do regular condition assessments and monitor changes • Return to Step 7 and feed field data into system for system calibration, 'learning', and improvements

Table 3-23: Process Summary

4. RESULTS AND DISCUSSION

4.1. Introduction

In this section, the remaining service life for each hospital is predicted by means of the proposed model, followed by discussions of the results, maintenance levels and service life prediction.

4.2. Results

In Figure 4-1 and Figure 4-2 below the service life prediction curves for the six hospital used to calibrate and test the proposed model are shown. Figure 4-1 applies to a 'slightly aggressive' external climate, while Figure 4-2 applies to a 'less favourable' external climate. The assessed conditions of each hospital are shown on the applicable graph. Condition 3 is assumed as minimum performance standard or level.

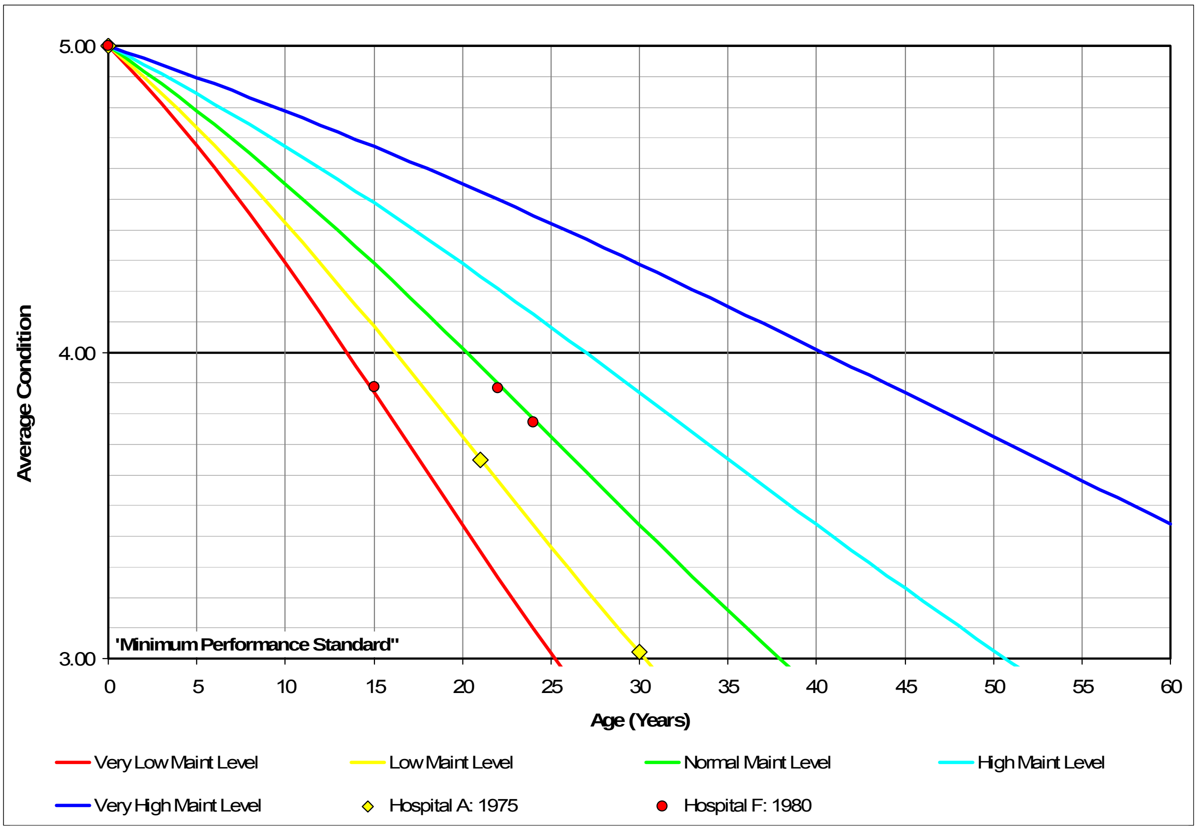


Figure 4-1: Service Life Prediction Graph for Hospitals A and F

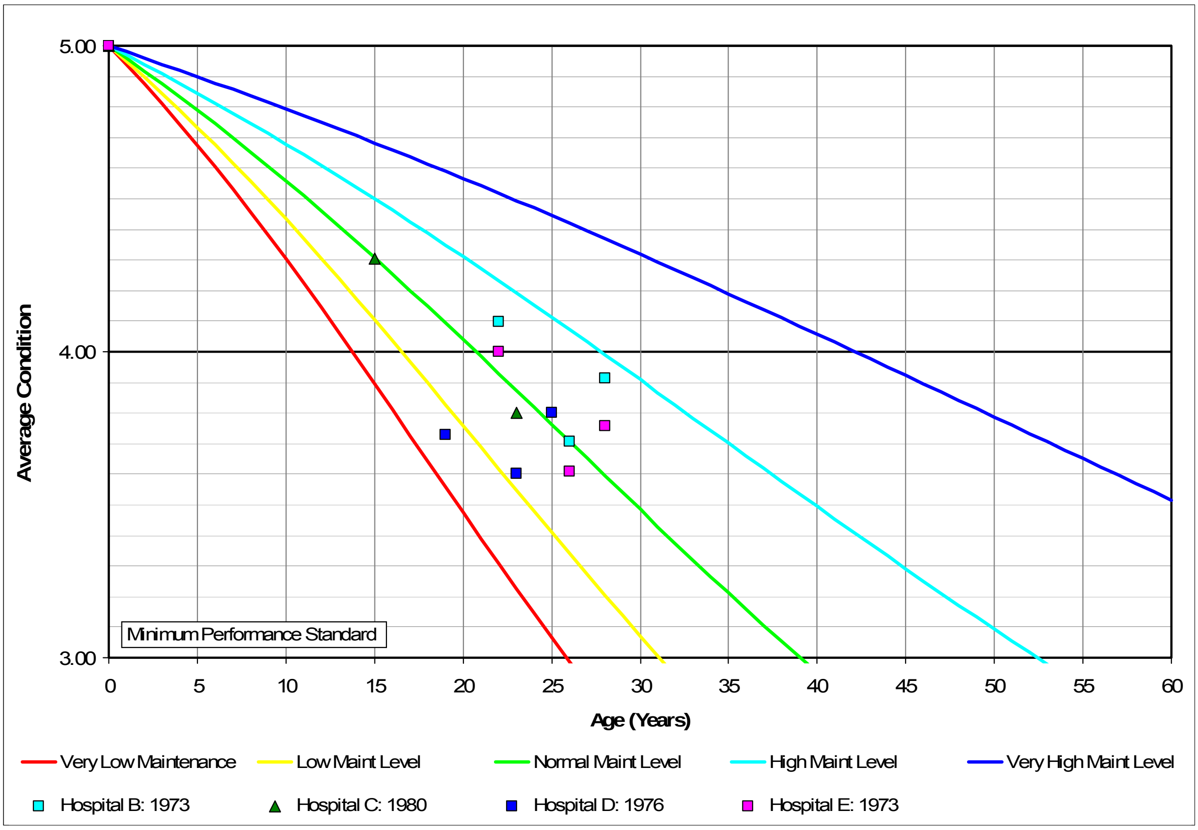


Figure 4-2: Service Life Prediction Graph for Hospitals B, C, D and E

Based on Figure 4-1 and Figure 4-2, and assuming a sustained current maintenance regime, the predicted service lives for the six hospitals are as follows:

Design service life = 50 years	Predicted service life	Current age	Remaining service life	Service life gain/(loss)
Hospital A:	30 years	30 years	0 years	(20 years)
Hospital B:	45 years	32 years	13 years	(5 years)
Hospital C:	34 years	25 years	9 years	(16 years)
Hospital D:	40 years	29 years	11 years	(10 years)
Hospital E:	42 years	32 years	10 years	(8 years)
Hospital F:	38 years	25 years	13 years	(12 years)

Table 4-1: Predicted service life for hospitals

4.3. Discussion

The average conditions of the six hospitals are shown on two different timelines in Figure 4-3 and Figure 4-4 below. In Figure 4-3 the average conditions of the six hospitals are shown on a calendar timeline, while in Figure 4-4, an age-based timeline is used. The calendar timeline in Figure 4-3 gives an indication of when the construction of these hospitals was completed, as well as the time of the condition assessments. Figure 4-4 provides a comparison of the condition status of the hospitals at the same age.

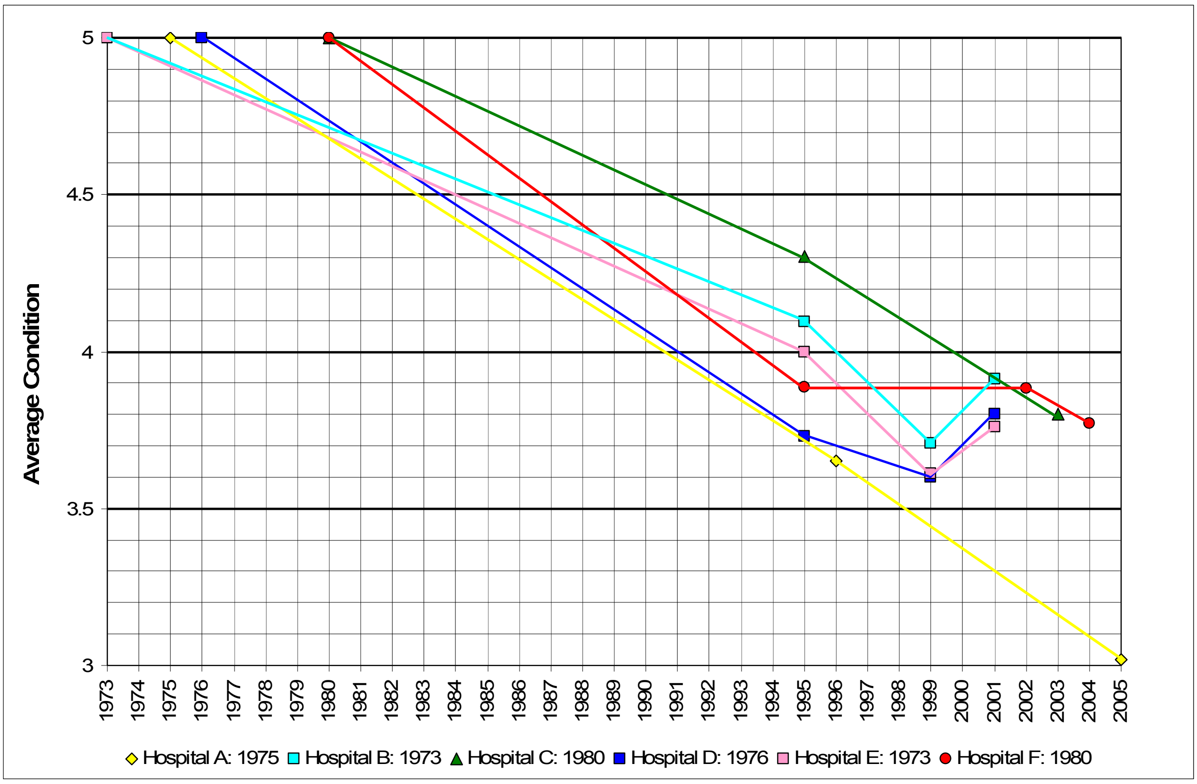


Figure 4-3: Performance of Pilot and Control Hospitals over Time (Calendar Years)

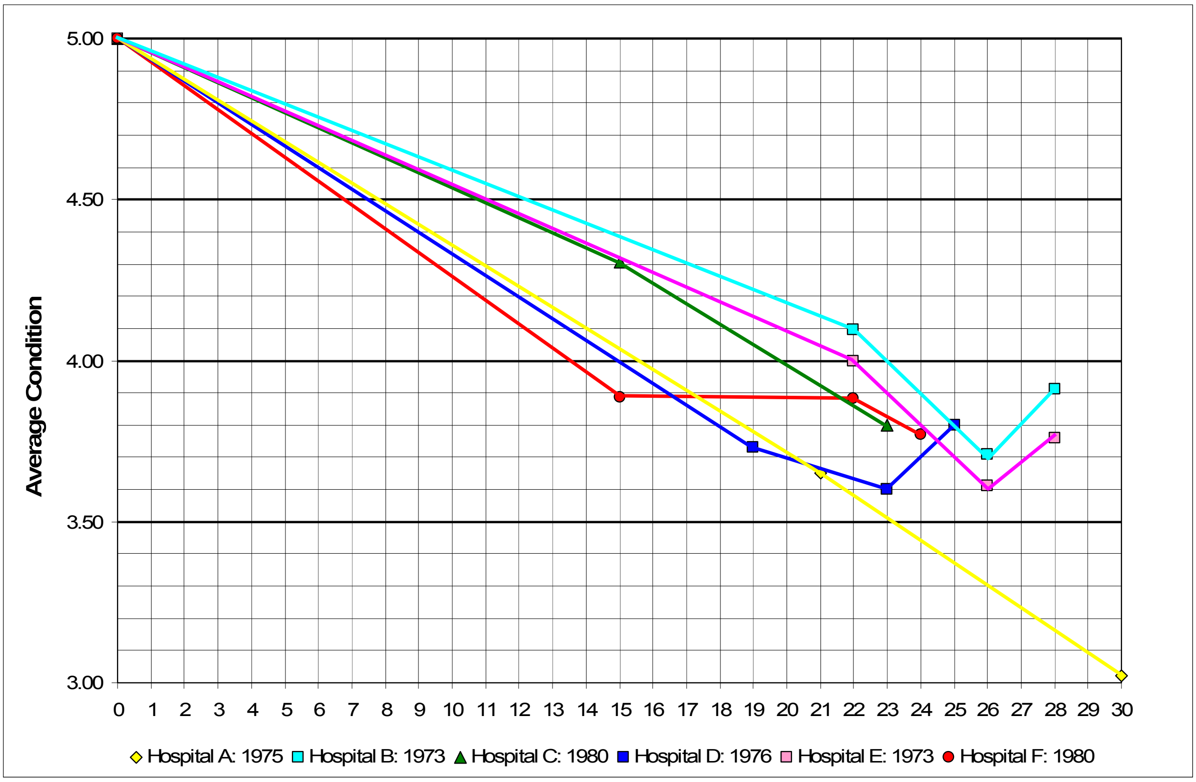


Figure 4-4: Performance of Pilot and Control Hospitals over Time (Age)

4.3.1. Hospitals

a.) Hospital A

Thirty years after commissioning, Hospital A has reached the end of its service life. The average condition of the facility has reached the minimum acceptable level and large sections of the facility have deteriorated beyond acceptable levels for a hospital. Approaching the hospital, the first impression from a distance is that the hospital is still in a good condition due to good quality face brick facade, and this perception has contributed to a large extent to its demise. Mechanical and electrical installations in general have a life expectancy of 20 to 30 years, and are due or overdue for replacement. The main hospital building has a floor area in excess of 230,000 m^2 with approximately 42 km of passages, which makes it very difficult to get a good perception of the general condition of the facility, unless regular condition assessments are performed, which unfortunately was not the case. From Figure 4-3 and Figure 4-4 it can clearly be seen that the degradation over a period of 30 years followed an almost straight line. There has been a loss of experienced artisans at the facility due to retirement, resignations, retrenchments and death, which contributed to the slight increase in the degradation rate.

Discussions with officials closely involved with the maintenance and operation of the hospital confirmed that most of the degradation factors stayed relatively constant throughout the 30-year life span of the facility, which makes it a good subject to base the proposed model on.

b.) Hospitals B, D and E

Control sites B, D and E are located in the same geographical area with a 'less favourable' macroclimate and display the same degradation patterns. The curves in Figure 3-28 and Figure 3-30 for 'less favourable' external climates are applicable. Hospitals B and E are very similar in most aspects, including age. From Figure 4-3, where all the sites are shown on the same calendar timeline, it appears that the 1995 NHFA was followed by a drop in the maintenance levels of Hospitals B and E, between 1995 and 1999 when the next assessment was done, probably due to the perception that these hospitals were in a good condition at that point in time. There was a slight decrease in the degradation rate of Hospital D during this same period, which can be attributed to rehabilitation of the steam, heating and air-condition installations and fire services of Hospital D, as shown in the Condition Matrices for the 1995 NHFA and 1999 audits in Appendix B. The upswing in the average condition of all three hospitals between 1999 and 2001, when the next assessments were done, can be attributed to a deliberate effort by the officials to improve the condition of the hospitals in this province, which was initiated by the hospital revitalisation program of the National Department of Health and funded by the European Community. Another assessment was recently completed, but the results are still not available for analysis.

c.) Hospital C

The 1995 NHFA assessment for Hospital C plots on the 'normal' maintenance level curve for a 'less favourable' external climate, which is a true reflection of the actual situation. There was however a slight drop between 1995 and 2003, when the next assessment was done, which can possibly be attributed to a change in management at the hospital during this period. Although there are differences between Hospital C and Hospital A in terms of the building envelope, design, external climate and maintenance level, an important similarity is the lack of reaction to the 1995 NHFA, unlike the other four hospitals, which makes Hospital C a good comparator for the proposed model.

d.) Hospital F

In Figure 4-3 Hospital F, also in a 'slightly aggressive' external climate similar to the pilot site Hospital A, plots exactly on the curves without any adjustments to the revised model for the pilot site Hospital A. At age 15 years the average condition of Hospital F plots on the 'Very Low' maintenance level curve and then jumps to the 'Normal' maintenance level curve at ages 22 and 24 years. This can be attributed to a number of reasons. Records for the period prior to the 1995/6 NHFA is unfortunately hard to come by and it is assumed that the maintenance level was 'Very Low' during the period between completion of construction in 1980 and the NHFA in 1995 based on the general tendency to 'neglect' a new facility because it is new and does not require attention while other older facilities do require attention due to occupant/user complaints and demands. Therefore, it is quite possible, but very difficult to establish or confirm that the hospital's maintenance was indeed on a 'Very Low' level. The sudden jump to a 'Normal' maintenance level seven years later is attributed to two major events. Firstly, the officials in that province paid attention to the results of the NHFA, reacted in a positive manner by doing regular condition assessments, and implementing a computer system, developed by the CSIR and used for the NHFA. The information collected during these annual assessments was used to update the database in the computer system and formed the basis for management decisions. The second event is the implementation of a hospital revitalisation programme resulting in upgrades and additions to the hospital. During the period 1995 and 2002, 15,400 m^2 or 18% of floor area, was added, which also had an impact on the average condition. What is however of interest is that the average condition for 2004 plots on the 'Normal' maintenance curve.

4.3.2. Maintenance level

From Figure 4-1 and Figure 4-2 above it can clearly be seen that only in the case of Hospitals A and C was there no reaction to the 1995 NHFA. At Hospital A, the maintenance regime and the degradation rate did not change, while at Hospital C there has been a change in the on-site management of the maintenance resulting in a slight increase in the degradation. Both hospitals are therefore regarded to be ideal for calibration of the system. As far as the other control sites are concerned, there was a clear reaction to the assessments for the better and it would be interested, and essential for research, to monitor the change in condition at these hospitals over time. A major concern however remains the lack of appreciation of the importance of continuous assessment and monitoring amongst decision makers in the public sector.

Academic hospitals in South Africa are generally under-maintained. Indications are that the annual maintenance budgets are less than 2% of the estimated current construction cost, which is the current cost to replace the existing building with the same material and technology as the original (replacement cost is often confused with the cost to replace an existing building with 'new technology' resulting in an uneven comparison between buildings with different ages). For an academic hospital, in fact, all health care facilities, the maintenance level should be 'High' and the maintenance budget should be at least 4% per annum throughout the service life of the building. For proper maintenance management the maintenance budget should be based at component level and not building level because component types have different service lives. The different components will reach the end of their respective service lives at different points in time resulting in replacements or upgrades and fluctuations in the cashflow, which should be taken into consideration. Therefore, although 4% should be the general norm, the variation in service life should be taken into consideration and provision should be made for scheduled rehabilitations, upgrades or replacement of components during the service life of a building.

Condition	Budget Req'd as % of Replacement Cost	Preservation Type Required
Very Good	**2 - 3%**	Preventative Maintenance
Good	**4 - 6%**	Condition-based Maintenance
Fair	**20 - 30%**	Major repairs
Bad	**50 - 60%**	Rehabilitation
Very Bad	**100 - 110%**	Replacement

Table 4-2: Rough Guide of Annual Budget Allowances for Different Condition Ratings (Mc Duling, 2005)

Table 4-2, based on practical experience, gives a rough guide of annual budget allowances for different condition ratings and illustrates the increase in maintenance cost as the condition worsens. However, working with a single figure average condition will result in an under-estimation of the budget required, and should be avoided. The correct way is to calculate the budget requirement for each condition category individually and ad it all together. According to the National Department of Health, the cut-off point for rehabilitation or replacement decisions is when the rehabilitation or redevelopment cost reaches 60% of the replacement cost, which is in line with Table 4-2.

The recent assessment and redevelopment evaluation of Hospital A has confirmed that the minimum acceptable performance standard (condition) for an academic hospital is Condition 3 and minimum acceptable maintenance level is 'high' (level 4).

4.3.3. Service life prediction

Ignorance of the consequences of maintenance levels on service life of buildings and components is a major problem. It is said *"Ignorance is bliss"* (Thomas Gray, eighteenth-century English poet), but also *"Ignorance of the law excuses no man"* (John Selden, English antiquarian and jurist, 1584-1654).

In the case of Hospital A, the facility has reached the end of its service life, yet the process to rehabilitate, refurbish, redevelop or replace has only started at the end of the service life of the facility. It will take another eight to twelve years (or more) to complete the planning design and construction phases, whatever the decision. In the mean time, the existing facility needs to be operated and maintained at increasing costs and risk. Key mechanical and electrical installations need replacement and this has to be considered in the decision process. This should have been foreseen and planned for in advance, and illustrates the importance of service life prediction.

The following example illustrates the consequences of loss in service life because of too low maintenance levels. Assume a hospital with a present day construction cost of R1,000,000,000 (US$154,000,000 ±), and a design service life of 50 years when it will be replaced with an identical hospital at the same cost, ignoring inflation. Assuming an appropriate maintenance level to achieve the design service life, the present value (PV) of the investment required to be able to replace the hospital in 50 years time amounts to R54,300,000 at a rate of 6% per year. Should the maintenance level be too low and the actual service life reduces to 30 years, the PV of the required investment increases to R174,100,000. The analysis of the predicted service life of the six hospitals has shown that a reduction in service life of up to 20 years is possible. The consequence of a 20-year loss in service life is an investment more than three times larger.

In Figure 4-5 below, the anticipated condition profiles, when the minimum acceptable performance level is reached, for a low maintenance and a high maintenance level are shown. It is important to note that although the anticipated condition profiles are almost identical, the profile for low maintenance level occurs at age 30 years, while the high maintenance level profile occurs at age 50 years..

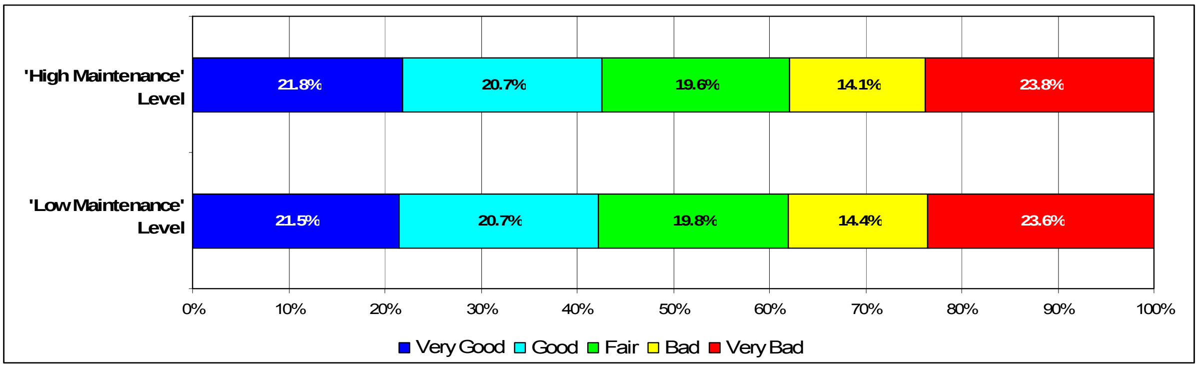


Figure 4-5: Anticipated condition profiles at end of service life (average condition 3)

The maintenance costs, rehabilitation/refurbishment and other costs should however also be considered for meaningful comparisons. Another consideration, especially in the case of health care facilities, is the rate of change in health care technology. New developments in health care technology and practices might render existing buildings outdated and result in changed accommodation demands long before the design service life is reached. It is from this point of view that the 50-year design service life of health care facilities is questionable. In the case of Hospital A, the planning and design started about 20 years before construction was completed, which means that although the physical structure is only 30 years old, the design is already 50 years old and quite outdated in terms of modern practice. Fifty years ago, the health care practice and accommodation demands were very different to modern practice.

4.3.4. Current Regime vs Proposed Model

The failure of the industry over the last 30 years to take on board mathematical techniques could perhaps be attributed to the input required to make existing models work being too complicated. The Markov method is widely recognised as an acceptable solution for service life prediction with broad application possibilities, but the lack of reliable historical performance data limits and complicates its implementation. This could be the motivation for the Factor Method being the current state of the art for service life prediction.

Figure 4-3 above clearly shows that the current practice of regular inspections with adjustments to the maintenance regime as necessary is a reactive approach. It is however, the first step towards the implementation of the proposed model and strategic maintenance management as it provides for the collection of the required historical performance data. The importance of reliable and consistent performance assessment data has only recently been realised, and available data is still scarce and inconsistent. Until such time when the available historical performance data will be sufficient to ensure reliable service life prediction results, the proposed model could be used to bridge the gap. The self-learning neural network module of the model, which does not form part of the scope of this thesis, will use the performance assessment data as it is continuously collected over time to calibrate the system and improve its reliability, while decreasing the role of the domain expert.

Until sufficient historical performance data has been collected through regular and consistent condition assessments, the proposed model can be used to develop transitional probabilities enabling the application of the Markovian model to predict condition changes over time and service life of buildings and components. This ability to predict condition changes can be used to prevent loss of service life due to inappropriate maintenance levels, which is not possible with the current practice of regular inspections with adjustments to the maintenance regime as necessary.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Introduction

The global importance of and need for sustainable development, requires an informed decision-making process from the built environment to ensure optimum service life.During the development of a method to calculate a condition-based maintenance budget for buildings and quantify the consequences of deferred maintenance, the need to quantify the change in condition over time was identified. The exploration of the existing knowledge base enabled a better understanding of the problem and identify potential solutions such as the Markov Chain, which has been identified as the preferred method for calculation of condition changes. The population of the Markov transitional probability matrix is however a problem due to limited historical performance data on the actual degradation of materials and components.

The proposed model, based on the Markov Chain approach, translates expert knowledge and reasoning into probability values through the application of Fuzzy Logic Artificial Intelligence to supplement limited historical performance data on degradation of building materials for the development of Markov Chain transitional probability matrices to predict service life, condition changes over time, and consequences of maintenance levels on service life of buildings.

Degradation and durability factors, similar to those identified in the state-of-the–art 'Factor Method' for service life prediction, are taken into consideration. The model also brings the current condition into the equation, which gives it an added dimension, especially when dealing with existing buildings where the remaining service life could be a crucial factor in investment decisions. The ability to predict changes in condition profiles and average condition makes scenario analysis and quantification of the consequences of maintenance levels and deferred maintenance possible leading to an informed decision-making process.

5.2. Conclusions

Based on the problem statements and hypotheses (refer sections 1.2 and 1.3), the following conclusions have been made:

5.2.1. Conclusion No. 1:

Problem Statement No. 1:

The ‘state-of-the-art’ Factor Method for service life prediction only calculates the estimated service life of a building or component, and cannot quantify changes in condition over time or determine the effect of maintenance level on service life.

Hypothesis No. 1:

The Markov Chain can be used to calculate the estimated service life of a building or component, quantify changes in condition over time and determine the effect of maintenance levels on service life.

The Markov Chain, which formed the basis of the proposed model to predict service life, quantify changes in condition over time and determine the effect of maintenance levels on service life of a building or component, is a stochastic approach used to simulate the transition from one state (condition) to another over time. It was also used in the NRCC’s Belcam project on roofing systems *“to predict the remaining service life of building envelope components and procedures to optimize their maintenance”* and the study by Morcous *et al* (2003) to identify environmental categories for bridge decks.

The model was tested with condition assessment data for six academic hospitals in South Africa and yielded realistic results. It was illustrated that the ability to calculate the anticipated change in condition over time for variable degradation and durability factors enables the user to calculate the estimated service life and quantify the effect of maintenance levels on service life. There is good correlation between the transitional probability matrices developed for the proposed model and other Markov applications in concrete bridge deck deterioration and roof maintenance models (BELCAM-project). In both instances, the transition probabilities are based on assessment data collected over extended periods, which makes the correlation more significant. It is therefore concluded that Hypothesis No. 1 is correct, the Markov Chain can be used to calculate the estimated service life of a building or component, quantify changes in condition over time and determine the effect of maintenance levels on service life.

5.2.2. Conclusion No. 2:

Problem Statement No. 2:

The application of the Markov Chain to predict service life, quantify changes in condition over time and determine the effect of maintenance levels on service life, is restricted by the limited availability of historic performance data on degradation of building materials to develop transition probability matrices for the Markov Chain.

Hypothesis No. 2:

The limited availability of historic performance data on degradation of building materials can be supplemented with expert knowledge and reasoning, to develop transition probability matrices for the Markov Chain.

Due to the limited availability of reliable historic performance data, expert knowledge and reasoning were used to develop initial transition probability matrices for the proposed model. However, the initial model produced unrealistic results and available historic performance data was used to calibrate the model. After calibration, the model produced realistic results, which compared well with historic performance data for other hospitals.

According to Lounis *et al* (1998b, p.5) *"The development of the Markovian model requires a relatively limited amount of historical performance data at two or more points in time."* This statement is supported by the results of the proposed model. However, instead of using the limited available historic performance data to develop the Markovian transition probability matrices, the proposed model reverses the process by using expert knowledge and reasoning, and supplements it with available historic performance data to calibrate the model.

Comprehensive historic performance data on the actual degradation process takes years to collect. Until sufficient historic performance data has been collected, expert knowledge and reasoning can be used to supplement or even substitute historic performance data. Historic performance data should however not be used indiscriminately. The degradation and durability factors could vary considerably between assessments and these potential variations should be taken into consideration.

The hypothesis is correct, the limited availability of historic performance data on degradation of building materials can be supplemented with expert knowledge and reasoning, to develop transition probability matrices for the Markov Chain.

5.2.3. Conclusion No. 3:

Problem Statement No. 3:

Experts do not usually think in probability values and cannot always express their knowledge or explain their reasoning in terms of rules. This expert knowledge and reasoning need to be translated into probability values to develop transitional probability matrices for the Markov Chain to predict the change in condition or performance over time and service life of a building or component.

Hypothesis No. 3:

Expert knowledge and reasoning can be expressed in terms of 'IF-THEN' rules, and translated into probability values for the transitional probability matrices of the Markov Chain through the application of Fuzzy Logic Artificial Intelligence.

It was illustrated how expert knowledge and reasoning can easily be expressed in terms of 'IF-THEN' rules and translated into crisp probability values through Fuzzy Logic Artificial Intelligence, which deals with vague, imprecise and uncertain knowledge and data. According to Negnevisky (2002, p.1-21) *"Fuzzy logic is concerned with the use of fuzzy values that capture the meaning of words, human reasoning and decision making"*. It encodes and applies *"human knowledge in a form that accurately reflects an expert's understanding of difficult, complex problems."*

The hypothesis is correct, expert knowledge and reasoning can be expressed in terms of 'IF-THEN' rules, and translated into probability values for the transitional probability matrices of the Markov Chain through the application of Fuzzy Logic Artificial Intelligence.

5.2.4. Conclusion No. 4:

Problem Statement No. 4:

Many buildings are under-maintained because decision-makers are ignorant of the consequences of reduced service life due to inappropriate maintenance levels, deferred maintenance and maintenance budgets cuts.

Hypothesis No. 4:

The reduction in service life due to inappropriate maintenance levels, deferred maintenance and maintenance budgets cuts can be quantified through the application of the proposed Markov Chain model.

It was illustrated how the proposed Markov Chain model, supplemented by a simple discounted cashflow analysis, can be applied to calculate the reduction in service life due to inappropriate maintenance levels. The same principles apply to deferred maintenance and maintenance budgets cuts. The hypothesis is correct, the reduction in service life due to inappropriate maintenance levels, deferred maintenance and maintenance budgets cuts can be quantified through the application of the proposed Markov Chain model.

All the problem statements have been addressed and the hypotheses proven correct. The main objective of this thesis, which is the development of a model to translate expert knowledge and reasoning into probability values through the application of Fuzzy Logic Artificial Intelligence supplementing limited historical performance data on degradation of building materials for the development of Markov Chain transitional probability matrices to predict service life, condition changes over time, and consequences of maintenance levels on service life of buildings, has therefore been achieved.

The ability of the proposed model to predict condition changes can be used to prevent loss of service life due to inappropriate maintenance levels, which is not possible with the current practice of regular inspections with adjustments to the maintenance regime as necessary. Appropriate maintenance levels will also enhance the sustainability of natural resources by limiting the consumption of material and energy, and limiting waste caused by degradation. It is therefore of critical importance to understand the degradation process and be able to quantify degradation over time. Although the development of the proposed model was focussed on buildings, the basic principles also apply to other types of infrastructure, and can be extended to accommodate all types of immovable assets.

5.3. Contribution to Knowledge Base of Engineering Science and Practice

The Markov Chain methodology has been identified by numerous international experts on building degradation and durability as the preferred method for service life prediction and quantification of changes in condition over time. The current limited availability and consistency of performance assessment data, required to populate the Markovian transitional probability matrix, however limits the application of the Markovian model. The proposed Neuro-Fuzzy model has the ability to translate expert knowledge and reasoning on building degradation and durability, expressed in linguistic terms, into transitional probabilities and contributed to the knowledge base of engineering science and practice by providing an alternative method to develop transitional probabilities for the application of the Markov Chain methodology.

The proposed model, which is also applicable to other types of infrastructure (roads, municipal services, etc.), enables the user to add value to condition assessments previously not possible, and provides the user with a means to estimate life cycle costs and analyse the impact and consequences of maintenance levels and maintenance funding on the service life of buildings and components .

5.4. Recommendations

It is recommended that the following issues be investigated further:

- Historical performance data on actual degradation of buildings or components is inconsistent and takes time to accumulate. Continuity is a problem and data covers only snapshots in the service life span of a building or component. There is an urgent need for regular and consistent condition assessments on a national basis. The Bill for the Government-wide Immovable Asset Management Act (GIAMA) provides for regular assessments and preparation of annual strategic management plans for government owned property.. It is expected that GIAMA will provide the necessary motivation for regular and consistent condition assessments on a national basis. Although GIAMA could take some time to become effective, it provides an excellent opportunity to ensure continuity, consistency and reliability of much needed data on degradation of building materials and components. There are however, a number of issues that need to be considered:

    - National consensus should be obtained on the extent and format of the data to be collected, to ensure uniformity and consistency. Care should be exercised not to collect unnecessary or 'nice-to-know' data. Identification of data to be collected (input) should be determined through a process of reverse engineering starting with the identification and proper motivation of the desired output.

    - Field assessments and data collection are expensive, time consuming and exhausting exercises and should be carefully defined, planned and controlled. Proper rating systems, assessment and capture procedures need to be developed.

    - All assessments should be done by properly trained and calibrated assessment staff using the same assessment procedures, ratings and forms to ensure consistency and reliability of data.

    - Development and continuous maintenance of a national assessment database. A database like this could result in savings many times more than the actual cost to compile and maintain it. It is proposed that the CSIR as an 'organ of state' and national research body be tasked with this responsibility, especially for health and educational facilities.

- An analysis of all the assessments of hospitals in South Africa to date, starting with the 1995/6 NHFA, and to include the maintenance expenditures in order to determine the level of maintenance and other interventions such as upgrades, revitalisation, demolished buildings and addition of new buildings, etc.

- The neuro-fuzzy system should be developed further to include other types of buildings and components. The proposed system must be calibrated and refined through integration of expert knowledge with performance assessment data and enablement of the learning ability of the neural network module.

- Further research into the effect of external climate on degradation rate of building materials and components is required. In particular, the demarcation of external climate zones should be investigated.

- Collection and analysis of data on maintenance expenditure and activities to establish current levels and types of maintenance for the various types of facilities.

- Appropriate maintenance levels and strategies for different types of facilities/components/ materials and in-use or operation environments should be explored.

- The definition and rating of durability and degradation factors should be reviewed to ensure common and consistent interpretation.

- The impact of specifications, quality of materials and design details on service life during the early planning phases should be explored.

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APPENDIX A: IF-THEN FUZZY RULE BLOCKS

A.1. IF-THEN FUZZY RULE BLOCK 1

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
High	High	High	1.00	High
Very High	Very High	Very High	1.00	Very High
Very Low	Very Low	Very Low	1.00	Very Low
Medium	Medium	Medium	1.00	Medium
Low	Very Low	Very Low	0.66	Very Low
Very Low	Low	Very Low	0.66	Very Low
Low	Very Low	Very Low	0.34	Low
Very Low	Low	Very Low	0.34	Low
Low	Low	Very Low	0.34	Very Low
Low	Low	Very Low	0.66	Low
Medium	Very Low	Very Low	0.66	Very Low
Very Low	Medium	Very Low	0.66	Very Low
Medium	Very Low	Very Low	0.34	Medium
Very Low	Medium	Very Low	0.34	Medium
High	Very Low	Very Low	0.66	Very Low
Very Low	High	Very Low	0.66	Very Low
High	Very Low	Very Low	0.34	High
Very Low	High	Very Low	0.34	High
Medium	Low	Very Low	0.34	Very Low
Low	Medium	Very Low	0.34	Very Low
Medium	Low	Very Low	0.34	Low
Low	Medium	Very Low	0.34	Low
Medium	Low	Very Low	0.34	Medium
Low	Medium	Very Low	0.34	Medium
Very High	Very Low	Very Low	0.66	Very Low
Very High	Very Low	Very Low	0.34	Very High
Very Low	Very High	Very Low	0.66	Very Low
Very Low	Very High	Very Low	0.34	Very High
High	Low	Very Low	0.34	Very Low
Low	High	Very Low	0.34	Very Low
High	Low	Very Low	0.34	Low
Low	High	Very Low	0.34	Low

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
High	Low	Very Low	0.34	High
Low	High	Very Low	0.34	High
Medium	Medium	Very Low	0.66	Medium
Medium	Medium	Very Low	0.34	Very Low
Very High	Low	Very Low	0.34	Very Low
Low	Very High	Very Low	0.34	Very Low
Very High	Low	Very Low	0.34	Low
Low	Very High	Very Low	0.34	Low
Very High	Low	Very Low	0.34	Very High
Low	Very High	Very Low	0.34	Very High
High	Medium	Very Low	0.34	Very Low
Medium	High	Very Low	0.34	Very Low
High	Medium	Very Low	0.34	Medium
Medium	High	Very Low	0.34	Medium
High	Medium	Very Low	0.34	High
Medium	High	Very Low	0.34	High
Very High	Medium	Very Low	0.34	Very Low
Medium	Very High	Very Low	0.34	Very Low
Very High	Medium	Very Low	0.34	Medium
Medium	Very High	Very Low	0.34	Medium
Very High	Medium	Very Low	0.34	Very High
Medium	Very High	Very Low	0.34	Very High
High	High	Very Low	0.34	Very Low
High	High	Very Low	0.66	High
Very High	High	Very Low	0.34	Very Low
High	Very High	Very Low	0.34	Very Low
Very High	High	Very Low	0.34	High
High	Very High	Very Low	0.34	High
Very High	High	Very Low	0.34	Very High
High	Very High	Very Low	0.34	Very High
Very High	Very High	Very Low	0.34	Very Low
Very High	Very High	Very Low	0.66	Very High
Low	Low	Low	1.00	Low
Very Low	Very Low	Low	0.66	Very Low
Very Low	Very Low	Low	0.34	Low
Low	Very Low	Low	0.66	Low

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
Very Low	Low	Low	0.66	Low
Low	Very Low	Low	0.34	Very Low
Very Low	Low	Low	0.34	Very Low
Medium	Very Low	Low	0.34	Very Low
Very Low	Medium	Low	0.34	Very Low
Medium	Very Low	Low	0.34	Low
Very Low	Medium	Low	0.34	Low
Medium	Very Low	Low	0.34	Medium
Very Low	Medium	Low	0.34	Medium
High	Very Low	Low	0.34	Very Low
Very Low	High	Low	0.34	Very Low
High	Very Low	Low	0.34	Low
Very Low	High	Low	0.34	Low
High	Very Low	Low	0.34	High
Very Low	High	Low	0.34	High
Medium	Low	Low	0.66	Low
Low	Medium	Low	0.66	Low
Medium	Low	Low	0.34	Medium
Low	Medium	Low	0.34	Medium
Very High	Very Low	Low	0.34	Very Low
Very Low	Very High	Low	0.34	Very Low
Very High	Very Low	Low	0.34	Low
Very Low	Very High	Low	0.34	Low
Very High	Very Low	Low	0.34	Very High
Very Low	Very High	Low	0.34	Very High
High	Low	Low	0.66	Low
Low	High	Low	0.66	Low
High	Low	Low	0.34	High
Low	High	Low	0.34	High
Medium	Medium	Low	0.34	Low
Medium	Medium	Low	0.66	Medium
Very High	Low	Low	0.66	Low
Low	Very High	Low	0.66	Low
Very High	Low	Low	0.34	Very High
Low	Very High	Low	0.34	Very High
High	Medium	Low	0.34	Low

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
Medium	High	Low	0.34	Low
High	Medium	Low	0.34	Medium
Medium	High	Low	0.34	Medium
High	Medium	Low	0.34	High
Medium	High	Low	0.34	High
Very High	Medium	Low	0.34	Low
Medium	Very High	Low	0.34	Low
Very High	Medium	Low	0.34	Medium
Medium	Very High	Low	0.34	Medium
Very High	Medium	Low	0.34	Very High
Medium	Very High	Low	0.34	Very High
High	High	Low	0.34	Low
High	High	Low	0.66	High
Very High	High	Low	0.34	Low
High	Very High	Low	0.34	Low
Very High	High	Low	0.34	High
High	Very High	Low	0.34	High
Very High	High	Low	0.34	Very High
High	Very High	Low	0.34	Very High
Very High	Very High	Low	0.34	Low
Very High	Very High	Low	0.66	Very High
Very Low	Very Low	Medium	0.66	Very Low
Very Low	Very Low	Medium	0.34	Medium
Low	Very Low	Medium	0.34	Very Low
Very Low	Low	Medium	0.34	Very Low
Low	Very Low	Medium	0.34	Low
Very Low	Low	Medium	0.34	Low
Low	Very Low	Medium	0.34	Medium
Very Low	Low	Medium	0.34	Medium
Medium	Very Low	Medium	0.66	Medium
Very Low	Medium	Medium	0.66	Medium
Medium	Very Low	Medium	0.34	Very Low
Very Low	Medium	Medium	0.34	Very Low
Low	Low	Medium	0.66	Low
Low	Low	Medium	0.34	Medium
High	Very Low	Medium	0.34	Very Low

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
Very Low	High	Medium	0.34	Very Low
High	Very Low	Medium	0.34	Medium
Very Low	High	Medium	0.34	Medium
High	Very Low	Medium	0.34	High
Very Low	High	Medium	0.34	High
Medium	Low	Medium	0.66	Medium
Low	Medium	Medium	0.66	Medium
Medium	Low	Medium	0.34	Low
Low	Medium	Medium	0.34	Low
Very High	Very Low	Medium	0.34	Very Low
Very Low	Very High	Medium	0.34	Very Low
Very High	Very Low	Medium	0.34	Medium
Very Low	Very High	Medium	0.34	Medium
Very High	Very Low	Medium	0.34	Very High
Very Low	Very High	Medium	0.34	Very High
High	Low	Medium	0.34	Low
Low	High	Medium	0.34	Low
High	Low	Medium	0.34	Medium
Low	High	Medium	0.34	Medium
High	Low	Medium	0.34	High
Low	High	Medium	0.34	High
Very High	Low	Medium	0.34	Low
Low	Very High	Medium	0.34	Low
Very High	Low	Medium	0.34	Medium
Low	Very High	Medium	0.34	Medium
Very High	Low	Medium	0.34	Very High
Low	Very High	Medium	0.34	Very High
High	Medium	Medium	0.66	Medium
Medium	High	Medium	0.66	Medium
High	Medium	Medium	0.34	High
Medium	High	Medium	0.34	High
Very High	Medium	Medium	0.66	Medium
Medium	Very High	Medium	0.66	Medium
Very High	Medium	Medium	0.34	Very High
Medium	Very High	Medium	0.34	Very High
High	High	Medium	0.34	Medium

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
High	High	Medium	0.66	High
Very High	High	Medium	0.34	Medium
High	Very High	Medium	0.34	Medium
Very High	High	Medium	0.34	High
High	Very High	Medium	0.34	High
Very High	High	Medium	0.34	Very High
High	Very High	Medium	0.34	Very High
Very High	Very High	Medium	0.34	Medium
Very High	Very High	Medium	0.66	Very High
Very Low	Very Low	High	0.66	Very Low
Very Low	Very Low	High	0.34	High
Low	Very Low	High	0.34	Very Low
Very Low	Low	High	0.34	Very Low
Low	Very Low	High	0.34	Low
Very Low	Low	High	0.34	Low
Low	Very Low	High	0.34	High
Very Low	Low	High	0.34	High
Medium	Very Low	High	0.34	Very Low
Very Low	Medium	High	0.34	Very Low
Medium	Very Low	High	0.34	Medium
Very Low	Medium	High	0.34	Medium
Medium	Very Low	High	0.34	High
Very Low	Medium	High	0.34	High
Low	Low	High	0.66	Low
Low	Low	High	0.34	High
High	Very Low	High	0.34	Very Low
Very Low	High	High	0.34	Very Low
High	Very Low	High	0.66	High
Very Low	High	High	0.66	High
Medium	Low	High	0.34	Low
Low	Medium	High	0.34	Low
Medium	Low	High	0.34	Medium
Low	Medium	High	0.34	Medium
Medium	Low	High	0.34	High
Low	Medium	High	0.34	High
Very High	Very Low	High	0.34	Very Low

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
Very Low	Very High	High	0.34	Very Low
Very High	Very Low	High	0.34	High
Very Low	Very High	High	0.34	High
Very High	Very Low	High	0.34	Very High
Very Low	Very High	High	0.34	Very High
High	Low	High	0.34	Low
Low	High	High	0.34	Low
High	Low	High	0.66	High
Low	High	High	0.66	High
Medium	Medium	High	0.66	Medium
Medium	Medium	High	0.34	High
Very High	Low	High	0.34	Low
Low	Very High	High	0.34	Low
Very High	Low	High	0.34	High
Low	Very High	High	0.34	High
Very High	Low	High	0.34	Very High
Low	Very High	High	0.34	Very High
High	Medium	High	0.34	Medium
Medium	High	High	0.34	Medium
High	Medium	High	0.66	High
Medium	High	High	0.66	High
Very High	Medium	High	0.34	Medium
Medium	Very High	High	0.34	Medium
Very High	Medium	High	0.34	High
Medium	Very High	High	0.34	High
Very High	Medium	High	0.34	Very High
Medium	Very High	High	0.34	Very High
Very High	High	High	0.66	High
High	Very High	High	0.66	High
Very High	High	High	0.34	Very High
High	Very High	High	0.34	Very High
Very High	Very High	High	0.34	High
Very High	Very High	High	0.66	Very High
Very Low	Very Low	Very High	0.66	Very Low
Very Low	Very Low	Very High	0.34	Very High
Low	Very Low	Very High	0.34	Very Low

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
Very Low	Low	Very High	0.34	Very Low
Low	Very Low	Very High	0.34	Low
Very Low	Low	Very High	0.34	Low
Low	Very Low	Very High	0.34	Very High
Very Low	Low	Very High	0.34	Very High
Medium	Very Low	Very High	0.34	Very Low
Very Low	Medium	Very High	0.34	Very Low
Medium	Very Low	Very High	0.34	Medium
Very Low	Medium	Very High	0.34	Medium
Medium	Very Low	Very High	0.34	Very High
Very Low	Medium	Very High	0.34	Very High
Low	Low	Very High	0.66	Low
Low	Low	Very High	0.34	Very High
High	Very Low	Very High	0.34	Very Low
Very Low	High	Very High	0.34	Very Low
High	Very Low	Very High	0.34	High
Very Low	High	Very High	0.34	High
High	Very Low	Very High	0.34	Very High
Very Low	High	Very High	0.34	Very High
Medium	Low	Very High	0.34	Low
Low	Medium	Very High	0.34	Low
Medium	Low	Very High	0.34	Medium
Low	Medium	Very High	0.34	Medium
Medium	Low	Very High	0.34	Very High
Low	Medium	Very High	0.34	Very High
Very High	Very Low	Very High	0.34	Very Low
Very Low	Very High	Very High	0.34	Very Low
Very High	Very Low	Very High	0.66	Very High
Very Low	Very High	Very High	0.66	Very High
High	Low	Very High	0.34	Low
Low	High	Very High	0.34	Low
High	Low	Very High	0.34	High
Low	High	Very High	0.34	High
High	Low	Very High	0.34	Very High
Low	High	Very High	0.34	Very High
Medium	Medium	Very High	0.66	Medium

IF			THEN	
Design Level	Material	Workmanship	DoS	Durability
Medium	Medium	Very High	0.34	Very High
Very High	Low	Very High	0.34	Low
Low	Very High	Very High	0.34	Low
Very High	Low	Very High	0.66	Very High
Low	Very High	Very High	0.66	Very High
High	Medium	Very High	0.34	Medium
Medium	High	Very High	0.34	Medium
High	Medium	Very High	0.34	High
Medium	High	Very High	0.34	High
High	Medium	Very High	0.34	Very High
Medium	High	Very High	0.34	Very High
Very High	Medium	Very High	0.34	Medium
Medium	Very High	Very High	0.34	Medium
Very High	Medium	Very High	0.66	Very High
Medium	Very High	Very High	0.66	Very High
High	High	Very High	0.66	High
High	High	Very High	0.34	Very High
Very High	High	Very High	0.34	High
High	Very High	Very High	0.34	High
Very High	High	Very High	0.66	Very High
High	Very High	Very High	0.66	Very High

Table A-1: IF-THEN Rules for Rule Block 1

A.2. IF-THEN FUZZY RULE BLOCK 2

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Internal Component	Very Aggressive	Very Aggressive	1.00	Very Aggressive
Internal Component	Aggressive	Aggressive	1.00	Aggressive
Internal Component	Slightly Aggressive	Slightly Aggressive	1.00	Slightly Aggressive
Internal Component	Less Favourable	Less Favourable	1.00	Less Favourable
Internal Component	Favourable	Favourable	1.00	Favourable
Internal Component	Aggressive	Very Aggressive	0.50	Very Aggressive
Internal Component	Very Aggressive	Aggressive	0.50	Very Aggressive
Internal Component	Aggressive	Very Aggressive	0.50	Aggressive
Internal Component	Very Aggressive	Aggressive	0.50	Aggressive
Internal Component	Slightly Aggressive	Very Aggressive	0.50	Very Aggressive

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Internal Component	Very Aggressive	Slightly Aggressive	0.50	Very Aggressive
Internal Component	Slightly Aggressive	Very Aggressive	0.50	Slightly Aggressive
Internal Component	Very Aggressive	Slightly Aggressive	0.50	Slightly Aggressive
Internal Component	Less Favourable	Very Aggressive	0.50	Very Aggressive
Internal Component	Very Aggressive	Less Favourable	0.50	Very Aggressive
Internal Component	Less Favourable	Very Aggressive	0.50	Less Favourable
Internal Component	Very Aggressive	Less Favourable	0.50	Less Favourable
Internal Component	Slightly Aggressive	Aggressive	0.50	Aggressive
Internal Component	Aggressive	Slightly Aggressive	0.50	Aggressive
Internal Component	Slightly Aggressive	Aggressive	0.50	Slightly Aggressive
Internal Component	Aggressive	Slightly Aggressive	0.50	Slightly Aggressive
Internal Component	Favourable	Very Aggressive	0.50	Very Aggressive
Internal Component	Very Aggressive	Favourable	0.50	Very Aggressive
Internal Component	Favourable	Very Aggressive	0.50	Favourable
Internal Component	Very Aggressive	Favourable	0.50	Favourable
Internal Component	Less Favourable	Aggressive	0.50	Aggressive
Internal Component	Aggressive	Less Favourable	0.50	Aggressive
Internal Component	Less Favourable	Aggressive	0.50	Less Favourable
Internal Component	Aggressive	Less Favourable	0.50	Less Favourable
Internal Component	Favourable	Aggressive	0.50	Aggressive
Internal Component	Aggressive	Favourable	0.50	Aggressive
Internal Component	Favourable	Aggressive	0.50	Favourable
Internal Component	Aggressive	Favourable	0.50	Favourable
Internal Component	Less Favourable	Slightly Aggressive	0.50	Slightly Aggressive
Internal Component	Slightly Aggressive	Less Favourable	0.50	Slightly Aggressive
Internal Component	Less Favourable	Slightly Aggressive	0.50	Less Favourable
Internal Component	Slightly Aggressive	Less Favourable	0.50	Less Favourable
Internal Component	Favourable	Slightly Aggressive	0.50	Slightly Aggressive
Internal Component	Slightly Aggressive	Favourable	0.50	Slightly Aggressive
Internal Component	Favourable	Slightly Aggressive	0.50	Favourable
Internal Component	Slightly Aggressive	Favourable	0.50	Favourable
Internal Component	Favourable	Less Favourable	0.50	Less Favourable
Internal Component	Less Favourable	Favourable	0.50	Less Favourable
Internal Component	Favourable	Less Favourable	0.50	Favourable
Internal Component	Less Favourable	Favourable	0.50	Favourable
Very Aggressive	External Component	Very Aggressive	1.00	Very Aggressive

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Aggressive	External Component	Aggressive	1.00	Aggressive
Slightly Aggressive	External Component	Slightly Aggressive	1.00	Slightly Aggressive
Less Favourable	External Component	Less Favourable	1.00	Less Favourable
Favourable	External Component	Favourable	1.00	Favourable
Aggressive	External Component	Very Aggressive	0.50	Very Aggressive
Very Aggressive	External Component	Aggressive	0.50	Very Aggressive
Aggressive	External Component	Very Aggressive	0.50	Aggressive
Very Aggressive	External Component	Aggressive	0.50	Aggressive
Slightly Aggressive	External Component	Very Aggressive	0.50	Very Aggressive
Very Aggressive	External Component	Slightly Aggressive	0.50	Very Aggressive
Slightly Aggressive	External Component	Very Aggressive	0.50	Slightly Aggressive
Very Aggressive	External Component	Slightly Aggressive	0.50	Slightly Aggressive
Less Favourable	External Component	Very Aggressive	0.50	Very Aggressive
Very Aggressive	External Component	Less Favourable	0.50	Very Aggressive
Less Favourable	External Component	Very Aggressive	0.50	Less Favourable
Very Aggressive	External Component	Less Favourable	0.50	Less Favourable
Favourable	External Component	Very Aggressive	0.50	Very Aggressive
Very Aggressive	External Component	Favourable	0.50	Very Aggressive
Favourable	External Component	Very Aggressive	0.50	Favourable
Very Aggressive	External Component	Favourable	0.50	Favourable
Slightly Aggressive	External Component	Aggressive	0.50	Aggressive
Aggressive	External Component	Slightly Aggressive	0.50	Aggressive
Slightly Aggressive	External Component	Aggressive	0.50	Slightly Aggressive
Aggressive	External Component	Slightly Aggressive	0.50	Slightly Aggressive
Less Favourable	External Component	Aggressive	0.50	Aggressive
Aggressive	External Component	Less Favourable	0.50	Aggressive
Less Favourable	External Component	Aggressive	0.50	Less Favourable
Aggressive	External Component	Less Favourable	0.50	Less Favourable
Favourable	External Component	Aggressive	0.50	Aggressive
Aggressive	External Component	Favourable	0.50	Aggressive
Favourable	External Component	Aggressive	0.50	Favourable
Aggressive	External Component	Favourable	0.50	Favourable
Less Favourable	External Component	Slightly Aggressive	0.50	Slightly Aggressive
Slightly Aggressive	External Component	Less Favourable	0.50	Slightly Aggressive
Less Favourable	External Component	Slightly Aggressive	0.50	Less Favourable
Slightly Aggressive	External Component	Less Favourable	0.50	Less Favourable

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Favourable	External Component	Slightly Aggressive	0.50	Slightly Aggressive
Slightly Aggressive	External Component	Favourable	0.50	Slightly Aggressive
Favourable	External Component	Slightly Aggressive	0.50	Favourable
Slightly Aggressive	External Component	Favourable	0.50	Favourable
Favourable	External Component	Less Favourable	0.50	Less Favourable
Less Favourable	External Component	Favourable	0.50	Less Favourable
Favourable	External Component	Less Favourable	0.50	Favourable
Less Favourable	External Component	Favourable	0.50	Favourable
Very Aggressive	Very Aggressive	Very Aggressive	1.00	Very Aggressive
Aggressive	Aggressive	Aggressive	1.00	Aggressive
Slightly Aggressive	Slightly Aggressive	Slightly Aggressive	1.00	Slightly Aggressive
Less Favourable	Less Favourable	Less Favourable	1.00	Less Favourable
Favourable	Favourable	Favourable	1.00	Favourable
Very Aggressive	Very Aggressive	Favourable	0.66	Very Aggressive
Very Aggressive	Very Aggressive	Favourable	0.34	Favourable
Aggressive	Very Aggressive	Favourable	0.34	Very Aggressive
Very Aggressive	Aggressive	Favourable	0.34	Very Aggressive
Aggressive	Very Aggressive	Favourable	0.34	Aggressive
Very Aggressive	Aggressive	Favourable	0.34	Aggressive
Aggressive	Very Aggressive	Favourable	0.34	Favourable
Very Aggressive	Aggressive	Favourable	0.34	Favourable
Slightly Aggressive	Very Aggressive	Favourable	0.34	Very Aggressive
Very Aggressive	Slightly Aggressive	Favourable	0.34	Very Aggressive
Slightly Aggressive	Very Aggressive	Favourable	0.34	Slightly Aggressive
Very Aggressive	Slightly Aggressive	Favourable	0.34	Slightly Aggressive
Slightly Aggressive	Very Aggressive	Favourable	0.34	Favourable
Very Aggressive	Slightly Aggressive	Favourable	0.34	Favourable
Aggressive	Aggressive	Favourable	0.66	Aggressive
Aggressive	Aggressive	Favourable	0.34	Favourable
Less Favourable	Very Aggressive	Favourable	0.34	Very Aggressive
Very Aggressive	Less Favourable	Favourable	0.34	Very Aggressive
Less Favourable	Very Aggressive	Favourable	0.34	Less Favourable
Very Aggressive	Less Favourable	Favourable	0.34	Less Favourable
Less Favourable	Very Aggressive	Favourable	0.34	Favourable
Very Aggressive	Less Favourable	Favourable	0.34	Favourable
Slightly Aggressive	Aggressive	Favourable	0.34	Aggressive

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Aggressive	Slightly Aggressive	Favourable	0.34	Aggressive
Slightly Aggressive	Aggressive	Favourable	0.34	Slightly Aggressive
Aggressive	Slightly Aggressive	Favourable	0.34	Slightly Aggressive
Slightly Aggressive	Aggressive	Favourable	0.34	Favourable
Aggressive	Slightly Aggressive	Favourable	0.34	Favourable
Favourable	Very Aggressive	Favourable	0.34	Very Aggressive
Very Aggressive	Favourable	Favourable	0.34	Very Aggressive
Favourable	Very Aggressive	Favourable	0.66	Favourable
Very Aggressive	Favourable	Favourable	0.66	Favourable
Less Favourable	Aggressive	Favourable	0.34	Aggressive
Aggressive	Less Favourable	Favourable	0.34	Aggressive
Less Favourable	Aggressive	Favourable	0.34	Less Favourable
Aggressive	Less Favourable	Favourable	0.34	Less Favourable
Less Favourable	Aggressive	Favourable	0.34	Favourable
Aggressive	Less Favourable	Favourable	0.34	Favourable
Slightly Aggressive	Slightly Aggressive	Favourable	0.66	Slightly Aggressive
Slightly Aggressive	Slightly Aggressive	Favourable	0.34	Favourable
Favourable	Aggressive	Favourable	0.34	Aggressive
Aggressive	Favourable	Favourable	0.34	Aggressive
Favourable	Aggressive	Favourable	0.66	Favourable
Aggressive	Favourable	Favourable	0.66	Favourable
Less Favourable	Slightly Aggressive	Favourable	0.34	Slightly Aggressive
Slightly Aggressive	Less Favourable	Favourable	0.34	Slightly Aggressive
Less Favourable	Slightly Aggressive	Favourable	0.34	Less Favourable
Slightly Aggressive	Less Favourable	Favourable	0.34	Less Favourable
Less Favourable	Slightly Aggressive	Favourable	0.34	Favourable
Slightly Aggressive	Less Favourable	Favourable	0.34	Favourable
Favourable	Slightly Aggressive	Favourable	0.34	Slightly Aggressive
Slightly Aggressive	Favourable	Favourable	0.34	Slightly Aggressive
Favourable	Slightly Aggressive	Favourable	0.66	Favourable
Slightly Aggressive	Favourable	Favourable	0.66	Favourable
Less Favourable	Less Favourable	Favourable	0.66	Less Favourable
Less Favourable	Less Favourable	Favourable	0.34	Favourable
Favourable	Less Favourable	Favourable	0.34	Less Favourable
Less Favourable	Favourable	Favourable	0.34	Less Favourable
Favourable	Less Favourable	Favourable	0.66	Favourable

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Less Favourable	Favourable	Favourable	0.66	Favourable
Very Aggressive	Very Aggressive	Less Favourable	0.66	Very Aggressive
Very Aggressive	Very Aggressive	Less Favourable	0.34	Less Favourable
Aggressive	Very Aggressive	Less Favourable	0.34	Very Aggressive
Very Aggressive	Aggressive	Less Favourable	0.34	Very Aggressive
Aggressive	Very Aggressive	Less Favourable	0.34	Aggressive
Very Aggressive	Aggressive	Less Favourable	0.34	Aggressive
Aggressive	Very Aggressive	Less Favourable	0.34	Less Favourable
Very Aggressive	Aggressive	Less Favourable	0.34	Less Favourable
Slightly Aggressive	Very Aggressive	Less Favourable	0.34	Very Aggressive
Very Aggressive	Slightly Aggressive	Less Favourable	0.34	Very Aggressive
Slightly Aggressive	Very Aggressive	Less Favourable	0.34	Slightly Aggressive
Very Aggressive	Slightly Aggressive	Less Favourable	0.34	Slightly Aggressive
Slightly Aggressive	Very Aggressive	Less Favourable	0.34	Less Favourable
Very Aggressive	Slightly Aggressive	Less Favourable	0.34	Less Favourable
Aggressive	Aggressive	Less Favourable	0.66	Aggressive
Aggressive	Aggressive	Less Favourable	0.34	Less Favourable
Less Favourable	Very Aggressive	Less Favourable	0.34	Very Aggressive
Very Aggressive	Less Favourable	Less Favourable	0.34	Very Aggressive
Less Favourable	Very Aggressive	Less Favourable	0.66	Less Favourable
Very Aggressive	Less Favourable	Less Favourable	0.66	Less Favourable
Slightly Aggressive	Aggressive	Less Favourable	0.34	Aggressive
Aggressive	Slightly Aggressive	Less Favourable	0.34	Aggressive
Slightly Aggressive	Aggressive	Less Favourable	0.34	Slightly Aggressive
Aggressive	Slightly Aggressive	Less Favourable	0.34	Slightly Aggressive
Slightly Aggressive	Aggressive	Less Favourable	0.34	Less Favourable
Aggressive	Slightly Aggressive	Less Favourable	0.34	Less Favourable
Favourable	Very Aggressive	Less Favourable	0.34	Very Aggressive
Very Aggressive	Favourable	Less Favourable	0.34	Very Aggressive
Favourable	Very Aggressive	Less Favourable	0.34	Less Favourable
Very Aggressive	Favourable	Less Favourable	0.34	Less Favourable
Favourable	Very Aggressive	Less Favourable	0.34	Favourable
Very Aggressive	Favourable	Less Favourable	0.34	Favourable
Less Favourable	Aggressive	Less Favourable	0.34	Aggressive
Aggressive	Less Favourable	Less Favourable	0.34	Aggressive
Less Favourable	Aggressive	Less Favourable	0.66	Less Favourable

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Aggressive	Less Favourable	Less Favourable	0.66	Less Favourable
Slightly Aggressive	Slightly Aggressive	Less Favourable	0.66	Slightly Aggressive
Slightly Aggressive	Slightly Aggressive	Less Favourable	0.34	Less Favourable
Favourable	Aggressive	Less Favourable	0.34	Aggressive
Aggressive	Favourable	Less Favourable	0.34	Aggressive
Favourable	Aggressive	Less Favourable	0.34	Less Favourable
Aggressive	Favourable	Less Favourable	0.34	Less Favourable
Favourable	Aggressive	Less Favourable	0.34	Favourable
Aggressive	Favourable	Less Favourable	0.34	Favourable
Less Favourable	Slightly Aggressive	Less Favourable	0.34	Slightly Aggressive
Slightly Aggressive	Less Favourable	Less Favourable	0.34	Slightly Aggressive
Less Favourable	Slightly Aggressive	Less Favourable	0.66	Less Favourable
Slightly Aggressive	Less Favourable	Less Favourable	0.66	Less Favourable
Favourable	Slightly Aggressive	Less Favourable	0.34	Slightly Aggressive
Slightly Aggressive	Favourable	Less Favourable	0.34	Slightly Aggressive
Favourable	Slightly Aggressive	Less Favourable	0.34	Less Favourable
Slightly Aggressive	Favourable	Less Favourable	0.34	Less Favourable
Favourable	Slightly Aggressive	Less Favourable	0.34	Favourable
Slightly Aggressive	Favourable	Less Favourable	0.34	Favourable
Favourable	Less Favourable	Less Favourable	0.66	Less Favourable
Less Favourable	Favourable	Less Favourable	0.66	Less Favourable
Favourable	Less Favourable	Less Favourable	0.34	Favourable
Less Favourable	Favourable	Less Favourable	0.34	Favourable
Favourable	Favourable	Less Favourable	0.34	Less Favourable
Favourable	Favourable	Less Favourable	0.66	Favourable
Very Aggressive	Very Aggressive	Slightly Aggressive	0.66	Very Aggressive
Very Aggressive	Very Aggressive	Slightly Aggressive	0.34	Slightly Aggressive
Aggressive	Very Aggressive	Slightly Aggressive	0.34	Very Aggressive
Very Aggressive	Aggressive	Slightly Aggressive	0.34	Very Aggressive
Aggressive	Very Aggressive	Slightly Aggressive	0.34	Aggressive
Very Aggressive	Aggressive	Slightly Aggressive	0.34	Aggressive
Aggressive	Very Aggressive	Slightly Aggressive	0.34	Slightly Aggressive
Very Aggressive	Aggressive	Slightly Aggressive	0.34	Slightly Aggressive
Slightly Aggressive	Very Aggressive	Slightly Aggressive	0.34	Very Aggressive
Very Aggressive	Slightly Aggressive	Slightly Aggressive	0.34	Very Aggressive
Slightly Aggressive	Very Aggressive	Slightly Aggressive	0.66	Slightly Aggressive

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Very Aggressive	Slightly Aggressive	Slightly Aggressive	0.66	Slightly Aggressive
Aggressive	Aggressive	Slightly Aggressive	0.66	Aggressive
Aggressive	Aggressive	Slightly Aggressive	0.34	Slightly Aggressive
Less Favourable	Very Aggressive	Slightly Aggressive	0.34	Very Aggressive
Very Aggressive	Less Favourable	Slightly Aggressive	0.34	Very Aggressive
Less Favourable	Very Aggressive	Slightly Aggressive	0.34	Slightly Aggressive
Very Aggressive	Less Favourable	Slightly Aggressive	0.34	Slightly Aggressive
Less Favourable	Very Aggressive	Slightly Aggressive	0.34	Less Favourable
Very Aggressive	Less Favourable	Slightly Aggressive	0.34	Less Favourable
Slightly Aggressive	Aggressive	Slightly Aggressive	0.34	Aggressive
Aggressive	Slightly Aggressive	Slightly Aggressive	0.34	Aggressive
Slightly Aggressive	Aggressive	Slightly Aggressive	0.66	Slightly Aggressive
Aggressive	Slightly Aggressive	Slightly Aggressive	0.66	Slightly Aggressive
Favourable	Very Aggressive	Slightly Aggressive	0.34	Very Aggressive
Very Aggressive	Favourable	Slightly Aggressive	0.34	Very Aggressive
Favourable	Very Aggressive	Slightly Aggressive	0.34	Slightly Aggressive
Very Aggressive	Favourable	Slightly Aggressive	0.34	Slightly Aggressive
Favourable	Very Aggressive	Slightly Aggressive	0.34	Favourable
Very Aggressive	Favourable	Slightly Aggressive	0.34	Favourable
Less Favourable	Aggressive	Slightly Aggressive	0.34	Aggressive
Aggressive	Less Favourable	Slightly Aggressive	0.34	Aggressive
Less Favourable	Aggressive	Slightly Aggressive	0.34	Slightly Aggressive
Aggressive	Less Favourable	Slightly Aggressive	0.34	Slightly Aggressive
Less Favourable	Aggressive	Slightly Aggressive	0.34	Less Favourable
Aggressive	Less Favourable	Slightly Aggressive	0.34	Less Favourable
Favourable	Aggressive	Slightly Aggressive	0.34	Aggressive
Aggressive	Favourable	Slightly Aggressive	0.34	Aggressive
Favourable	Aggressive	Slightly Aggressive	0.34	Slightly Aggressive
Aggressive	Favourable	Slightly Aggressive	0.34	Slightly Aggressive
Favourable	Aggressive	Slightly Aggressive	0.34	Favourable
Aggressive	Favourable	Slightly Aggressive	0.34	Favourable
Less Favourable	Slightly Aggressive	Slightly Aggressive	0.66	Slightly Aggressive
Slightly Aggressive	Less Favourable	Slightly Aggressive	0.66	Slightly Aggressive
Less Favourable	Slightly Aggressive	Slightly Aggressive	0.34	Less Favourable
Slightly Aggressive	Less Favourable	Slightly Aggressive	0.34	Less Favourable
Favourable	Slightly Aggressive	Slightly Aggressive	0.66	Slightly Aggressive

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Slightly Aggressive	Favourable	Slightly Aggressive	0.66	Slightly Aggressive
Favourable	Slightly Aggressive	Slightly Aggressive	0.34	Favourable
Slightly Aggressive	Favourable	Slightly Aggressive	0.34	Favourable
Less Favourable	Less Favourable	Slightly Aggressive	0.34	Slightly Aggressive
Less Favourable	Less Favourable	Slightly Aggressive	0.66	Less Favourable
Favourable	Less Favourable	Slightly Aggressive	0.34	Slightly Aggressive
Less Favourable	Favourable	Slightly Aggressive	0.34	Slightly Aggressive
Favourable	Less Favourable	Slightly Aggressive	0.34	Less Favourable
Less Favourable	Favourable	Slightly Aggressive	0.34	Less Favourable
Favourable	Less Favourable	Slightly Aggressive	0.34	Favourable
Less Favourable	Favourable	Slightly Aggressive	0.34	Favourable
Favourable	Favourable	Slightly Aggressive	0.34	Slightly Aggressive
Favourable	Favourable	Slightly Aggressive	0.66	Favourable
Very Aggressive	Very Aggressive	Aggressive	0.66	Very Aggressive
Very Aggressive	Very Aggressive	Aggressive	0.34	Aggressive
Aggressive	Very Aggressive	Aggressive	0.34	Very Aggressive
Very Aggressive	Aggressive	Aggressive	0.34	Very Aggressive
Aggressive	Very Aggressive	Aggressive	0.66	Aggressive
Very Aggressive	Aggressive	Aggressive	0.66	Aggressive
Slightly Aggressive	Very Aggressive	Aggressive	0.34	Very Aggressive
Very Aggressive	Slightly Aggressive	Aggressive	0.34	Very Aggressive
Slightly Aggressive	Very Aggressive	Aggressive	0.34	Aggressive
Very Aggressive	Slightly Aggressive	Aggressive	0.34	Aggressive
Slightly Aggressive	Very Aggressive	Aggressive	0.34	Slightly Aggressive
Very Aggressive	Slightly Aggressive	Aggressive	0.34	Slightly Aggressive
Less Favourable	Very Aggressive	Aggressive	0.34	Very Aggressive
Very Aggressive	Less Favourable	Aggressive	0.34	Very Aggressive
Less Favourable	Very Aggressive	Aggressive	0.34	Aggressive
Very Aggressive	Less Favourable	Aggressive	0.34	Aggressive
Less Favourable	Very Aggressive	Aggressive	0.34	Less Favourable
Very Aggressive	Less Favourable	Aggressive	0.34	Less Favourable
Slightly Aggressive	Aggressive	Aggressive	0.66	Aggressive
Aggressive	Slightly Aggressive	Aggressive	0.66	Aggressive
Slightly Aggressive	Aggressive	Aggressive	0.34	Slightly Aggressive
Aggressive	Slightly Aggressive	Aggressive	0.34	Slightly Aggressive
Favourable	Very Aggressive	Aggressive	0.34	Very Aggressive

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Very Aggressive	Favourable	Aggressive	0.34	Very Aggressive
Favourable	Very Aggressive	Aggressive	0.34	Aggressive
Very Aggressive	Favourable	Aggressive	0.34	Aggressive
Favourable	Very Aggressive	Aggressive	0.34	Favourable
Very Aggressive	Favourable	Aggressive	0.34	Favourable
Less Favourable	Aggressive	Aggressive	0.66	Aggressive
Aggressive	Less Favourable	Aggressive	0.66	Aggressive
Less Favourable	Aggressive	Aggressive	0.34	Less Favourable
Aggressive	Less Favourable	Aggressive	0.34	Less Favourable
Slightly Aggressive	Slightly Aggressive	Aggressive	0.34	Aggressive
Slightly Aggressive	Slightly Aggressive	Aggressive	0.66	Slightly Aggressive
Favourable	Aggressive	Aggressive	0.66	Aggressive
Aggressive	Favourable	Aggressive	0.66	Aggressive
Favourable	Aggressive	Aggressive	0.34	Favourable
Aggressive	Favourable	Aggressive	0.34	Favourable
Less Favourable	Slightly Aggressive	Aggressive	0.34	Aggressive
Slightly Aggressive	Less Favourable	Aggressive	0.34	Aggressive
Less Favourable	Slightly Aggressive	Aggressive	0.34	Slightly Aggressive
Slightly Aggressive	Less Favourable	Aggressive	0.34	Slightly Aggressive
Less Favourable	Slightly Aggressive	Aggressive	0.34	Less Favourable
Slightly Aggressive	Less Favourable	Aggressive	0.34	Less Favourable
Favourable	Slightly Aggressive	Aggressive	0.34	Aggressive
Slightly Aggressive	Favourable	Aggressive	0.34	Aggressive
Favourable	Slightly Aggressive	Aggressive	0.34	Slightly Aggressive
Slightly Aggressive	Favourable	Aggressive	0.34	Slightly Aggressive
Favourable	Slightly Aggressive	Aggressive	0.34	Favourable
Slightly Aggressive	Favourable	Aggressive	0.34	Favourable
Less Favourable	Less Favourable	Aggressive	0.34	Aggressive
Less Favourable	Less Favourable	Aggressive	0.66	Less Favourable
Favourable	Less Favourable	Aggressive	0.34	Aggressive
Less Favourable	Favourable	Aggressive	0.34	Aggressive
Favourable	Less Favourable	Aggressive	0.34	Less Favourable
Less Favourable	Favourable	Aggressive	0.34	Less Favourable
Favourable	Less Favourable	Aggressive	0.34	Favourable
Less Favourable	Favourable	Aggressive	0.34	Favourable
Favourable	Favourable	Aggressive	0.34	Aggressive

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Favourable	Favourable	Aggressive	0.66	Favourable
Aggressive	Very Aggressive	Very Aggressive	0.66	Very Aggressive
Very Aggressive	Aggressive	Very Aggressive	0.66	Very Aggressive
Aggressive	Very Aggressive	Very Aggressive	0.34	Aggressive
Very Aggressive	Aggressive	Very Aggressive	0.34	Aggressive
Slightly Aggressive	Very Aggressive	Very Aggressive	0.66	Very Aggressive
Very Aggressive	Slightly Aggressive	Very Aggressive	0.66	Very Aggressive
Slightly Aggressive	Very Aggressive	Very Aggressive	0.34	Slightly Aggressive
Very Aggressive	Slightly Aggressive	Very Aggressive	0.34	Slightly Aggressive
Aggressive	Aggressive	Very Aggressive	0.34	Very Aggressive
Aggressive	Aggressive	Very Aggressive	0.66	Aggressive
Less Favourable	Very Aggressive	Very Aggressive	0.66	Very Aggressive
Very Aggressive	Less Favourable	Very Aggressive	0.66	Very Aggressive
Less Favourable	Very Aggressive	Very Aggressive	0.34	Less Favourable
Very Aggressive	Less Favourable	Very Aggressive	0.34	Less Favourable
Slightly Aggressive	Aggressive	Very Aggressive	0.34	Very Aggressive
Aggressive	Slightly Aggressive	Very Aggressive	0.34	Very Aggressive
Slightly Aggressive	Aggressive	Very Aggressive	0.34	Aggressive
Aggressive	Slightly Aggressive	Very Aggressive	0.34	Aggressive
Slightly Aggressive	Aggressive	Very Aggressive	0.34	Slightly Aggressive
Aggressive	Slightly Aggressive	Very Aggressive	0.34	Slightly Aggressive
Favourable	Very Aggressive	Very Aggressive	0.66	Very Aggressive
Very Aggressive	Favourable	Very Aggressive	0.66	Very Aggressive
Favourable	Very Aggressive	Very Aggressive	0.34	Favourable
Very Aggressive	Favourable	Very Aggressive	0.34	Favourable
Less Favourable	Aggressive	Very Aggressive	0.34	Very Aggressive
Aggressive	Less Favourable	Very Aggressive	0.34	Very Aggressive
Less Favourable	Aggressive	Very Aggressive	0.34	Aggressive
Aggressive	Less Favourable	Very Aggressive	0.34	Aggressive
Less Favourable	Aggressive	Very Aggressive	0.34	Less Favourable
Aggressive	Less Favourable	Very Aggressive	0.34	Less Favourable
Slightly Aggressive	Slightly Aggressive	Very Aggressive	0.34	Very Aggressive
Slightly Aggressive	Slightly Aggressive	Very Aggressive	0.66	Slightly Aggressive
Favourable	Aggressive	Very Aggressive	0.34	Very Aggressive
Aggressive	Favourable	Very Aggressive	0.34	Very Aggressive
Favourable	Aggressive	Very Aggressive	0.34	Aggressive

IF			THEN	
External Climate	Internal Climate	Operational Environment	DoS	Environment
Aggressive	Favourable	Very Aggressive	0.34	Aggressive
Favourable	Aggressive	Very Aggressive	0.34	Favourable
Aggressive	Favourable	Very Aggressive	0.34	Favourable
Less Favourable	Slightly Aggressive	Very Aggressive	0.34	Very Aggressive
Slightly Aggressive	Less Favourable	Very Aggressive	0.34	Very Aggressive
Less Favourable	Slightly Aggressive	Very Aggressive	0.34	Slightly Aggressive
Slightly Aggressive	Less Favourable	Very Aggressive	0.34	Slightly Aggressive
Less Favourable	Slightly Aggressive	Very Aggressive	0.34	Less Favourable
Slightly Aggressive	Less Favourable	Very Aggressive	0.34	Less Favourable
Favourable	Slightly Aggressive	Very Aggressive	0.34	Very Aggressive
Slightly Aggressive	Favourable	Very Aggressive	0.34	Very Aggressive
Favourable	Slightly Aggressive	Very Aggressive	0.34	Slightly Aggressive
Slightly Aggressive	Favourable	Very Aggressive	0.34	Slightly Aggressive
Favourable	Slightly Aggressive	Very Aggressive	0.34	Favourable
Slightly Aggressive	Favourable	Very Aggressive	0.34	Favourable
Less Favourable	Less Favourable	Very Aggressive	0.34	Very Aggressive
Less Favourable	Less Favourable	Very Aggressive	0.66	Less Favourable
Favourable	Less Favourable	Very Aggressive	0.34	Very Aggressive
Less Favourable	Favourable	Very Aggressive	0.34	Very Aggressive
Favourable	Less Favourable	Very Aggressive	0.34	Less Favourable
Less Favourable	Favourable	Very Aggressive	0.34	Less Favourable
Favourable	Less Favourable	Very Aggressive	0.34	Favourable
Less Favourable	Favourable	Very Aggressive	0.34	Favourable
Favourable	Favourable	Very Aggressive	0.34	Very Aggressive
Favourable	Favourable	Very Aggressive	0.66	Favourable

Table A-2: IF – THEN Rules for Rule Block 2

A.3. IF-THEN FUZZY RULE BLOCK 3

IF				**THEN**	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	Very Low	Very Aggressive	Very Low	0.75	Very Fast
Very Bad	Very Low	Very Aggressive	Very Low	0.25	Very Slow
Very Bad	Very Low	Very Aggressive	Low	0.75	Very Fast
Very Bad	Very Low	Very Aggressive	Low	0.25	Fast
Very Bad	Very Low	Very Aggressive	Low	0.25	Very Slow
Very Bad	Very Low	Very Aggressive	Normal	0.50	Very Fast

IF				**THEN**	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	Very Low	Very Aggressive	Normal	0.25	Medium
Very Bad	Very Low	Very Aggressive	Normal	0.25	Very Slow
Very Bad	Very Low	Very Aggressive	High	0.50	Very Fast
Very Bad	Very Low	Very Aggressive	High	0.25	Very Slow
Very Bad	Very Low	Very Aggressive	High	0.25	Slow
Very Bad	Very Low	Very Aggressive	Very High	0.50	Very Slow
Very Bad	Very Low	Very Aggressive	Very High	0.50	Very Fast
Bad	Very Low	Very Aggressive	Very Low	0.75	Very Fast
Bad	Very Low	Very Aggressive	Very Low	0.25	Fast
Bad	Very Low	Very Aggressive	Low	0.50	Very Fast
Bad	Very Low	Very Aggressive	Low	0.50	Fast
Bad	Very Low	Very Aggressive	Normal	0.50	Very Fast
Bad	Very Low	Very Aggressive	Normal	0.25	Fast
Bad	Very Low	Very Aggressive	Normal	0.25	Medium
Bad	Very Low	Very Aggressive	High	0.50	Very Fast
Bad	Very Low	Very Aggressive	High	0.25	Fast
Bad	Very Low	Very Aggressive	High	0.25	Slow
Bad	Very Low	Very Aggressive	Very High	0.50	Very Fast
Bad	Very Low	Very Aggressive	Very High	0.25	Very Slow
Bad	Very Low	Very Aggressive	Very High	0.25	Fast
Fair	Very Low	Very Aggressive	Very Low	1.00	Very Fast
Fair	Very Low	Very Aggressive	Low	0.75	Very Fast
Fair	Very Low	Very Aggressive	Low	0.25	Fast
Fair	Very Low	Very Aggressive	Normal	0.75	Very Fast
Fair	Very Low	Very Aggressive	Normal	0.25	Medium
Fair	Very Low	Very Aggressive	High	0.75	Very Fast
Fair	Very Low	Very Aggressive	High	0.25	Slow
Fair	Very Low	Very Aggressive	Very High	0.75	Very Fast
Fair	Very Low	Very Aggressive	Very High	0.25	Very Slow
Good	Very Low	Very Aggressive	Very Low	0.75	Very Fast
Good	Very Low	Very Aggressive	Very Low	0.25	Medium
Good	Very Low	Very Aggressive	Low	0.50	Very Fast
Good	Very Low	Very Aggressive	Low	0.25	Fast
Good	Very Low	Very Aggressive	Low	0.25	Medium
Good	Very Low	Very Aggressive	Normal	0.50	Very Fast
Good	Very Low	Very Aggressive	Normal	0.50	Medium

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Good	Very Low	Very Aggressive	High	0.50	Very Fast
Good	Very Low	Very Aggressive	High	0.25	Medium
Good	Very Low	Very Aggressive	High	0.25	Slow
Good	Very Low	Very Aggressive	Very High	0.50	Very Fast
Good	Very Low	Very Aggressive	Very High	0.25	Medium
Good	Very Low	Very Aggressive	Very High	0.25	Very Slow
Very Good	Very Low	Very Aggressive	Very Low	0.75	Very Fast
Very Good	Very Low	Very Aggressive	Very Low	0.25	Slow
Very Good	Very Low	Very Aggressive	Low	0.50	Very Fast
Very Good	Very Low	Very Aggressive	Low	0.25	Fast
Very Good	Very Low	Very Aggressive	Low	0.25	Slow
Very Good	Very Low	Very Aggressive	Normal	0.50	Very Fast
Very Good	Very Low	Very Aggressive	Normal	0.25	Medium
Very Good	Very Low	Very Aggressive	Normal	0.25	Slow
Very Good	Very Low	Very Aggressive	High	0.50	Very Fast
Very Good	Very Low	Very Aggressive	High	0.50	Slow
Very Good	Very Low	Very Aggressive	Very High	0.50	Very Fast
Very Good	Very Low	Very Aggressive	Very High	0.25	Slow
Very Good	Very Low	Very Aggressive	Very High	0.25	Very Slow
Very Bad	Very Low	Aggressive	Very Low	0.50	Very Fast
Very Bad	Very Low	Aggressive	Very Low	0.25	Very Slow
Very Bad	Very Low	Aggressive	Very Low	0.25	Fast
Very Bad	Very Low	Aggressive	Low	0.25	Very Fast
Very Bad	Very Low	Aggressive	Low	0.50	Fast
Very Bad	Very Low	Aggressive	Low	0.25	Very Slow
Very Bad	Very Low	Aggressive	Normal	0.25	Very Fast
Very Bad	Very Low	Aggressive	Normal	0.25	Fast
Very Bad	Very Low	Aggressive	Normal	0.25	Medium
Very Bad	Very Low	Aggressive	Normal	0.25	Very Slow
Very Bad	Very Low	Aggressive	High	0.25	Very Fast
Very Bad	Very Low	Aggressive	High	0.25	Fast
Very Bad	Very Low	Aggressive	High	0.25	Slow
Very Bad	Very Low	Aggressive	High	0.25	Very Slow
Very Bad	Very Low	Aggressive	Very High	0.25	Very Fast
Very Bad	Very Low	Aggressive	Very High	0.25	Fast
Very Bad	Very Low	Aggressive	Very High	0.50	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Bad	Very Low	Aggressive	Very Low	0.50	Very Fast
Bad	Very Low	Aggressive	Very Low	0.50	Fast
Bad	Very Low	Aggressive	Low	0.25	Very Fast
Bad	Very Low	Aggressive	Low	0.75	Fast
Bad	Very Low	Aggressive	Normal	0.25	Very Fast
Bad	Very Low	Aggressive	Normal	0.50	Fast
Bad	Very Low	Aggressive	Normal	0.25	Medium
Bad	Very Low	Aggressive	High	0.25	Very Fast
Bad	Very Low	Aggressive	High	0.50	Fast
Bad	Very Low	Aggressive	High	0.25	Slow
Bad	Very Low	Aggressive	Very High	0.25	Very Fast
Bad	Very Low	Aggressive	Very High	0.50	Fast
Bad	Very Low	Aggressive	Very High	0.25	Very Slow
Fair	Very Low	Aggressive	Very Low	0.75	Very Fast
Fair	Very Low	Aggressive	Very Low	0.25	Fast
Fair	Very Low	Aggressive	Low	0.50	Very Fast
Fair	Very Low	Aggressive	Low	0.50	Fast
Fair	Very Low	Aggressive	Normal	0.50	Very Fast
Fair	Very Low	Aggressive	Normal	0.25	Fast
Fair	Very Low	Aggressive	Normal	0.25	Medium
Fair	Very Low	Aggressive	High	0.50	Very Fast
Fair	Very Low	Aggressive	High	0.25	Fast
Fair	Very Low	Aggressive	High	0.25	Slow
Fair	Very Low	Aggressive	Very High	0.50	Very Fast
Fair	Very Low	Aggressive	Very High	0.25	Fast
Fair	Very Low	Aggressive	Very High	0.25	Very Slow
Good	Very Low	Aggressive	Very Low	0.50	Very Fast
Good	Very Low	Aggressive	Very Low	0.25	Fast
Good	Very Low	Aggressive	Very Low	0.25	Medium
Good	Very Low	Aggressive	Low	0.25	Very Fast
Good	Very Low	Aggressive	Low	0.50	Fast
Good	Very Low	Aggressive	Low	0.25	Medium
Good	Very Low	Aggressive	Normal	0.25	Very Fast
Good	Very Low	Aggressive	Normal	0.25	Fast
Good	Very Low	Aggressive	Normal	0.50	Medium
Good	Very Low	Aggressive	High	0.25	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Good	Very Low	Aggressive	High	0.25	Fast
Good	Very Low	Aggressive	High	0.25	Medium
Good	Very Low	Aggressive	High	0.25	Slow
Good	Very Low	Aggressive	Very High	0.25	Very Fast
Good	Very Low	Aggressive	Very High	0.25	Fast
Good	Very Low	Aggressive	Very High	0.25	Medium
Good	Very Low	Aggressive	Very High	0.25	Very Slow
Very Good	Very Low	Aggressive	Very Low	0.50	Very Fast
Very Good	Very Low	Aggressive	Very Low	0.25	Fast
Very Good	Very Low	Aggressive	Very Low	0.25	Slow
Very Good	Very Low	Aggressive	Low	0.25	Very Fast
Very Good	Very Low	Aggressive	Low	0.50	Fast
Very Good	Very Low	Aggressive	Low	0.25	Slow
Very Good	Very Low	Aggressive	Normal	0.25	Very Fast
Very Good	Very Low	Aggressive	Normal	0.25	Fast
Very Good	Very Low	Aggressive	Normal	0.25	Medium
Very Good	Very Low	Aggressive	Normal	0.25	Slow
Very Good	Very Low	Aggressive	High	0.25	Very Fast
Very Good	Very Low	Aggressive	High	0.25	Fast
Very Good	Very Low	Aggressive	High	0.50	Slow
Very Good	Very Low	Aggressive	Very High	0.25	Very Fast
Very Good	Very Low	Aggressive	Very High	0.25	Fast
Very Good	Very Low	Aggressive	Very High	0.25	Slow
Very Good	Very Low	Aggressive	Very High	0.25	Very Slow
Very Bad	Very Low	Slightly Aggressive	Very Low	0.50	Very Fast
Very Bad	Very Low	Slightly Aggressive	Very Low	0.25	Medium
Very Bad	Very Low	Slightly Aggressive	Very Low	0.25	Very Slow
Very Bad	Very Low	Slightly Aggressive	Low	0.25	Very Fast
Very Bad	Very Low	Slightly Aggressive	Low	0.25	Fast
Very Bad	Very Low	Slightly Aggressive	Low	0.25	Medium
Very Bad	Very Low	Slightly Aggressive	Low	0.25	Very Slow
Very Bad	Very Low	Slightly Aggressive	Normal	0.25	Very Fast
Very Bad	Very Low	Slightly Aggressive	Normal	0.50	Medium
Very Bad	Very Low	Slightly Aggressive	Normal	0.25	Very Slow
Very Bad	Very Low	Slightly Aggressive	High	0.25	Very Fast
Very Bad	Very Low	Slightly Aggressive	High	0.25	Medium

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	Very Low	Slightly Aggressive	High	0.25	Slow
Very Bad	Very Low	Slightly Aggressive	High	0.25	Very Slow
Very Bad	Very Low	Slightly Aggressive	Very High	0.50	Very Slow
Very Bad	Very Low	Slightly Aggressive	Very High	0.25	Very Fast
Very Bad	Very Low	Slightly Aggressive	Very High	0.25	Medium
Bad	Very Low	Slightly Aggressive	Very Low	0.50	Very Fast
Bad	Very Low	Slightly Aggressive	Very Low	0.25	Fast
Bad	Very Low	Slightly Aggressive	Very Low	0.25	Medium
Bad	Very Low	Slightly Aggressive	Low	0.25	Very Fast
Bad	Very Low	Slightly Aggressive	Low	0.50	Fast
Bad	Very Low	Slightly Aggressive	Low	0.25	Medium
Bad	Very Low	Slightly Aggressive	Normal	0.25	Very Fast
Bad	Very Low	Slightly Aggressive	Normal	0.25	Fast
Bad	Very Low	Slightly Aggressive	Normal	0.50	Medium
Bad	Very Low	Slightly Aggressive	High	0.25	Very Fast
Bad	Very Low	Slightly Aggressive	High	0.25	Fast
Bad	Very Low	Slightly Aggressive	High	0.25	Medium
Bad	Very Low	Slightly Aggressive	High	0.25	Slow
Bad	Very Low	Slightly Aggressive	Very High	0.25	Very Fast
Bad	Very Low	Slightly Aggressive	Very High	0.25	Fast
Bad	Very Low	Slightly Aggressive	Very High	0.25	Medium
Bad	Very Low	Slightly Aggressive	Very High	0.25	Very Slow
Fair	Very Low	Slightly Aggressive	Very Low	0.75	Very Fast
Fair	Very Low	Slightly Aggressive	Very Low	0.25	Medium
Fair	Very Low	Slightly Aggressive	Low	0.50	Very Fast
Fair	Very Low	Slightly Aggressive	Low	0.25	Fast
Fair	Very Low	Slightly Aggressive	Low	0.25	Medium
Fair	Very Low	Slightly Aggressive	Normal	0.50	Very Fast
Fair	Very Low	Slightly Aggressive	Normal	0.50	Medium
Fair	Very Low	Slightly Aggressive	High	0.50	Very Fast
Fair	Very Low	Slightly Aggressive	High	0.25	Medium
Fair	Very Low	Slightly Aggressive	High	0.25	Slow
Fair	Very Low	Slightly Aggressive	Very High	0.50	Very Fast
Fair	Very Low	Slightly Aggressive	Very High	0.25	Medium
Fair	Very Low	Slightly Aggressive	Very High	0.25	Very Slow
Good	Very Low	Slightly Aggressive	Very Low	0.50	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Good	Very Low	Slightly Aggressive	Very Low	0.50	Medium
Good	Very Low	Slightly Aggressive	Low	0.25	Very Fast
Good	Very Low	Slightly Aggressive	Low	0.25	Fast
Good	Very Low	Slightly Aggressive	Low	0.50	Medium
Good	Very Low	Slightly Aggressive	Normal	0.25	Very Fast
Good	Very Low	Slightly Aggressive	Normal	0.75	Medium
Good	Very Low	Slightly Aggressive	High	0.25	Very Fast
Good	Very Low	Slightly Aggressive	High	0.50	Medium
Good	Very Low	Slightly Aggressive	High	0.25	Slow
Good	Very Low	Slightly Aggressive	Very High	0.25	Very Fast
Good	Very Low	Slightly Aggressive	Very High	0.50	Medium
Good	Very Low	Slightly Aggressive	Very High	0.25	Very Slow
Very Good	Very Low	Slightly Aggressive	Very Low	0.50	Very Fast
Very Good	Very Low	Slightly Aggressive	Very Low	0.25	Medium
Very Good	Very Low	Slightly Aggressive	Very Low	0.25	Slow
Very Good	Very Low	Slightly Aggressive	Low	0.25	Very Fast
Very Good	Very Low	Slightly Aggressive	Low	0.25	Fast
Very Good	Very Low	Slightly Aggressive	Low	0.25	Medium
Very Good	Very Low	Slightly Aggressive	Low	0.25	Slow
Very Good	Very Low	Slightly Aggressive	Normal	0.25	Very Fast
Very Good	Very Low	Slightly Aggressive	Normal	0.50	Medium
Very Good	Very Low	Slightly Aggressive	Normal	0.25	Slow
Very Good	Very Low	Slightly Aggressive	High	0.25	Very Fast
Very Good	Very Low	Slightly Aggressive	High	0.25	Medium
Very Good	Very Low	Slightly Aggressive	High	0.50	Slow
Very Good	Very Low	Slightly Aggressive	Very High	0.25	Very Fast
Very Good	Very Low	Slightly Aggressive	Very High	0.25	Medium
Very Good	Very Low	Slightly Aggressive	Very High	0.25	Slow
Very Good	Very Low	Slightly Aggressive	Very High	0.25	Very Slow
Very Bad	Very Low	Less Favourable	Very Low	0.50	Very Fast
Very Bad	Very Low	Less Favourable	Very Low	0.25	Slow
Very Bad	Very Low	Less Favourable	Very Low	0.25	Very Slow
Very Bad	Very Low	Less Favourable	Low	0.25	Very Fast
Very Bad	Very Low	Less Favourable	Low	0.25	Fast
Very Bad	Very Low	Less Favourable	Low	0.25	Slow
Very Bad	Very Low	Less Favourable	Low	0.25	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	Very Low	Less Favourable	Normal	0.25	Very Fast
Very Bad	Very Low	Less Favourable	Normal	0.25	Medium
Very Bad	Very Low	Less Favourable	Normal	0.25	Slow
Very Bad	Very Low	Less Favourable	Normal	0.25	Very Slow
Very Bad	Very Low	Less Favourable	High	0.25	Very Fast
Very Bad	Very Low	Less Favourable	High	0.50	Slow
Very Bad	Very Low	Less Favourable	High	0.25	Very Slow
Very Bad	Very Low	Less Favourable	Very High	0.25	Very Fast
Very Bad	Very Low	Less Favourable	Very High	0.25	Slow
Very Bad	Very Low	Less Favourable	Very High	0.50	Very Slow
Bad	Very Low	Less Favourable	Very Low	0.50	Very Fast
Bad	Very Low	Less Favourable	Very Low	0.25	Fast
Bad	Very Low	Less Favourable	Very Low	0.25	Slow
Bad	Very Low	Less Favourable	Low	0.25	Very Fast
Bad	Very Low	Less Favourable	Low	0.50	Fast
Bad	Very Low	Less Favourable	Low	0.25	Slow
Bad	Very Low	Less Favourable	Normal	0.25	Very Fast
Bad	Very Low	Less Favourable	Normal	0.25	Medium
Bad	Very Low	Less Favourable	Normal	0.25	Fast
Bad	Very Low	Less Favourable	Normal	0.25	Slow
Bad	Very Low	Less Favourable	High	0.25	Very Fast
Bad	Very Low	Less Favourable	High	0.25	Fast
Bad	Very Low	Less Favourable	High	0.50	Slow
Bad	Very Low	Less Favourable	Very High	0.25	Very Fast
Bad	Very Low	Less Favourable	Very High	0.25	Fast
Bad	Very Low	Less Favourable	Very High	0.25	Slow
Bad	Very Low	Less Favourable	Very High	0.25	Very Slow
Fair	Very Low	Less Favourable	Very Low	0.75	Very Fast
Fair	Very Low	Less Favourable	Very Low	0.25	Slow
Fair	Very Low	Less Favourable	Low	0.50	Very Fast
Fair	Very Low	Less Favourable	Low	0.25	Fast
Fair	Very Low	Less Favourable	Low	0.25	Slow
Fair	Very Low	Less Favourable	Normal	0.50	Very Fast
Fair	Very Low	Less Favourable	Normal	0.25	Medium
Fair	Very Low	Less Favourable	Normal	0.25	Slow
Fair	Very Low	Less Favourable	High	0.50	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Very Low	Less Favourable	High	0.50	Slow
Fair	Very Low	Less Favourable	Very High	0.50	Very Fast
Fair	Very Low	Less Favourable	Very High	0.25	Slow
Fair	Very Low	Less Favourable	Very High	0.25	Very Slow
Good	Very Low	Less Favourable	Very Low	0.50	Very Fast
Good	Very Low	Less Favourable	Very Low	0.25	Medium
Good	Very Low	Less Favourable	Very Low	0.25	Slow
Good	Very Low	Less Favourable	Low	0.25	Very Fast
Good	Very Low	Less Favourable	Low	0.25	Fast
Good	Very Low	Less Favourable	Low	0.25	Medium
Good	Very Low	Less Favourable	Low	0.25	Slow
Good	Very Low	Less Favourable	Normal	0.25	Very Fast
Good	Very Low	Less Favourable	Normal	0.50	Medium
Good	Very Low	Less Favourable	Normal	0.25	Slow
Good	Very Low	Less Favourable	High	0.25	Very Fast
Good	Very Low	Less Favourable	High	0.25	Medium
Good	Very Low	Less Favourable	High	0.50	Slow
Good	Very Low	Less Favourable	Very High	0.25	Very Fast
Good	Very Low	Less Favourable	Very High	0.25	Medium
Good	Very Low	Less Favourable	Very High	0.25	Slow
Good	Very Low	Less Favourable	Very High	0.25	Very Slow
Very Good	Very Low	Less Favourable	Very Low	0.50	Very Fast
Very Good	Very Low	Less Favourable	Very Low	0.50	Slow
Very Good	Very Low	Less Favourable	Low	0.25	Very Fast
Very Good	Very Low	Less Favourable	Low	0.25	Fast
Very Good	Very Low	Less Favourable	Low	0.50	Slow
Very Good	Very Low	Less Favourable	Normal	0.25	Very Fast
Very Good	Very Low	Less Favourable	Normal	0.25	Medium
Very Good	Very Low	Less Favourable	Normal	0.50	Slow
Very Good	Very Low	Less Favourable	High	0.25	Very Fast
Very Good	Very Low	Less Favourable	High	0.75	Slow
Very Good	Very Low	Less Favourable	Very High	0.25	Very Fast
Very Good	Very Low	Less Favourable	Very High	0.50	Slow
Very Good	Very Low	Less Favourable	Very High	0.25	Very Slow
Very Bad	Very Low	Favourable	Very Low	0.50	Very Fast
Very Bad	Very Low	Favourable	Very Low	0.50	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	Very Low	Favourable	Low	0.25	Very Fast
Very Bad	Very Low	Favourable	Low	0.25	Fast
Very Bad	Very Low	Favourable	Low	0.50	Very Slow
Very Bad	Very Low	Favourable	Normal	0.25	Very Fast
Very Bad	Very Low	Favourable	Normal	0.25	Medium
Very Bad	Very Low	Favourable	Normal	0.50	Very Slow
Very Bad	Very Low	Favourable	High	0.25	Very Fast
Very Bad	Very Low	Favourable	High	0.25	Slow
Very Bad	Very Low	Favourable	High	0.50	Very Slow
Very Bad	Very Low	Favourable	Very High	0.25	Very Fast
Very Bad	Very Low	Favourable	Very High	0.75	Very Slow
Bad	Very Low	Favourable	Very Low	0.50	Very Fast
Bad	Very Low	Favourable	Very Low	0.25	Fast
Bad	Very Low	Favourable	Very Low	0.25	Very Slow
Bad	Very Low	Favourable	Low	0.25	Very Fast
Bad	Very Low	Favourable	Low	0.50	Fast
Bad	Very Low	Favourable	Low	0.25	Very Slow
Bad	Very Low	Favourable	Normal	0.25	Very Fast
Bad	Very Low	Favourable	Normal	0.25	Fast
Bad	Very Low	Favourable	Normal	0.25	Medium
Bad	Very Low	Favourable	Normal	0.25	Very Slow
Bad	Very Low	Favourable	High	0.25	Very Fast
Bad	Very Low	Favourable	High	0.25	Fast
Bad	Very Low	Favourable	High	0.25	Slow
Bad	Very Low	Favourable	High	0.25	Very Slow
Bad	Very Low	Favourable	Very High	0.25	Very Fast
Bad	Very Low	Favourable	Very High	0.25	Fast
Bad	Very Low	Favourable	Very High	0.50	Very Slow
Fair	Very Low	Favourable	Very Low	0.75	Very Fast
Fair	Very Low	Favourable	Very Low	0.25	Very Slow
Fair	Very Low	Favourable	Low	0.50	Very Fast
Fair	Very Low	Favourable	Low	0.25	Fast
Fair	Very Low	Favourable	Low	0.25	Very Slow
Fair	Very Low	Favourable	Normal	0.50	Very Fast
Fair	Very Low	Favourable	Normal	0.25	Medium
Fair	Very Low	Favourable	Normal	0.25	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Very Low	Favourable	High	0.50	Very Fast
Fair	Very Low	Favourable	High	0.25	Slow
Fair	Very Low	Favourable	High	0.25	Very Slow
Fair	Very Low	Favourable	Very High	0.50	Very Fast
Fair	Very Low	Favourable	Very High	0.50	Very Slow
Good	Very Low	Favourable	Very Low	0.50	Very Fast
Good	Very Low	Favourable	Very Low	0.25	Medium
Good	Very Low	Favourable	Very Low	0.25	Very Slow
Good	Very Low	Favourable	Low	0.25	Very Fast
Good	Very Low	Favourable	Low	0.25	Fast
Good	Very Low	Favourable	Low	0.25	Medium
Good	Very Low	Favourable	Low	0.25	Very Slow
Good	Very Low	Favourable	Normal	0.25	Very Fast
Good	Very Low	Favourable	Normal	0.50	Medium
Good	Very Low	Favourable	Normal	0.25	Very Slow
Good	Very Low	Favourable	High	0.25	Very Fast
Good	Very Low	Favourable	High	0.25	Medium
Good	Very Low	Favourable	High	0.25	Slow
Good	Very Low	Favourable	High	0.25	Very Slow
Good	Very Low	Favourable	Very High	0.25	Very Fast
Good	Very Low	Favourable	Very High	0.25	Medium
Good	Very Low	Favourable	Very High	0.50	Very Slow
Very Good	Very Low	Favourable	Very Low	0.50	Very Fast
Very Good	Very Low	Favourable	Very Low	0.25	Slow
Very Good	Very Low	Favourable	Very Low	0.25	Very Slow
Very Good	Very Low	Favourable	Low	0.25	Very Fast
Very Good	Very Low	Favourable	Low	0.25	Fast
Very Good	Very Low	Favourable	Low	0.25	Slow
Very Good	Very Low	Favourable	Low	0.25	Very Slow
Very Good	Very Low	Favourable	Normal	0.25	Very Fast
Very Good	Very Low	Favourable	Normal	0.25	Medium
Very Good	Very Low	Favourable	Normal	0.25	Slow
Very Good	Very Low	Favourable	Normal	0.25	Very Slow
Very Good	Very Low	Favourable	High	0.25	Very Fast
Very Good	Very Low	Favourable	High	0.50	Slow
Very Good	Very Low	Favourable	High	0.25	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Very Low	Favourable	Very High	0.25	Very Fast
Very Good	Very Low	Favourable	Very High	0.25	Slow
Very Good	Very Low	Favourable	Very High	0.50	Very Slow
Very Bad	Low	Very Aggressive	Very Low	0.50	Very Fast
Very Bad	Low	Very Aggressive	Very Low	0.25	Fast
Very Bad	Low	Very Aggressive	Very Low	0.25	Very Slow
Very Bad	Low	Very Aggressive	Low	0.25	Very Fast
Very Bad	Low	Very Aggressive	Low	0.50	Fast
Very Bad	Low	Very Aggressive	Low	0.25	Very Slow
Very Bad	Low	Very Aggressive	Normal	0.25	Very Fast
Very Bad	Low	Very Aggressive	Normal	0.25	Fast
Very Bad	Low	Very Aggressive	Normal	0.25	Medium
Very Bad	Low	Very Aggressive	Normal	0.25	Very Slow
Very Bad	Low	Very Aggressive	High	0.25	Very Fast
Very Bad	Low	Very Aggressive	High	0.25	Fast
Very Bad	Low	Very Aggressive	High	0.25	Slow
Very Bad	Low	Very Aggressive	High	0.25	Very Slow
Very Bad	Low	Very Aggressive	Very High	0.25	Very Fast
Very Bad	Low	Very Aggressive	Very High	0.25	Fast
Very Bad	Low	Very Aggressive	Very High	0.50	Very Slow
Bad	Low	Very Aggressive	Very Low	0.50	Very Fast
Bad	Low	Very Aggressive	Very Low	0.50	Fast
Bad	Low	Very Aggressive	Low	0.25	Very Fast
Bad	Low	Very Aggressive	Low	0.75	Fast
Bad	Low	Very Aggressive	Normal	0.25	Very Fast
Bad	Low	Very Aggressive	Normal	0.50	Fast
Bad	Low	Very Aggressive	Normal	0.25	Medium
Bad	Low	Very Aggressive	High	0.25	Very Fast
Bad	Low	Very Aggressive	High	0.50	Fast
Bad	Low	Very Aggressive	High	0.25	Slow
Bad	Low	Very Aggressive	Very High	0.25	Very Fast
Bad	Low	Very Aggressive	Very High	0.50	Fast
Bad	Low	Very Aggressive	Very High	0.25	Very Slow
Fair	Low	Very Aggressive	Very Low	0.75	Very Fast
Fair	Low	Very Aggressive	Very Low	0.25	Fast
Fair	Low	Very Aggressive	Low	0.50	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Low	Very Aggressive	Low	0.50	Fast
Fair	Low	Very Aggressive	Normal	0.50	Very Fast
Fair	Low	Very Aggressive	Normal	0.25	Fast
Fair	Low	Very Aggressive	Normal	0.25	Medium
Fair	Low	Very Aggressive	High	0.50	Very Fast
Fair	Low	Very Aggressive	High	0.25	Fast
Fair	Low	Very Aggressive	High	0.25	Slow
Fair	Low	Very Aggressive	Very High	0.50	Very Fast
Fair	Low	Very Aggressive	Very High	0.25	Fast
Fair	Low	Very Aggressive	Very High	0.25	Very Slow
Good	Low	Very Aggressive	Very Low	0.50	Very Fast
Good	Low	Very Aggressive	Very Low	0.25	Fast
Good	Low	Very Aggressive	Very Low	0.25	Medium
Good	Low	Very Aggressive	Low	0.25	Very Fast
Good	Low	Very Aggressive	Low	0.50	Fast
Good	Low	Very Aggressive	Low	0.25	Medium
Good	Low	Very Aggressive	Normal	0.25	Very Fast
Good	Low	Very Aggressive	Normal	0.25	Fast
Good	Low	Very Aggressive	Normal	0.50	Medium
Good	Low	Very Aggressive	High	0.25	Very Fast
Good	Low	Very Aggressive	High	0.25	Fast
Good	Low	Very Aggressive	High	0.25	Medium
Good	Low	Very Aggressive	High	0.25	Slow
Good	Low	Very Aggressive	Very High	0.25	Very Fast
Good	Low	Very Aggressive	Very High	0.25	Fast
Good	Low	Very Aggressive	Very High	0.25	Medium
Good	Low	Very Aggressive	Very High	0.25	Very Slow
Very Good	Low	Very Aggressive	Very Low	0.50	Very Fast
Very Good	Low	Very Aggressive	Very Low	0.25	Fast
Very Good	Low	Very Aggressive	Very Low	0.25	Slow
Very Good	Low	Very Aggressive	Low	0.25	Very Fast
Very Good	Low	Very Aggressive	Low	0.50	Fast
Very Good	Low	Very Aggressive	Low	0.25	Slow
Very Good	Low	Very Aggressive	Normal	0.25	Very Fast
Very Good	Low	Very Aggressive	Normal	0.25	Fast
Very Good	Low	Very Aggressive	Normal	0.25	Medium

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Low	Very Aggressive	Normal	0.25	Slow
Very Good	Low	Very Aggressive	High	0.25	Very Fast
Very Good	Low	Very Aggressive	High	0.25	Fast
Very Good	Low	Very Aggressive	High	0.50	Slow
Very Good	Low	Very Aggressive	Very High	0.25	Very Fast
Very Good	Low	Very Aggressive	Very High	0.25	Fast
Very Good	Low	Very Aggressive	Very High	0.25	Slow
Very Good	Low	Very Aggressive	Very High	0.25	Very Slow
Very Bad	Low	Aggressive	Very Low	0.25	Very Fast
Very Bad	Low	Aggressive	Very Low	0.50	Fast
Very Bad	Low	Aggressive	Very Low	0.25	Very Slow
Very Bad	Low	Aggressive	Low	0.75	Fast
Very Bad	Low	Aggressive	Low	0.25	Very Slow
Very Bad	Low	Aggressive	Normal	0.50	Fast
Very Bad	Low	Aggressive	Normal	0.25	Medium
Very Bad	Low	Aggressive	Normal	0.25	Very Slow
Very Bad	Low	Aggressive	High	0.50	Fast
Very Bad	Low	Aggressive	High	0.25	Slow
Very Bad	Low	Aggressive	High	0.25	Very Slow
Very Bad	Low	Aggressive	Very High	0.50	Fast
Very Bad	Low	Aggressive	Very High	0.50	Very Slow
Bad	Low	Aggressive	Very Low	0.75	Fast
Bad	Low	Aggressive	Very Low	0.25	Very Fast
Bad	Low	Aggressive	Low	1.00	Fast
Bad	Low	Aggressive	Normal	0.75	Fast
Bad	Low	Aggressive	Normal	0.25	Medium
Bad	Low	Aggressive	High	0.75	Fast
Bad	Low	Aggressive	High	0.25	Slow
Bad	Low	Aggressive	Very High	0.75	Fast
Bad	Low	Aggressive	Very High	0.25	Very Slow
Fair	Low	Aggressive	Very Low	0.50	Very Fast
Fair	Low	Aggressive	Very Low	0.50	Fast
Fair	Low	Aggressive	Low	0.25	Very Fast
Fair	Low	Aggressive	Low	0.75	Fast
Fair	Low	Aggressive	Normal	0.25	Very Fast
Fair	Low	Aggressive	Normal	0.50	Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Low	Aggressive	Normal	0.25	Medium
Fair	Low	Aggressive	High	0.25	Very Fast
Fair	Low	Aggressive	High	0.50	Fast
Fair	Low	Aggressive	High	0.25	Slow
Fair	Low	Aggressive	Very High	0.25	Very Fast
Fair	Low	Aggressive	Very High	0.50	Fast
Fair	Low	Aggressive	Very High	0.25	Very Slow
Good	Low	Aggressive	Very Low	0.25	Very Fast
Good	Low	Aggressive	Very Low	0.50	Fast
Good	Low	Aggressive	Very Low	0.25	Medium
Good	Low	Aggressive	Low	0.75	Fast
Good	Low	Aggressive	Low	0.25	Medium
Good	Low	Aggressive	Normal	0.50	Fast
Good	Low	Aggressive	Normal	0.50	Medium
Good	Low	Aggressive	High	0.50	Fast
Good	Low	Aggressive	High	0.25	Medium
Good	Low	Aggressive	High	0.25	Slow
Good	Low	Aggressive	Very High	0.50	Fast
Good	Low	Aggressive	Very High	0.25	Medium
Good	Low	Aggressive	Very High	0.25	Very Slow
Very Good	Low	Aggressive	Very Low	0.25	Very Fast
Very Good	Low	Aggressive	Very Low	0.50	Fast
Very Good	Low	Aggressive	Very Low	0.25	Slow
Very Good	Low	Aggressive	Low	0.75	Fast
Very Good	Low	Aggressive	Low	0.25	Slow
Very Good	Low	Aggressive	Normal	0.50	Fast
Very Good	Low	Aggressive	Normal	0.25	Medium
Very Good	Low	Aggressive	Normal	0.25	Slow
Very Good	Low	Aggressive	High	0.50	Fast
Very Good	Low	Aggressive	High	0.50	Slow
Very Good	Low	Aggressive	Very High	0.50	Fast
Very Good	Low	Aggressive	Very High	0.25	Slow
Very Good	Low	Aggressive	Very High	0.25	Very Slow
Very Bad	Low	Slightly Aggressive	Very Low	0.25	Very Fast
Very Bad	Low	Slightly Aggressive	Very Low	0.25	Fast
Very Bad	Low	Slightly Aggressive	Very Low	0.25	Medium

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	Low	Slightly Aggressive	Very Low	0.25	Very Slow
Very Bad	Low	Slightly Aggressive	Low	0.50	Fast
Very Bad	Low	Slightly Aggressive	Low	0.25	Medium
Very Bad	Low	Slightly Aggressive	Low	0.25	Very Slow
Very Bad	Low	Slightly Aggressive	Normal	0.25	Fast
Very Bad	Low	Slightly Aggressive	Normal	0.50	Medium
Very Bad	Low	Slightly Aggressive	Normal	0.25	Very Slow
Very Bad	Low	Slightly Aggressive	High	0.25	Fast
Very Bad	Low	Slightly Aggressive	High	0.25	Medium
Very Bad	Low	Slightly Aggressive	High	0.25	Slow
Very Bad	Low	Slightly Aggressive	High	0.25	Very Slow
Very Bad	Low	Slightly Aggressive	Very High	0.25	Fast
Very Bad	Low	Slightly Aggressive	Very High	0.25	Medium
Very Bad	Low	Slightly Aggressive	Very High	0.50	Very Slow
Bad	Low	Slightly Aggressive	Very Low	0.25	Very Fast
Bad	Low	Slightly Aggressive	Very Low	0.50	Fast
Bad	Low	Slightly Aggressive	Very Low	0.25	Medium
Bad	Low	Slightly Aggressive	Low	0.75	Fast
Bad	Low	Slightly Aggressive	Low	0.25	Medium
Bad	Low	Slightly Aggressive	Normal	0.50	Fast
Bad	Low	Slightly Aggressive	Normal	0.50	Medium
Bad	Low	Slightly Aggressive	High	0.50	Fast
Bad	Low	Slightly Aggressive	High	0.25	Medium
Bad	Low	Slightly Aggressive	High	0.25	Slow
Bad	Low	Slightly Aggressive	Very High	0.50	Fast
Bad	Low	Slightly Aggressive	Very High	0.25	Medium
Bad	Low	Slightly Aggressive	Very High	0.25	Very Slow
Fair	Low	Slightly Aggressive	Very Low	0.50	Very Fast
Fair	Low	Slightly Aggressive	Very Low	0.25	Fast
Fair	Low	Slightly Aggressive	Very Low	0.25	Medium
Fair	Low	Slightly Aggressive	Low	0.25	Very Fast
Fair	Low	Slightly Aggressive	Low	0.50	Fast
Fair	Low	Slightly Aggressive	Low	0.25	Medium
Fair	Low	Slightly Aggressive	Normal	0.25	Very Fast
Fair	Low	Slightly Aggressive	Normal	0.25	Fast
Fair	Low	Slightly Aggressive	Normal	0.50	Medium

IF				**THEN**	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Low	Slightly Aggressive	High	0.25	Very Fast
Fair	Low	Slightly Aggressive	High	0.25	Fast
Fair	Low	Slightly Aggressive	High	0.25	Medium
Fair	Low	Slightly Aggressive	High	0.25	Slow
Fair	Low	Slightly Aggressive	Very High	0.25	Very Fast
Fair	Low	Slightly Aggressive	Very High	0.25	Fast
Fair	Low	Slightly Aggressive	Very High	0.25	Medium
Fair	Low	Slightly Aggressive	Very High	0.25	Very Slow
Good	Low	Slightly Aggressive	Very Low	0.25	Very Fast
Good	Low	Slightly Aggressive	Very Low	0.25	Fast
Good	Low	Slightly Aggressive	Very Low	0.50	Medium
Good	Low	Slightly Aggressive	Low	0.50	Fast
Good	Low	Slightly Aggressive	Low	0.50	Medium
Good	Low	Slightly Aggressive	Normal	0.75	Medium
Good	Low	Slightly Aggressive	Normal	0.25	Fast
Good	Low	Slightly Aggressive	High	0.25	Fast
Good	Low	Slightly Aggressive	High	0.50	Medium
Good	Low	Slightly Aggressive	High	0.25	Slow
Good	Low	Slightly Aggressive	Very High	0.25	Fast
Good	Low	Slightly Aggressive	Very High	0.50	Medium
Good	Low	Slightly Aggressive	Very High	0.25	Very Slow
Very Good	Low	Slightly Aggressive	Very Low	0.25	Very Fast
Very Good	Low	Slightly Aggressive	Very Low	0.25	Fast
Very Good	Low	Slightly Aggressive	Very Low	0.25	Medium
Very Good	Low	Slightly Aggressive	Very Low	0.25	Slow
Very Good	Low	Slightly Aggressive	Low	0.50	Fast
Very Good	Low	Slightly Aggressive	Low	0.25	Medium
Very Good	Low	Slightly Aggressive	Low	0.25	Slow
Very Good	Low	Slightly Aggressive	Normal	0.25	Fast
Very Good	Low	Slightly Aggressive	Normal	0.50	Medium
Very Good	Low	Slightly Aggressive	Normal	0.25	Slow
Very Good	Low	Slightly Aggressive	High	0.25	Fast
Very Good	Low	Slightly Aggressive	High	0.25	Medium
Very Good	Low	Slightly Aggressive	High	0.50	Slow
Very Good	Low	Slightly Aggressive	Very High	0.25	Fast
Very Good	Low	Slightly Aggressive	Very High	0.25	Medium

IF				**THEN**	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Low	Slightly Aggressive	Very High	0.25	Slow
Very Good	Low	Slightly Aggressive	Very High	0.25	Very Slow
Very Bad	Low	Less Favourable	Very Low	0.25	Very Fast
Very Bad	Low	Less Favourable	Very Low	0.25	Fast
Very Bad	Low	Less Favourable	Very Low	0.25	Slow
Very Bad	Low	Less Favourable	Very Low	0.25	Very Slow
Very Bad	Low	Less Favourable	Low	0.50	Fast
Very Bad	Low	Less Favourable	Low	0.25	Slow
Very Bad	Low	Less Favourable	Low	0.25	Very Slow
Very Bad	Low	Less Favourable	Normal	0.25	Fast
Very Bad	Low	Less Favourable	Normal	0.25	Medium
Very Bad	Low	Less Favourable	Normal	0.25	Slow
Very Bad	Low	Less Favourable	Normal	0.25	Very Slow
Very Bad	Low	Less Favourable	High	0.25	Fast
Very Bad	Low	Less Favourable	High	0.50	Slow
Very Bad	Low	Less Favourable	High	0.25	Very Slow
Very Bad	Low	Less Favourable	Very High	0.25	Fast
Very Bad	Low	Less Favourable	Very High	0.25	Slow
Very Bad	Low	Less Favourable	Very High	0.50	Very Slow
Bad	Low	Less Favourable	Very Low	0.25	Very Fast
Bad	Low	Less Favourable	Very Low	0.50	Fast
Bad	Low	Less Favourable	Very Low	0.25	Slow
Bad	Low	Less Favourable	Low	0.75	Fast
Bad	Low	Less Favourable	Low	0.25	Slow
Bad	Low	Less Favourable	Normal	0.50	Fast
Bad	Low	Less Favourable	Normal	0.25	Medium
Bad	Low	Less Favourable	Normal	0.25	Slow
Bad	Low	Less Favourable	High	0.50	Fast
Bad	Low	Less Favourable	High	0.50	Slow
Bad	Low	Less Favourable	Very High	0.50	Fast
Bad	Low	Less Favourable	Very High	0.25	Slow
Bad	Low	Less Favourable	Very High	0.25	Very Slow
Fair	Low	Less Favourable	Very Low	0.50	Very Fast
Fair	Low	Less Favourable	Very Low	0.25	Fast
Fair	Low	Less Favourable	Very Low	0.25	Slow
Fair	Low	Less Favourable	Low	0.25	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Low	Less Favourable	Low	0.50	Fast
Fair	Low	Less Favourable	Low	0.25	Slow
Fair	Low	Less Favourable	Normal	0.25	Very Fast
Fair	Low	Less Favourable	Normal	0.25	Fast
Fair	Low	Less Favourable	Normal	0.25	Medium
Fair	Low	Less Favourable	Normal	0.25	Slow
Fair	Low	Less Favourable	High	0.25	Very Fast
Fair	Low	Less Favourable	High	0.25	Fast
Fair	Low	Less Favourable	High	0.50	Slow
Fair	Low	Less Favourable	Very High	0.25	Very Fast
Fair	Low	Less Favourable	Very High	0.25	Fast
Fair	Low	Less Favourable	Very High	0.25	Slow
Fair	Low	Less Favourable	Very High	0.25	Very Slow
Good	Low	Less Favourable	Very Low	0.25	Very Fast
Good	Low	Less Favourable	Very Low	0.25	Fast
Good	Low	Less Favourable	Very Low	0.25	Medium
Good	Low	Less Favourable	Very Low	0.25	Slow
Good	Low	Less Favourable	Low	0.50	Fast
Good	Low	Less Favourable	Low	0.25	Medium
Good	Low	Less Favourable	Low	0.25	Slow
Good	Low	Less Favourable	Normal	0.25	Fast
Good	Low	Less Favourable	Normal	0.50	Medium
Good	Low	Less Favourable	Normal	0.25	Slow
Good	Low	Less Favourable	High	0.25	Fast
Good	Low	Less Favourable	High	0.25	Medium
Good	Low	Less Favourable	High	0.50	Slow
Good	Low	Less Favourable	Very High	0.25	Fast
Good	Low	Less Favourable	Very High	0.25	Medium
Good	Low	Less Favourable	Very High	0.25	Slow
Good	Low	Less Favourable	Very High	0.25	Very Slow
Very Good	Low	Less Favourable	Very Low	0.25	Very Fast
Very Good	Low	Less Favourable	Very Low	0.25	Fast
Very Good	Low	Less Favourable	Very Low	0.50	Slow
Very Good	Low	Less Favourable	Low	0.50	Fast
Very Good	Low	Less Favourable	Low	0.50	Slow
Very Good	Low	Less Favourable	Normal	0.25	Fast

IF				**THEN**	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Low	Less Favourable	Normal	0.25	Medium
Very Good	Low	Less Favourable	Normal	0.50	Slow
Very Good	Low	Less Favourable	High	0.25	Fast
Very Good	Low	Less Favourable	High	0.75	Slow
Very Good	Low	Less Favourable	Very High	0.25	Fast
Very Good	Low	Less Favourable	Very High	0.50	Slow
Very Good	Low	Less Favourable	Very High	0.25	Very Slow
Very Bad	Low	Favourable	Very Low	0.25	Very Fast
Very Bad	Low	Favourable	Very Low	0.25	Fast
Very Bad	Low	Favourable	Very Low	0.50	Very Slow
Very Bad	Low	Favourable	Low	0.50	Fast
Very Bad	Low	Favourable	Low	0.50	Very Slow
Very Bad	Low	Favourable	Normal	0.25	Fast
Very Bad	Low	Favourable	Normal	0.25	Medium
Very Bad	Low	Favourable	Normal	0.50	Very Slow
Very Bad	Low	Favourable	High	0.25	Fast
Very Bad	Low	Favourable	High	0.25	Slow
Very Bad	Low	Favourable	High	0.50	Very Slow
Very Bad	Low	Favourable	Very High	0.25	Fast
Very Bad	Low	Favourable	Very High	0.75	Very Slow
Bad	Low	Favourable	Very Low	0.25	Very Fast
Bad	Low	Favourable	Very Low	0.50	Fast
Bad	Low	Favourable	Very Low	0.25	Very Slow
Bad	Low	Favourable	Low	0.75	Fast
Bad	Low	Favourable	Low	0.25	Very Slow
Bad	Low	Favourable	Normal	0.50	Fast
Bad	Low	Favourable	Normal	0.25	Medium
Bad	Low	Favourable	Normal	0.25	Very Slow
Bad	Low	Favourable	High	0.50	Fast
Bad	Low	Favourable	High	0.25	Slow
Bad	Low	Favourable	High	0.25	Very Slow
Bad	Low	Favourable	Very High	0.50	Fast
Bad	Low	Favourable	Very High	0.50	Very Slow
Fair	Low	Favourable	Very Low	0.50	Very Fast
Fair	Low	Favourable	Very Low	0.25	Fast
Fair	Low	Favourable	Very Low	0.25	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Low	Favourable	Low	0.25	Very Fast
Fair	Low	Favourable	Low	0.50	Fast
Fair	Low	Favourable	Low	0.25	Very Slow
Fair	Low	Favourable	Normal	0.25	Very Fast
Fair	Low	Favourable	Normal	0.25	Fast
Fair	Low	Favourable	Normal	0.25	Medium
Fair	Low	Favourable	Normal	0.25	Very Slow
Fair	Low	Favourable	High	0.25	Very Fast
Fair	Low	Favourable	High	0.25	Fast
Fair	Low	Favourable	High	0.25	Slow
Fair	Low	Favourable	High	0.25	Very Slow
Fair	Low	Favourable	Very High	0.25	Very Fast
Fair	Low	Favourable	Very High	0.25	Fast
Fair	Low	Favourable	Very High	0.50	Very Slow
Good	Low	Favourable	Very Low	0.25	Very Fast
Good	Low	Favourable	Very Low	0.25	Fast
Good	Low	Favourable	Very Low	0.25	Medium
Good	Low	Favourable	Very Low	0.25	Very Slow
Good	Low	Favourable	Low	0.50	Fast
Good	Low	Favourable	Low	0.25	Medium
Good	Low	Favourable	Low	0.25	Very Slow
Good	Low	Favourable	Normal	0.25	Fast
Good	Low	Favourable	Normal	0.50	Medium
Good	Low	Favourable	Normal	0.25	Very Slow
Good	Low	Favourable	High	0.25	Fast
Good	Low	Favourable	High	0.25	Medium
Good	Low	Favourable	High	0.25	Slow
Good	Low	Favourable	High	0.25	Very Slow
Good	Low	Favourable	Very High	0.25	Fast
Good	Low	Favourable	Very High	0.25	Medium
Good	Low	Favourable	Very High	0.50	Very Slow
Very Good	Low	Favourable	Very Low	0.25	Very Fast
Very Good	Low	Favourable	Very Low	0.25	Fast
Very Good	Low	Favourable	Very Low	0.25	Slow
Very Good	Low	Favourable	Very Low	0.25	Very Slow
Very Good	Low	Favourable	Low	0.50	Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Low	Favourable	Low	0.25	Slow
Very Good	Low	Favourable	Low	0.25	Very Slow
Very Good	Low	Favourable	Normal	0.25	Fast
Very Good	Low	Favourable	Normal	0.25	Medium
Very Good	Low	Favourable	Normal	0.25	Slow
Very Good	Low	Favourable	Normal	0.25	Very Slow
Very Good	Low	Favourable	High	0.25	Fast
Very Good	Low	Favourable	High	0.50	Slow
Very Good	Low	Favourable	High	0.25	Very Slow
Very Good	Low	Favourable	Very High	0.25	Fast
Very Good	Low	Favourable	Very High	0.25	Slow
Very Good	Low	Favourable	Very High	0.50	Very Slow
Very Bad	Medium	Very Aggressive	Very Low	0.50	Very Fast
Very Bad	Medium	Very Aggressive	Very Low	0.25	Medium
Very Bad	Medium	Very Aggressive	Very Low	0.25	Very Slow
Very Bad	Medium	Very Aggressive	Low	0.25	Very Fast
Very Bad	Medium	Very Aggressive	Low	0.25	Fast
Very Bad	Medium	Very Aggressive	Low	0.25	Medium
Very Bad	Medium	Very Aggressive	Low	0.25	Very Slow
Very Bad	Medium	Very Aggressive	Normal	0.25	Very Fast
Very Bad	Medium	Very Aggressive	Normal	0.50	Medium
Very Bad	Medium	Very Aggressive	Normal	0.25	Very Slow
Very Bad	Medium	Very Aggressive	High	0.25	Very Fast
Very Bad	Medium	Very Aggressive	High	0.25	Medium
Very Bad	Medium	Very Aggressive	High	0.25	Slow
Very Bad	Medium	Very Aggressive	High	0.25	Very Slow
Very Bad	Medium	Very Aggressive	Very High	0.25	Very Fast
Very Bad	Medium	Very Aggressive	Very High	0.25	Medium
Very Bad	Medium	Very Aggressive	Very High	0.50	Very Slow
Bad	Medium	Very Aggressive	Very Low	0.50	Very Fast
Bad	Medium	Very Aggressive	Very Low	0.25	Fast
Bad	Medium	Very Aggressive	Very Low	0.25	Medium
Bad	Medium	Very Aggressive	Low	0.25	Very Fast
Bad	Medium	Very Aggressive	Low	0.50	Fast
Bad	Medium	Very Aggressive	Low	0.25	Medium
Bad	Medium	Very Aggressive	Normal	0.25	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Bad	Medium	Very Aggressive	Normal	0.25	Fast
Bad	Medium	Very Aggressive	Normal	0.50	Medium
Bad	Medium	Very Aggressive	High	0.25	Very Fast
Bad	Medium	Very Aggressive	High	0.25	Fast
Bad	Medium	Very Aggressive	High	0.25	Medium
Bad	Medium	Very Aggressive	High	0.25	Slow
Bad	Medium	Very Aggressive	Very High	0.25	Very Fast
Bad	Medium	Very Aggressive	Very High	0.25	Fast
Bad	Medium	Very Aggressive	Very High	0.25	Medium
Bad	Medium	Very Aggressive	Very High	0.25	Very Slow
Fair	Medium	Very Aggressive	Very Low	0.75	Very Fast
Fair	Medium	Very Aggressive	Very Low	0.25	Medium
Fair	Medium	Very Aggressive	Low	0.50	Very Fast
Fair	Medium	Very Aggressive	Low	0.25	Fast
Fair	Medium	Very Aggressive	Low	0.25	Medium
Fair	Medium	Very Aggressive	Normal	0.50	Very Fast
Fair	Medium	Very Aggressive	Normal	0.50	Medium
Fair	Medium	Very Aggressive	High	0.50	Very Fast
Fair	Medium	Very Aggressive	High	0.25	Medium
Fair	Medium	Very Aggressive	High	0.25	Slow
Fair	Medium	Very Aggressive	Very High	0.50	Very Fast
Fair	Medium	Very Aggressive	Very High	0.25	Medium
Fair	Medium	Very Aggressive	Very High	0.25	Very Slow
Good	Medium	Very Aggressive	Very Low	0.50	Very Fast
Good	Medium	Very Aggressive	Very Low	0.50	Medium
Good	Medium	Very Aggressive	Low	0.25	Very Fast
Good	Medium	Very Aggressive	Low	0.25	Fast
Good	Medium	Very Aggressive	Low	0.50	Medium
Good	Medium	Very Aggressive	Normal	0.25	Very Fast
Good	Medium	Very Aggressive	Normal	0.75	Medium
Good	Medium	Very Aggressive	High	0.25	Very Fast
Good	Medium	Very Aggressive	High	0.50	Medium
Good	Medium	Very Aggressive	High	0.25	Slow
Good	Medium	Very Aggressive	Very High	0.25	Very Fast
Good	Medium	Very Aggressive	Very High	0.50	Medium
Good	Medium	Very Aggressive	Very High	0.25	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Medium	Very Aggressive	Very Low	0.50	Very Fast
Very Good	Medium	Very Aggressive	Very Low	0.25	Medium
Very Good	Medium	Very Aggressive	Very Low	0.25	Slow
Very Good	Medium	Very Aggressive	Low	0.25	Very Fast
Very Good	Medium	Very Aggressive	Low	0.25	Fast
Very Good	Medium	Very Aggressive	Low	0.25	Medium
Very Good	Medium	Very Aggressive	Low	0.25	Slow
Very Good	Medium	Very Aggressive	Normal	0.25	Very Fast
Very Good	Medium	Very Aggressive	Normal	0.50	Medium
Very Good	Medium	Very Aggressive	Normal	0.25	Slow
Very Good	Medium	Very Aggressive	High	0.25	Very Fast
Very Good	Medium	Very Aggressive	High	0.25	Medium
Very Good	Medium	Very Aggressive	High	0.50	Slow
Very Good	Medium	Very Aggressive	Very High	0.25	Very Fast
Very Good	Medium	Very Aggressive	Very High	0.25	Medium
Very Good	Medium	Very Aggressive	Very High	0.25	Slow
Very Good	Medium	Very Aggressive	Very High	0.25	Very Slow
Very Bad	Medium	Aggressive	Very Low	0.25	Very Fast
Very Bad	Medium	Aggressive	Very Low	0.25	Fast
Very Bad	Medium	Aggressive	Very Low	0.25	Medium
Very Bad	Medium	Aggressive	Very Low	0.25	Very Slow
Very Bad	Medium	Aggressive	Low	0.50	Fast
Very Bad	Medium	Aggressive	Low	0.25	Medium
Very Bad	Medium	Aggressive	Low	0.25	Very Slow
Very Bad	Medium	Aggressive	Normal	0.25	Fast
Very Bad	Medium	Aggressive	Normal	0.50	Medium
Very Bad	Medium	Aggressive	Normal	0.25	Very Slow
Very Bad	Medium	Aggressive	High	0.25	Fast
Very Bad	Medium	Aggressive	High	0.25	Medium
Very Bad	Medium	Aggressive	High	0.25	Slow
Very Bad	Medium	Aggressive	High	0.25	Very Slow
Very Bad	Medium	Aggressive	Very High	0.25	Fast
Very Bad	Medium	Aggressive	Very High	0.25	Medium
Very Bad	Medium	Aggressive	Very High	0.50	Very Slow
Bad	Medium	Aggressive	Very Low	0.25	Very Fast
Bad	Medium	Aggressive	Very Low	0.50	Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Bad	Medium	Aggressive	Very Low	0.25	Medium
Bad	Medium	Aggressive	Low	0.75	Fast
Bad	Medium	Aggressive	Low	0.25	Medium
Bad	Medium	Aggressive	Normal	0.50	Fast
Bad	Medium	Aggressive	Normal	0.50	Medium
Bad	Medium	Aggressive	High	0.50	Fast
Bad	Medium	Aggressive	High	0.25	Medium
Bad	Medium	Aggressive	High	0.25	Slow
Bad	Medium	Aggressive	Very High	0.50	Fast
Bad	Medium	Aggressive	Very High	0.25	Medium
Bad	Medium	Aggressive	Very High	0.25	Very Slow
Fair	Medium	Aggressive	Very Low	0.50	Very Fast
Fair	Medium	Aggressive	Very Low	0.25	Fast
Fair	Medium	Aggressive	Very Low	0.25	Medium
Fair	Medium	Aggressive	Low	0.25	Very Fast
Fair	Medium	Aggressive	Low	0.50	Fast
Fair	Medium	Aggressive	Low	0.25	Medium
Fair	Medium	Aggressive	Normal	0.25	Very Fast
Fair	Medium	Aggressive	Normal	0.50	Medium
Fair	Medium	Aggressive	Normal	0.25	Fast
Fair	Medium	Aggressive	High	0.25	Very Fast
Fair	Medium	Aggressive	High	0.25	Fast
Fair	Medium	Aggressive	High	0.25	Medium
Fair	Medium	Aggressive	High	0.25	Slow
Fair	Medium	Aggressive	Very High	0.25	Very Fast
Fair	Medium	Aggressive	Very High	0.25	Fast
Fair	Medium	Aggressive	Very High	0.25	Medium
Fair	Medium	Aggressive	Very High	0.25	Very Slow
Good	Medium	Aggressive	Very Low	0.25	Very Fast
Good	Medium	Aggressive	Very Low	0.25	Fast
Good	Medium	Aggressive	Very Low	0.50	Medium
Good	Medium	Aggressive	Low	0.50	Fast
Good	Medium	Aggressive	Low	0.50	Medium
Good	Medium	Aggressive	Normal	0.25	Fast
Good	Medium	Aggressive	Normal	0.75	Medium
Good	Medium	Aggressive	High	0.25	Fast

IF				THEN	
Condition	Durability	Environment	Maintenance Level	DoS	Degradation Rate
Good	Medium	Aggressive	High	0.50	Medium
Good	Medium	Aggressive	High	0.25	Slow
Good	Medium	Aggressive	Very High	0.25	Fast
Good	Medium	Aggressive	Very High	0.50	Medium
Good	Medium	Aggressive	Very High	0.25	Very Slow
Very Good	Medium	Aggressive	Very Low	0.25	Very Fast
Very Good	Medium	Aggressive	Very Low	0.25	Fast
Very Good	Medium	Aggressive	Very Low	0.25	Medium
Very Good	Medium	Aggressive	Very Low	0.25	Slow
Very Good	Medium	Aggressive	Low	0.50	Fast
Very Good	Medium	Aggressive	Low	0.25	Medium
Very Good	Medium	Aggressive	Low	0.25	Slow
Very Good	Medium	Aggressive	Normal	0.25	Fast
Very Good	Medium	Aggressive	Normal	0.50	Medium
Very Good	Medium	Aggressive	Normal	0.25	Slow
Very Good	Medium	Aggressive	High	0.25	Fast
Very Good	Medium	Aggressive	High	0.25	Medium
Very Good	Medium	Aggressive	High	0.50	Slow
Very Good	Medium	Aggressive	Very High	0.25	Fast
Very Good	Medium	Aggressive	Very High	0.25	Medium
Very Good	Medium	Aggressive	Very High	0.25	Slow
Very Good	Medium	Aggressive	Very High	0.25	Very Slow
Very Bad	Medium	Slightly Aggressive	Very Low	0.25	Very Fast
Very Bad	Medium	Slightly Aggressive	Very Low	0.50	Medium
Very Bad	Medium	Slightly Aggressive	Very Low	0.25	Very Slow
Very Bad	Medium	Slightly Aggressive	Low	0.25	Fast
Very Bad	Medium	Slightly Aggressive	Low	0.50	Medium
Very Bad	Medium	Slightly Aggressive	Low	0.25	Very Slow
Very Bad	Medium	Slightly Aggressive	Normal	0.75	Medium
Very Bad	Medium	Slightly Aggressive	Normal	0.25	Very Slow
Very Bad	Medium	Slightly Aggressive	High	0.50	Medium
Very Bad	Medium	Slightly Aggressive	High	0.25	Slow
Very Bad	Medium	Slightly Aggressive	High	0.25	Very Slow
Very Bad	Medium	Slightly Aggressive	Very High	0.50	Medium
Very Bad	Medium	Slightly Aggressive	Very High	0.50	Very Slow
Bad	Medium	Slightly Aggressive	Very Low	0.25	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Bad	Medium	Slightly Aggressive	Very Low	0.25	Fast
Bad	Medium	Slightly Aggressive	Very Low	0.50	Medium
Bad	Medium	Slightly Aggressive	Low	0.50	Medium
Bad	Medium	Slightly Aggressive	Low	0.50	Fast
Bad	Medium	Slightly Aggressive	Normal	0.25	Fast
Bad	Medium	Slightly Aggressive	Normal	0.75	Medium
Bad	Medium	Slightly Aggressive	High	0.25	Fast
Bad	Medium	Slightly Aggressive	High	0.50	Medium
Bad	Medium	Slightly Aggressive	High	0.25	Slow
Bad	Medium	Slightly Aggressive	Very High	0.25	Fast
Bad	Medium	Slightly Aggressive	Very High	0.50	Medium
Bad	Medium	Slightly Aggressive	Very High	0.25	Very Slow
Fair	Medium	Slightly Aggressive	Very Low	0.50	Very Fast
Fair	Medium	Slightly Aggressive	Very Low	0.50	Medium
Fair	Medium	Slightly Aggressive	Low	0.25	Very Fast
Fair	Medium	Slightly Aggressive	Low	0.25	Fast
Fair	Medium	Slightly Aggressive	Low	0.50	Medium
Fair	Medium	Slightly Aggressive	Normal	0.25	Very Fast
Fair	Medium	Slightly Aggressive	Normal	0.75	Medium
Fair	Medium	Slightly Aggressive	High	0.25	Very Fast
Fair	Medium	Slightly Aggressive	High	0.50	Medium
Fair	Medium	Slightly Aggressive	High	0.25	Slow
Fair	Medium	Slightly Aggressive	Very High	0.25	Very Fast
Fair	Medium	Slightly Aggressive	Very High	0.50	Medium
Fair	Medium	Slightly Aggressive	Very High	0.25	Very Slow
Good	Medium	Slightly Aggressive	Very Low	0.25	Very Fast
Good	Medium	Slightly Aggressive	Very Low	0.75	Medium
Good	Medium	Slightly Aggressive	Low	0.25	Fast
Good	Medium	Slightly Aggressive	Low	0.75	Medium
Good	Medium	Slightly Aggressive	Normal	1.00	Medium
Good	Medium	Slightly Aggressive	High	0.75	Medium
Good	Medium	Slightly Aggressive	High	0.25	Slow
Good	Medium	Slightly Aggressive	Very High	0.75	Medium
Good	Medium	Slightly Aggressive	Very High	0.25	Very Slow
Very Good	Medium	Slightly Aggressive	Very Low	0.25	Very Fast
Very Good	Medium	Slightly Aggressive	Very Low	0.50	Medium

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Medium	Slightly Aggressive	Very Low	0.25	Slow
Very Good	Medium	Slightly Aggressive	Low	0.25	Fast
Very Good	Medium	Slightly Aggressive	Low	0.50	Medium
Very Good	Medium	Slightly Aggressive	Low	0.25	Slow
Very Good	Medium	Slightly Aggressive	Normal	0.75	Medium
Very Good	Medium	Slightly Aggressive	Normal	0.25	Slow
Very Good	Medium	Slightly Aggressive	High	0.50	Medium
Very Good	Medium	Slightly Aggressive	High	0.50	Slow
Very Good	Medium	Slightly Aggressive	Very High	0.50	Medium
Very Good	Medium	Slightly Aggressive	Very High	0.25	Slow
Very Good	Medium	Slightly Aggressive	Very High	0.25	Very Slow
Very Bad	Medium	Less Favourable	Very Low	0.25	Very Fast
Very Bad	Medium	Less Favourable	Very Low	0.25	Medium
Very Bad	Medium	Less Favourable	Very Low	0.25	Slow
Very Bad	Medium	Less Favourable	Very Low	0.25	Very Slow
Very Bad	Medium	Less Favourable	Low	0.25	Fast
Very Bad	Medium	Less Favourable	Low	0.25	Medium
Very Bad	Medium	Less Favourable	Low	0.25	Slow
Very Bad	Medium	Less Favourable	Low	0.25	Very Slow
Very Bad	Medium	Less Favourable	Normal	0.50	Medium
Very Bad	Medium	Less Favourable	Normal	0.25	Slow
Very Bad	Medium	Less Favourable	Normal	0.25	Very Slow
Very Bad	Medium	Less Favourable	High	0.25	Medium
Very Bad	Medium	Less Favourable	High	0.50	Slow
Very Bad	Medium	Less Favourable	High	0.25	Very Slow
Very Bad	Medium	Less Favourable	Very High	0.25	Medium
Very Bad	Medium	Less Favourable	Very High	0.25	Slow
Very Bad	Medium	Less Favourable	Very High	0.50	Very Slow
Bad	Medium	Less Favourable	Very Low	0.25	Very Fast
Bad	Medium	Less Favourable	Very Low	0.25	Fast
Bad	Medium	Less Favourable	Very Low	0.25	Medium
Bad	Medium	Less Favourable	Very Low	0.25	Slow
Bad	Medium	Less Favourable	Low	0.50	Fast
Bad	Medium	Less Favourable	Low	0.25	Medium
Bad	Medium	Less Favourable	Low	0.25	Slow
Bad	Medium	Less Favourable	Normal	0.25	Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Bad	Medium	Less Favourable	Normal	0.50	Medium
Bad	Medium	Less Favourable	Normal	0.25	Slow
Bad	Medium	Less Favourable	High	0.25	Fast
Bad	Medium	Less Favourable	High	0.25	Medium
Bad	Medium	Less Favourable	High	0.50	Slow
Bad	Medium	Less Favourable	Very High	0.25	Fast
Bad	Medium	Less Favourable	Very High	0.25	Medium
Bad	Medium	Less Favourable	Very High	0.25	Slow
Bad	Medium	Less Favourable	Very High	0.25	Very Slow
Fair	Medium	Less Favourable	Very Low	0.50	Very Fast
Fair	Medium	Less Favourable	Very Low	0.25	Medium
Fair	Medium	Less Favourable	Very Low	0.25	Slow
Fair	Medium	Less Favourable	Low	0.25	Very Fast
Fair	Medium	Less Favourable	Low	0.25	Fast
Fair	Medium	Less Favourable	Low	0.25	Medium
Fair	Medium	Less Favourable	Low	0.25	Slow
Fair	Medium	Less Favourable	Normal	0.25	Very Fast
Fair	Medium	Less Favourable	Normal	0.50	Medium
Fair	Medium	Less Favourable	Normal	0.25	Slow
Fair	Medium	Less Favourable	High	0.25	Very Fast
Fair	Medium	Less Favourable	High	0.25	Medium
Fair	Medium	Less Favourable	High	0.50	Slow
Fair	Medium	Less Favourable	Very High	0.25	Very Fast
Fair	Medium	Less Favourable	Very High	0.25	Medium
Fair	Medium	Less Favourable	Very High	0.25	Slow
Fair	Medium	Less Favourable	Very High	0.25	Very Slow
Good	Medium	Less Favourable	Very Low	0.25	Very Fast
Good	Medium	Less Favourable	Very Low	0.50	Medium
Good	Medium	Less Favourable	Very Low	0.25	Slow
Good	Medium	Less Favourable	Low	0.25	Fast
Good	Medium	Less Favourable	Low	0.50	Medium
Good	Medium	Less Favourable	Low	0.25	Slow
Good	Medium	Less Favourable	Normal	0.75	Medium
Good	Medium	Less Favourable	Normal	0.25	Slow
Good	Medium	Less Favourable	High	0.50	Medium
Good	Medium	Less Favourable	High	0.50	Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Good	Medium	Less Favourable	Very High	0.50	Medium
Good	Medium	Less Favourable	Very High	0.25	Slow
Good	Medium	Less Favourable	Very High	0.25	Very Slow
Very Good	Medium	Less Favourable	Very Low	0.25	Very Fast
Very Good	Medium	Less Favourable	Very Low	0.25	Medium
Very Good	Medium	Less Favourable	Very Low	0.50	Slow
Very Good	Medium	Less Favourable	Low	0.25	Fast
Very Good	Medium	Less Favourable	Low	0.25	Medium
Very Good	Medium	Less Favourable	Low	0.50	Slow
Very Good	Medium	Less Favourable	Normal	0.50	Medium
Very Good	Medium	Less Favourable	Normal	0.50	Slow
Very Good	Medium	Less Favourable	High	0.25	Medium
Very Good	Medium	Less Favourable	High	0.75	Slow
Very Good	Medium	Less Favourable	Very High	0.25	Medium
Very Good	Medium	Less Favourable	Very High	0.50	Slow
Very Good	Medium	Less Favourable	Very High	0.25	Very Slow
Very Bad	Medium	Favourable	Very Low	0.25	Very Fast
Very Bad	Medium	Favourable	Very Low	0.25	Medium
Very Bad	Medium	Favourable	Very Low	0.50	Very Slow
Very Bad	Medium	Favourable	Low	0.25	Fast
Very Bad	Medium	Favourable	Low	0.25	Medium
Very Bad	Medium	Favourable	Low	0.50	Very Slow
Very Bad	Medium	Favourable	Normal	0.50	Medium
Very Bad	Medium	Favourable	Normal	0.50	Very Slow
Very Bad	Medium	Favourable	High	0.25	Medium
Very Bad	Medium	Favourable	High	0.25	Slow
Very Bad	Medium	Favourable	High	0.50	Very Slow
Very Bad	Medium	Favourable	Very High	0.25	Medium
Very Bad	Medium	Favourable	Very High	0.75	Very Slow
Bad	Medium	Favourable	Very Low	0.25	Very Fast
Bad	Medium	Favourable	Very Low	0.25	Fast
Bad	Medium	Favourable	Very Low	0.25	Medium
Bad	Medium	Favourable	Very Low	0.25	Very Slow
Bad	Medium	Favourable	Low	0.50	Fast
Bad	Medium	Favourable	Low	0.25	Medium
Bad	Medium	Favourable	Low	0.25	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Bad	Medium	Favourable	Normal	0.25	Fast
Bad	Medium	Favourable	Normal	0.50	Medium
Bad	Medium	Favourable	Normal	0.25	Very Slow
Bad	Medium	Favourable	High	0.25	Fast
Bad	Medium	Favourable	High	0.25	Medium
Bad	Medium	Favourable	High	0.25	Slow
Bad	Medium	Favourable	High	0.25	Very Slow
Bad	Medium	Favourable	Very High	0.25	Fast
Bad	Medium	Favourable	Very High	0.25	Medium
Bad	Medium	Favourable	Very High	0.50	Very Slow
Fair	Medium	Favourable	Very Low	0.50	Very Fast
Fair	Medium	Favourable	Very Low	0.25	Medium
Fair	Medium	Favourable	Very Low	0.25	Very Slow
Fair	Medium	Favourable	Low	0.25	Very Fast
Fair	Medium	Favourable	Low	0.25	Fast
Fair	Medium	Favourable	Low	0.25	Medium
Fair	Medium	Favourable	Low	0.25	Very Slow
Fair	Medium	Favourable	Normal	0.25	Very Fast
Fair	Medium	Favourable	Normal	0.50	Medium
Fair	Medium	Favourable	Normal	0.25	Very Slow
Fair	Medium	Favourable	High	0.25	Very Fast
Fair	Medium	Favourable	High	0.25	Medium
Fair	Medium	Favourable	High	0.25	Slow
Fair	Medium	Favourable	High	0.25	Very Slow
Fair	Medium	Favourable	Very High	0.25	Very Fast
Fair	Medium	Favourable	Very High	0.25	Medium
Fair	Medium	Favourable	Very High	0.50	Very Slow
Good	Medium	Favourable	Very Low	0.25	Very Fast
Good	Medium	Favourable	Very Low	0.50	Medium
Good	Medium	Favourable	Very Low	0.25	Very Slow
Good	Medium	Favourable	Low	0.25	Fast
Good	Medium	Favourable	Low	0.50	Medium
Good	Medium	Favourable	Low	0.25	Very Slow
Good	Medium	Favourable	Normal	0.75	Medium
Good	Medium	Favourable	Normal	0.25	Very Slow
Good	Medium	Favourable	High	0.50	Medium

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Good	Medium	Favourable	High	0.25	Slow
Good	Medium	Favourable	High	0.25	Very Slow
Good	Medium	Favourable	Very High	0.50	Medium
Good	Medium	Favourable	Very High	0.50	Very Slow
Very Good	Medium	Favourable	Very Low	0.25	Very Fast
Very Good	Medium	Favourable	Very Low	0.25	Medium
Very Good	Medium	Favourable	Very Low	0.25	Slow
Very Good	Medium	Favourable	Very Low	0.25	Very Slow
Very Good	Medium	Favourable	Low	0.25	Fast
Very Good	Medium	Favourable	Low	0.25	Medium
Very Good	Medium	Favourable	Low	0.25	Slow
Very Good	Medium	Favourable	Low	0.25	Very Slow
Very Good	Medium	Favourable	Normal	0.50	Medium
Very Good	Medium	Favourable	Normal	0.25	Slow
Very Good	Medium	Favourable	Normal	0.25	Very Slow
Very Good	Medium	Favourable	High	0.25	Medium
Very Good	Medium	Favourable	High	0.50	Slow
Very Good	Medium	Favourable	High	0.25	Very Slow
Very Good	Medium	Favourable	Very High	0.25	Medium
Very Good	Medium	Favourable	Very High	0.25	Slow
Very Good	Medium	Favourable	Very High	0.50	Very Slow
Very Bad	High	Very Aggressive	Very Low	0.50	Very Fast
Very Bad	High	Very Aggressive	Very Low	0.25	Very Slow
Very Bad	High	Very Aggressive	Very Low	0.25	Slow
Very Bad	High	Very Aggressive	Low	0.25	Very Fast
Very Bad	High	Very Aggressive	Low	0.25	Fast
Very Bad	High	Very Aggressive	Low	0.25	Slow
Very Bad	High	Very Aggressive	Low	0.25	Very Slow
Very Bad	High	Very Aggressive	Normal	0.25	Very Fast
Very Bad	High	Very Aggressive	Normal	0.25	Medium
Very Bad	High	Very Aggressive	Normal	0.25	Slow
Very Bad	High	Very Aggressive	Normal	0.25	Very Slow
Very Bad	High	Very Aggressive	High	0.25	Very Fast
Very Bad	High	Very Aggressive	High	0.50	Slow
Very Bad	High	Very Aggressive	High	0.25	Very Slow
Very Bad	High	Very Aggressive	Very High	0.25	Very Fast

IF				**THEN**	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	High	Very Aggressive	Very High	0.25	Slow
Very Bad	High	Very Aggressive	Very High	0.50	Very Slow
Bad	High	Very Aggressive	Very Low	0.50	Very Fast
Bad	High	Very Aggressive	Very Low	0.25	Fast
Bad	High	Very Aggressive	Very Low	0.25	Slow
Bad	High	Very Aggressive	Low	0.25	Very Fast
Bad	High	Very Aggressive	Low	0.50	Fast
Bad	High	Very Aggressive	Low	0.25	Slow
Bad	High	Very Aggressive	Normal	0.25	Very Fast
Bad	High	Very Aggressive	Normal	0.25	Fast
Bad	High	Very Aggressive	Normal	0.25	Medium
Bad	High	Very Aggressive	Normal	0.25	Slow
Bad	High	Very Aggressive	High	0.25	Very Fast
Bad	High	Very Aggressive	High	0.25	Fast
Bad	High	Very Aggressive	High	0.50	Slow
Bad	High	Very Aggressive	Very High	0.25	Very Fast
Bad	High	Very Aggressive	Very High	0.25	Fast
Bad	High	Very Aggressive	Very High	0.25	Slow
Bad	High	Very Aggressive	Very High	0.25	Very Slow
Fair	High	Very Aggressive	Very Low	0.75	Very Fast
Fair	High	Very Aggressive	Very Low	0.25	Slow
Fair	High	Very Aggressive	Low	0.50	Very Fast
Fair	High	Very Aggressive	Low	0.25	Fast
Fair	High	Very Aggressive	Low	0.25	Slow
Fair	High	Very Aggressive	Normal	0.50	Very Fast
Fair	High	Very Aggressive	Normal	0.25	Medium
Fair	High	Very Aggressive	Normal	0.25	Slow
Fair	High	Very Aggressive	High	0.50	Very Fast
Fair	High	Very Aggressive	High	0.50	Slow
Fair	High	Very Aggressive	Very High	0.50	Very Fast
Fair	High	Very Aggressive	Very High	0.25	Slow
Fair	High	Very Aggressive	Very High	0.25	Very Slow
Good	High	Very Aggressive	Very Low	0.50	Very Fast
Good	High	Very Aggressive	Very Low	0.25	Medium
Good	High	Very Aggressive	Very Low	0.25	Slow
Good	High	Very Aggressive	Low	0.25	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Good	High	Very Aggressive	Low	0.25	Fast
Good	High	Very Aggressive	Low	0.25	Medium
Good	High	Very Aggressive	Low	0.25	Slow
Good	High	Very Aggressive	Normal	0.25	Very Fast
Good	High	Very Aggressive	Normal	0.50	Medium
Good	High	Very Aggressive	Normal	0.25	Slow
Good	High	Very Aggressive	High	0.25	Very Fast
Good	High	Very Aggressive	High	0.25	Medium
Good	High	Very Aggressive	High	0.50	Slow
Good	High	Very Aggressive	Very High	0.25	Very Fast
Good	High	Very Aggressive	Very High	0.25	Medium
Good	High	Very Aggressive	Very High	0.25	Slow
Good	High	Very Aggressive	Very High	0.25	Very Slow
Very Good	High	Very Aggressive	Very Low	0.50	Very Fast
Very Good	High	Very Aggressive	Very Low	0.50	Slow
Very Good	High	Very Aggressive	Low	0.25	Very Fast
Very Good	High	Very Aggressive	Low	0.25	Fast
Very Good	High	Very Aggressive	Low	0.50	Slow
Very Good	High	Very Aggressive	Normal	0.25	Very Fast
Very Good	High	Very Aggressive	Normal	0.25	Medium
Very Good	High	Very Aggressive	Normal	0.50	Slow
Very Good	High	Very Aggressive	High	0.25	Very Fast
Very Good	High	Very Aggressive	High	0.75	Slow
Very Good	High	Very Aggressive	Very High	0.25	Very Fast
Very Good	High	Very Aggressive	Very High	0.50	Slow
Very Good	High	Very Aggressive	Very High	0.25	Very Slow
Very Bad	High	Aggressive	Very Low	0.25	Very Fast
Very Bad	High	Aggressive	Very Low	0.25	Fast
Very Bad	High	Aggressive	Very Low	0.25	Slow
Very Bad	High	Aggressive	Very Low	0.25	Very Slow
Very Bad	High	Aggressive	Low	0.50	Fast
Very Bad	High	Aggressive	Low	0.25	Slow
Very Bad	High	Aggressive	Low	0.25	Very Slow
Very Bad	High	Aggressive	Normal	0.25	Fast
Very Bad	High	Aggressive	Normal	0.25	Medium
Very Bad	High	Aggressive	Normal	0.25	Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	High	Aggressive	Normal	0.25	Very Slow
Very Bad	High	Aggressive	High	0.25	Fast
Very Bad	High	Aggressive	High	0.50	Slow
Very Bad	High	Aggressive	High	0.25	Very Slow
Very Bad	High	Aggressive	Very High	0.25	Fast
Very Bad	High	Aggressive	Very High	0.25	Slow
Very Bad	High	Aggressive	Very High	0.50	Very Slow
Bad	High	Aggressive	Very Low	0.25	Very Fast
Bad	High	Aggressive	Very Low	0.50	Fast
Bad	High	Aggressive	Very Low	0.25	Slow
Bad	High	Aggressive	Low	0.75	Fast
Bad	High	Aggressive	Low	0.25	Slow
Bad	High	Aggressive	Normal	0.50	Fast
Bad	High	Aggressive	Normal	0.25	Medium
Bad	High	Aggressive	Normal	0.25	Slow
Bad	High	Aggressive	High	0.50	Fast
Bad	High	Aggressive	High	0.50	Slow
Bad	High	Aggressive	Very High	0.50	Fast
Bad	High	Aggressive	Very High	0.25	Slow
Bad	High	Aggressive	Very High	0.25	Very Slow
Fair	High	Aggressive	Very Low	0.50	Very Fast
Fair	High	Aggressive	Very Low	0.25	Fast
Fair	High	Aggressive	Very Low	0.25	Slow
Fair	High	Aggressive	Low	0.25	Very Fast
Fair	High	Aggressive	Low	0.50	Fast
Fair	High	Aggressive	Low	0.25	Slow
Fair	High	Aggressive	Normal	0.25	Very Fast
Fair	High	Aggressive	Normal	0.25	Fast
Fair	High	Aggressive	Normal	0.25	Medium
Fair	High	Aggressive	Normal	0.25	Slow
Fair	High	Aggressive	High	0.25	Very Fast
Fair	High	Aggressive	High	0.25	Fast
Fair	High	Aggressive	High	0.50	Slow
Fair	High	Aggressive	Very High	0.25	Very Fast
Fair	High	Aggressive	Very High	0.25	Fast
Fair	High	Aggressive	Very High	0.25	Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	High	Aggressive	Very High	0.25	Very Slow
Good	High	Aggressive	Very Low	0.25	Very Fast
Good	High	Aggressive	Very Low	0.25	Fast
Good	High	Aggressive	Very Low	0.25	Medium
Good	High	Aggressive	Very Low	0.25	Slow
Good	High	Aggressive	Low	0.50	Fast
Good	High	Aggressive	Low	0.25	Medium
Good	High	Aggressive	Low	0.25	Slow
Good	High	Aggressive	Normal	0.25	Fast
Good	High	Aggressive	Normal	0.50	Medium
Good	High	Aggressive	Normal	0.25	Slow
Good	High	Aggressive	High	0.25	Fast
Good	High	Aggressive	High	0.25	Medium
Good	High	Aggressive	High	0.50	Slow
Good	High	Aggressive	Very High	0.25	Fast
Good	High	Aggressive	Very High	0.25	Medium
Good	High	Aggressive	Very High	0.25	Slow
Good	High	Aggressive	Very High	0.25	Very Slow
Very Good	High	Aggressive	Very Low	0.25	Very Fast
Very Good	High	Aggressive	Very Low	0.25	Fast
Very Good	High	Aggressive	Very Low	0.50	Slow
Very Good	High	Aggressive	Low	0.50	Fast
Very Good	High	Aggressive	Low	0.50	Slow
Very Good	High	Aggressive	Normal	0.25	Fast
Very Good	High	Aggressive	Normal	0.25	Medium
Very Good	High	Aggressive	Normal	0.50	Slow
Very Good	High	Aggressive	High	0.25	Fast
Very Good	High	Aggressive	High	0.75	Slow
Very Good	High	Aggressive	Very High	0.25	Fast
Very Good	High	Aggressive	Very High	0.50	Slow
Very Good	High	Aggressive	Very High	0.25	Very Slow
Very Bad	High	Slightly Aggressive	Very Low	0.25	Very Fast
Very Bad	High	Slightly Aggressive	Very Low	0.25	Medium
Very Bad	High	Slightly Aggressive	Very Low	0.25	Slow
Very Bad	High	Slightly Aggressive	Very Low	0.25	Very Slow
Very Bad	High	Slightly Aggressive	Low	0.25	Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	High	Slightly Aggressive	Low	0.25	Medium
Very Bad	High	Slightly Aggressive	Low	0.25	Slow
Very Bad	High	Slightly Aggressive	Low	0.25	Very Slow
Very Bad	High	Slightly Aggressive	Normal	0.50	Medium
Very Bad	High	Slightly Aggressive	Normal	0.25	Slow
Very Bad	High	Slightly Aggressive	Normal	0.25	Very Slow
Very Bad	High	Slightly Aggressive	High	0.25	Medium
Very Bad	High	Slightly Aggressive	High	0.50	Slow
Very Bad	High	Slightly Aggressive	High	0.25	Very Slow
Very Bad	High	Slightly Aggressive	Very High	0.25	Medium
Very Bad	High	Slightly Aggressive	Very High	0.25	Slow
Very Bad	High	Slightly Aggressive	Very High	0.50	Very Slow
Bad	High	Slightly Aggressive	Very Low	0.25	Very Fast
Bad	High	Slightly Aggressive	Very Low	0.25	Fast
Bad	High	Slightly Aggressive	Very Low	0.25	Medium
Bad	High	Slightly Aggressive	Very Low	0.25	Slow
Bad	High	Slightly Aggressive	Low	0.50	Fast
Bad	High	Slightly Aggressive	Low	0.25	Medium
Bad	High	Slightly Aggressive	Low	0.25	Slow
Bad	High	Slightly Aggressive	Normal	0.25	Fast
Bad	High	Slightly Aggressive	Normal	0.50	Medium
Bad	High	Slightly Aggressive	Normal	0.25	Slow
Bad	High	Slightly Aggressive	High	0.25	Fast
Bad	High	Slightly Aggressive	High	0.25	Medium
Bad	High	Slightly Aggressive	High	0.50	Slow
Bad	High	Slightly Aggressive	Very High	0.25	Fast
Bad	High	Slightly Aggressive	Very High	0.25	Medium
Bad	High	Slightly Aggressive	Very High	0.25	Slow
Bad	High	Slightly Aggressive	Very High	0.25	Very Slow
Fair	High	Slightly Aggressive	Very Low	0.50	Very Fast
Fair	High	Slightly Aggressive	Very Low	0.25	Medium
Fair	High	Slightly Aggressive	Very Low	0.25	Slow
Fair	High	Slightly Aggressive	Low	0.25	Very Fast
Fair	High	Slightly Aggressive	Low	0.25	Fast
Fair	High	Slightly Aggressive	Low	0.25	Medium
Fair	High	Slightly Aggressive	Low	0.25	Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	High	Slightly Aggressive	Normal	0.25	Very Fast
Fair	High	Slightly Aggressive	Normal	0.50	Medium
Fair	High	Slightly Aggressive	Normal	0.25	Slow
Fair	High	Slightly Aggressive	High	0.25	Very Fast
Fair	High	Slightly Aggressive	High	0.25	Medium
Fair	High	Slightly Aggressive	High	0.50	Slow
Fair	High	Slightly Aggressive	Very High	0.25	Very Fast
Fair	High	Slightly Aggressive	Very High	0.25	Medium
Fair	High	Slightly Aggressive	Very High	0.25	Slow
Fair	High	Slightly Aggressive	Very High	0.25	Very Slow
Good	High	Slightly Aggressive	Very Low	0.25	Very Fast
Good	High	Slightly Aggressive	Very Low	0.50	Medium
Good	High	Slightly Aggressive	Very Low	0.25	Slow
Good	High	Slightly Aggressive	Low	0.25	Fast
Good	High	Slightly Aggressive	Low	0.50	Medium
Good	High	Slightly Aggressive	Low	0.25	Slow
Good	High	Slightly Aggressive	Normal	0.75	Medium
Good	High	Slightly Aggressive	Normal	0.25	Slow
Good	High	Slightly Aggressive	High	0.50	Medium
Good	High	Slightly Aggressive	High	0.50	Slow
Good	High	Slightly Aggressive	Very High	0.50	Medium
Good	High	Slightly Aggressive	Very High	0.25	Slow
Good	High	Slightly Aggressive	Very High	0.25	Very Slow
Very Good	High	Slightly Aggressive	Very Low	0.25	Very Fast
Very Good	High	Slightly Aggressive	Very Low	0.25	Medium
Very Good	High	Slightly Aggressive	Very Low	0.50	Slow
Very Good	High	Slightly Aggressive	Low	0.25	Fast
Very Good	High	Slightly Aggressive	Low	0.25	Medium
Very Good	High	Slightly Aggressive	Low	0.50	Slow
Very Good	High	Slightly Aggressive	Normal	0.50	Medium
Very Good	High	Slightly Aggressive	Normal	0.50	Slow
Very Good	High	Slightly Aggressive	High	0.25	Medium
Very Good	High	Slightly Aggressive	High	0.75	Slow
Very Good	High	Slightly Aggressive	Very High	0.25	Medium
Very Good	High	Slightly Aggressive	Very High	0.50	Slow
Very Good	High	Slightly Aggressive	Very High	0.25	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	High	Less Favourable	Very Low	0.25	Very Fast
Very Bad	High	Less Favourable	Very Low	0.50	Slow
Very Bad	High	Less Favourable	Very Low	0.25	Very Slow
Very Bad	High	Less Favourable	Low	0.25	Fast
Very Bad	High	Less Favourable	Low	0.50	Slow
Very Bad	High	Less Favourable	Low	0.25	Very Slow
Very Bad	High	Less Favourable	Normal	0.25	Medium
Very Bad	High	Less Favourable	Normal	0.50	Slow
Very Bad	High	Less Favourable	Normal	0.25	Very Slow
Very Bad	High	Less Favourable	High	0.75	Slow
Very Bad	High	Less Favourable	High	0.25	Very Slow
Very Bad	High	Less Favourable	Very High	0.50	Slow
Very Bad	High	Less Favourable	Very High	0.50	Very Slow
Bad	High	Less Favourable	Very Low	0.25	Very Fast
Bad	High	Less Favourable	Very Low	0.25	Fast
Bad	High	Less Favourable	Very Low	0.50	Slow
Bad	High	Less Favourable	Low	0.50	Fast
Bad	High	Less Favourable	Low	0.50	Slow
Bad	High	Less Favourable	Normal	0.25	Fast
Bad	High	Less Favourable	Normal	0.25	Medium
Bad	High	Less Favourable	Normal	0.50	Slow
Bad	High	Less Favourable	High	0.25	Fast
Bad	High	Less Favourable	High	0.75	Slow
Bad	High	Less Favourable	Very High	0.25	Fast
Bad	High	Less Favourable	Very High	0.50	Slow
Bad	High	Less Favourable	Very High	0.25	Very Slow
Fair	High	Less Favourable	Very Low	0.50	Very Fast
Fair	High	Less Favourable	Very Low	0.50	Slow
Fair	High	Less Favourable	Low	0.25	Very Fast
Fair	High	Less Favourable	Low	0.25	Fast
Fair	High	Less Favourable	Low	0.50	Slow
Fair	High	Less Favourable	Normal	0.25	Very Fast
Fair	High	Less Favourable	Normal	0.25	Medium
Fair	High	Less Favourable	Normal	0.50	Slow
Fair	High	Less Favourable	High	0.25	Very Fast
Fair	High	Less Favourable	High	0.75	Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	High	Less Favourable	Very High	0.25	Very Fast
Fair	High	Less Favourable	Very High	0.50	Slow
Fair	High	Less Favourable	Very High	0.25	Very Slow
Good	High	Less Favourable	Very Low	0.25	Very Fast
Good	High	Less Favourable	Very Low	0.25	Medium
Good	High	Less Favourable	Very Low	0.50	Slow
Good	High	Less Favourable	Low	0.25	Fast
Good	High	Less Favourable	Low	0.25	Medium
Good	High	Less Favourable	Low	0.50	Slow
Good	High	Less Favourable	Normal	0.50	Medium
Good	High	Less Favourable	Normal	0.50	Slow
Good	High	Less Favourable	High	0.25	Medium
Good	High	Less Favourable	High	0.75	Slow
Good	High	Less Favourable	Very High	0.25	Medium
Good	High	Less Favourable	Very High	0.50	Slow
Good	High	Less Favourable	Very High	0.25	Very Slow
Very Good	High	Less Favourable	Very Low	0.25	Very Fast
Very Good	High	Less Favourable	Very Low	0.75	Slow
Very Good	High	Less Favourable	Low	0.25	Fast
Very Good	High	Less Favourable	Low	0.75	Slow
Very Good	High	Less Favourable	Normal	0.25	Medium
Very Good	High	Less Favourable	Normal	0.75	Slow
Very Good	High	Less Favourable	High	1.00	Slow
Very Good	High	Less Favourable	Very High	0.75	Slow
Very Good	High	Less Favourable	Very High	0.25	Very Slow
Very Bad	High	Favourable	Very Low	0.25	Very Fast
Very Bad	High	Favourable	Very Low	0.25	Slow
Very Bad	High	Favourable	Very Low	0.50	Very Slow
Very Bad	High	Favourable	Low	0.25	Fast
Very Bad	High	Favourable	Low	0.25	Slow
Very Bad	High	Favourable	Low	0.50	Very Slow
Very Bad	High	Favourable	Normal	0.25	Medium
Very Bad	High	Favourable	Normal	0.25	Slow
Very Bad	High	Favourable	Normal	0.50	Very Slow
Very Bad	High	Favourable	High	0.50	Slow
Very Bad	High	Favourable	High	0.50	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Bad	High	Favourable	Very High	0.25	Slow
Very Bad	High	Favourable	Very High	0.75	Very Slow
Bad	High	Favourable	Very Low	0.25	Very Fast
Bad	High	Favourable	Very Low	0.25	Fast
Bad	High	Favourable	Very Low	0.25	Slow
Bad	High	Favourable	Very Low	0.25	Very Slow
Bad	High	Favourable	Low	0.50	Fast
Bad	High	Favourable	Low	0.25	Slow
Bad	High	Favourable	Low	0.25	Very Slow
Bad	High	Favourable	Normal	0.25	Fast
Bad	High	Favourable	Normal	0.25	Medium
Bad	High	Favourable	Normal	0.25	Slow
Bad	High	Favourable	Normal	0.25	Very Slow
Bad	High	Favourable	High	0.25	Fast
Bad	High	Favourable	High	0.50	Slow
Bad	High	Favourable	High	0.25	Very Slow
Bad	High	Favourable	Very High	0.25	Fast
Bad	High	Favourable	Very High	0.25	Slow
Bad	High	Favourable	Very High	0.50	Very Slow
Fair	High	Favourable	Very Low	0.50	Very Fast
Fair	High	Favourable	Very Low	0.25	Slow
Fair	High	Favourable	Very Low	0.25	Very Slow
Fair	High	Favourable	Low	0.25	Very Fast
Fair	High	Favourable	Low	0.25	Fast
Fair	High	Favourable	Low	0.25	Slow
Fair	High	Favourable	Low	0.25	Very Slow
Fair	High	Favourable	Normal	0.25	Very Fast
Fair	High	Favourable	Normal	0.25	Medium
Fair	High	Favourable	Normal	0.25	Slow
Fair	High	Favourable	Normal	0.25	Very Slow
Fair	High	Favourable	High	0.25	Very Fast
Fair	High	Favourable	High	0.50	Slow
Fair	High	Favourable	High	0.25	Very Slow
Fair	High	Favourable	Very High	0.25	Very Fast
Fair	High	Favourable	Very High	0.25	Slow
Fair	High	Favourable	Very High	0.50	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Good	High	Favourable	Very Low	0.25	Very Fast
Good	High	Favourable	Very Low	0.25	Medium
Good	High	Favourable	Very Low	0.25	Slow
Good	High	Favourable	Very Low	0.25	Very Slow
Good	High	Favourable	Low	0.25	Fast
Good	High	Favourable	Low	0.25	Medium
Good	High	Favourable	Low	0.25	Slow
Good	High	Favourable	Low	0.25	Very Slow
Good	High	Favourable	Normal	0.50	Medium
Good	High	Favourable	Normal	0.25	Slow
Good	High	Favourable	Normal	0.25	Very Slow
Good	High	Favourable	High	0.25	Medium
Good	High	Favourable	High	0.50	Slow
Good	High	Favourable	High	0.25	Very Slow
Good	High	Favourable	Very High	0.25	Medium
Good	High	Favourable	Very High	0.25	Slow
Good	High	Favourable	Very High	0.50	Very Slow
Very Good	High	Favourable	Very Low	0.25	Very Fast
Very Good	High	Favourable	Very Low	0.50	Slow
Very Good	High	Favourable	Very Low	0.25	Very Slow
Very Good	High	Favourable	Low	0.25	Fast
Very Good	High	Favourable	Low	0.50	Slow
Very Good	High	Favourable	Low	0.25	Very Slow
Very Good	High	Favourable	Normal	0.25	Medium
Very Good	High	Favourable	Normal	0.50	Slow
Very Good	High	Favourable	Normal	0.25	Very Slow
Very Good	High	Favourable	High	0.75	Slow
Very Good	High	Favourable	High	0.25	Very Slow
Very Good	High	Favourable	Very High	0.50	Slow
Very Good	High	Favourable	Very High	0.50	Very Slow
Very Bad	Very High	Very Aggressive	Very Low	0.50	Very Fast
Very Bad	Very High	Very Aggressive	Very Low	0.50	Very Slow
Very Bad	Very High	Very Aggressive	Low	0.25	Very Fast
Very Bad	Very High	Very Aggressive	Low	0.25	Fast
Very Bad	Very High	Very Aggressive	Low	0.50	Very Slow
Very Bad	Very High	Very Aggressive	Normal	0.25	Very Fast

IF				THEN	
Condition	Durability	Environment	Maintenance Level	DoS	Degradation Rate
Very Bad	Very High	Very Aggressive	Normal	0.25	Medium
Very Bad	Very High	Very Aggressive	Normal	0.50	Very Slow
Very Bad	Very High	Very Aggressive	High	0.25	Very Fast
Very Bad	Very High	Very Aggressive	High	0.25	Slow
Very Bad	Very High	Very Aggressive	High	0.50	Very Slow
Very Bad	Very High	Very Aggressive	Very High	0.25	Very Fast
Very Bad	Very High	Very Aggressive	Very High	0.75	Very Slow
Bad	Very High	Very Aggressive	Very Low	0.50	Very Fast
Bad	Very High	Very Aggressive	Very Low	0.25	Fast
Bad	Very High	Very Aggressive	Very Low	0.25	Very Slow
Bad	Very High	Very Aggressive	Low	0.25	Very Fast
Bad	Very High	Very Aggressive	Low	0.50	Fast
Bad	Very High	Very Aggressive	Low	0.25	Very Slow
Bad	Very High	Very Aggressive	Normal	0.25	Very Fast
Bad	Very High	Very Aggressive	Normal	0.25	Fast
Bad	Very High	Very Aggressive	Normal	0.25	Medium
Bad	Very High	Very Aggressive	Normal	0.25	Very Slow
Bad	Very High	Very Aggressive	High	0.25	Very Fast
Bad	Very High	Very Aggressive	High	0.25	Fast
Bad	Very High	Very Aggressive	High	0.25	Slow
Bad	Very High	Very Aggressive	High	0.25	Very Slow
Bad	Very High	Very Aggressive	Very High	0.25	Very Fast
Bad	Very High	Very Aggressive	Very High	0.25	Fast
Bad	Very High	Very Aggressive	Very High	0.50	Very Slow
Fair	Very High	Very Aggressive	Very Low	0.75	Very Fast
Fair	Very High	Very Aggressive	Very Low	0.25	Very Slow
Fair	Very High	Very Aggressive	Low	0.50	Very Fast
Fair	Very High	Very Aggressive	Low	0.25	Fast
Fair	Very High	Very Aggressive	Low	0.25	Very Slow
Fair	Very High	Very Aggressive	Normal	0.50	Very Fast
Fair	Very High	Very Aggressive	Normal	0.25	Medium
Fair	Very High	Very Aggressive	Normal	0.25	Very Slow
Fair	Very High	Very Aggressive	High	0.50	Very Fast
Fair	Very High	Very Aggressive	High	0.25	Slow
Fair	Very High	Very Aggressive	High	0.25	Very Slow
Fair	Very High	Very Aggressive	Very High	0.50	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Very High	Very Aggressive	Very High	0.50	Very Slow
Good	Very High	Very Aggressive	Very Low	0.50	Very Fast
Good	Very High	Very Aggressive	Very Low	0.25	Medium
Good	Very High	Very Aggressive	Very Low	0.25	Very Slow
Good	Very High	Very Aggressive	Low	0.25	Very Fast
Good	Very High	Very Aggressive	Low	0.25	Fast
Good	Very High	Very Aggressive	Low	0.25	Medium
Good	Very High	Very Aggressive	Low	0.25	Very Slow
Good	Very High	Very Aggressive	Normal	0.25	Very Fast
Good	Very High	Very Aggressive	Normal	0.50	Medium
Good	Very High	Very Aggressive	Normal	0.25	Very Slow
Good	Very High	Very Aggressive	High	0.25	Very Fast
Good	Very High	Very Aggressive	High	0.25	Medium
Good	Very High	Very Aggressive	High	0.25	Slow
Good	Very High	Very Aggressive	High	0.25	Very Slow
Good	Very High	Very Aggressive	Very High	0.25	Very Fast
Good	Very High	Very Aggressive	Very High	0.25	Medium
Good	Very High	Very Aggressive	Very High	0.50	Very Slow
Very Good	Very High	Very Aggressive	Very Low	0.50	Very Fast
Very Good	Very High	Very Aggressive	Very Low	0.25	Slow
Very Good	Very High	Very Aggressive	Very Low	0.25	Very Slow
Very Good	Very High	Very Aggressive	Low	0.25	Very Fast
Very Good	Very High	Very Aggressive	Low	0.25	Fast
Very Good	Very High	Very Aggressive	Low	0.25	Slow
Very Good	Very High	Very Aggressive	Low	0.25	Very Slow
Very Good	Very High	Very Aggressive	Normal	0.25	Very Fast
Very Good	Very High	Very Aggressive	Normal	0.25	Medium
Very Good	Very High	Very Aggressive	Normal	0.25	Slow
Very Good	Very High	Very Aggressive	Normal	0.25	Very Slow
Very Good	Very High	Very Aggressive	High	0.25	Very Fast
Very Good	Very High	Very Aggressive	High	0.50	Slow
Very Good	Very High	Very Aggressive	High	0.25	Very Slow
Very Good	Very High	Very Aggressive	Very High	0.25	Very Fast
Very Good	Very High	Very Aggressive	Very High	0.25	Slow
Very Good	Very High	Very Aggressive	Very High	0.50	Very Slow
Very Bad	Very High	Aggressive	Very Low	0.25	Very Fast

IF				THEN	
Condition	Durability	Environment	Maintenance Level	DoS	Degradation Rate
Very Bad	Very High	Aggressive	Very Low	0.25	Fast
Very Bad	Very High	Aggressive	Very Low	0.50	Very Slow
Very Bad	Very High	Aggressive	Low	0.50	Fast
Very Bad	Very High	Aggressive	Low	0.50	Very Slow
Very Bad	Very High	Aggressive	Normal	0.25	Fast
Very Bad	Very High	Aggressive	Normal	0.25	Medium
Very Bad	Very High	Aggressive	Normal	0.50	Very Slow
Very Bad	Very High	Aggressive	High	0.25	Fast
Very Bad	Very High	Aggressive	High	0.25	Slow
Very Bad	Very High	Aggressive	High	0.50	Very Slow
Very Bad	Very High	Aggressive	Very High	0.25	Fast
Very Bad	Very High	Aggressive	Very High	0.75	Very Slow
Bad	Very High	Aggressive	Very Low	0.25	Very Fast
Bad	Very High	Aggressive	Very Low	0.50	Fast
Bad	Very High	Aggressive	Very Low	0.25	Very Slow
Bad	Very High	Aggressive	Low	0.75	Fast
Bad	Very High	Aggressive	Low	0.25	Very Slow
Bad	Very High	Aggressive	Normal	0.50	Fast
Bad	Very High	Aggressive	Normal	0.25	Medium
Bad	Very High	Aggressive	Normal	0.25	Very Slow
Bad	Very High	Aggressive	High	0.50	Fast
Bad	Very High	Aggressive	High	0.25	Slow
Bad	Very High	Aggressive	High	0.25	Very Slow
Bad	Very High	Aggressive	Very High	0.50	Fast
Bad	Very High	Aggressive	Very High	0.50	Very Slow
Fair	Very High	Aggressive	Very Low	0.50	Very Fast
Fair	Very High	Aggressive	Very Low	0.25	Fast
Fair	Very High	Aggressive	Very Low	0.25	Very Slow
Fair	Very High	Aggressive	Low	0.25	Very Fast
Fair	Very High	Aggressive	Low	0.50	Fast
Fair	Very High	Aggressive	Low	0.25	Very Slow
Fair	Very High	Aggressive	Normal	0.25	Very Fast
Fair	Very High	Aggressive	Normal	0.25	Fast
Fair	Very High	Aggressive	Normal	0.25	Medium
Fair	Very High	Aggressive	Normal	0.25	Very Slow
Fair	Very High	Aggressive	High	0.25	Very Fast

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Very High	Aggressive	High	0.25	Fast
Fair	Very High	Aggressive	High	0.25	Slow
Fair	Very High	Aggressive	High	0.25	Very Slow
Fair	Very High	Aggressive	Very High	0.25	Very Fast
Fair	Very High	Aggressive	Very High	0.25	Fast
Fair	Very High	Aggressive	Very High	0.50	Very Slow
Good	Very High	Aggressive	Very Low	0.25	Very Fast
Good	Very High	Aggressive	Very Low	0.25	Fast
Good	Very High	Aggressive	Very Low	0.25	Medium
Good	Very High	Aggressive	Very Low	0.25	Very Slow
Good	Very High	Aggressive	Low	0.50	Fast
Good	Very High	Aggressive	Low	0.25	Medium
Good	Very High	Aggressive	Low	0.25	Very Slow
Good	Very High	Aggressive	Normal	0.25	Fast
Good	Very High	Aggressive	Normal	0.50	Medium
Good	Very High	Aggressive	Normal	0.25	Very Slow
Good	Very High	Aggressive	High	0.25	Fast
Good	Very High	Aggressive	High	0.25	Medium
Good	Very High	Aggressive	High	0.25	Slow
Good	Very High	Aggressive	High	0.25	Very Slow
Good	Very High	Aggressive	Very High	0.25	Fast
Good	Very High	Aggressive	Very High	0.25	Medium
Good	Very High	Aggressive	Very High	0.50	Very Slow
Very Good	Very High	Aggressive	Very Low	0.25	Very Fast
Very Good	Very High	Aggressive	Very Low	0.25	Fast
Very Good	Very High	Aggressive	Very Low	0.25	Slow
Very Good	Very High	Aggressive	Very Low	0.25	Very Slow
Very Good	Very High	Aggressive	Low	0.50	Fast
Very Good	Very High	Aggressive	Low	0.25	Slow
Very Good	Very High	Aggressive	Low	0.25	Very Slow
Very Good	Very High	Aggressive	Normal	0.25	Fast
Very Good	Very High	Aggressive	Normal	0.25	Medium
Very Good	Very High	Aggressive	Normal	0.25	Slow
Very Good	Very High	Aggressive	Normal	0.25	Very Slow
Very Good	Very High	Aggressive	High	0.25	Fast
Very Good	Very High	Aggressive	High	0.50	Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Very High	Aggressive	High	0.25	Very Slow
Very Good	Very High	Aggressive	Very High	0.25	Fast
Very Good	Very High	Aggressive	Very High	0.25	Slow
Very Good	Very High	Aggressive	Very High	0.50	Very Slow
Very Bad	Very High	Slightly Aggressive	Very Low	0.25	Very Fast
Very Bad	Very High	Slightly Aggressive	Very Low	0.25	Medium
Very Bad	Very High	Slightly Aggressive	Very Low	0.50	Very Slow
Very Bad	Very High	Slightly Aggressive	Low	0.25	Fast
Very Bad	Very High	Slightly Aggressive	Low	0.25	Medium
Very Bad	Very High	Slightly Aggressive	Low	0.50	Very Slow
Very Bad	Very High	Slightly Aggressive	Normal	0.50	Medium
Very Bad	Very High	Slightly Aggressive	Normal	0.50	Very Slow
Very Bad	Very High	Slightly Aggressive	High	0.25	Medium
Very Bad	Very High	Slightly Aggressive	High	0.25	Slow
Very Bad	Very High	Slightly Aggressive	High	0.50	Very Slow
Very Bad	Very High	Slightly Aggressive	Very High	0.25	Medium
Very Bad	Very High	Slightly Aggressive	Very High	0.75	Very Slow
Bad	Very High	Slightly Aggressive	Very Low	0.25	Very Fast
Bad	Very High	Slightly Aggressive	Very Low	0.25	Fast
Bad	Very High	Slightly Aggressive	Very Low	0.25	Medium
Bad	Very High	Slightly Aggressive	Very Low	0.25	Very Slow
Bad	Very High	Slightly Aggressive	Low	0.50	Fast
Bad	Very High	Slightly Aggressive	Low	0.25	Medium
Bad	Very High	Slightly Aggressive	Low	0.25	Very Slow
Bad	Very High	Slightly Aggressive	Normal	0.25	Fast
Bad	Very High	Slightly Aggressive	Normal	0.50	Medium
Bad	Very High	Slightly Aggressive	Normal	0.25	Very Slow
Bad	Very High	Slightly Aggressive	High	0.25	Fast
Bad	Very High	Slightly Aggressive	High	0.25	Medium
Bad	Very High	Slightly Aggressive	High	0.25	Slow
Bad	Very High	Slightly Aggressive	High	0.25	Very Slow
Bad	Very High	Slightly Aggressive	Very High	0.25	Fast
Bad	Very High	Slightly Aggressive	Very High	0.25	Medium
Bad	Very High	Slightly Aggressive	Very High	0.50	Very Slow
Fair	Very High	Slightly Aggressive	Very Low	0.50	Very Fast
Fair	Very High	Slightly Aggressive	Very Low	0.25	Medium

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Very High	Slightly Aggressive	Very Low	0.25	Very Slow
Fair	Very High	Slightly Aggressive	Low	0.25	Very Fast
Fair	Very High	Slightly Aggressive	Low	0.25	Fast
Fair	Very High	Slightly Aggressive	Low	0.25	Medium
Fair	Very High	Slightly Aggressive	Low	0.25	Very Slow
Fair	Very High	Slightly Aggressive	Normal	0.25	Very Fast
Fair	Very High	Slightly Aggressive	Normal	0.50	Medium
Fair	Very High	Slightly Aggressive	Normal	0.25	Very Slow
Fair	Very High	Slightly Aggressive	High	0.25	Very Fast
Fair	Very High	Slightly Aggressive	High	0.25	Medium
Fair	Very High	Slightly Aggressive	High	0.25	Slow
Fair	Very High	Slightly Aggressive	High	0.25	Very Slow
Fair	Very High	Slightly Aggressive	Very High	0.25	Very Fast
Fair	Very High	Slightly Aggressive	Very High	0.25	Medium
Fair	Very High	Slightly Aggressive	Very High	0.50	Very Slow
Good	Very High	Slightly Aggressive	Very Low	0.25	Very Fast
Good	Very High	Slightly Aggressive	Very Low	0.50	Medium
Good	Very High	Slightly Aggressive	Very Low	0.25	Very Slow
Good	Very High	Slightly Aggressive	Low	0.25	Fast
Good	Very High	Slightly Aggressive	Low	0.50	Medium
Good	Very High	Slightly Aggressive	Low	0.25	Very Slow
Good	Very High	Slightly Aggressive	Normal	0.75	Medium
Good	Very High	Slightly Aggressive	Normal	0.25	Very Slow
Good	Very High	Slightly Aggressive	High	0.50	Medium
Good	Very High	Slightly Aggressive	High	0.25	Slow
Good	Very High	Slightly Aggressive	High	0.25	Very Slow
Good	Very High	Slightly Aggressive	Very High	0.50	Medium
Good	Very High	Slightly Aggressive	Very High	0.50	Very Slow
Very Good	Very High	Slightly Aggressive	Very Low	0.25	Very Fast
Very Good	Very High	Slightly Aggressive	Very Low	0.25	Medium
Very Good	Very High	Slightly Aggressive	Very Low	0.25	Slow
Very Good	Very High	Slightly Aggressive	Very Low	0.25	Very Slow
Very Good	Very High	Slightly Aggressive	Low	0.25	Fast
Very Good	Very High	Slightly Aggressive	Low	0.25	Medium
Very Good	Very High	Slightly Aggressive	Low	0.25	Slow
Very Good	Very High	Slightly Aggressive	Low	0.25	Very Slow

IF				**THEN**	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Very High	Slightly Aggressive	Normal	0.50	Medium
Very Good	Very High	Slightly Aggressive	Normal	0.25	Slow
Very Good	Very High	Slightly Aggressive	Normal	0.25	Very Slow
Very Good	Very High	Slightly Aggressive	High	0.25	Medium
Very Good	Very High	Slightly Aggressive	High	0.50	Slow
Very Good	Very High	Slightly Aggressive	High	0.25	Very Slow
Very Good	Very High	Slightly Aggressive	Very High	0.25	Medium
Very Good	Very High	Slightly Aggressive	Very High	0.25	Slow
Very Good	Very High	Slightly Aggressive	Very High	0.50	Very Slow
Very Bad	Very High	Less Favourable	Very Low	0.25	Very Fast
Very Bad	Very High	Less Favourable	Very Low	0.25	Slow
Very Bad	Very High	Less Favourable	Very Low	0.50	Very Slow
Very Bad	Very High	Less Favourable	Low	0.25	Fast
Very Bad	Very High	Less Favourable	Low	0.25	Slow
Very Bad	Very High	Less Favourable	Low	0.50	Very Slow
Very Bad	Very High	Less Favourable	Normal	0.25	Medium
Very Bad	Very High	Less Favourable	Normal	0.25	Slow
Very Bad	Very High	Less Favourable	Normal	0.50	Very Slow
Very Bad	Very High	Less Favourable	High	0.50	Slow
Very Bad	Very High	Less Favourable	High	0.50	Very Slow
Very Bad	Very High	Less Favourable	Very High	0.25	Slow
Very Bad	Very High	Less Favourable	Very High	0.75	Very Slow
Bad	Very High	Less Favourable	Very Low	0.25	Very Fast
Bad	Very High	Less Favourable	Very Low	0.25	Fast
Bad	Very High	Less Favourable	Very Low	0.25	Slow
Bad	Very High	Less Favourable	Very Low	0.25	Very Slow
Bad	Very High	Less Favourable	Low	0.50	Fast
Bad	Very High	Less Favourable	Low	0.25	Slow
Bad	Very High	Less Favourable	Low	0.25	Very Slow
Bad	Very High	Less Favourable	Normal	0.25	Fast
Bad	Very High	Less Favourable	Normal	0.25	Medium
Bad	Very High	Less Favourable	Normal	0.25	Slow
Bad	Very High	Less Favourable	Normal	0.25	Very Slow
Bad	Very High	Less Favourable	High	0.25	Fast
Bad	Very High	Less Favourable	High	0.50	Slow
Bad	Very High	Less Favourable	High	0.25	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Bad	Very High	Less Favourable	Very High	0.25	Fast
Bad	Very High	Less Favourable	Very High	0.25	Slow
Bad	Very High	Less Favourable	Very High	0.50	Very Slow
Fair	Very High	Less Favourable	Very Low	0.50	Very Fast
Fair	Very High	Less Favourable	Very Low	0.25	Slow
Fair	Very High	Less Favourable	Very Low	0.25	Very Slow
Fair	Very High	Less Favourable	Low	0.25	Very Fast
Fair	Very High	Less Favourable	Low	0.25	Fast
Fair	Very High	Less Favourable	Low	0.25	Slow
Fair	Very High	Less Favourable	Low	0.25	Very Slow
Fair	Very High	Less Favourable	Normal	0.25	Very Fast
Fair	Very High	Less Favourable	Normal	0.25	Medium
Fair	Very High	Less Favourable	Normal	0.25	Slow
Fair	Very High	Less Favourable	Normal	0.25	Very Slow
Fair	Very High	Less Favourable	High	0.25	Very Fast
Fair	Very High	Less Favourable	High	0.50	Slow
Fair	Very High	Less Favourable	High	0.25	Very Slow
Fair	Very High	Less Favourable	Very High	0.25	Very Fast
Fair	Very High	Less Favourable	Very High	0.25	Slow
Fair	Very High	Less Favourable	Very High	0.50	Very Slow
Good	Very High	Less Favourable	Very Low	0.25	Very Fast
Good	Very High	Less Favourable	Very Low	0.25	Medium
Good	Very High	Less Favourable	Very Low	0.25	Slow
Good	Very High	Less Favourable	Very Low	0.25	Very Slow
Good	Very High	Less Favourable	Low	0.25	Fast
Good	Very High	Less Favourable	Low	0.25	Medium
Good	Very High	Less Favourable	Low	0.25	Slow
Good	Very High	Less Favourable	Low	0.25	Very Slow
Good	Very High	Less Favourable	Normal	0.50	Medium
Good	Very High	Less Favourable	Normal	0.25	Slow
Good	Very High	Less Favourable	Normal	0.25	Very Slow
Good	Very High	Less Favourable	High	0.25	Medium
Good	Very High	Less Favourable	High	0.50	Slow
Good	Very High	Less Favourable	High	0.25	Very Slow
Good	Very High	Less Favourable	Very High	0.25	Medium
Good	Very High	Less Favourable	Very High	0.25	Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Good	Very High	Less Favourable	Very High	0.50	Very Slow
Very Good	Very High	Less Favourable	Very Low	0.25	Very Fast
Very Good	Very High	Less Favourable	Very Low	0.50	Slow
Very Good	Very High	Less Favourable	Very Low	0.25	Very Slow
Very Good	Very High	Less Favourable	Low	0.25	Fast
Very Good	Very High	Less Favourable	Low	0.50	Slow
Very Good	Very High	Less Favourable	Low	0.25	Very Slow
Very Good	Very High	Less Favourable	Normal	0.25	Medium
Very Good	Very High	Less Favourable	Normal	0.50	Slow
Very Good	Very High	Less Favourable	Normal	0.25	Very Slow
Very Good	Very High	Less Favourable	High	0.75	Slow
Very Good	Very High	Less Favourable	High	0.25	Very Slow
Very Good	Very High	Less Favourable	Very High	0.50	Slow
Very Good	Very High	Less Favourable	Very High	0.50	Very Slow
Very Bad	Very High	Favourable	Very Low	0.25	Very Fast
Very Bad	Very High	Favourable	Very Low	0.75	Very Slow
Very Bad	Very High	Favourable	Low	0.25	Fast
Very Bad	Very High	Favourable	Low	0.75	Very Slow
Very Bad	Very High	Favourable	Normal	0.25	Medium
Very Bad	Very High	Favourable	Normal	0.75	Very Slow
Very Bad	Very High	Favourable	High	0.25	Slow
Very Bad	Very High	Favourable	High	0.75	Very Slow
Very Bad	Very High	Favourable	Very High	1.00	Very Slow
Bad	Very High	Favourable	Very Low	0.25	Very Fast
Bad	Very High	Favourable	Very Low	0.25	Fast
Bad	Very High	Favourable	Very Low	0.50	Very Slow
Bad	Very High	Favourable	Low	0.50	Fast
Bad	Very High	Favourable	Low	0.50	Very Slow
Bad	Very High	Favourable	Normal	0.25	Fast
Bad	Very High	Favourable	Normal	0.25	Medium
Bad	Very High	Favourable	Normal	0.50	Very Slow
Bad	Very High	Favourable	High	0.25	Fast
Bad	Very High	Favourable	High	0.25	Slow
Bad	Very High	Favourable	High	0.50	Very Slow
Bad	Very High	Favourable	Very High	0.25	Fast
Bad	Very High	Favourable	Very High	0.75	Very Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Fair	Very High	Favourable	Very Low	0.50	Very Fast
Fair	Very High	Favourable	Very Low	0.50	Very Slow
Fair	Very High	Favourable	Low	0.25	Very Fast
Fair	Very High	Favourable	Low	0.25	Fast
Fair	Very High	Favourable	Low	0.50	Very Slow
Fair	Very High	Favourable	Normal	0.25	Very Fast
Fair	Very High	Favourable	Normal	0.25	Medium
Fair	Very High	Favourable	Normal	0.50	Very Slow
Fair	Very High	Favourable	High	0.25	Very Fast
Fair	Very High	Favourable	High	0.25	Slow
Fair	Very High	Favourable	High	0.50	Very Slow
Fair	Very High	Favourable	Very High	0.25	Very Fast
Fair	Very High	Favourable	Very High	0.75	Very Slow
Good	Very High	Favourable	Very Low	0.25	Very Fast
Good	Very High	Favourable	Very Low	0.25	Medium
Good	Very High	Favourable	Very Low	0.50	Very Slow
Good	Very High	Favourable	Low	0.25	Fast
Good	Very High	Favourable	Low	0.25	Medium
Good	Very High	Favourable	Low	0.50	Very Slow
Good	Very High	Favourable	Normal	0.50	Medium
Good	Very High	Favourable	Normal	0.50	Very Slow
Good	Very High	Favourable	High	0.25	Medium
Good	Very High	Favourable	High	0.25	Slow
Good	Very High	Favourable	High	0.50	Very Slow
Good	Very High	Favourable	Very High	0.25	Medium
Good	Very High	Favourable	Very High	0.75	Very Slow
Very Good	Very High	Favourable	Very Low	0.25	Very Fast
Very Good	Very High	Favourable	Very Low	0.25	Slow
Very Good	Very High	Favourable	Very Low	0.50	Very Slow
Very Good	Very High	Favourable	Low	0.25	Fast
Very Good	Very High	Favourable	Low	0.25	Slow
Very Good	Very High	Favourable	Low	0.50	Very Slow
Very Good	Very High	Favourable	Normal	0.25	Medium
Very Good	Very High	Favourable	Normal	0.25	Slow
Very Good	Very High	Favourable	Normal	0.50	Very Slow
Very Good	Very High	Favourable	High	0.50	Slow

IF				THEN	
Condition	**Durability**	**Environment**	**Maintenance Level**	**DoS**	**Degradation Rate**
Very Good	Very High	Favourable	High	0.50	Very Slow
Very Good	Very High	Favourable	Very High	0.25	Slow
Very Good	Very High	Favourable	Very High	0.75	Very Slow

Table A-3: IF-THEN Rules for Rule Block 3

Rule Block 1 — Workmanship Quality (columns, by Material Quality) × Design Level (rows)

Workmanship Quality: Very Low

Design Level \ Material Quality	Very Low	Low	Medium	High	Very High
Very Low	VL=1.0 L=0.0 M=0.0 H=0.0 VH=0.0	VL=0.67 L=0.33 M=0.0 H=0.0 VH=0.0	VL=0.67 L=0.0 M=0.33 H=0.0 VH=0.0	VL=0.67 L=0.0 M=0.0 H=0.33 VH=0.0	VL=0.67 L=0.0 M=0.0 H=0.0 VH=0.33
Low	VL=0.67 L=0.33 M=0.0 H=0.0 VH=0.0	VL=0.33 L=0.67 M=0.0 H=0.0 VH=0.0	VL=0.33 L=0.33 M=0.33 H=0.0 VH=0.0	VL=0.33 L=0.33 M=0.0 H=0.33 VH=0.0	VL=0.33 L=0.33 M=0.0 H=0.0 VH=0.33
Medium	VL=0.67 L=0.0 M=0.33 H=0.0 VH=0.0	VL=0.33 L=0.33 M=0.33 H=0.0 VH=0.0	VL=0.33 L=0.0 M=0.67 H=0.0 VH=0.0	VL=0.33 L=0.0 M=0.33 H=0.33 VH=0.0	VL=0.33 L=0.0 M=0.33 H=0.0 VH=0.33
High	VL=0.67 L=0.0 M=0.0 H=0.33 VH=0.0	VL=0.33 L=0.33 M=0.0 H=0.33 VH=0.0	VL=0.33 L=0.0 M=0.33 H=0.33 VH=0.0	VL=0.33 L=0.0 M=0.0 H=0.67 VH=0.0	VL=0.33 L=0.0 M=0.0 H=0.33 VH=0.33
Very High	VL=0.67 L=0.0 M=0.0 H=0.0 VH=0.33	VL=0.33 L=0.33 M=0.0 H=0.0 VH=0.33	VL=0.33 L=0.0 M=0.33 H=0.0 VH=0.33	VL=0.33 L=0.0 M=0.0 H=0.33 VH=0.33	VL=0.33 L=0.0 M=0.0 H=0.0 VH=0.67

Workmanship Quality: Low

Design Level \ Material Quality	Very Low	Low	Medium	High	Very High
Very Low	VL=0.67 L=0.33 M=0.0 H=0.0 VH=0.0	VL=0.33 L=0.67 M=0.0 H=0.0 VH=0.0	VL=0.33 L=0.33 M=0.33 H=0.0 VH=0.0	VL=0.33 L=0.33 M=0.0 H=0.33 VH=0.0	VL=0.33 L=0.33 M=0.0 H=0.0 VH=0.33
Low	VL=0.33 L=0.67 M=0.0 H=0.0 VH=0.0	VL=0.0 L=1.0 M=0.0 H=0.0 VH=0.0	VL=0.0 L=0.67 M=0.33 H=0.0 VH=0.0	VL=0.00 L=0.67 M=0.0 H=0.33 VH=0.0	VL=0.0 L=0.67 M=0.0 H=0.0 VH=0.33
Medium	VL=0.33 L=0.33 M=0.33 H=0.0 VH=0.0	VL=0.0 L=0.67 M=0.33 H=0.0 VH=0.0	VL=0.0 L=0.33 M=0.67 H=0.0 VH=0.0	VL=0.0 L=0.33 M=0.33 H=0.33 VH=0.0	VL=0.0 L=0.33 M=0.33 H=0.0 VH=0.33
High	VL=0.33 L=0.33 M=0.0 H=0.33 VH=0.0	VL=0.00 L=0.67 M=0.0 H=0.33 VH=0.0	VL=0.0 L=0.33 M=0.33 H=0.33 VH=0.0	VL=0.0 L=0.33 M=0.0 H=0.67 VH=0.0	VL=0.0 L=0.33 M=0.0 H=0.33 VH=0.33
Very High	VL=0.33 L=0.33 M=0.0 H=0.0 VH=0.33	VL=0.0 L=0.67 M=0.0 H=0.0 VH=0.33	VL=0.0 L=0.33 M=0.33 H=0.0 VH=0.33	VL=0.0 L=0.33 M=0.0 H=0.33 VH=0.33	VL=0.0 L=0.33 M=0.0 H=0.0 VH=0.67

Workmanship Quality: Medium

Design Level \ Material Quality	Very Low	Low	Medium	High	Very High
Very Low	VL=0.67 L=0.0 M=0.33 H=0.0 VH=0.0	VL=0.33 L=0.33 M=0.33 H=0.0 VH=0.0	VL=0.33 L=0.0 M=0.67 H=0.0 VH=0.0	VL=0.33 L=0.0 M=0.33 H=0.33 VH=0.0	VL=0.33 L=0.0 M=0.33 H=0.0 VH=0.33
Low	VL=0.33 L=0.33 M=0.33 H=0.0 VH=0.0	VL=0.0 L=0.67 M=0.33 H=0.0 VH=0.0	VL=0.0 L=0.33 M=0.67 H=0.0 VH=0.0	VL=0.0 L=0.33 M=0.33 H=0.33 VH=0.0	VL=0.0 L=0.33 M=0.33 H=0.0 VH=0.33
Medium	VL=0.33 L=0.0 M=0.67 H=0.0 VH=0.0	VL=0.0 L=0.33 M=0.67 H=0.0 VH=0.0	VL=0.0 L=0.0 M=1.0 H=0.0 VH=0.0	VL=0.0 L=0.0 M=0.67 H=0.33 VH=0.0	VL=0.0 L=0.0 M=0.67 H=0.0 VH=0.33
High	VL=0.33 L=0.0 M=0.33 H=0.33 VH=0.0	VL=0.0 L=0.33 M=0.33 H=0.33 VH=0.0	VL=0.0 L=0.0 M=0.67 H=0.33 VH=0.0	VL=0.0 L=0.0 M=0.33 H=0.67 VH=0.0	VL=0.0 L=0.0 M=0.33 H=0.33 VH=0.33
Very High	VL=0.33 L=0.0 M=0.33 H=0.0 VH=0.33	VL=0.0 L=0.33 M=0.33 H=0.0 VH=0.33	VL=0.0 L=0.0 M=0.67 H=0.0 VH=0.33	VL=0.0 L=0.0 M=0.33 H=0.33 VH=0.33	VL=0.0 L=0.0 M=0.33 H=0.0 VH=0.67

Workmanship Quality: High

Design Level \ Material Quality	Very Low	Low	Medium	High	Very High
Very Low	VL=0.67 L=0.0 M=0.0 H=0.33 VH=0.0	VL=0.33 L=0.33 M=0.0 H=0.33 VH=0.0	VL=0.33 L=0.0 M=0.33 H=0.33 VH=0.0	VL=0.33 L=0.0 M=0.0 H=0.67 VH=0.0	VL=0.33 L=0.0 M=0.0 H=0.33 VH=0.33
Low	VL=0.33 L=0.33 M=0.0 H=0.33 VH=0.0	VL=0.0 L=0.67 M=0.0 H=0.33 VH=0.0	VL=0.0 L=0.33 M=0.33 H=0.33 VH=0.0	VL=0.0 L=0.33 M=0.0 H=0.67 VH=0.0	VL=0.0 L=0.33 M=0.0 H=0.33 VH=0.33
Medium	VL=0.33 L=0.0 M=0.33 H=0.33 VH=0.0	VL=0.0 L=0.33 M=0.33 H=0.33 VH=0.0	VL=0.00 L=0.0 M=0.67 H=0.33 VH=0.0	VL=0.0 L=0.0 M=0.33 H=0.67 VH=0.0	VL=0.0 L=0.0 M=0.33 H=0.33 VH=0.33
High	VL=0.33 L=0.0 M=0.0 H=0.67 VH=0.0	VL=0.0 L=0.33 M=0.0 H=0.67 VH=0.0	VL=0.0 L=0.0 M=0.33 H=0.67 VH=0.0	VL=0.0 L=0.0 M=0.0 H=1.0 VH=0.0	VL=0.0 L=0.0 M=0.0 H=0.67 VH=0.33
Very High	VL=0.33 L=0.0 M=0.0 H=0.33 VH=0.33	VL=0.0 L=0.33 M=0.0 H=0.33 VH=0.33	VL=0.0 L=0.0 M=0.33 H=0.33 VH=0.33	VL=0.0 L=0.0 M=0.0 H=0.67 VH=0.33	VL=0.0 L=0.0 M=0.0 H=0.33 VH=0.67

Workmanship Quality: Very High

Design Level \ Material Quality	Very Low	Low	Medium	High	Very High
Very Low	VL=0.67 L=0.0 M=0.0 H=0.0 VH=0.33	VL=0.33 L=0.33 M=0.0 H=0.0 VH=0.33	VL=0.33 L=0.0 M=0.33 H=0.0 VH=0.33	VL=0.33 L=0.0 M=0.0 H=0.33 VH=0.33	VL=0.33 L=0.0 M=0.0 H=0.0 VH=0.67
Low	VL=0.33 L=0.33 M=0.0 H=0.0 VH=0.33	VL=0.0 L=0.67 M=0.0 H=0.0 VH=0.33	VL=0.0 L=0.33 M=0.33 H=0.0 VH=0.33	VL=0.0 L=0.33 M=0.0 H=0.33 VH=0.33	VL=0.0 L=0.33 M=0.0 H=0.0 VH=0.67
Medium	VL=0.33 L=0.0 M=0.33 H=0.0 VH=0.33	VL=0.0 L=0.33 M=0.33 H=0.0 VH=0.33	VL=0.0 L=0.0 M=0.67 H=0.0 VH=0.33	VL=0.0 L=0.0 M=0.33 H=0.33 VH=0.33	VL=0.0 L=0.0 M=0.33 H=0.0 VH=0.67
High	VL=0.33 L=0.0 M=0.0 H=0.33 VH=0.33	VL=0.0 L=0.33 M=0.0 H=0.33 VH=0.33	VL=0.0 L=0.0 M=0.33 H=0.33 VH=0.33	VL=0.0 L=0.0 M=0.0 H=0.67 VH=0.33	VL=0.0 L=0.0 M=0.0 H=0.33 VH=0.67
Very High	VL=0.33 L=0.0 M=0.0 H=0.0 VH=0.67	VL=0.0 L=0.33 M=0.0 H=0.0 VH=0.67	VL=0.0 L=0.0 M=0.33 H=0.0 VH=0.67	VL=0.0 L=0.0 M=0.0 H=0.33 VH=0.67	VL=0.0 L=0.0 M=0.0 H=0.0 VH=1.0

Table A-4: Fuzzy Rule Block 1

Rule Block 2 — Operational Environment (columns, by Internal Climate) × External Climate (rows)

Operational Environment: Very Aggressive

External Climate \ Internal Climate	External Element	Very Aggressive	Aggressive	Slightly Aggressive	Less Favourable	Favourable
Internal Element		VA=1.0 A=0.0 SA=0.0 LF=0.0 F=0.0	VA=0.5 A=0.5 SA=0.0 LF=0.0 F=0.0	VA=0.5 A=0.0 SA=0.5 LF=0.0 F=0.0	VA=0.5 A=0.0 SA=0.0 LF=0.5 F=0.0	VA=0.5 A=0.0 SA=0.0 LF=0.0 F=0.5
Very Aggressive	VA=1.0 A=0.0 SA=0.0 LF=0.0 F=0.0	VA=1.0 A=0.0 SA=0.0 LF=0.0 F=0.0	VA=0.67 A=0.33 SA=0.0 LF=0.0 F=0.0	VA=0.67 A=0.0 SA=0.33 LF=0.0 F=0.0	VA=0.67 A=0.0 SA=0.0 LF=0.33 F=0.0	VA=0.67 A=0.0 SA=0.0 LF=0.0 F=0.33
Aggressive	VA=0.5 A=0.5 SA=0.0 LF=0.0 F=0.0	VA=0.67 A=0.33 SA=0.0 LF=0.0 F=0.0	VA=0.33 A=0.67 SA=0.0 LF=0.0 F=0.0	VA=0.33 A=0.33 SA=0.33 LF=0.0 F=0.0	VA=0.33 A=0.33 SA=0.0 LF=0.33 F=0.0	VA=0.33 A=0.33 SA=0.0 LF=0.0 F=0.33
Slightly Aggressive	VA=0.5 A=0.0 SA=0.5 LF=0.0 F=0.0	VA=0.67 A=0.0 SA=0.33 LF=0.0 F=0.0	VA=0.33 A=0.33 SA=0.33 LF=0.0 F=0.0	VA=0.33 A=0.0 SA=0.67 LF=0.0 F=0.0	VA=0.33 A=0.0 SA=0.33 LF=0.33 F=0.0	VA=0.33 A=0.0 SA=0.33 LF=0.0 F=0.33
Less Favourable	VA=0.5 A=0.0 SA=0.0 LF=0.5 F=0.0	VA=0.67 A=0.0 SA=0.0 LF=0.33 F=0.0	VA=0.33 A=0.33 SA=0.0 LF=0.33 F=0.0	VA=0.33 A=0.0 SA=0.33 LF=0.33 F=0.0	VA=0.33 A=0.0 SA=0.0 LF=0.67 F=0.0	VA=0.33 A=0.0 SA=0.0 LF=0.33 F=0.33
Favourable	VA=0.5 A=0.0 SA=0.0 LF=0.0 F=0.5	VA=0.67 A=0.0 SA=0.0 LF=0.0 F=0.33	VA=0.33 A=0.33 SA=0.0 LF=0.0 F=0.33	VA=0.33 A=0.0 SA=0.33 LF=0.0 F=0.33	VA=0.33 A=0.0 SA=0.0 LF=0.33 F=0.33	VA=0.33 A=0.0 SA=0.0 LF=0.0 F=0.67

Operational Environment: Aggressive

External Climate \ Internal Climate	External Element	Very Aggressive	Aggressive	Slightly Aggressive	Less Favourable	Favourable
Internal Element		VA=0.5 A=0.5 SA=0.0 LF=0.0 F=0.0	VA=0.0 A=0.0 SA=1.0 LF=0.0 F=0.0	VA=0.0 A=0.5 SA=0.5 LF=0.0 F=0.0	VA=0.0 A=0.5 SA=0.0 LF=0.5 F=0.0	VA=0.0 A=0.5 SA=0.0 LF=0.0 F=0.5
Very Aggressive	VA=0.5 A=0.5 SA=0.0 LF=0.0 F=0.0	VA=0.67 A=0.33 SA=0.0 LF=0.0 F=0.0	VA=0.33 A=0.67 SA=0.0 LF=0.0 F=0.0	VA=0.33 A=0.33 SA=0.33 LF=0.0 F=0.0	VA=0.33 A=0.33 SA=0.0 LF=0.33 F=0.0	VA=0.33 A=0.33 SA=0.0 LF=0.0 F=0.33
Aggressive	VA=0.0 A=0.0 SA=1.0 LF=0.0 F=0.0	VA=0.33 A=0.67 SA=0.0 LF=0.0 F=0.0	VA=0.0 A=0.0 SA=1.0 LF=0.0 F=0.0	VA=0.0 A=0.67 SA=0.33 LF=0.0 F=0.0	VA=0.0 A=0.67 SA=0.0 LF=0.33 F=0.0	VA=0.0 A=0.67 SA=0.0 LF=0.0 F=0.33
Slightly Aggressive	VA=0.0 A=0.5 SA=0.5 LF=0.0 F=0.0	VA=0.33 A=0.33 SA=0.33 LF=0.0 F=0.0	VA=0.0 A=0.67 SA=0.33 LF=0.0 F=0.0	VA=0.0 A=0.33 SA=0.67 LF=0.0 F=0.0	VA=0.0 A=0.33 SA=0.33 LF=0.33 F=0.0	VA=0.0 A=0.33 SA=0.33 LF=0.0 F=0.33
Less Favourable	VA=0.0 A=0.5 SA=0.0 LF=0.5 F=0.0	VA=0.33 A=0.33 SA=0.0 LF=0.33 F=0.0	VA=0.0 A=0.67 SA=0.0 LF=0.33 F=0.0	VA=0.0 A=0.33 SA=0.33 LF=0.33 F=0.0	VA=0.0 A=0.33 SA=0.0 LF=0.67 F=0.0	VA=0.0 A=0.33 SA=0.0 LF=0.33 F=0.33
Favourable	VA=0.0 A=0.5 SA=0.0 LF=0.0 F=0.5	VA=0.33 A=0.33 SA=0.0 LF=0.0 F=0.33	VA=0.0 A=0.67 SA=0.0 LF=0.0 F=0.33	VA=0.0 A=0.33 SA=0.33 LF=0.0 F=0.33	VA=0.0 A=0.33 SA=0.0 LF=0.33 F=0.33	VA=0.0 A=0.33 SA=0.0 LF=0.0 F=0.67

Operational Environment: Slightly Aggressive

External Climate \ Internal Climate	External Element	Very Aggressive	Aggressive	Slightly Aggressive	Less Favourable	Favourable
Internal Element		VA=0.5 A=0.0 SA=0.5 LF=0.0 F=0.0	VA=0.0 A=0.5 SA=0.5 LF=0.0 F=0.0	VA=0.0 A=0.0 SA=1.0 LF=0.0 F=0.0	VA=0.0 A=0.0 SA=0.5 LF=0.5 F=0.0	VA=0.0 A=0.0 SA=0.5 LF=0.0 F=0.5
Very Aggressive	VA=0.5 A=0.0 SA=0.5 LF=0.0 F=0.0	VA=0.67 A=0.0 SA=0.33 LF=0.0 F=0.0	VA=0.33 A=0.33 SA=0.33 LF=0.0 F=0.0	VA=0.33 A=0.0 SA=0.67 LF=0.0 F=0.0	VA=0.33 A=0.0 SA=0.33 LF=0.33 F=0.0	VA=0.33 A=0.0 SA=0.33 LF=0.0 F=0.33
Aggressive	VA=0.0 A=0.5 SA=0.5 LF=0.0 F=0.0	VA=0.33 A=0.33 SA=0.33 LF=0.0 F=0.0	VA=0.0 A=0.67 SA=0.33 LF=0.0 F=0.0	VA=0.0 A=0.33 SA=0.67 LF=0.0 F=0.0	VA=0.0 A=0.33 SA=0.33 LF=0.33 F=0.0	VA=0.0 A=0.33 SA=0.33 LF=0.0 F=0.33
Slightly Aggressive	VA=0.0 A=0.0 SA=1.0 LF=0.0 F=0.0	VA=0.33 A=0.0 SA=0.67 LF=0.0 F=0.0	VA=0.0 A=0.33 SA=0.67 LF=0.0 F=0.0	VA=0.0 A=0.0 SA=1.0 LF=0.0 F=0.0	VA=0.0 A=0.0 SA=0.67 LF=0.33 F=0.0	VA=0.0 A=0.0 SA=0.67 LF=0.0 F=0.33
Less Favourable	VA=0.0 A=0.0 SA=0.5 LF=0.5 F=0.0	VA=0.33 A=0.0 SA=0.33 LF=0.33 F=0.0	VA=0.0 A=0.33 SA=0.33 LF=0.33 F=0.0	VA=0.0 A=0.0 SA=0.67 LF=0.33 F=0.0	VA=0.0 A=0.0 SA=0.33 LF=0.67 F=0.0	VA=0.0 A=0.0 SA=0.33 LF=0.33 F=0.33
Favourable	VA=0.0 A=0.0 SA=0.5 LF=0.0 F=0.5	VA=0.33 A=0.0 SA=0.33 LF=0.0 F=0.33	VA=0.0 A=0.33 SA=0.33 LF=0.0 F=0.33	VA=0.0 A=0.0 SA=0.67 LF=0.0 F=0.33	VA=0.0 A=0.0 SA=0.33 LF=0.33 F=0.33	VA=0.0 A=0.0 SA=0.33 LF=0.0 F=0.67

Operational Environment: Less Favourable

External Climate \ Internal Climate	External Element	Very Aggressive	Aggressive	Slightly Aggressive	Less Favourable	Favourable
Internal Element		VA=0.5 A=0.0 SA=0.0 LF=0.5 F=0.0	VA=0.0 A=0.5 SA=0.0 LF=0.5 F=0.0	VA=0.0 A=0.0 SA=0.5 LF=0.5 F=0.0	VA=0.0 A=0.0 SA=0.0 LF=1.0 F=0.0	VA=0.0 A=0.0 SA=0.0 LF=0.5 F=0.5
Very Aggressive	VA=0.5 A=0.0 SA=0.0 LF=0.5 F=0.0	VA=0.67 A=0.0 SA=0.0 LF=0.33 F=0.0	VA=0.33 A=0.33 SA=0.0 LF=0.33 F=0.0	VA=0.33 A=0.0 SA=0.33 LF=0.33 F=0.0	VA=0.33 A=0.0 SA=0.0 LF=0.67 F=0.0	VA=0.33 A=0.0 SA=0.0 LF=0.33 F=0.33
Aggressive	VA=0.0 A=0.5 SA=0.0 LF=0.5 F=0.0	VA=0.33 A=0.33 SA=0.0 LF=0.33 F=0.0	VA=0.0 A=0.67 SA=0.0 LF=0.33 F=0.0	VA=0.0 A=0.33 SA=0.33 LF=0.33 F=0.0	VA=0.0 A=0.33 SA=0.0 LF=0.67 F=0.0	VA=0.0 A=0.33 SA=0.0 LF=0.33 F=0.33
Slightly Aggressive	VA=0.0 A=0.0 SA=0.5 LF=0.5 F=0.0	VA=0.33 A=0.0 SA=0.33 LF=0.33 F=0.0	VA=0.0 A=0.33 SA=0.33 LF=0.33 F=0.0	VA=0.00 A=0.0 SA=0.67 LF=0.33 F=0.0	VA=0.0 A=0.0 SA=0.33 LF=0.67 F=0.0	VA=0.0 A=0.0 SA=0.33 LF=0.33 F=0.33
Less Favourable	VA=0.0 A=0.0 SA=0.0 LF=1.0 F=0.0	VA=0.33 A=0.0 SA=0.0 LF=0.67 F=0.0	VA=0.0 A=0.33 SA=0.0 LF=0.67 F=0.0	VA=0.0 A=0.0 SA=0.33 LF=0.67 F=0.0	VA=0.0 A=0.0 SA=0.0 LF=1.0 F=0.0	VA=0.0 A=0.0 SA=0.0 LF=0.67 F=0.33
Favourable	VA=0.0 A=0.0 SA=0.0 LF=0.5 F=0.5	VA=0.33 A=0.0 SA=0.0 LF=0.33 F=0.33	VA=0.0 A=0.33 SA=0.0 LF=0.33 F=0.33	VA=0.0 A=0.0 SA=0.33 LF=0.33 F=0.33	VA=0.0 A=0.0 SA=0.0 LF=0.67 F=0.33	VA=0.0 A=0.0 SA=0.0 LF=0.33 F=0.67

Operational Environment: Favourable

External Climate \ Internal Climate	External Element	Very Aggressive	Aggressive	Slightly Aggressive	Less Favourable	Favourable
Internal Element		VA=0.5 A=0.0 SA=0.0 LF=0.0 F=0.5	VA=0.0 A=0.5 SA=0.0 LF=0.0 F=0.5	VA=0.0 A=0.0 SA=0.5 LF=0.0 F=0.5	VA=0.0 A=0.0 SA=0.0 LF=0.5 F=0.5	VA=0.0 A=0.0 SA=0.0 LF=0.0 F=1.0
Very Aggressive	VA=0.5 A=0.0 SA=0.0 LF=0.0 F=0.5	VA=0.67 A=0.0 SA=0.0 LF=0.0 F=0.33	VA=0.33 A=0.33 SA=0.0 LF=0.0 F=0.33	VA=0.33 A=0.0 SA=0.33 LF=0.0 F=0.33	VA=0.33 A=0.0 SA=0.0 LF=0.33 F=0.33	VA=0.33 A=0.0 SA=0.0 LF=0.0 F=0.67
Aggressive	VA=0.0 A=0.5 SA=0.0 LF=0.0 F=0.5	VA=0.33 A=0.33 SA=0.0 LF=0.0 F=0.33	VA=0.0 A=0.67 SA=0.0 LF=0.0 F=0.33	VA=0.0 A=0.33 SA=0.33 LF=0.0 F=0.33	VA=0.0 A=0.33 SA=0.0 LF=0.33 F=0.33	VA=0.0 A=0.33 SA=0.0 LF=0.0 F=0.67
Slightly Aggressive	VA=0.0 A=0.0 SA=0.5 LF=0.0 F=0.5	VA=0.33 A=0.0 SA=0.33 LF=0.0 F=0.33	VA=0.0 A=0.33 SA=0.33 LF=0.0 F=0.33	VA=0.0 A=0.0 SA=0.67 LF=0.0 F=0.33	VA=0.0 A=0.0 SA=0.33 LF=0.33 F=0.33	VA=0.0 A=0.0 SA=0.33 LF=0.0 F=0.67
Less Favourable	VA=0.0 A=0.0 SA=0.0 LF=0.5 F=0.5	VA=0.33 A=0.0 SA=0.0 LF=0.33 F=0.33	VA=0.0 A=0.33 SA=0.0 LF=0.33 F=0.33	VA=0.0 A=0.0 SA=0.33 LF=0.33 F=0.33	VA=0.0 A=0.0 SA=0.0 LF=0.67 F=0.33	VA=0.0 A=0.0 SA=0.0 LF=0.33 F=0.67
Favourable	VA=0.0 A=0.0 SA=0.0 LF=0.0 F=1.0	VA=0.33 A=0.0 SA=0.0 LF=0.0 F=0.67	VA=0.0 A=0.33 SA=0.0 LF=0.0 F=0.67	VA=0.0 A=0.0 SA=0.33 LF=0.0 F=0.67	VA=0.0 A=0.0 SA=0.0 LF=0.33 F=0.67	VA=0.0 A=0.0 SA=0.0 LF=0.0 F=1.0

Table A-5: Fuzzy Rule Block 2

Rule Block 3

Durability	Condition	Environment: Very Aggressive — Maintenance Level: Very Low	Low	Normal	High	Very High
Very Low	Very Bad	VF=1.0 F=0.0 M=0.0 S=0.0 VS=0.0	VF=0.75 F=0.25 M=0.0 S=0.0 VS=0.0	VF=0.75 F=0.0 M=0.25 S=0.0 VS=0.0	VF=0.75 F=0.0 M=0.0 S=0.25 VS=0.0	VF=0.75 F=0.0 M=0.0 S=0.0 VS=0.25
	Bad	VF=0.75 F=0.25 M=0.0 S=0.0 VS=0.0	VF=0.5 F=0.5 M=0.0 S=0.0 VS=0.0	VF=0.5 F=0.25 M=0.25 S=0.0 VS=0.0	VF=0.5 F=0.25 M=0.0 S=0.25 VS=0.0	VF=0.5 F=0.25 M=0.0 S=0.0 VS=0.25
	Fair	VF=0.75 F=0.0 M=0.25 S=0.0 VS=0.0	VF=0.5 F=0.25 M=0.25 S=0.0 VS=0.0	VF=0.5 F=0.0 M=0.5 S=0.0 VS=0.0	VF=0.5 F=0.0 M=0.25 S=0.25 VS=0.0	VF=0.5 F=0.0 M=0.25 S=0.25 VS=0.0
	Good	VF=0.75 F=0.0 M=0.0 S=0.25 VS=0.0	VF=0.5 F=0.25 M=0.0 S=0.25 VS=0.0	VF=0.5 F=0.0 M=0.25 S=0.25 VS=0.0	VF=0.5 F=0.0 M=0.0 S=0.5 VS=0.0	VF=0.5 F=0.0 M=0.0 S=0.25 VS=0.25
	Very Good	VF=0.75 F=0.0 M=0.0 S=0.0 VS=0.25	VF=0.5 F=0.25 M=0.0 S=0.0 VS=0.25	VF=0.5 F=0.0 M=0.25 S=0.0 VS=0.25	VF=0.5 F=0.0 M=0.0 S=0.25 VS=0.25	VF=0.5 F=0.0 M=0.0 S=0.0 VS=0.5

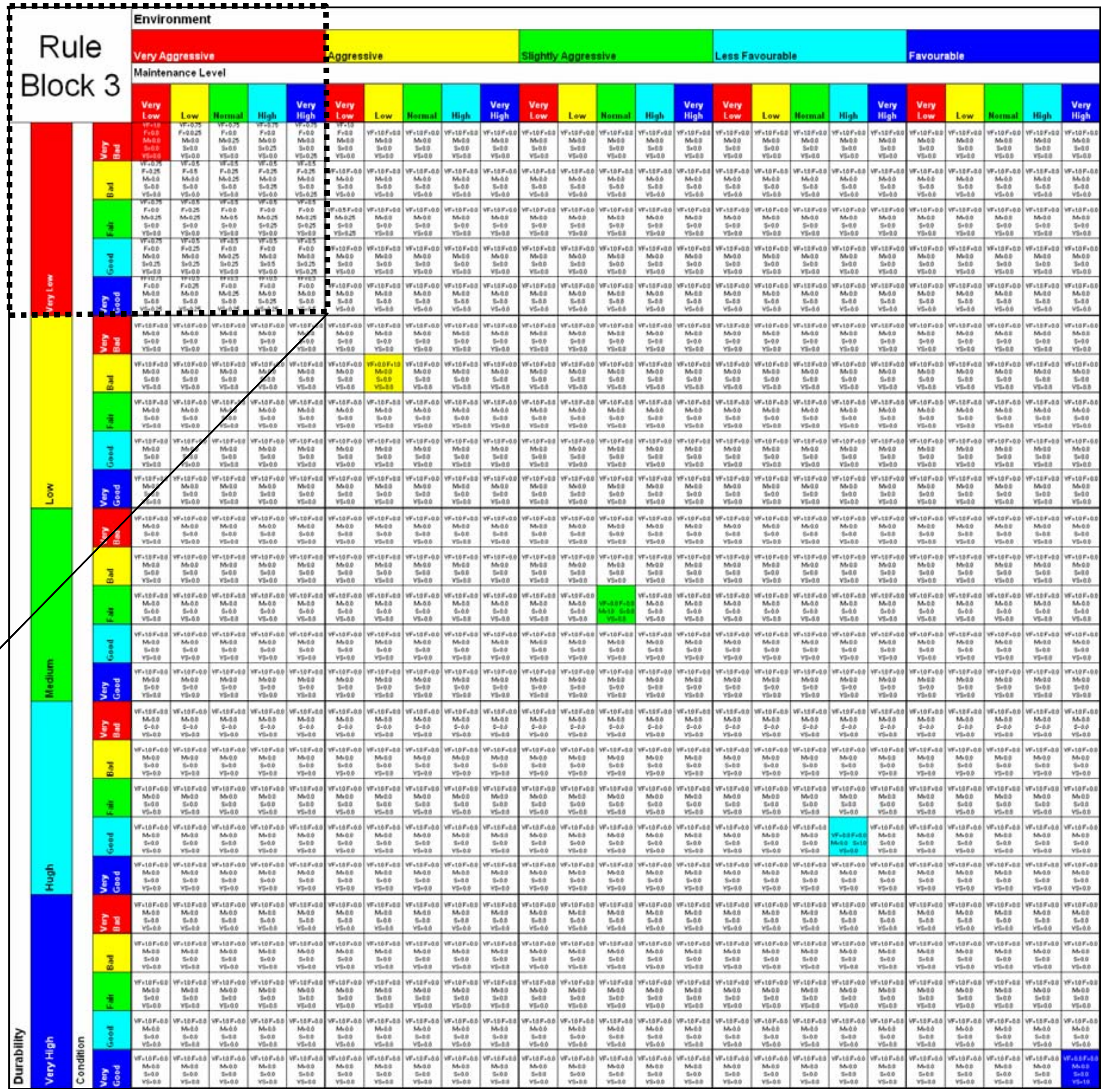
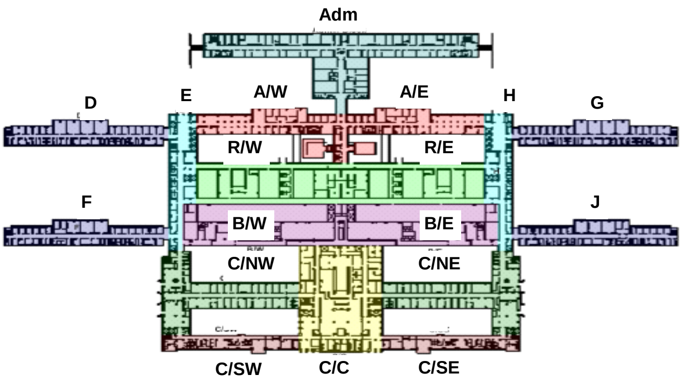


Table A-6: Fuzzy Rule Block 3

Appendix B: Condition Assessment Database

Block	Administration Block	Ward Block (North West)	Link Block (West)	ICU Block (West)	ICU Block (East)	Link Block (East)	Ward Block (North East)	Link & Support Block (West)	Link & Support Block (East)	Ward Block (South West)	Theatre Block (West)	Theatre Block (East)	Ward Block (South East)	Out-patients (North West)	Out-patients (South West)	OP & Theatres (Centre)	Out-patients (North East)	Out-patients (South East)
	Adm	D	E	A	A	H	G	R/W	R/E	F	B/W	B/E	J	C/NW	C/SW	C/C	C/NE	C/SE
13th Floor																3		
12th Floor			3	3	3	3								3	3	2.75	3	3
11th Floor		3	3	3	3	3	3							3	3	2.75	3	3
10th Floor		2.5	2.5	2.5	2.5	2.75	2.5							3	3.5	2.75	3	3.5
9th Floor		4	3	3	3	3	3.5						3	3.25	3	3.5	4	3.5
8th Floor		4	3	3.5	3	2.5	2.5						3.5	3	3	3	3	3.75
7th Floor		3.5	3	3.5	3.5	2.5	3.75						3	3.5	3.5	3	3	3.5
6th Floor		3.75	2.75	3	3	2.5	4				3	3	2.5	3	2.75	2.75	3	2.75
5th Floor		4	3	3	3.5	2.5	2.5	3	3	3	3	3	2.75	3	3	2.5	3	3
4th Floor		4	3	3	3	3	3	4	4	2.75	3	3	3.25	3.5	3	3	3	3.5
3rd Floor		4	3	2.5	2.5	3	2.75	3	3	2.75	3	3	3	3	4	2.5	3	3.5
2nd Floor		2.5	3	3.25	3.25	3	4	2.75	2.75	3	3	3	3	3	3.5	2.75	4	3
1st Floor	3.5	2.5	3	3.25	3	3	2	3	3	3.5	3	3	3	3	3.25	3	3.5	3
Ground Floor	3.75	3.5	3	3.75	3.5	3	2	3	3	3.5	2.5	2.5	3	3	3	3	3	3
Lower Ground Floor	3	2.5	2.5	3	3	2.5	2.5	2.5	2.5	2.5	2	3	2.5	2.5	2.5	2.5	2.5	2.5
Basement																		
Average / Block	3.42	3.39	2.90	3.10	3.06	2.78	2.92	3.04	3.04	3.00	2.80	2.92	2.95	3.06	3.16	2.84	3.15	3.20

3.02 **2005 Assessment : Main Hospital Building**



4.1 Hatched blocks indicate roof level plant rooms or full plant room floors

Block	Administration Block	Ward Block (North West)	Link Block (West)	ICU Block (West)	ICU Block (East)	Link Block (East)	Ward Block (North East)	Link & Support Block (West)	Link & Support Block (East)	Ward Block (South West)	Theatre Block (West)	Theatre Block (East)	Ward Block (South East)	Out-patients (North West)	Out-patients (South West)	OP & Theatres (Centre)	Out-patients (North East)	Out-patients (South East)
	Adm	D	E	A	A	H	G	R/W	R/E	F	B/W	B/E	J	C/NW	C/SW	C/C	C/NE	C/SE
13th Floor																4		
12th Floor			3.7	3.7	3.7	3.7								4	4	4	4	4
11th Floor		3.6	3.7	3.7	3.7	3.7	3.7							3.6	3.6	3.7	3.6	3.6
10th Floor		3.3	3.9	3.8	3.8	3.9	3.3							3.4	3.4	3.4	3.4	3.4
9th Floor		3.4	4	3.8	3.8	4	3.4						3.9	3.5	3.5	3.5	3.7	3.5
8th Floor		3.7	3.8	3.7	3.7	3.8	3.7						3.4	3.8	3.8	4.2	3.8	3.8
7th Floor		3.3	3.7	3.8	3.8	3.7	3.3						3.7	3.9	3.9	3.8	3.9	3.9
6th Floor		3.2	3.9	4.2	4.2	3.9	3.2				4.1	4.1	3.2	3.9	3.9	3.8	3.9	3.9
5th Floor		3.6	3.6	3.7	3.6	3.6	3.3	3.7	3.7	4	3.7	3.7	3.3	3.8	3.8	4.1	3.8	3.8
4th Floor		3.4	3.9	3.7	3.7	3.9	3.4	3.9	3.9	3.5	3.5	3.5	3.5	3.2	3.2	3.2	3.2	3.2
3rd Floor		3.3	3.6	3.3	3.3	3.6	3.3	3.7	3.7	3.3	3.2	3.2	3.3	3.8	3.8	3.2	3.8	3.8
2nd Floor		3.3	3.7	4.1	4.1	3.7	3.3	3.7	3.7	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
1st Floor	4.5	3.5	3.7	3.5	3.5	3.7	3.5	3.6	3.6	2.7	3.2	3.2	2.7	3.3	3.3	3.4	3.3	3.3
Ground Floor	4.6	3.6	3.9	3.6	3.6	3.9	3.6	3.7	3.7	3.4	4	4	3.4	3.7	3.6	4.3	3.7	4.1
Lower Ground Floor	4.5	3.4	3.3	3.3	3.3	3.3	3.4	3.3	3.8	3.8	3.7	4	3.8	3.8	3.8	3.9	3.8	3.8
Basement											3.7	3.7				3.7		
Average / Block	4.53	3.43	3.74	3.71	3.70	3.74	3.42	3.66	3.73	3.43	3.60	3.63	3.41	3.64	3.64	3.72	3.66	3.67

3.65 **1995/95 NHFA Assessment : Main Hospital Building**

5	Very good / Normal maintenance	value ≥ 4.5
4	Good / Condition-based maintenance	4.0 ≤ value < 4.5
3	Fair / Repairs	3.0 ≤ value < 4.0
2	Poor / Rehabilitation	2.0 ≤ value < 3.0
1	Very Poor / Replacement	1.0 ≤ value < 2.0

Hospital A CONDITION PROFILE

1

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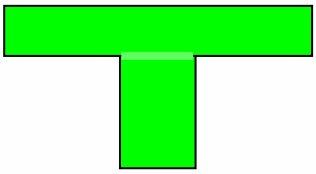
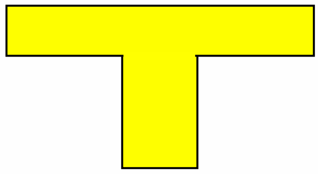


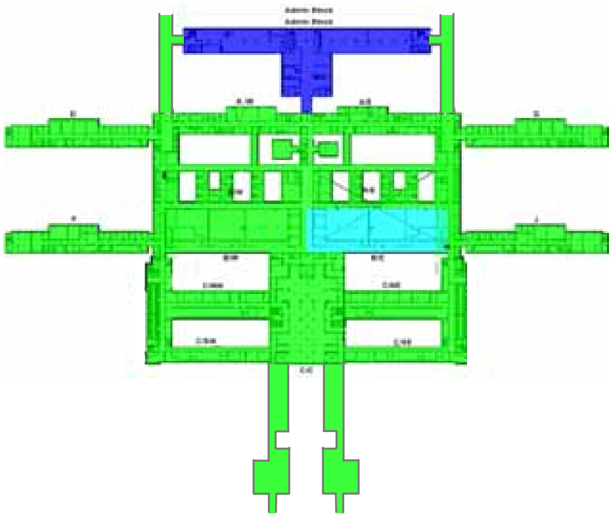
Basement
1995/96 NHFA **3.5**

Key Issues
-



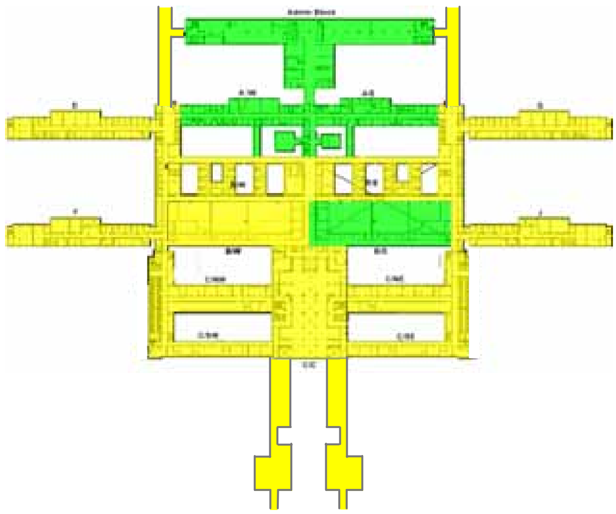
Basement
2005 Assessment **2.6**

Key Issues
- Poor ventilation
- Leaking sewers
- All pipes in bad condition
- Decaying food waste underneath kitchen



Lower Ground Floor
1995/96 NHFA **3.7**

Key Issues
- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- General air quality and thermal quality problematic
- Housekeeping in general



Lower Ground Floor
2005 Assessment **2.6**

Key Issues
- **Kitchen is serious health risk and must be redesigned and refurbished as matter of urgency**
- Leaking sewer & water pipes in service shafts
- Piping in bad condition
- In urgent need of rehabilitation
- Vinyl wall covering brittle & peeling
- Medical & other waste around building perimeter & open spaces
- Missing & damaged metal ceiling panels in passages
- Failing floor screeds and vinyl floor & wall covering

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

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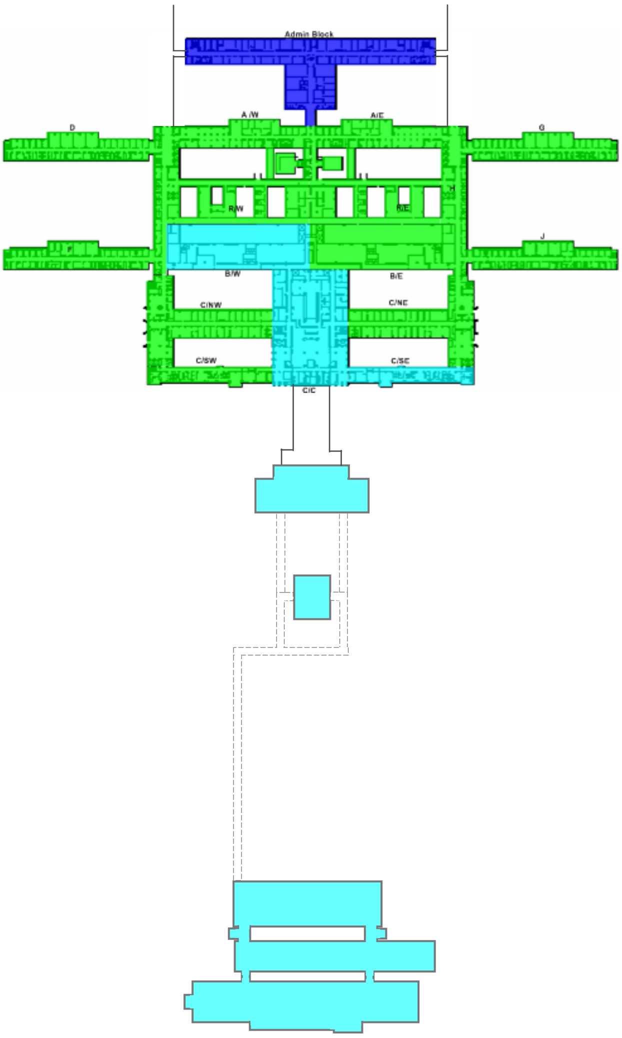
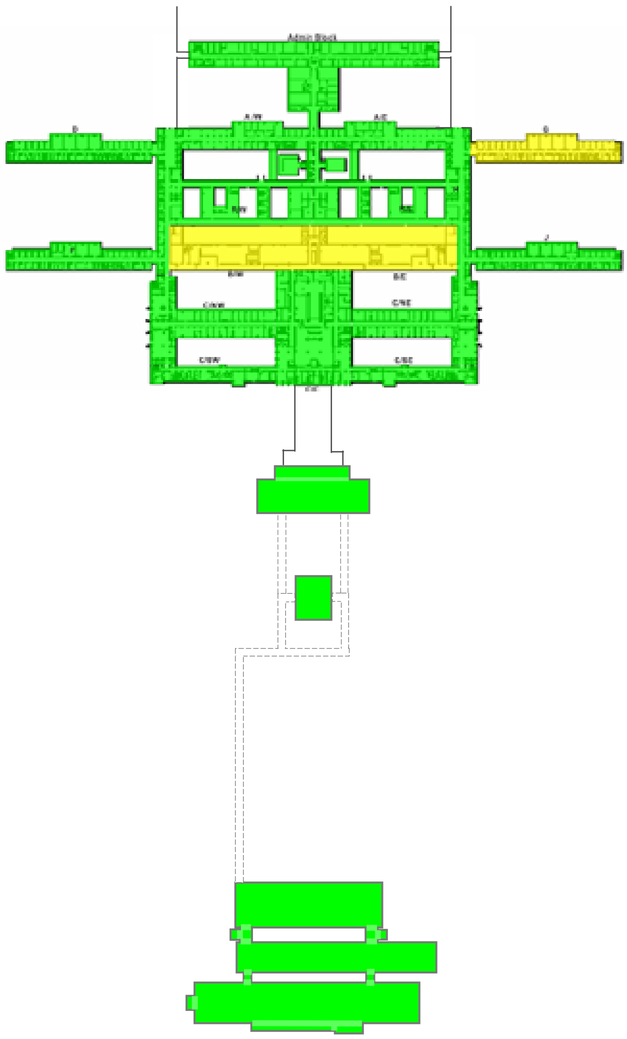
Hospital A
CONDITION PROFILE 4



Ground Floor
1995/96 NHFA **3.9**

Key Issues
- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general



Ground Floor
2005 Assessment **3.1**

Key Issues
- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

Hospital A
CONDITION PROFILE 5

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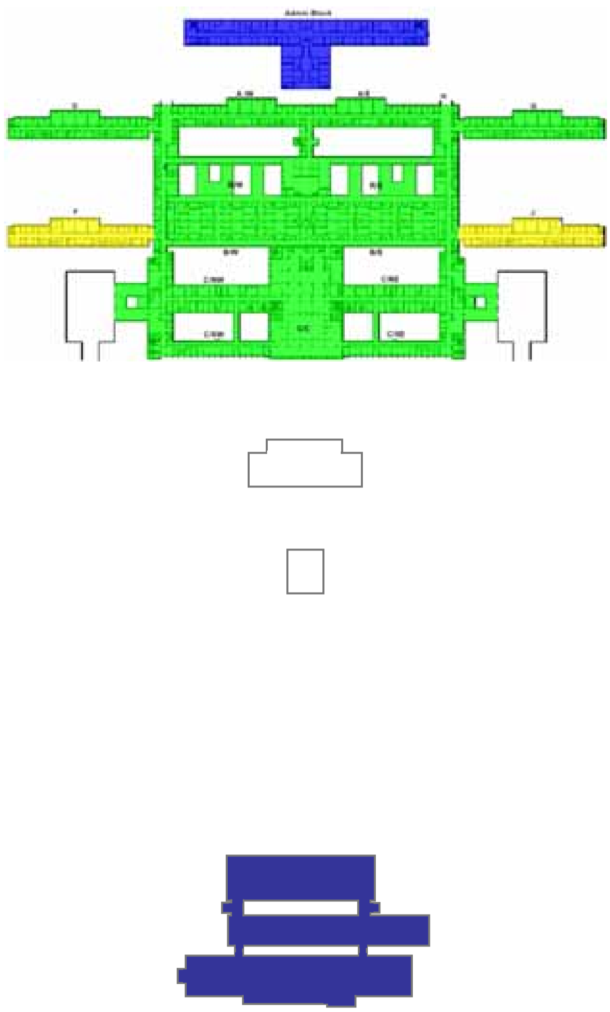
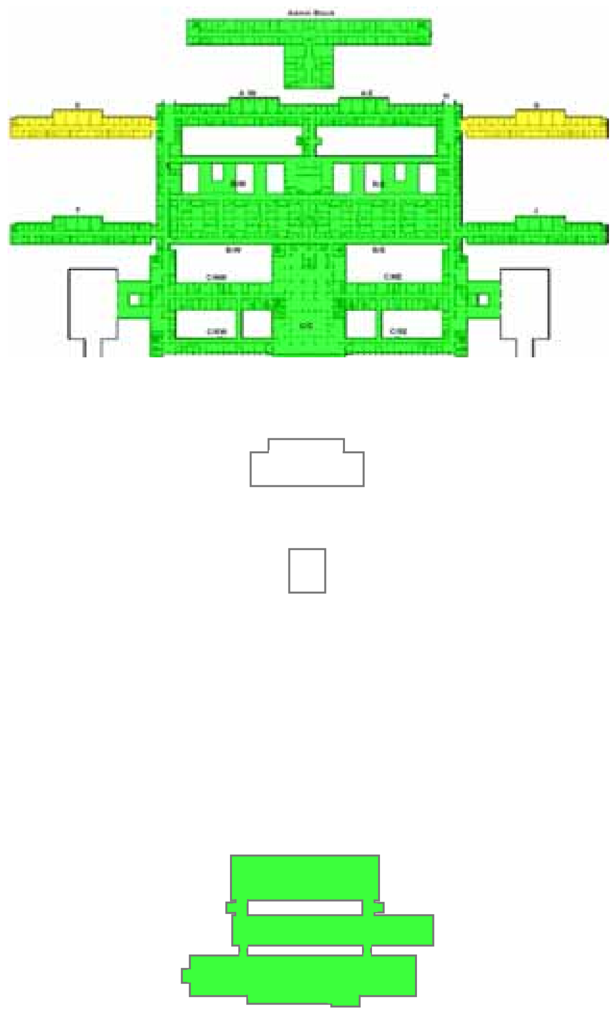
Appendix B-1: Hospital A Condition Assessments



First Floor
1995/96 NHFA **3.5**

Key Issues
- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general



First Floor
2005 Assessment **3.0**

Key Issues
- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

Hospital A
CONDITION PROFILE 6

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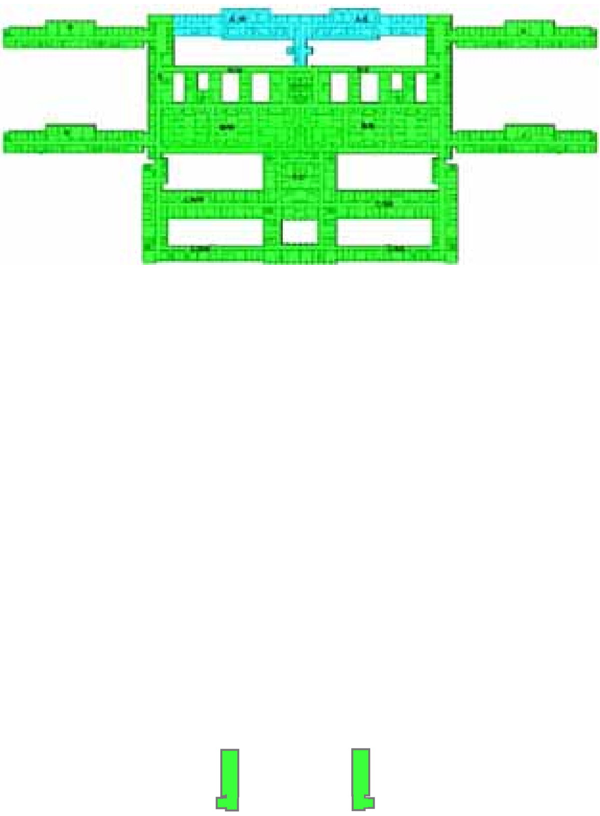
Appendix B-1: Hospital A Condition Assessments



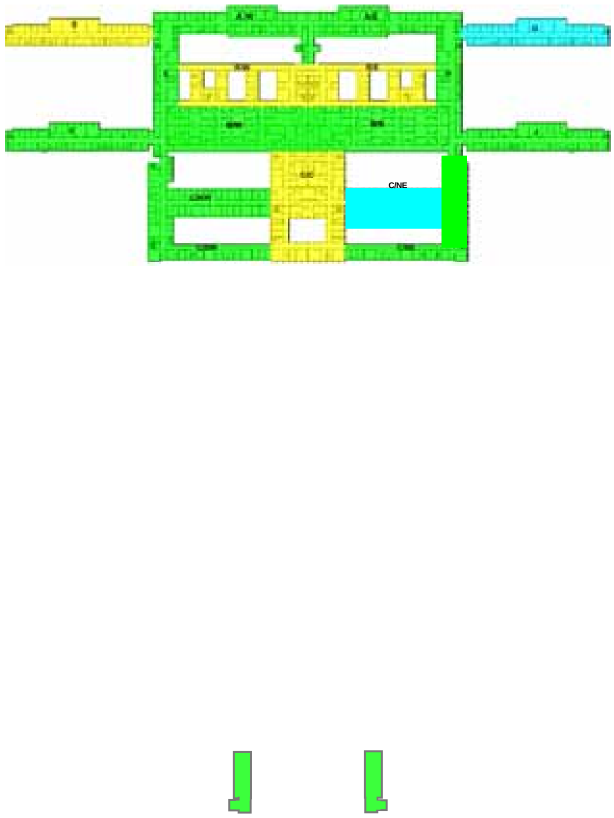
Second Floor

1995/96 NHFA

3.5

Key Issues

- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general



Second Floor

2005 Assessment

3.1

Key Issues

- Blocks C-NE and G – refurbished
- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

Hospital A

CONDITION PROFILE

7

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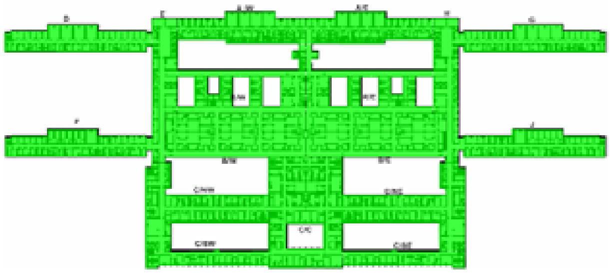
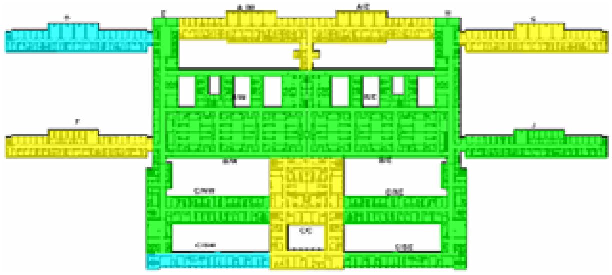


Third Floor

1995/96 NHFA **3.5**

Key Issues

- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
-

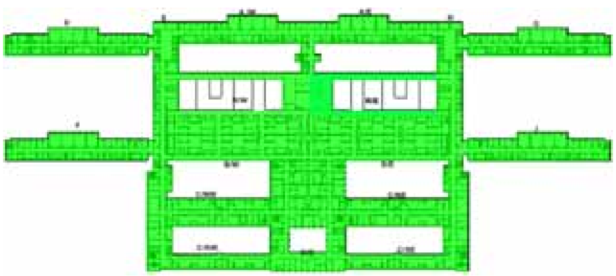


Third Floor

2005 Assessment **3.0**

Key Issues

- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked

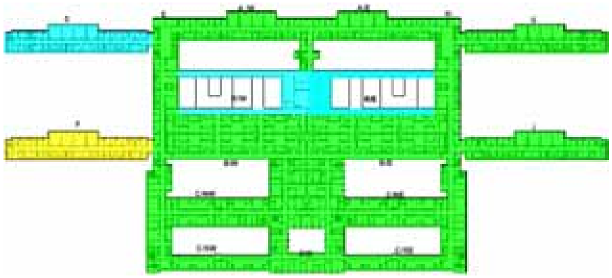


Fourth Floor

1995/96 NHFA **3.7**

Key Issues

- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally better condition than departments



Fourth Floor

2005 Assessment **3.2**

Key Issues

- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked
- Block F: Waterproofing on roof slabs replaced but leaching from slab still taking place

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

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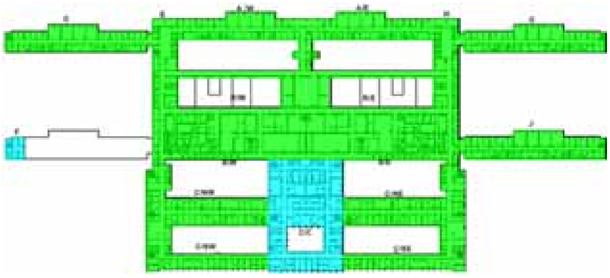
Hospital A
CONDITION PROFILE 8

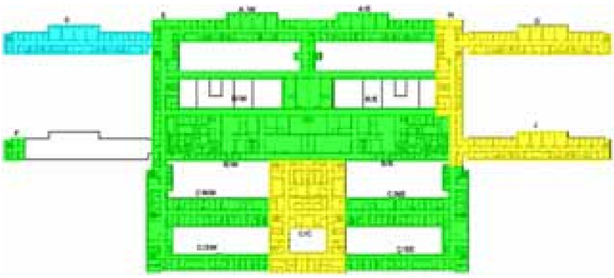


Fifth Floor

1995/96 NHFA 3.7

Key Issues

- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general

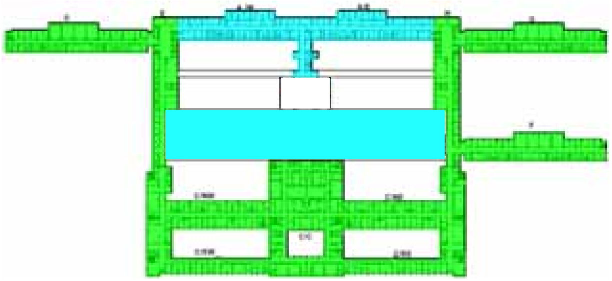


Fifth Floor

2005 Assessment 3.0

Key Issues

- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked

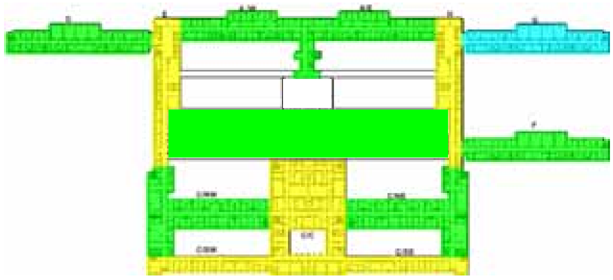


Sixth Floor

1995/96 NHFA 3.7

Key Issues

- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general



Sixth Floor

2005 Assessment 3.0

Key Issues

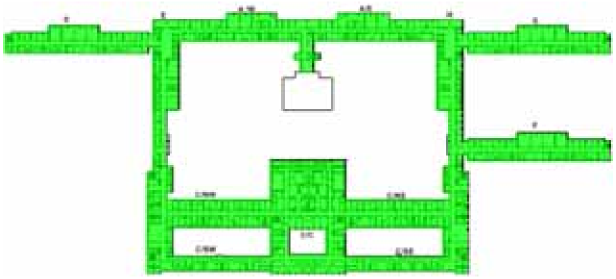
- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

CSIR : Final 3 October 2005

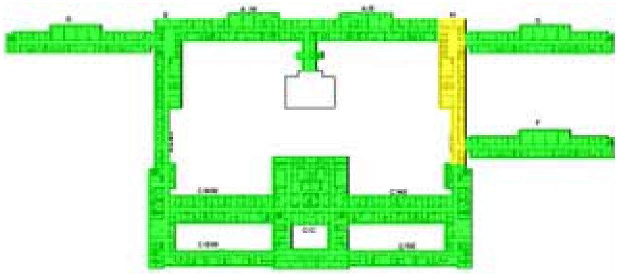
Hospital A

CONDITION PROFILE 9



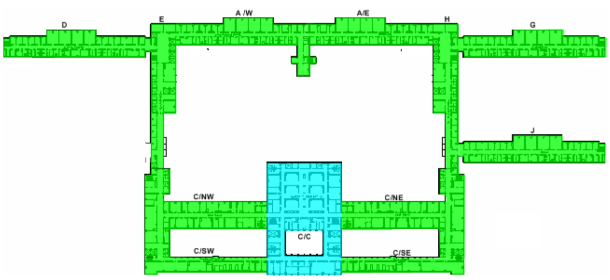
Seventh Floor
1995/96 NHFA 3.7

Key Issues
- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general



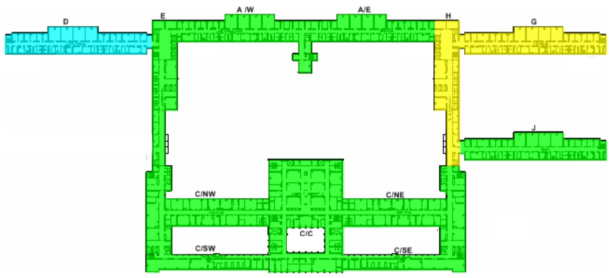
Seventh Floor
2005 Assessment 3.3

Key Issues
- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked



Eighth Floor
1995/96 NHFA 3.7

Key Issues
- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general



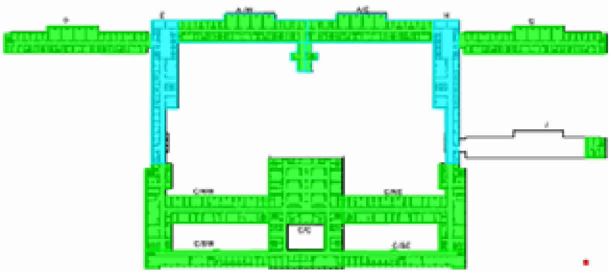
Eighth Floor
2005 Assessment 3.1

Key Issues
- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

CSIR : Final 3 October 2005

Hospital A
CONDITION PROFILE 10

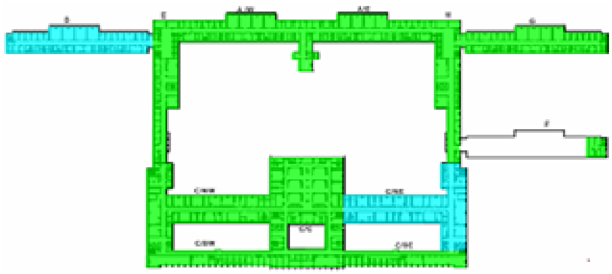


Ninth Floor

1995/96 NHFA **3.6**

Key Issues

- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general

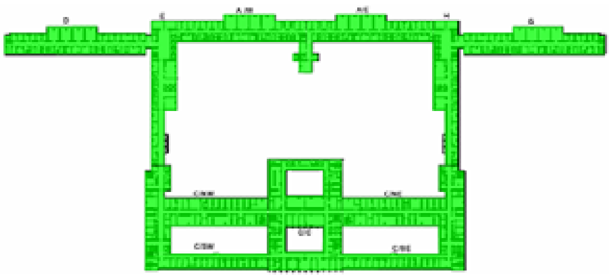


Ninth Floor

2005 Assessment **3.3**

Key Issues

- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked
- Blocks C/NE and D refurbished

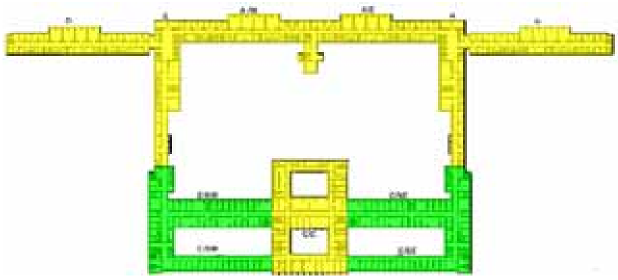


Tenth Floor

1995/96 NHFA **3.6**

Key Issues

- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general



Tenth Floor

2005 Assessment **2.8**

Key Issues

- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked
- Waterproofing on roof slabs to be replaced

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

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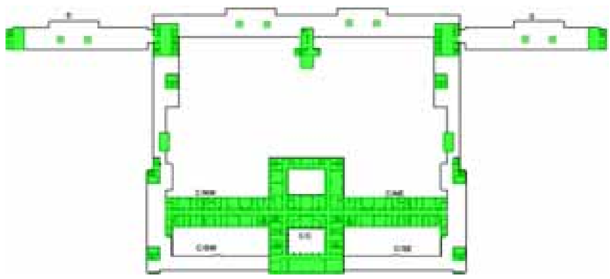
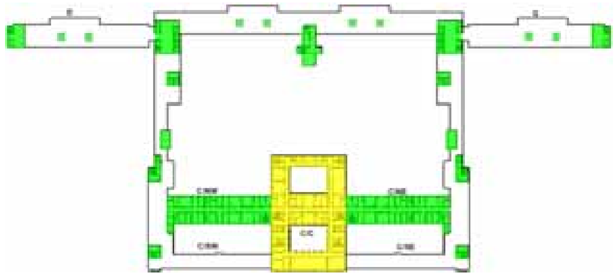
Hospital A

CONDITION PROFILE 11



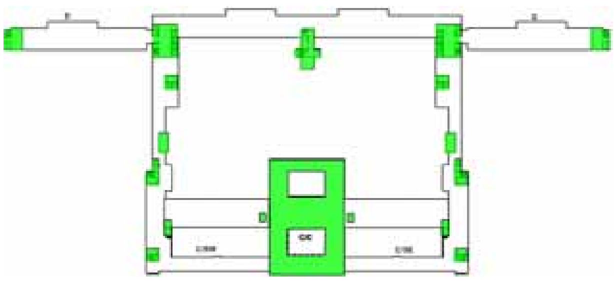
Eleventh Floor
1995/96 NHFA 3.7

Key Issues
- General problems highlighted (scoring 3 or below) include wall finishes, water supply (hot & cold), fire appliances, steam, vacuum, heating, ventilation and air-conditioning
- Primary circulation generally poorer condition than departments
- General air quality and thermal quality problematic
- Housekeeping in general



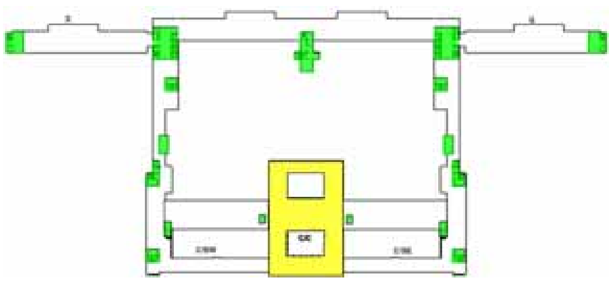
Eleventh Floor
2005 Assessment 2.9

Key Issues
- Failing wall & floor Vinyl covering
- Failing floor screeds under vinyl floor covering
- Missing & damaged metal ceiling panels in passages
- Leaking sewer & water pipes in service shafts
- Chilled and hot water piping
- Air handling units need replacement
- Lighting and power distribution are old and outdated
- Whole LV reticulation system should be replaced
- Fire doors:- springs defective, doors open or locked
- Waterproofing on roof slabs to be replaced



Twelfth Floor
1995/96 NHFA 3.9

Key Issues
- Waterproofing on roof needs replacement



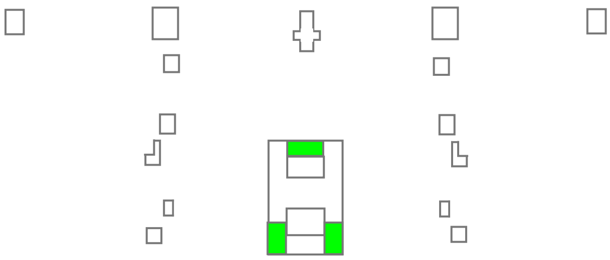
Twelfth Floor
2005 Assessment 2.8

Key Issues
- Waterproofing on roof needs replacement
- Leaks from plant on roof
- Damp in walls
- Lack of regular maintenance
- Storage of junk

5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

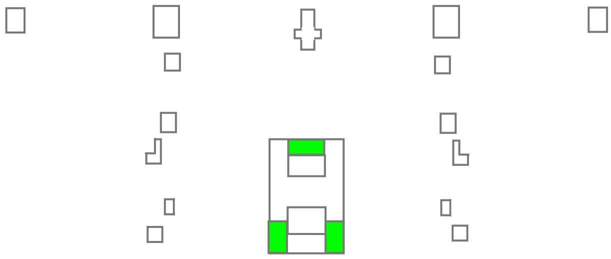
Hospital A
CONDITION PROFILE 12

CSIR : Final 3 October 2005



Thirteenth Floor
1995/96 NHFA **3.9**

Key Issues
- Waterproofing on roof needs replacement



Thirteenth Floor
2005 Assessment **3.0**

Key Issues
- Waterproofing on roof needs replacement

5	Very good / Normal maintenance	value ≥ 4.5
4	Good / Condition-based maintenance	4.0 ≤ value < 4.5
3	Fair / Repairs	3.0 ≤ value < 4.0
2	Poor / Rehabilitation	2.0 ≤ value < 3.0
1	Very Poor / Replacement	1.0 ≤ value < 2.0

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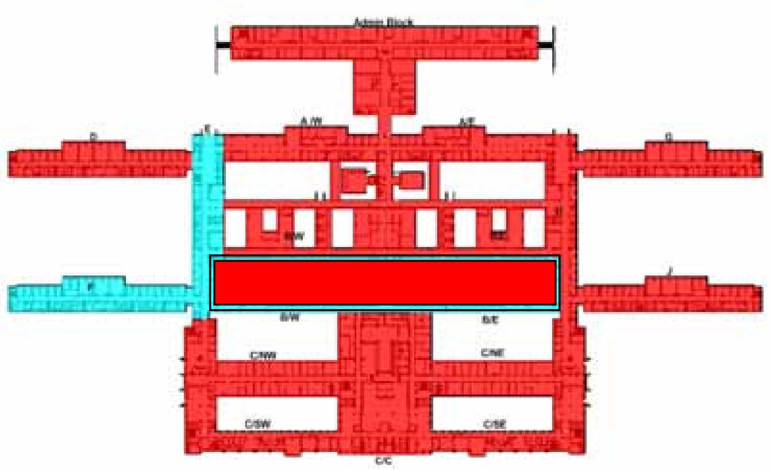
Hospital A
CONDITION PROFILE 13



Main Building Roofs
2005 Assessment

Key Issues
- Main Building:
  - Replace waterproofing on all roofs except Block A – East, Block E, Block F and ring around Block B
  - Block B (Theatre block) - Replace metal roof sheeting in total
- Mortuary: Replace waterproofing
- Block X and Boiler house: Repairs to roof cladding – Condition 3
- Pumphouses and substations: Replace waterproofing

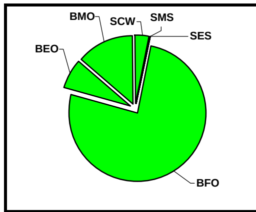
5	Very good / Normal maintenance	value ≥ 4.5	
4	Good / Condition-based maintenance	4.0 ≤ value	< 4.5
3	Fair / Repairs	3.0 ≤ value	< 4.0
2	Poor / Rehabilitation	2.0 ≤ value	< 3.0
1	Very Poor / Replacement	1.0 ≤ value	< 2.0

Hospital A
CONDITION PROFILE 14

CSIR : Final 3 October 2005

HOSPITAL C

AVERAGE FACILITY CONDITION	3.77



ELEMENT GROUP SUMMARY

BFO - Building Fabric
BEO - Building Electrical
BMO - Building Mechanical
SCW - Site Civil Works
SES - Site Electrical
SMS - Site Mechanical

SITEWORKS	3.82
SITE : CIVIL WORKS	3.82
Access Roads	3.8
Roads and driveways	3.7
Parking, paving	3.9
Signage	0.0
Landscaping and gardens	3.6
Site fencing and gates	2.8
Walling (Free Standing)	0.0
Retaining walls	4.0
Swimming pool	3.8
Sports fields	0.0
Sewerage	3.9
Stormwater	3.9
Water supply and reticulation	3.6
Fire Service	0.0
Special	0.0
SITE : ELECTRICAL SERVICES	4.00
Reticulation	4.0
Services	0.0
Power Generation	0.0
Communication & Data Systems	0.0
Security Systems	0.0
Special Systems	0.0
SITE : MECHANICAL SERVICES	0.00
Chilled Water Systems	0.0
Compressed Air	0.0
Steam Installations	0.0
Pumps	0.0
Medical Gas	0.0

CONDITION RATINGS:

Rating	Value
As new	5
Maintain	4
Repair	3
Rehabilitate	2
Replace	1
No service	0

Most recent update: '22 Jul 2004
Primary assessment date: '12 Dec 2003

BUILDING, FLOOR and ZONE - REFERENCE NUMBER and NAME

		B001 SECURITY / GATE HOUSE	B002 EMERGENCY GENERATORS / STORES	B003 BOILER HOUSE	F000: Z0001	F-01: Z0001	F-02: Z0001	B004 INCINERATORS	B005 STORES - REFUSE	B006 MAIN HOSPITAL BUILDING	F000: Z0001	F001: Z0001	F002: Z0001	F003: Z0001	F004: Z0001	F005: Z0001	F006: Z0001	F007: Z0001	F008: Z0001	F008: Z0002	F009: Z0001	F-01: Z0001	F010: Z0001	F011: Z0001	F012: Z0001	F-02: Z0001	B007 OUT PATIENTS - WEST	F000: Z0001	F001: Z0001	F-01: Z0001	F-02: Z0001
BUILDINGS	3.77	3.44	3.90	3.71				3.59	4.00	3.73																	3.97				
BUILDING FABRIC OVERALL	3.77	3.37	3.81	3.99	3.98	4.00	3.99	3.42	4.00	3.73	3.64	3.93	3.18	3.68	3.80	3.32	3.63	3.41	4.50	3.60	4.67	3.60	3.35	3.80	2.11	3.99	3.99	4.00	4.00	3.96	4.00
BUILDING / ZONE FABRIC	3.77	3.37	3.81	4.00	3.98	4.00	3.99	3.42	4.00	3.89	3.61	3.91	3.11	3.66	3.78	3.27	3.61	3.36	4.54	3.56	4.77	3.57	3.33	3.90	4.00	3.99	4.00	4.00	4.00	3.96	4.00
External walls and wall finishes	3.89	3.9	4.0	4.0	0.0	0.0	0.0	4.0	4.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
External Doors	3.89	3.0	4.0	4.0	0.0	0.0	0.0	0.0	4.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
Windows	3.89	3.9	3.8	3.9	0.0	0.0	0.0	0.0	4.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
Roofs	3.80	4.0	3.0	4.0	0.0	0.0	0.0	3.0	4.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
External floors and floor finishes	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
External ceilings and ceiling finishes	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Internal walls and wall finishes	3.70	3.9	3.8	0.0	3.8	4.0	4.0	0.0	0.0	0.0	3.7	3.9	3.4	3.6	3.8	3.8	3.5	3.7	4.0	3.7	4.0	3.5	3.7	3.3	4.0	4.0	0.0	4.0	4.0	3.8	0.0
Internal Doors	3.72	1.0	4.0	0.0	4.0	0.0	3.9	0.0	0.0	0.0	4.0	4.0	3.3	3.9	3.9	3.3	3.0	3.2	5.0	3.4	5.0	3.2	3.9	3.4	4.0	3.9	0.0	4.0	4.0	4.0	0.0
Internal floors and floor finishes	3.71	3.1	4.0	0.0	4.0	4.0	4.0	0.0	0.0	0.0	3.4	3.8	2.5	3.7	3.9	3.4	4.0	3.7	5.0	3.7	5.0	3.9	2.8	4.0	4.0	4.0	0.0	4.0	4.0	4.0	4.0
Internal ceilings and ceiling finishes	3.58	3.9	3.8	0.0	0.0	4.0	4.0	0.0	0.0	0.0	3.1	3.9	2.0	3.8	3.6	3.2	3.6	3.2	5.0	3.7	5.0	3.4	2.5	4.0	4.0	4.0	0.0	4.0	0.0	4.0	4.0
Plumbing	3.74	3.1	3.8	0.0	4.0	0.0	0.0	0.0	0.0	0.0	3.9	3.9	3.0	3.9	3.7	3.5	4.0	3.1	4.0	3.4	5.0	3.9	4.0	0.0	0.0	0.0	0.0	4.0	0.0	4.0	0.0
Fixtures and Fittings	3.60	2.2	4.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	3.7	4.0	3.5	3.5	3.4	2.5	3.0	2.2	4.0	3.1	5.0	3.4	4.0	0.0	0.0	0.0	0.0	4.0	0.0	4.0	0.0
Special	4.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BUILDING ELECTRICAL OVERALL	3.73	4.00	4.00	3.97				0.00	4.00	3.56																	4.00				
BUILDING / ZONE ELECTRICAL	3.73	4.00	4.00	0.00	3.96	4.00	0.00	0.00	4.00	0.00	3.88	4.00	3.61	3.91	3.97	3.85	3.85	3.85	4.19	4.00	4.25	4.00	3.48	3.60	2.01	4.00	0.00	4.00	4.00	4.00	4.00
Building Minor Electrical Installations	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reticulation	3.98	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	4.0	2.0	0.0	0.0	0.0	0.0	0.0	4.0
Services	3.94	4.0	4.0	0.0	3.9	4.0	0.0	0.0	4.0	0.0	3.9	4.0	3.6	3.9	4.0	3.9	3.9	3.9	4.1	4.0	4.3	4.0	3.9	4.0	4.0	4.0	0.0	4.0	0.0	4.0	4.0
Power Generation	3.97	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	4.0	4.0	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Communication & Data Systems	2.99	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	2.5	3.0	4.0	3.0	3.0	3.0	4.4	4.0	4.0	4.0	1.1	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0
Security Systems	4.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fire Protection	4.46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lifts & Escalators	3.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	2.0	0.0	0.0	0.0	4.0	0.0	0.0
Control & Monitoring Systems	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Special Systems	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BUILDING MECHANICAL OVERALL	3.77	0.00	0.00	3.58				3.68	0.00	3.84																	3.82				
BUILDING / ZONE MECHANICAL	3.77	0.00	0.00	3.58	0.00	0.00	0.00	3.68	0.00	3.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.82	0.00	0.00	0.00	0.00
Airconditioners : Packaged Units	3.84	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0
Airconditioners : Room Type	3.94	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chilled Water Systems	3.50	0.0	0.0	3.1	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0
Ventilation Installations	3.90	0.0	0.0	3.5	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0
Steam Installations	3.78	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Medical Gas and Compressed Air	3.52	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0
Central Heating	3.88	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0
Laundry Equipment	3.85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Autoclaves	3.81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigeration	3.53	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Incinerators	3.18	0.0	0.0	2.7	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kitchen Equipment	3.87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Workshop Equipment	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Special Doors	4.28	0.0	0.0	4.7	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fire Protection	3.93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pumping Plants	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Conveyor Systems	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cranes And Hoists	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heat Pump Installations	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Specialised Mechanical Services	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX B-2: EXTRACT FROM HOSPITAL C CONDITION MATRIX

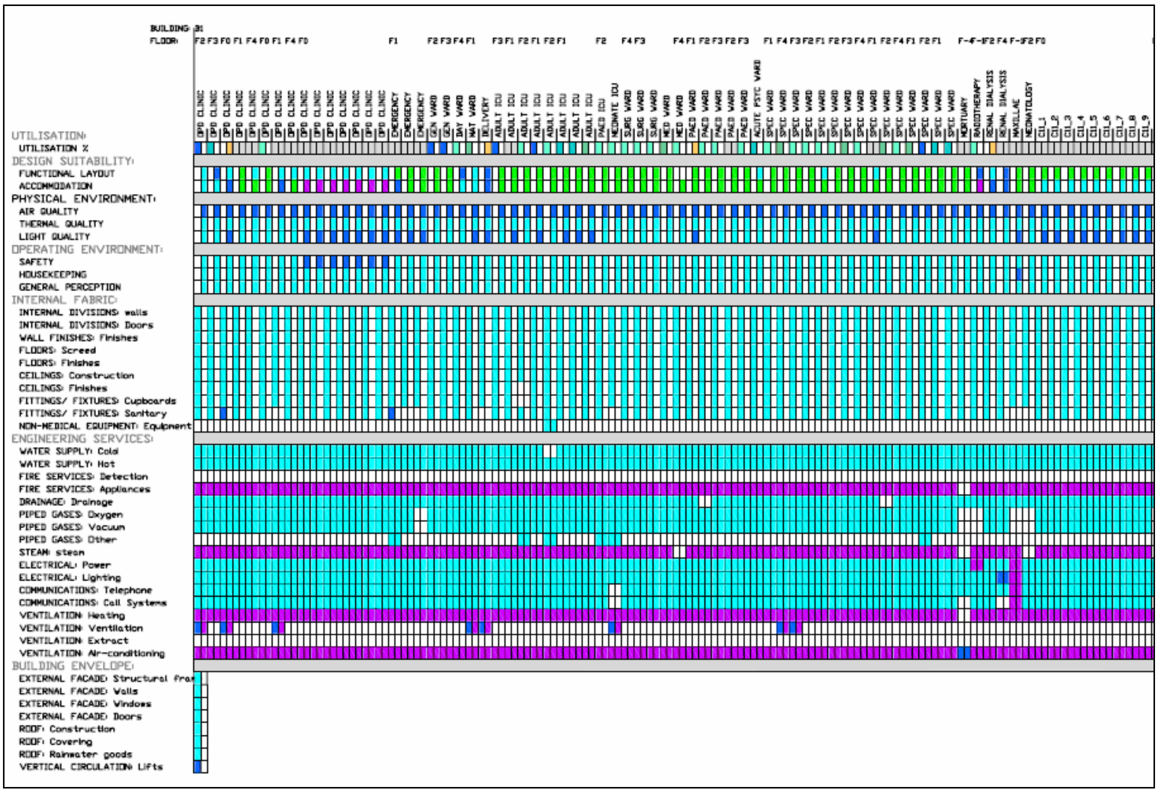


FIGURE B-3-1: CONDITION MATRIX FOR 1995 NHFA AUDIT

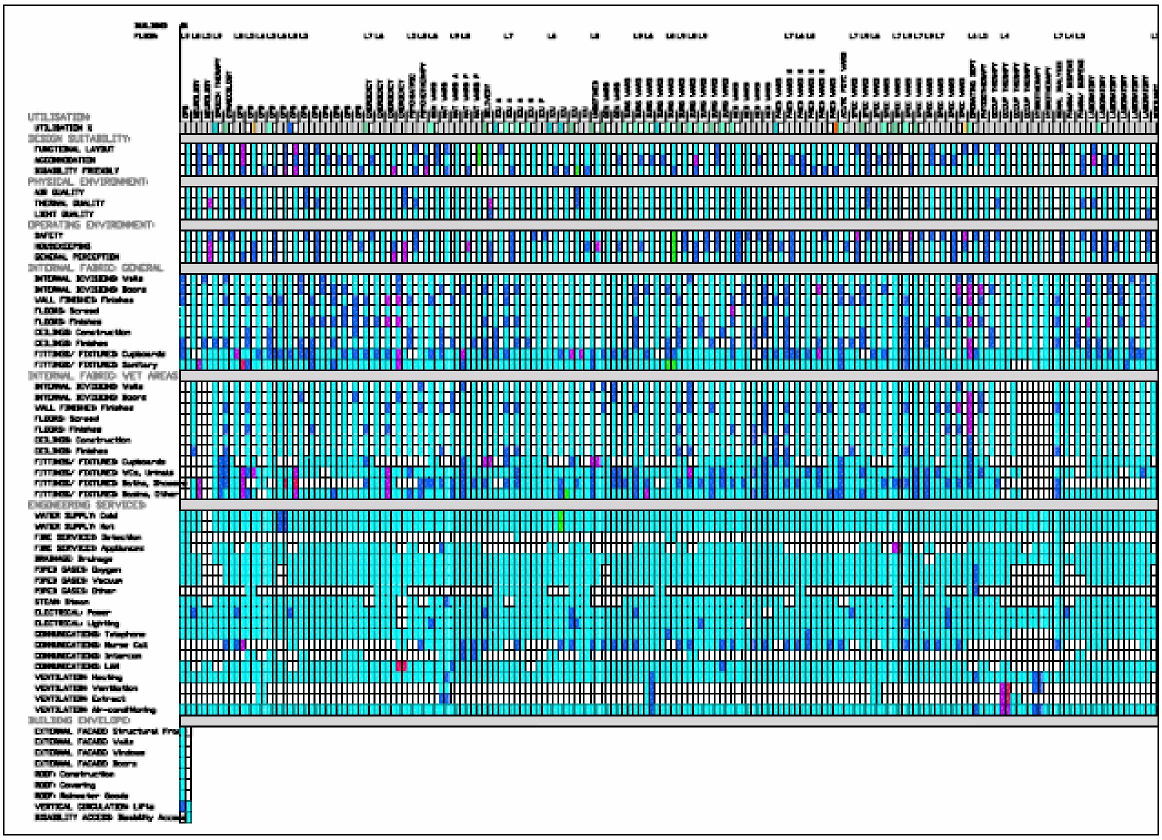


FIGURE B-3-2: CONDITION MATRIX FOR 1999 AUDIT

APPENDIX B-3: EXTRACTS FROM HOSPITAL D AUDIT

Appendix C: Transition Probability Matrices for Proposed Markovian Model

Hospital A

Facility Type	Tertiary Hospital (Academic - Government)			
Year construction completed	1975	Age	30 years	(2005)
Total Floor Area	218,603	m^2	Main building only	
No of levels	15			
Structural frame	Reinforced concrete			
External walls	Face brick			
External windows	Aluminium			
Roof	Flat concrete slabs with waterproofing			
Estimated current consruction cost	R 1,882,376,130			
	$289,596,328	± @ R6.50/US$1.00		

VARIABLES	**Rating**	
Design Level	4	High
Material	4	High
Workmanship	4	High
External Climate	3	Slightly Aggressive
Internal Climate	0	External Elements
Operational Environment	3.5	Less Favourable to Slightly Aggressive
Maintenance level	**2**	**Low**
Current Average Condition	**3.02**	**Fair**

CONDITION	5	4	3	2	1
% at t = 0	**100%**	**0%**	**0%**	**0%**	**0%**
Average Condition @ t = 0	5.00				

Markov Transition Probability Matrix		Condition at time t = 1				
		5	4	3	2	1
Condition at time t = 0	5	0.950	0.050	0	0	0
	4	0	0.915	0.085	0	0
	3	0	0	0.900	0.100	0
	2	0	0	0	0.875	0.125
	1	0	0	0	0	1
		Very Good	Good	Fair	Bad	Very Bad
		5	4	3	2	1

Year	Age	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1		Average Condition	
1975	0	100.000%	0.000%	0.000%	0.000%	0.000%		**5.00**	**1975: Completion of Construction**
1976	1	95.000%	5.000%	0.000%	0.000%	0.000%		**4.95**	
1977	2	90.250%	9.325%	0.425%	0.000%	0.000%		**4.90**	
1978	3	85.738%	13.045%	1.175%	0.043%	0.000%		**4.84**	
1979	4	81.451%	16.223%	2.166%	0.155%	0.005%		**4.79**	
1980	5	77.378%	18.917%	3.329%	0.352%	0.025%		**4.73**	
1981	6	73.509%	21.178%	4.604%	0.641%	0.069%		**4.67**	
1982	7	69.834%	23.053%	5.943%	1.021%	0.149%		**4.61**	
1983	8	66.342%	24.585%	7.309%	1.488%	0.276%		**4.55**	
1984	9	63.025%	25.812%	8.667%	2.033%	0.462%		**4.49**	
1985	10	59.874%	26.770%	9.995%	2.645%	0.716%		**4.42**	
1986	11	56.880%	27.488%	11.271%	3.314%	1.047%		**4.36**	
1987	12	54.036%	27.995%	12.480%	4.027%	1.461%		**4.29**	
1988	13	51.334%	28.318%	13.612%	4.772%	1.965%		**4.22**	
1989	14	48.767%	28.477%	14.658%	5.536%	2.561%		**4.15**	
1990	15	46.329%	28.495%	15.612%	6.310%	3.253%		**4.08**	
1991	16	44.013%	28.390%	16.473%	7.083%	4.042%		**4.01**	
1992	17	41.812%	28.177%	17.239%	7.845%	4.927%		**3.94**	
1993	18	39.721%	27.873%	17.910%	8.588%	5.908%		**3.87**	
1994	19	37.735%	27.489%	18.488%	9.305%	6.981%		**3.80**	
1995	20	35.849%	27.040%	18.976%	9.991%	8.145%		**3.72**	
1996	21	34.056%	26.534%	19.377%	10.640%	9.393%	*	**3.65**	**1996: NHF Audit**
1997	22	32.353%	25.981%	19.695%	11.248%	10.723%		**3.58**	
1998	23	30.736%	25.390%	19.933%	11.811%	12.129%		**3.51**	
1999	24	29.199%	24.769%	20.098%	12.328%	13.606%		**3.44**	
2000	25	27.739%	24.124%	20.194%	12.797%	15.147%		**3.37**	
2001	26	26.352%	23.460%	20.225%	13.217%	16.746%		**3.29**	
2002	27	25.034%	22.784%	20.197%	13.587%	18.398%		**3.22**	
2003	28	23.783%	22.099%	20.114%	13.908%	20.097%		**3.16**	
2004	29	22.594%	21.409%	19.981%	14.181%	21.835%		**3.09**	
2005	30	21.464%	20.719%	19.802%	14.407%	23.608%	*	**3.02**	**2005: CSIR Audit**

VARIABLES

Design Level	4	High
Material	4	High
Workmanship	4	High
External Climate	3	Slightly Aggressive
Internal Climate	0	External Elements
Operational Environme	3.5	Less Favourable to Slightly Aggressive
Maintenance level	**1**	**Very Low - No Maintenance**

CONDITION	5	4	3	2	1
% at t = 0	**100%**	**0%**	**0%**	**0%**	**0%**
Average Condition	5.00				

Markov Transition Probability Matrix		Condition at time = 1				
		5	4	3	2	1
Condition at time t = 0	5	94.000%	6.000%	0.000%	0.000%	0.000%
	4	0.000%	89.800%	10.200%	0.000%	0.000%
	3	0.000%	0.000%	88.000%	12.000%	0.000%
	2	0.000%	0.000%	0.000%	85.000%	15.000%
	1	0.000%	0.000%	0.000%	0.000%	100.000%

	Very Good 5	Good 4	Fair 3	Bad 2	Very Bad 1	
Age	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1	Average Condition
0	100.000%	0.000%	0.000%	0.000%	0.000%	**5.00**
1	94.000%	6.000%	0.000%	0.000%	0.000%	**4.94**
2	88.360%	11.028%	0.612%	0.000%	0.000%	**4.88**
3	83.058%	15.205%	1.663%	0.073%	0.000%	**4.81**
4	78.075%	18.637%	3.015%	0.262%	0.011%	**4.75**
5	73.390%	21.421%	4.554%	0.584%	0.050%	**4.68**
6	68.987%	23.639%	6.192%	1.043%	0.138%	**4.60**
7	64.848%	25.367%	7.861%	1.630%	0.294%	**4.53**
8	60.957%	26.671%	9.505%	2.329%	0.539%	**4.45**
9	57.299%	27.608%	11.085%	3.120%	0.888%	**4.37**
10	53.862%	28.230%	12.570%	3.982%	1.356%	**4.29**
11	50.630%	28.582%	13.941%	4.893%	1.954%	**4.21**
12	47.592%	28.704%	15.184%	5.832%	2.688%	**4.13**
13	44.737%	28.632%	16.290%	6.779%	3.562%	**4.04**
14	42.052%	28.396%	17.255%	7.717%	4.579%	**3.96**
15	39.529%	28.023%	18.081%	8.630%	5.737%	**3.87**
16	37.157%	27.536%	18.770%	9.505%	7.031%	**3.78**
17	34.928%	26.957%	19.326%	10.332%	8.457%	**3.70**
18	32.832%	26.303%	19.756%	11.101%	10.007%	**3.61**
19	30.862%	25.590%	20.069%	11.807%	11.672%	**3.52**
20	29.011%	24.831%	20.270%	12.444%	13.443%	**3.44**
21	27.270%	24.039%	20.371%	13.010%	15.310%	**3.35**
22	25.634%	23.224%	20.378%	13.503%	17.261%	**3.26**
23	24.096%	22.393%	20.302%	13.923%	19.287%	**3.18**
24	22.650%	21.554%	20.150%	14.271%	21.375%	**3.10**
25	21.291%	20.715%	19.930%	14.548%	23.516%	**3.02**
26	20.014%	19.879%	19.651%	14.757%	25.698%	**2.94**
27	18.813%	19.053%	19.321%	14.902%	27.912%	**2.86**
28	17.684%	18.238%	18.946%	14.985%	30.147%	**2.78**
29	16.623%	17.439%	18.533%	15.011%	32.395%	**2.71**
30	15.626%	16.657%	18.087%	14.983%	34.646%	**2.64**

VARIABLES	**Rating**	
Design Level	4	High
Material	4	High
Workmanship	4	High
External Climate	3	Slightly Aggressive
Internal Climate	0	External Elements
Operational Environment	3.5	Less Favourable to Slightly Aggressive
Maintenance level	**2**	**Low**

CONDITION	5	4	3	2	1
% at t = 0	**100%**	**0%**	**0%**	**0%**	**0%**
Average Condition @ t = 0	5.00				

Markov Transition Probability Matrix		Condition at time t = 1				
		5	4	3	2	1
Condition at time t = 0	5	0.950	0.050	0	0	0
	4	0	0.915	0.085	0	0
	3	0	0	0.900	0.100	0
	2	0	0	0	0.875	0.125
	1	0	0	0	0	1
		Very Good	Good	Fair	Bad	Very Bad
		5	4	3	2	1

Year	Age	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1		Average Condition
1975	0	100.000%	0.000%	0.000%	0.000%	0.000%		**5.00**
1976	1	95.000%	5.000%	0.000%	0.000%	0.000%		**4.95**
1977	2	90.250%	9.325%	0.425%	0.000%	0.000%		**4.90**
1978	3	85.738%	13.045%	1.175%	0.043%	0.000%		**4.84**
1979	4	81.451%	16.223%	2.166%	0.155%	0.005%		**4.79**
1980	5	77.378%	18.917%	3.329%	0.352%	0.025%		**4.73**
1981	6	73.509%	21.178%	4.604%	0.641%	0.069%		**4.67**
1982	7	69.834%	23.053%	5.943%	1.021%	0.149%		**4.61**
1983	8	66.342%	24.585%	7.309%	1.488%	0.276%		**4.55**
1984	9	63.025%	25.812%	8.667%	2.033%	0.462%		**4.49**
1985	10	59.874%	26.770%	9.995%	2.645%	0.716%		**4.42**
1986	11	56.880%	27.488%	11.271%	3.314%	1.047%		**4.36**
1987	12	54.036%	27.995%	12.480%	4.027%	1.461%		**4.29**
1988	13	51.334%	28.318%	13.612%	4.772%	1.965%		**4.22**
1989	14	48.767%	28.477%	14.658%	5.536%	2.561%		**4.15**
1990	15	46.329%	28.495%	15.612%	6.310%	3.253%		**4.08**
1991	16	44.013%	28.390%	16.473%	7.083%	4.042%		**4.01**
1992	17	41.812%	28.177%	17.239%	7.845%	4.927%		**3.94**
1993	18	39.721%	27.873%	17.910%	8.588%	5.908%		**3.87**
1994	19	37.735%	27.489%	18.488%	9.305%	6.981%		**3.80**
1995	20	35.849%	27.040%	18.976%	9.991%	8.145%		**3.72**
1996	21	34.056%	26.534%	19.377%	10.640%	9.393%	*	**3.65**
1997	22	32.353%	25.981%	19.695%	11.248%	10.723%		**3.58**
1998	23	30.736%	25.390%	19.933%	11.811%	12.129%		**3.51**
1999	24	29.199%	24.769%	20.098%	12.328%	13.606%		**3.44**
2000	25	27.739%	24.124%	20.194%	12.797%	15.147%		**3.37**
2001	26	26.352%	23.460%	20.225%	13.217%	16.746%		**3.29**
2002	27	25.034%	22.784%	20.197%	13.587%	18.398%		**3.22**
2003	28	23.783%	22.099%	20.114%	13.908%	20.097%		**3.16**
2004	29	22.594%	21.409%	19.981%	14.181%	21.835%		**3.09**
2005	30	21.464%	20.719%	19.802%	14.407%	23.608%	*	**3.02**

VARIABLES

Design Level	4	High
Material	4	High
Workmanship	4	High
External Climate	3	Slightly Aggressive
Internal Climate	0	External Elements
Operational Environme	3.5	Less Favourable to Slightly Aggressive
Maintenance level	**3**	**Medium**

CONDITION	5	4	3	2	1
% at t = 0	**100%**	**0%**	**0%**	**0%**	**0%**
Average Condition	5.00				

Markov Transition Probability Matrix		Condition at time = 1				
		5	4	3	2	1
Condition at time t = 0	5	96.000%	4.000%	0.000%	0.000%	0.000%
	4	0.000%	93.200%	6.800%	0.000%	0.000%
	3	0.000%	0.000%	92.000%	8.000%	0.000%
	2	0.000%	0.000%	0.000%	90.000%	10.000%
	1	0.000%	0.000%	0.000%	0.000%	100.000%
		Very Good	Good	Fair	Bad	Very Bad
		5	4	3	2	1

Age	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1	Average Condition
0	100.000%	0.000%	0.000%	0.000%	0.000%	**5.00**
1	96.000%	4.000%	0.000%	0.000%	0.000%	**4.96**
2	92.160%	7.568%	0.272%	0.000%	0.000%	**4.92**
3	88.474%	10.740%	0.765%	0.022%	0.000%	**4.88**
4	84.935%	13.548%	1.434%	0.081%	0.002%	**4.83**
5	81.537%	16.025%	2.241%	0.187%	0.010%	**4.79**
6	78.276%	18.196%	3.151%	0.348%	0.029%	**4.74**
7	75.145%	20.090%	4.136%	0.565%	0.064%	**4.70**
8	72.139%	21.730%	5.171%	0.840%	0.120%	**4.65**
9	69.253%	23.138%	6.235%	1.169%	0.204%	**4.60**
10	66.483%	24.334%	7.310%	1.551%	0.321%	**4.55**
11	63.824%	25.339%	8.380%	1.981%	0.476%	**4.50**
12	61.271%	26.169%	9.433%	2.453%	0.674%	**4.45**
13	58.820%	26.840%	10.457%	2.962%	0.920%	**4.40**
14	56.467%	27.368%	11.446%	3.503%	1.216%	**4.34**
15	54.209%	27.766%	12.391%	4.068%	1.566%	**4.29**
16	52.040%	28.046%	13.288%	4.653%	1.973%	**4.24**
17	49.959%	28.220%	14.132%	5.250%	2.438%	**4.18**
18	47.960%	28.300%	14.921%	5.856%	2.963%	**4.12**
19	46.042%	28.294%	15.651%	6.464%	3.549%	**4.07**
20	44.200%	28.211%	16.323%	7.070%	4.195%	**4.01**
21	42.432%	28.061%	16.936%	7.669%	4.902%	**3.95**
22	40.735%	27.850%	17.489%	8.257%	5.669%	**3.90**
23	39.106%	27.586%	17.984%	8.830%	6.495%	**3.84**
24	37.541%	27.274%	18.421%	9.386%	7.378%	**3.78**
25	36.040%	26.921%	18.802%	9.921%	8.316%	**3.72**
26	34.598%	26.532%	19.128%	10.433%	9.309%	**3.67**
27	33.214%	26.112%	19.402%	10.920%	10.352%	**3.61**
28	31.886%	25.665%	19.626%	11.380%	11.444%	**3.55**
29	30.610%	25.195%	19.801%	11.812%	12.582%	**3.49**
30	29.386%	24.706%	19.930%	12.215%	13.763%	**3.44**

VARIABLES	Rating	
Design Level	4	High
Material	4	High
Workmanship	4	High
External Climate	3	Slightly Aggressive
Internal Climate	0	External Elements
Operational Environment	3.5	Less Favourable to Slightly Aggressive
Maintenance level	**4**	**High**

CONDITION	5	4	3	2	1
% at t = 0	**100%**	**0%**	**0%**	**0%**	**0%**
Average Condition	5.00				

Markov Transition Probability Matrix		Condition at time = 1				
		5	4	3	2	1
Condition at time t = 0	5	97.000%	3.000%	0.000%	0.000%	0.000%
	4	0.000%	94.900%	5.100%	0.000%	0.000%
	3	0.000%	0.000%	94.000%	6.000%	0.000%
	2	0.000%	0.000%	0.000%	92.500%	7.500%
	1	0.000%	0.000%	0.000%	0.000%	100.000%

	Very Good 5	Good 4	Fair 3	Bad 2	Very Bad 1	
Age	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1	Average Condition
0	100.000%	0.000%	0.000%	0.000%	0.000%	**5.00**
1	97.000%	3.000%	0.000%	0.000%	0.000%	**4.97**
2	94.090%	5.757%	0.153%	0.000%	0.000%	**4.94**
3	91.267%	8.286%	0.437%	0.009%	0.000%	**4.91**
4	88.529%	10.602%	0.834%	0.035%	0.001%	**4.88**
5	85.873%	12.717%	1.324%	0.082%	0.003%	**4.84**
6	83.297%	14.644%	1.894%	0.155%	0.009%	**4.81**
7	80.798%	16.396%	2.527%	0.257%	0.021%	**4.78**
8	78.374%	17.984%	3.211%	0.390%	0.040%	**4.74**
9	76.023%	19.418%	3.936%	0.553%	0.070%	**4.71**
10	73.742%	20.709%	4.690%	0.748%	0.111%	**4.67**
11	71.530%	21.865%	5.465%	0.973%	0.167%	**4.64**
12	69.384%	22.895%	6.252%	1.228%	0.240%	**4.60**
13	67.303%	23.809%	7.045%	1.511%	0.332%	**4.56**
14	65.284%	24.614%	7.836%	1.820%	0.446%	**4.52**
15	63.325%	25.317%	8.621%	2.154%	0.582%	**4.49**
16	61.425%	25.926%	9.395%	2.510%	0.744%	**4.45**
17	59.583%	26.446%	10.154%	2.885%	0.932%	**4.41**
18	57.795%	26.885%	10.893%	3.278%	1.148%	**4.37**
19	56.061%	27.248%	11.611%	3.686%	1.394%	**4.33**
20	54.379%	27.540%	12.304%	4.106%	1.671%	**4.29**
21	52.748%	27.767%	12.970%	4.536%	1.979%	**4.25**
22	51.166%	27.933%	13.608%	4.974%	2.319%	**4.21**
23	49.631%	28.044%	14.216%	5.418%	2.692%	**4.17**
24	48.142%	28.102%	14.793%	5.864%	3.098%	**4.12**
25	46.697%	28.113%	15.339%	6.312%	3.538%	**4.08**
26	45.297%	28.080%	15.852%	6.759%	4.011%	**4.04**
27	43.938%	28.007%	16.333%	7.203%	4.518%	**4.00**
28	42.620%	27.897%	16.782%	7.643%	5.059%	**3.95**
29	41.341%	27.753%	17.198%	8.077%	5.632%	**3.91**
30	40.101%	27.578%	17.581%	8.503%	6.238%	**3.87**

VARIABLES

Design Level	4	High
Material	4	High
Workmanship	4	High
External Climate	3	Slightly Aggressive
Internal Climate	0	External Elements
Operational Environment	3.5	Less Favourable to Slightly Aggressive
Maintenance level	**5**	**Very High**

CONDITION	5	4	3	2	1
% at t = 0	**100%**	**0%**	**0%**	**0%**	**0%**
Average Condition	5.00				

Markov Transition Probability Matrix		Condition at time = 1				
		5	4	3	2	1
Condition at time t = 0	5	98.000%	2.000%	0.000%	0.000%	0.000%
	4	0.000%	96.600%	3.400%	0.000%	0.000%
	3	0.000%	0.000%	96.000%	4.000%	0.000%
	2	0.000%	0.000%	0.000%	95.000%	5.000%
	1	0.000%	0.000%	0.000%	0.000%	100.000%
		Very Good 5	Good 4	Fair 3	Bad 2	Very Bad 1

Age	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1	Average Condition
0	100.000%	0.000%	0.000%	0.000%	0.000%	**5.00**
1	98.000%	2.000%	0.000%	0.000%	0.000%	**4.98**
2	96.040%	3.892%	0.068%	0.000%	0.000%	**4.96**
3	94.119%	5.680%	0.198%	0.003%	0.000%	**4.94**
4	92.237%	7.370%	0.383%	0.010%	0.000%	**4.92**
5	90.392%	8.964%	0.618%	0.025%	0.001%	**4.90**
6	88.584%	10.467%	0.898%	0.049%	0.002%	**4.88**
7	86.813%	11.883%	1.218%	0.082%	0.004%	**4.85**
8	85.076%	13.215%	1.573%	0.127%	0.008%	**4.83**
9	83.375%	14.467%	1.960%	0.183%	0.015%	**4.81**
10	81.707%	15.643%	2.373%	0.253%	0.024%	**4.79**
11	80.073%	16.745%	2.810%	0.335%	0.037%	**4.76**
12	78.472%	17.777%	3.267%	0.431%	0.053%	**4.74**
13	76.902%	18.742%	3.741%	0.540%	0.075%	**4.72**
14	75.364%	19.643%	4.228%	0.662%	0.102%	**4.70**
15	73.857%	20.482%	4.727%	0.798%	0.135%	**4.67**
16	72.380%	21.263%	5.234%	0.948%	0.175%	**4.65**
17	70.932%	21.988%	5.748%	1.110%	0.222%	**4.62**
18	69.514%	22.659%	6.266%	1.284%	0.278%	**4.60**
19	68.123%	23.279%	6.786%	1.470%	0.342%	**4.57**
20	66.761%	23.850%	7.306%	1.668%	0.416%	**4.55**
21	65.426%	24.374%	7.824%	1.877%	0.499%	**4.52**
22	64.117%	24.854%	8.340%	2.096%	0.593%	**4.50**
23	62.835%	25.291%	8.851%	2.325%	0.698%	**4.47**
24	61.578%	25.688%	9.357%	2.563%	0.814%	**4.45**
25	60.346%	26.046%	9.856%	2.809%	0.942%	**4.42**
26	59.140%	26.368%	10.348%	3.063%	1.082%	**4.39**
27	57.957%	26.654%	10.830%	3.324%	1.236%	**4.37**
28	56.798%	26.907%	11.303%	3.591%	1.402%	**4.34**
29	55.662%	27.128%	11.766%	3.863%	1.581%	**4.31**
30	54.548%	27.319%	12.218%	4.141%	1.774%	**4.29**