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

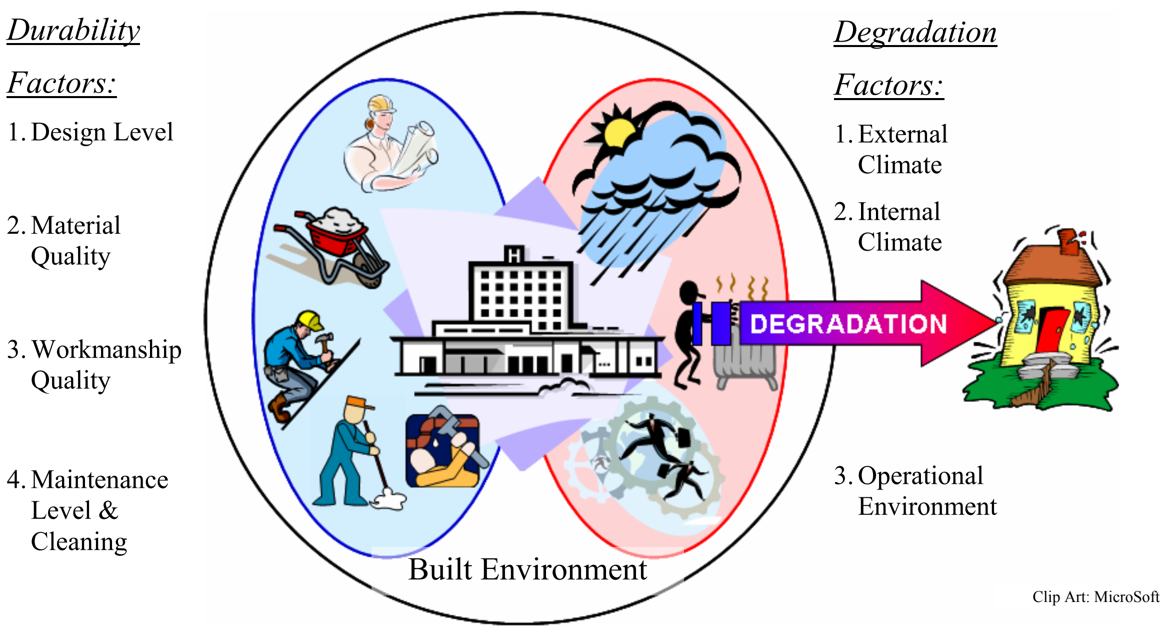


Figure 3-1: Degradation Process

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.

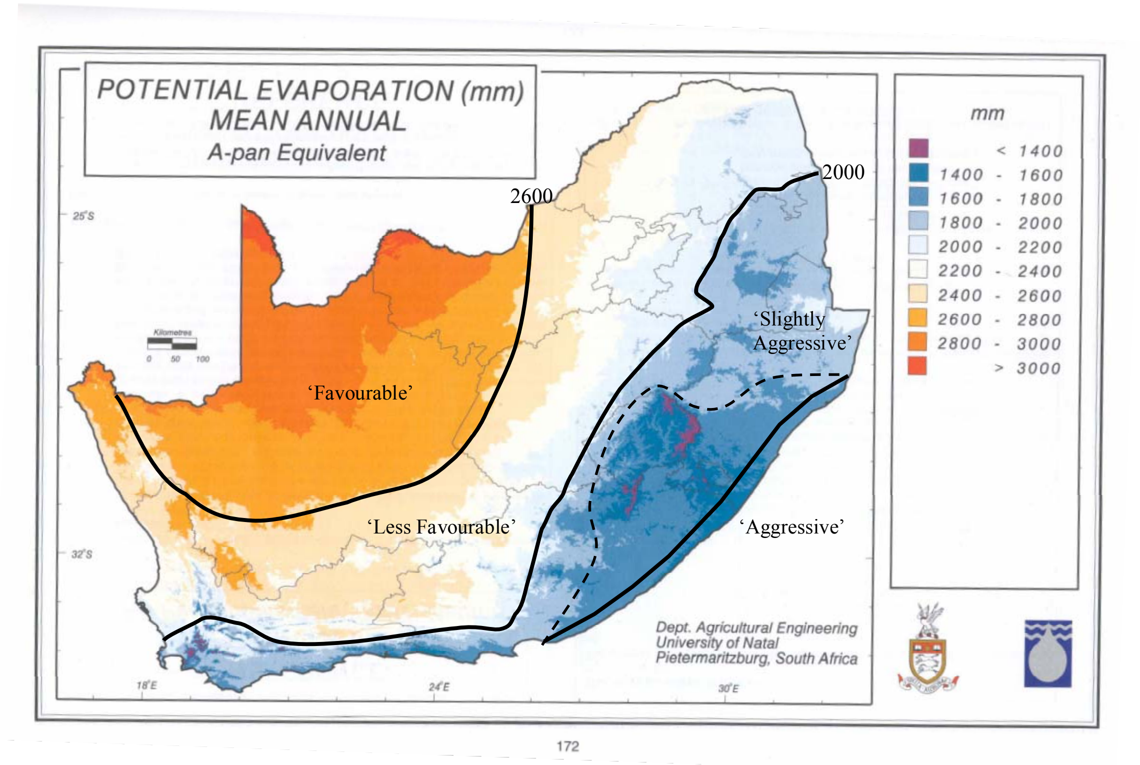


Figure 3-2: Proposed Macroclimate Zone Classification for Chemical and Biological Degradation Agents (Base map: University of Natal)

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.

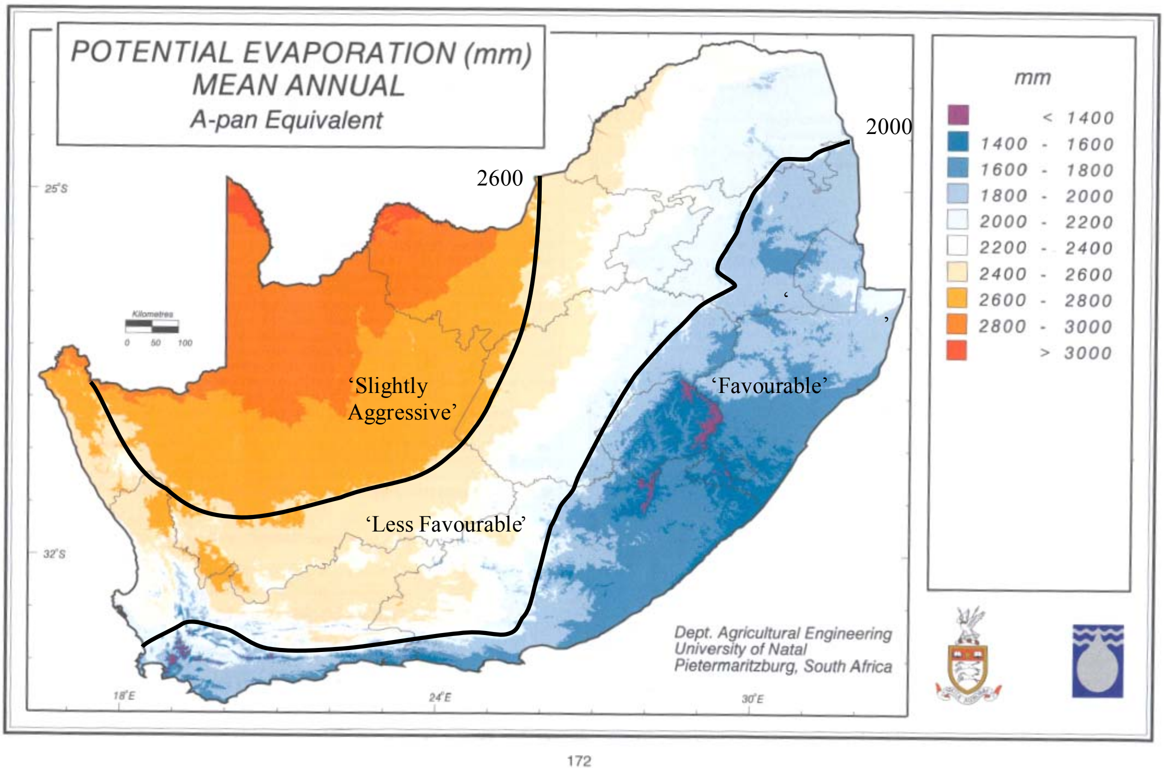


Figure 3-3: Proposed Macroclimate Zone Classification for Mechanical, Electro-magnetic and Thermal Degradation Agents (Base map: University of Natal)

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.

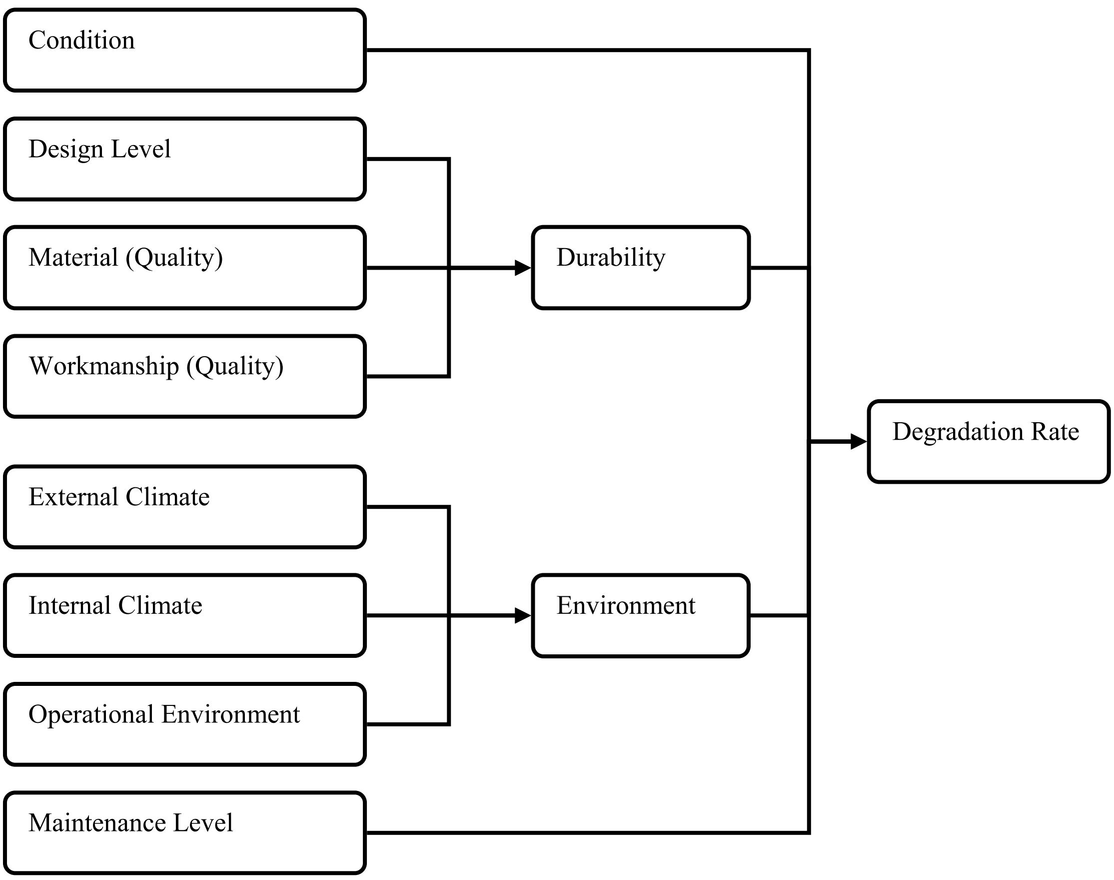


Figure 3-4: Diagram illustration the factors influencing degradation rate

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.

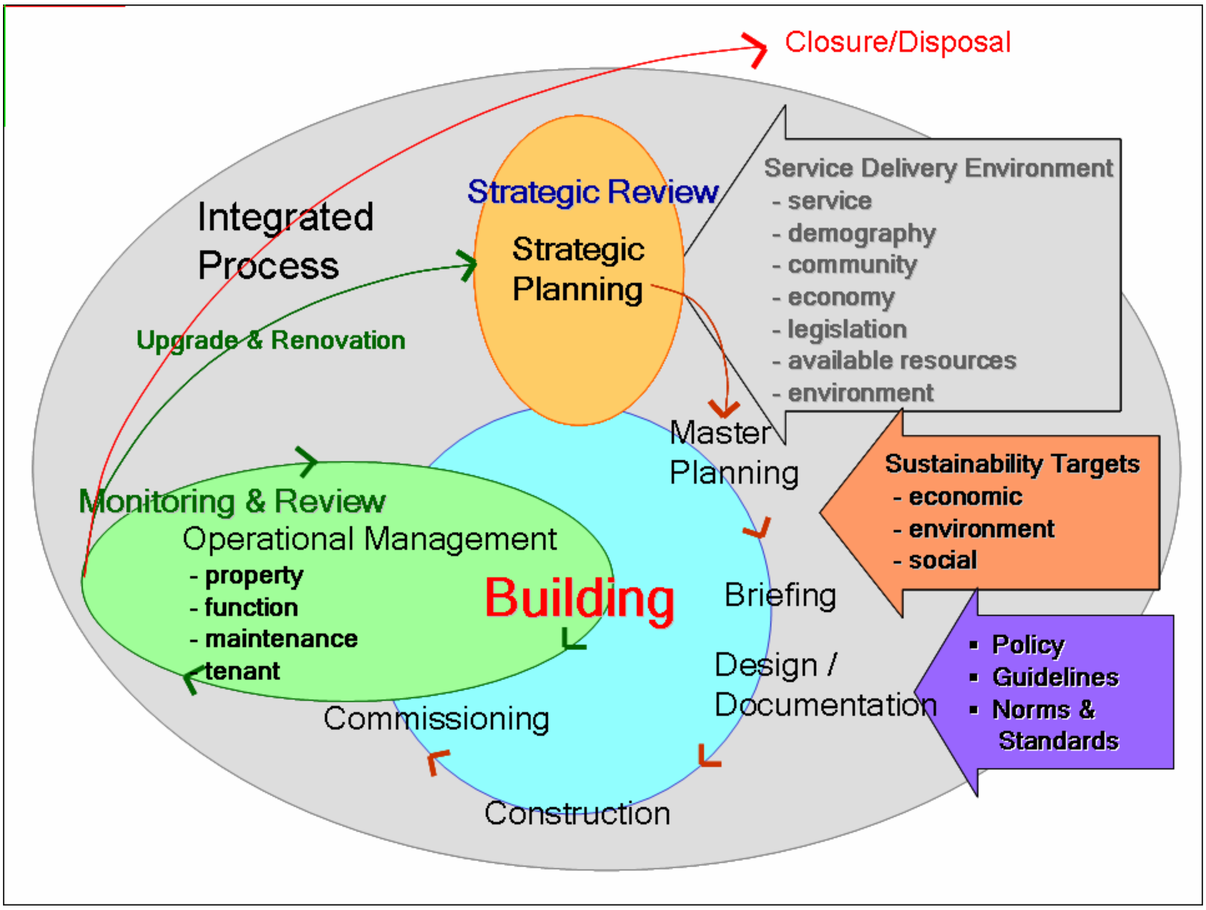


Figure 3-5: Building Life Cycle (Abbott, 2005)

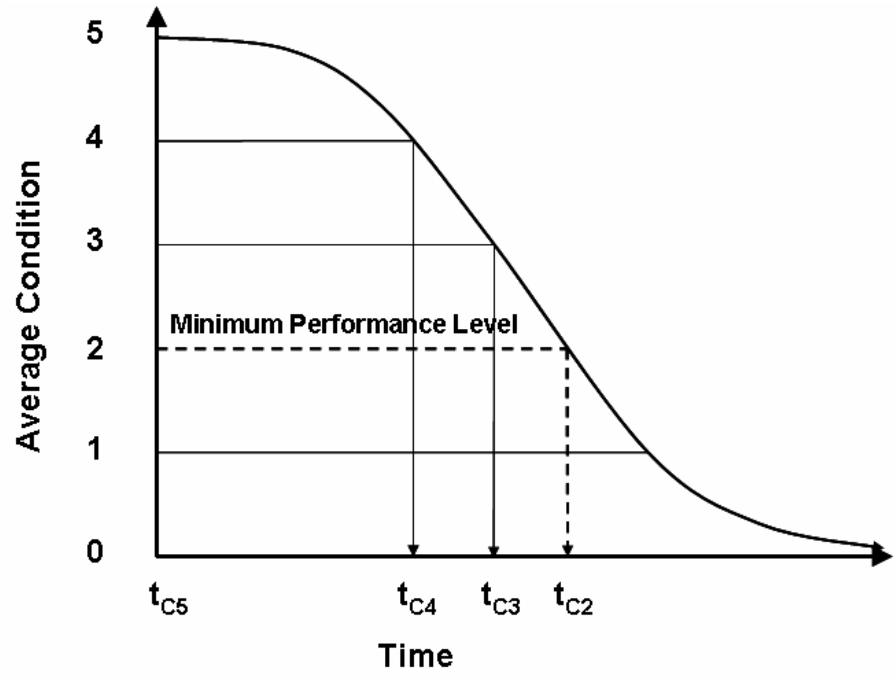


Figure 3-6: Change in condition over time (hypothetical)

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 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.

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

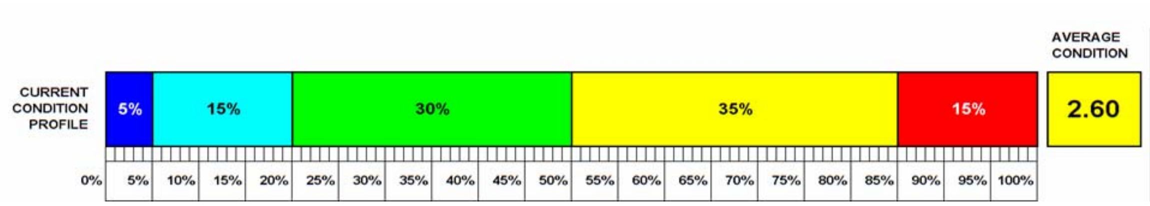


Figure 3-7: Typical Condition Profile

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.

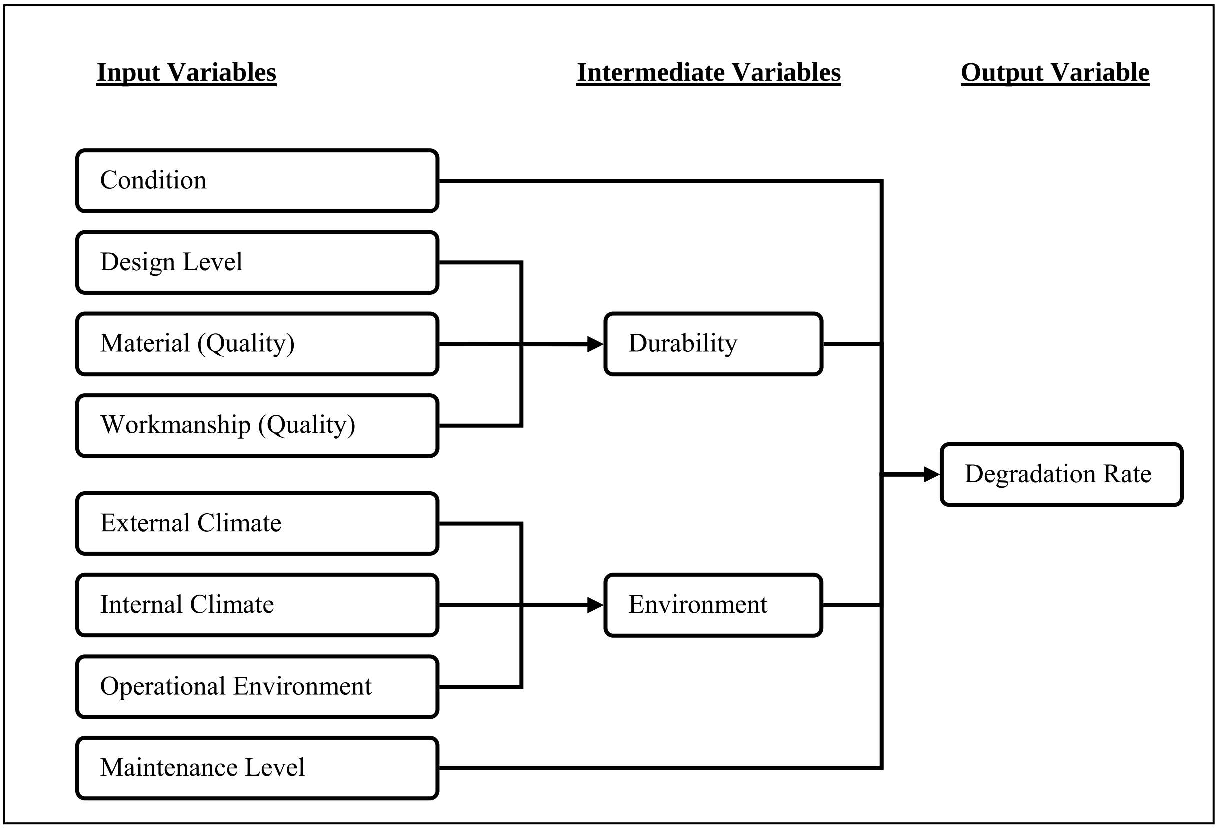


Figure 3-8: Structure of the Fuzzy Logic System

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.

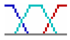
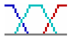
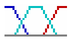
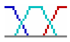
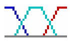
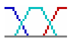
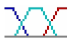
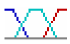
No	Variable Name	Fuzzification method	Unit	Min	Max	Default	Term Names
1	Condition		Units	1	5	4	Very Bad Bad Fair Good Very Good
2	Design Level		Units	1	5	4	Very Low Low Medium High Very High
3	External Climate		Units	0	5	4	Internal Element Very Aggressive Aggressive Slightly Aggressive Less Favourable 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) 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

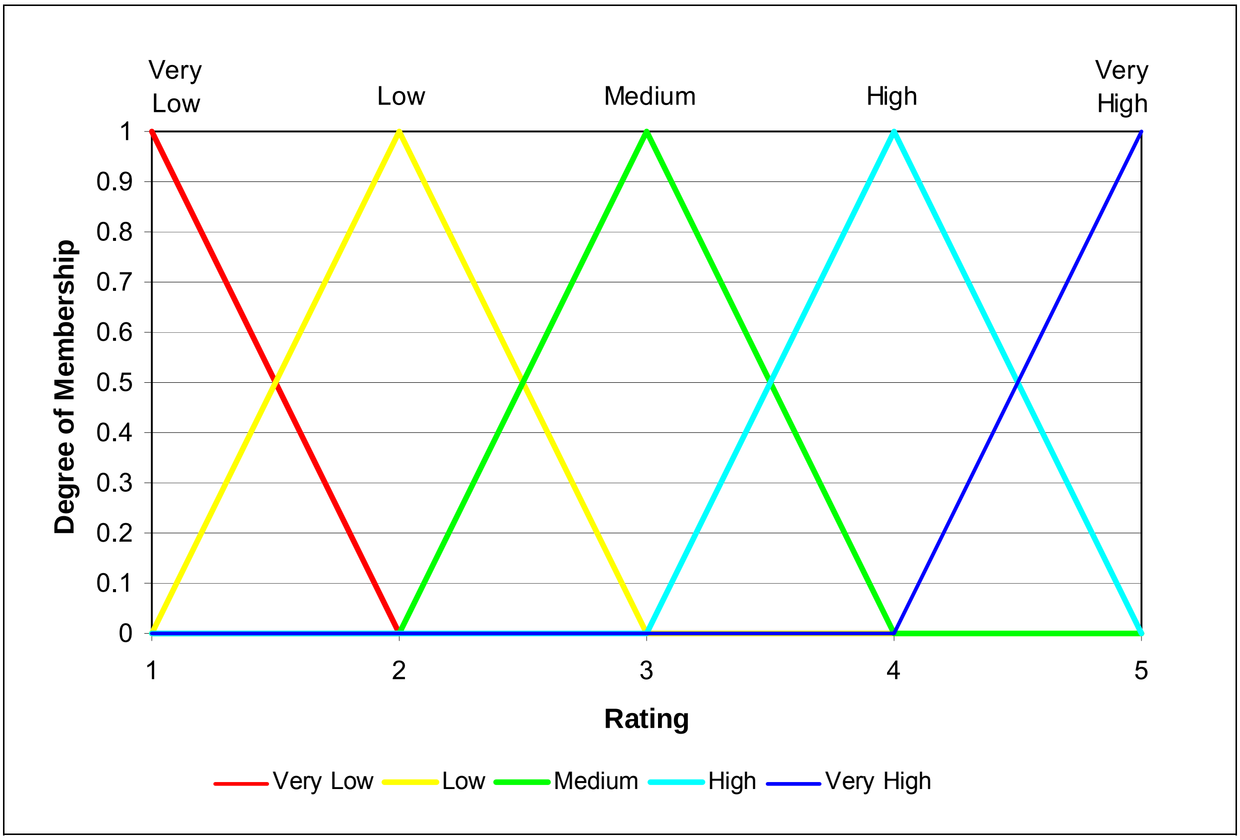


Figure 3-10: Fuzzy Sets for Design Level

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

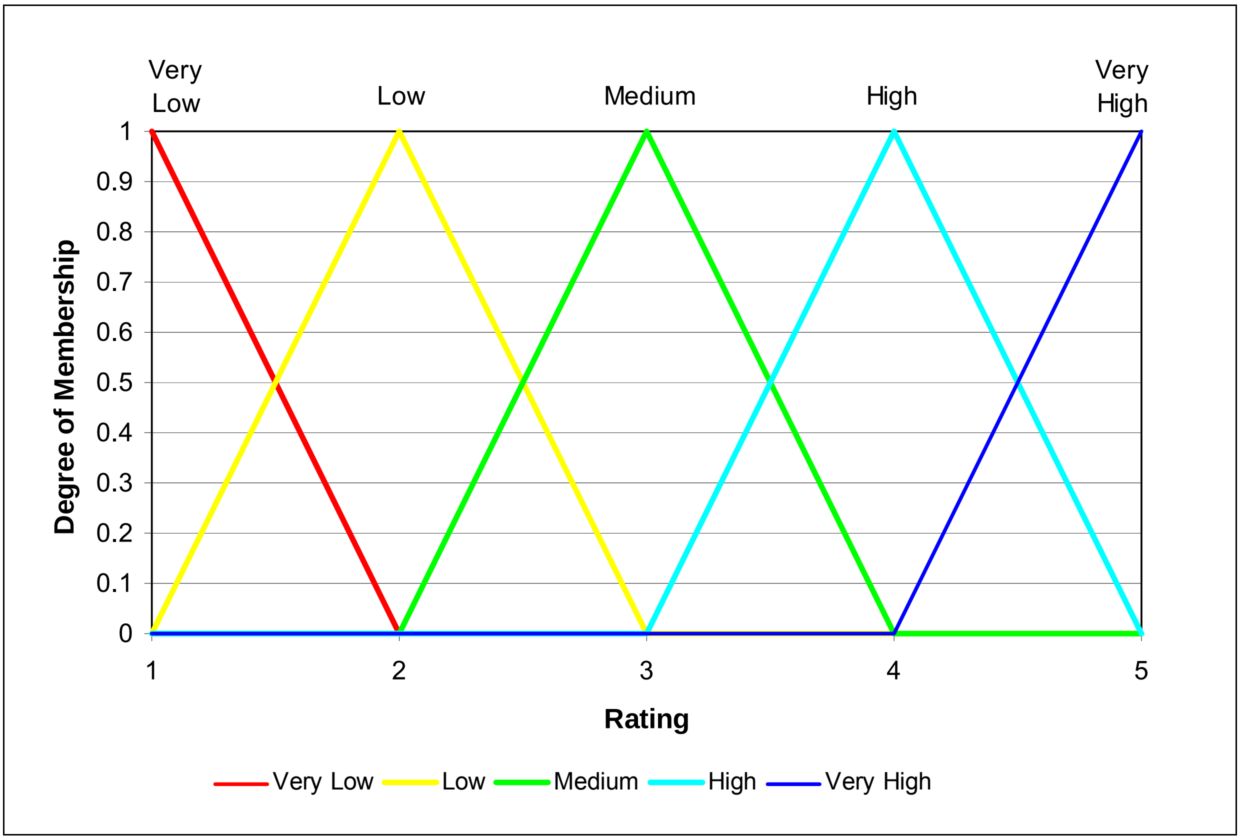


Figure 3-11: Fuzzy Sets for Material Quality

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

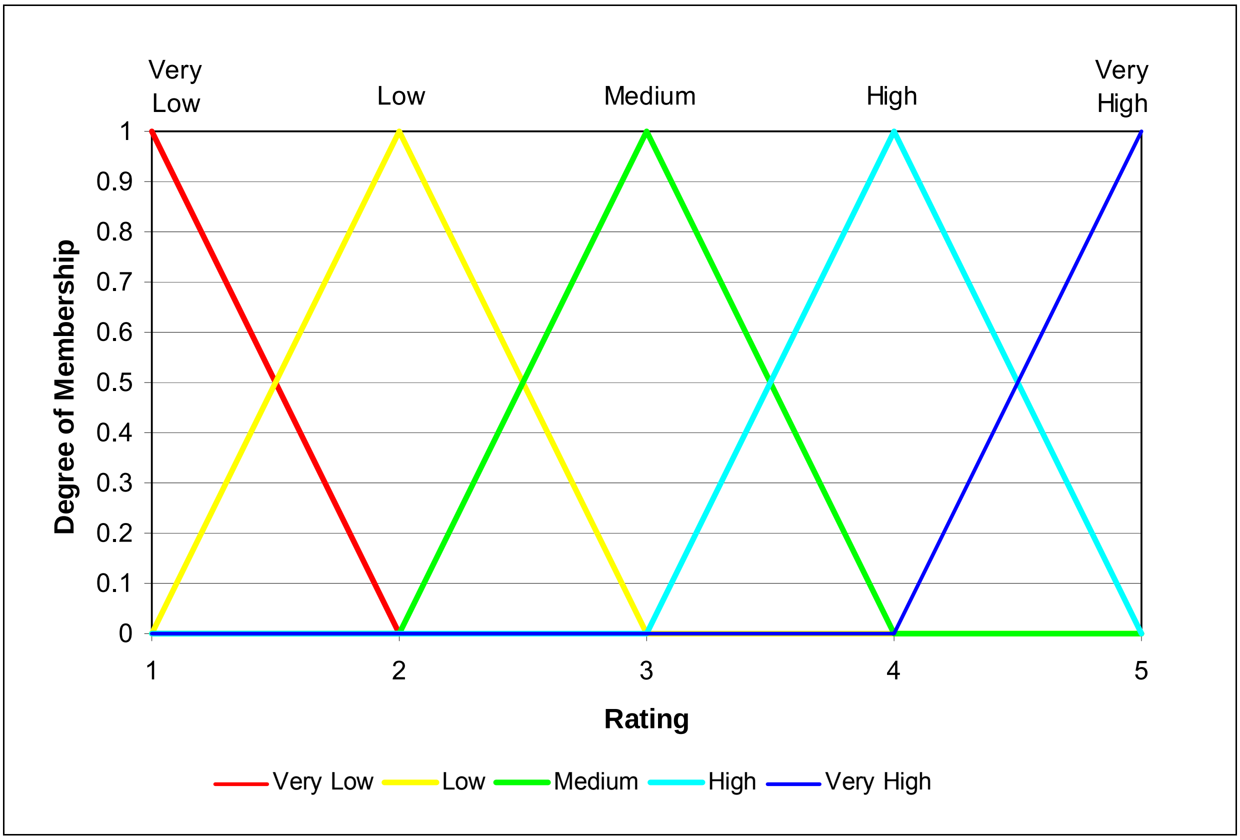


Figure 3-12: Fuzzy Sets for Workmanship Quality

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

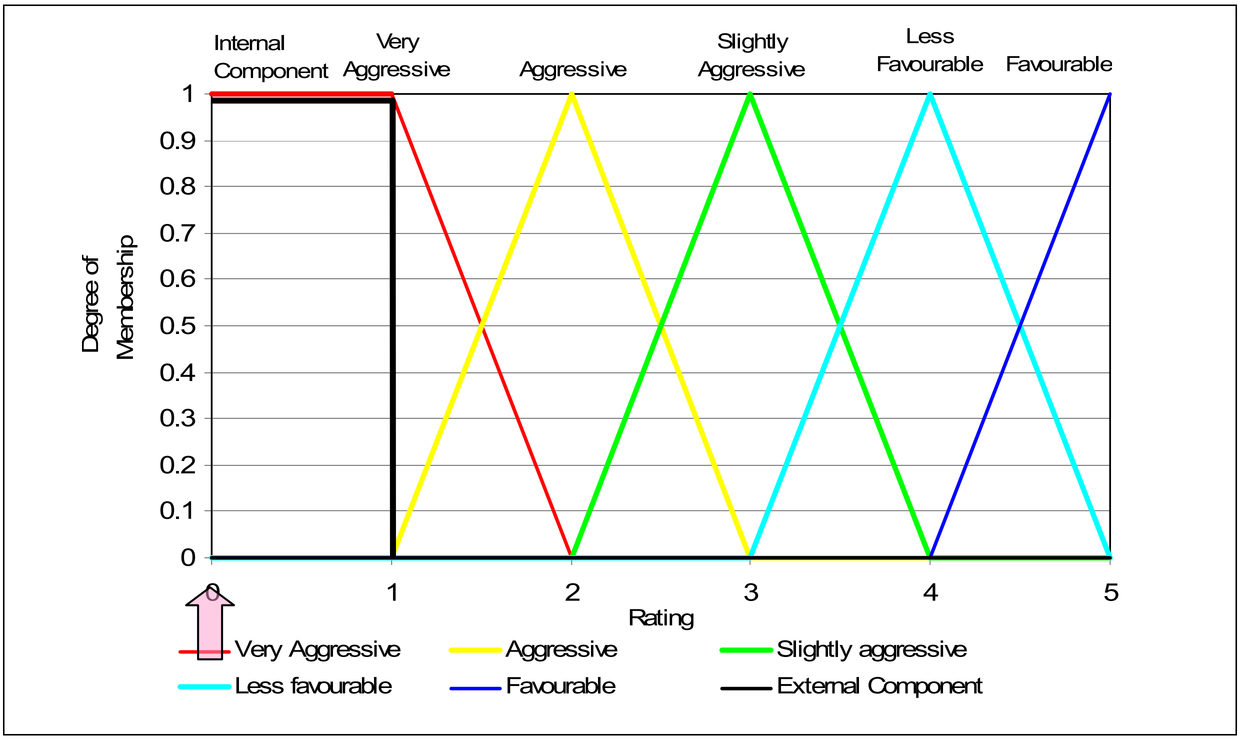


Figure 3-13: Fuzzy Sets for External Climate

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

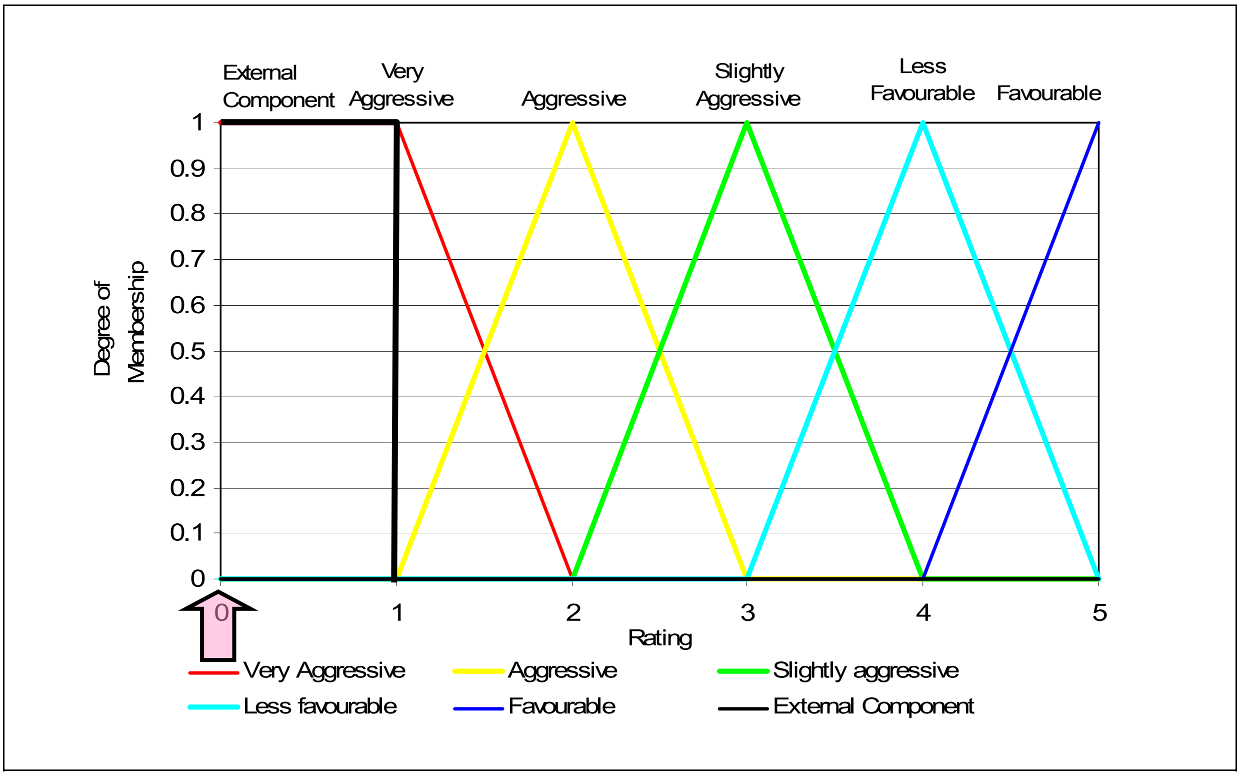


Figure 3-14: Fuzzy Sets for Internal Climate

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

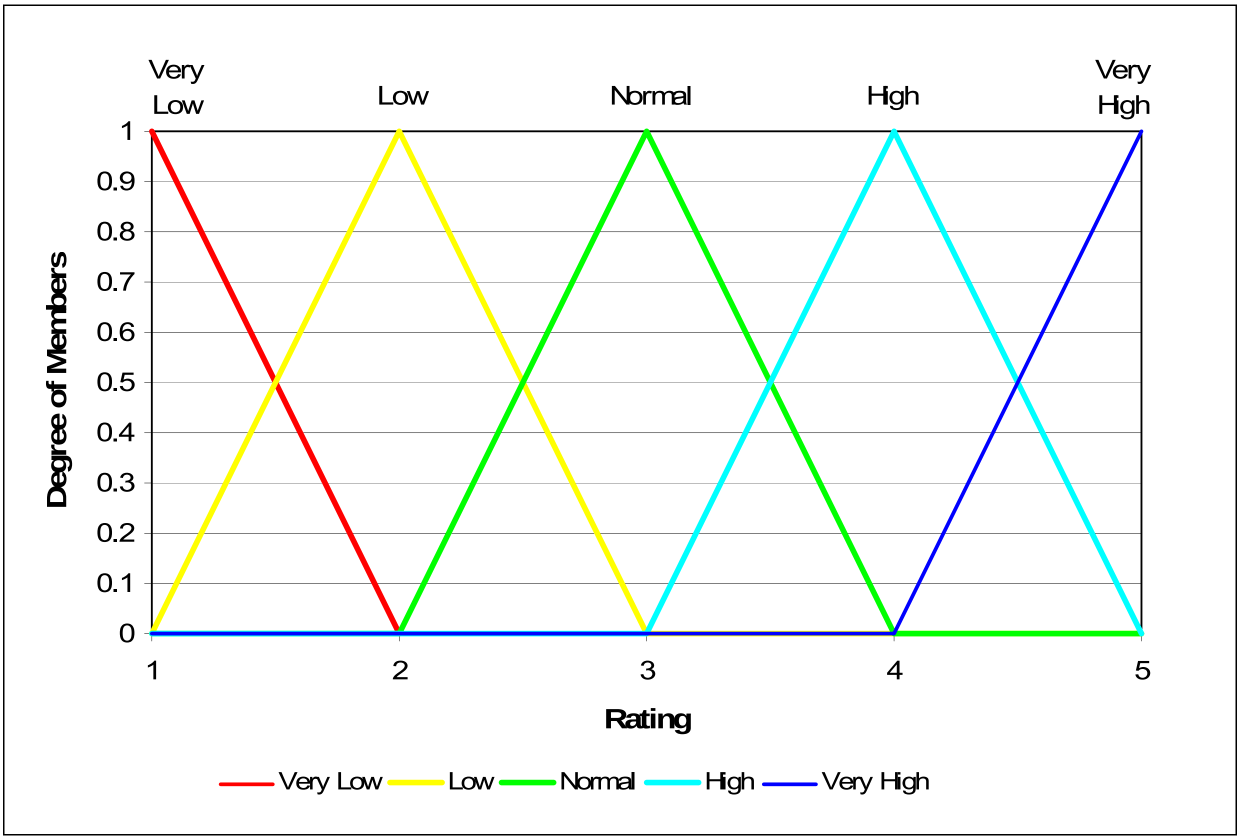


Figure 3-16: Fuzzy Sets for Maintenance Level

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

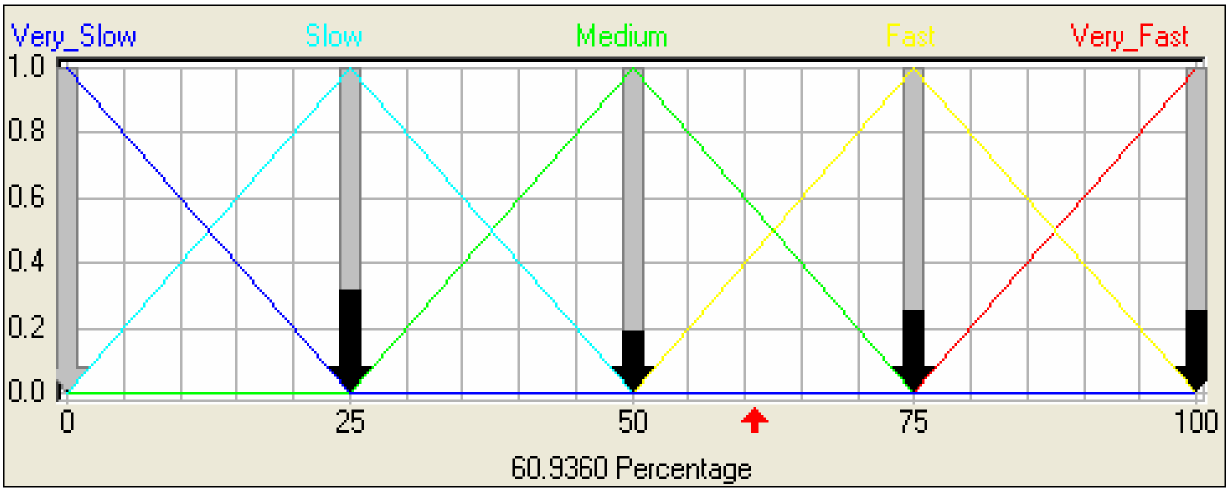


Figure 3-17: Fuzzy Sets for Degradation Rate

3.3.5. Fuzzy Rules

a.) Rule Block 1

<u>Input variables:</u>		<u>Intermediate Variable (Output):</u>
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.

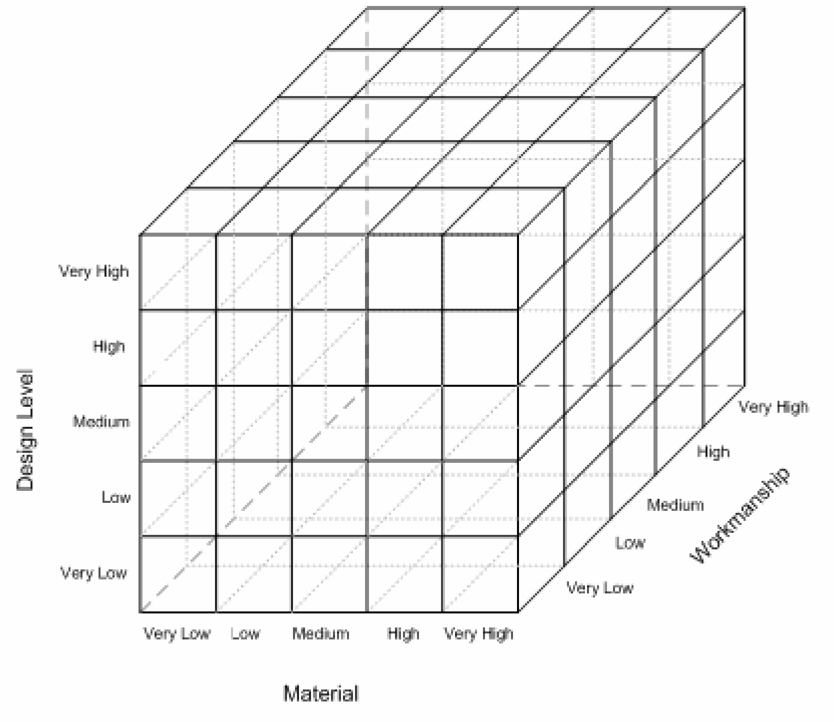


Figure 3-18: Cube Fuzzy Associative Memory (FAM) for Rule Block 1

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		

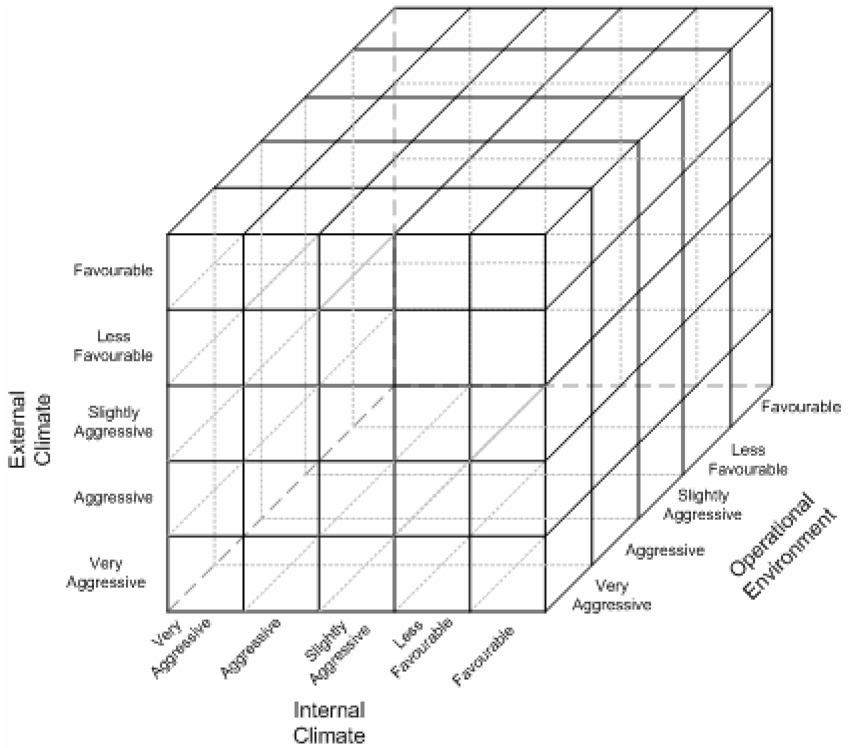
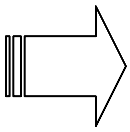


Figure 3-19: Cube Fuzzy Associative Memory (FAM) for Rule Block 2

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:		Output:
Durability		
Environment		Degradation Rate
Condition		
Maintenance Level		

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.

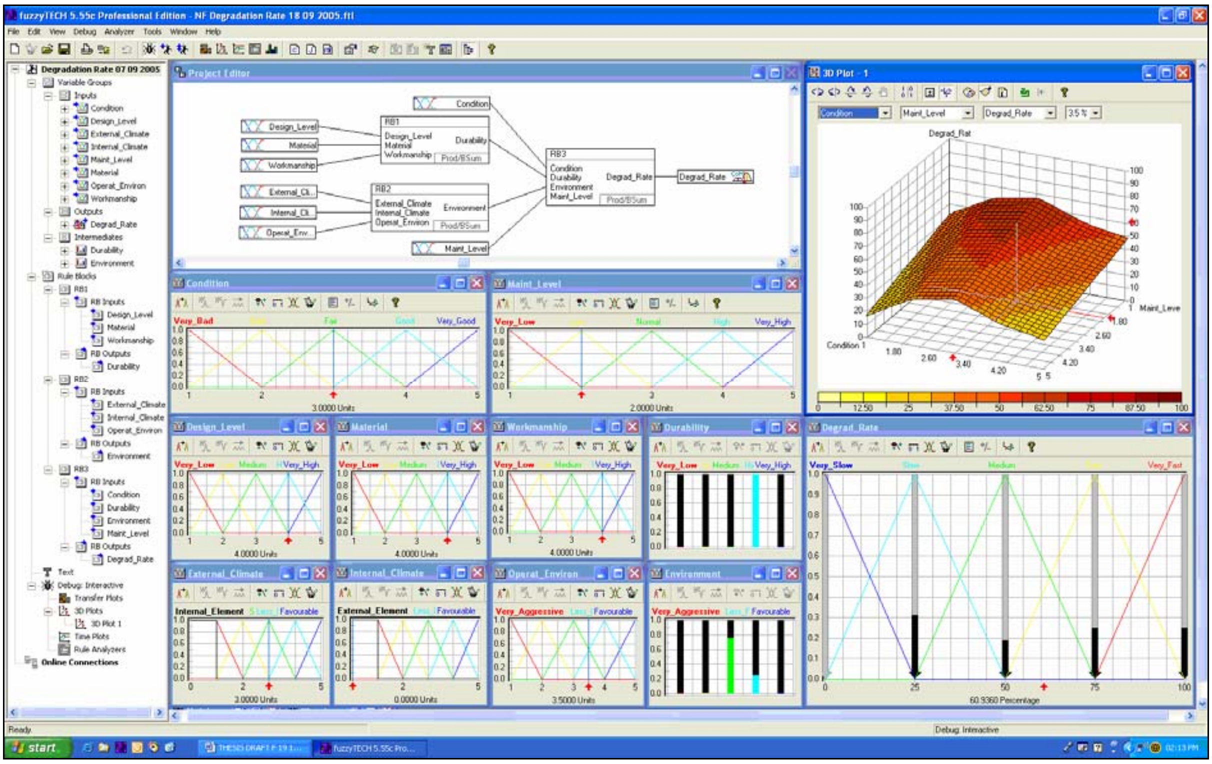


Figure 3-20: Screendump of ‘base-line’ fuzzyTECH model

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

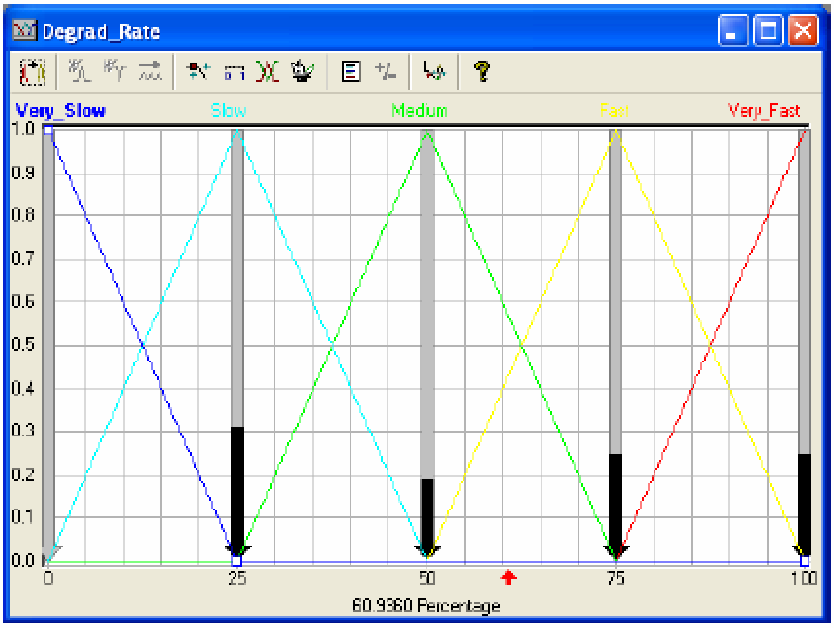


Figure 3-21: Degradation Rate window in 'base-line' fuzzyTECH model

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.

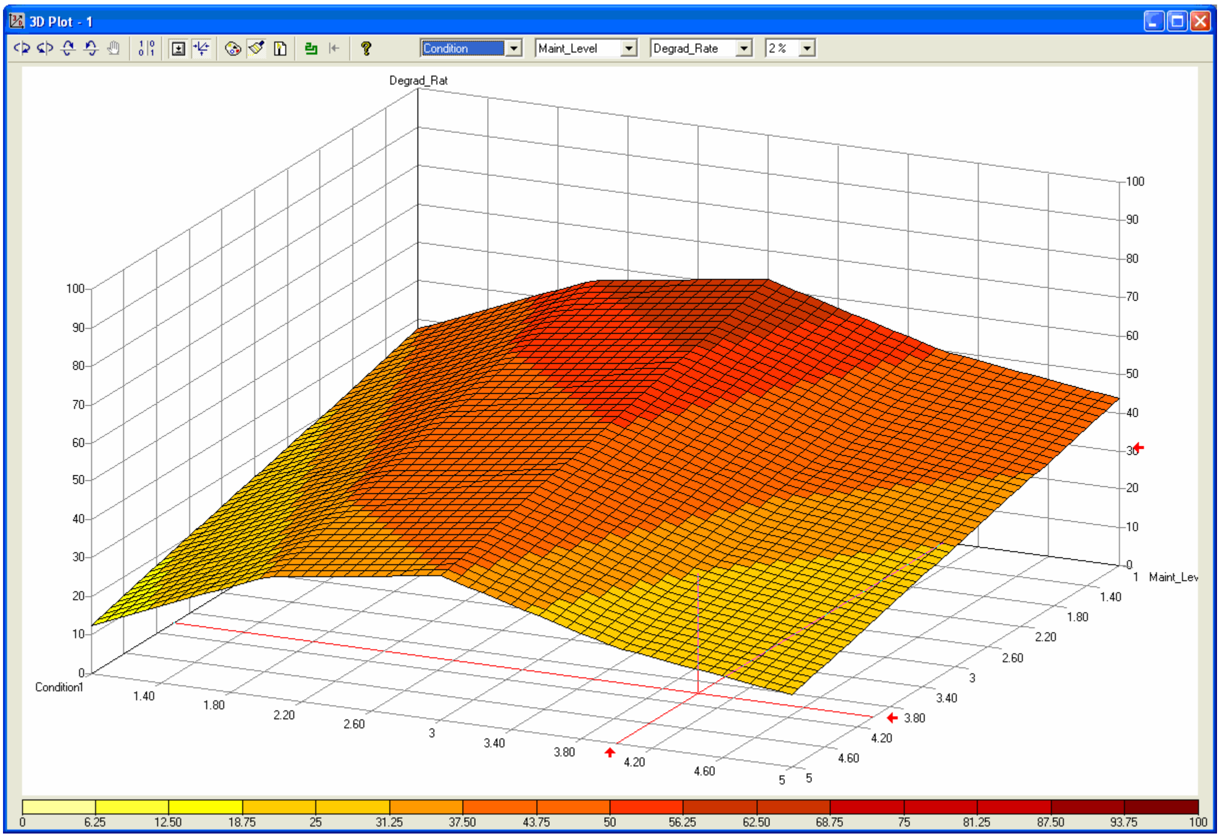


Figure 3-22: A 3-D Plot of the 'base-line' fuzzyTECH Model

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:

$$P = \begin{array}{c} (5) \\ (4) \\ (3) \\ (2) \\ (1) \end{array} \overset{\begin{array}{ccccc} [5] & [4] & [3] & [2] & [1] \end{array}}{\left| \begin{array}{ccccc} P(55) & P(54) & P(53) & P(52) & P(51) \\ P(45) & P(44) & P(43) & P(42) & P(41) \\ P(35) & P(34) & P(33) & P(32) & P(31) \\ P(25) & P(24) & P(23) & P(22) & P(21) \\ P(15) & P(14) & P(13) & P(12) & P(11) \end{array} \right|} \qquad \begin{array}{c} \sum P(5j) = 1 \\ \sum P(4j) = 1 \\ \sum P(3j) = 1 \\ \sum P(2j) = 1 \\ \sum P(1j) = 1 \end{array}$$

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:

$$P = \begin{array}{c|ccccc|c} & [5] & [4] & [3] & [2] & [1] & \\ (5) & P(55) & P(54) & 0 & 0 & 0 & \sum P(5j) = 1 \\ (4) & 0 & P(44) & P(43) & 0 & 0 & \sum P(4j) = 1 \\ (3) & 0 & 0 & P(33) & P(32) & 0 & \sum P(3j) = 1 \\ (2) & 0 & 0 & 0 & P(22) & P(21) & \sum P(2j) = 1 \\ (1) & 0 & 0 & 0 & 0 & 1 & \sum P(1j) = 1 \end{array}$$

$\sum P(ij) = 1$

$\therefore$ 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.

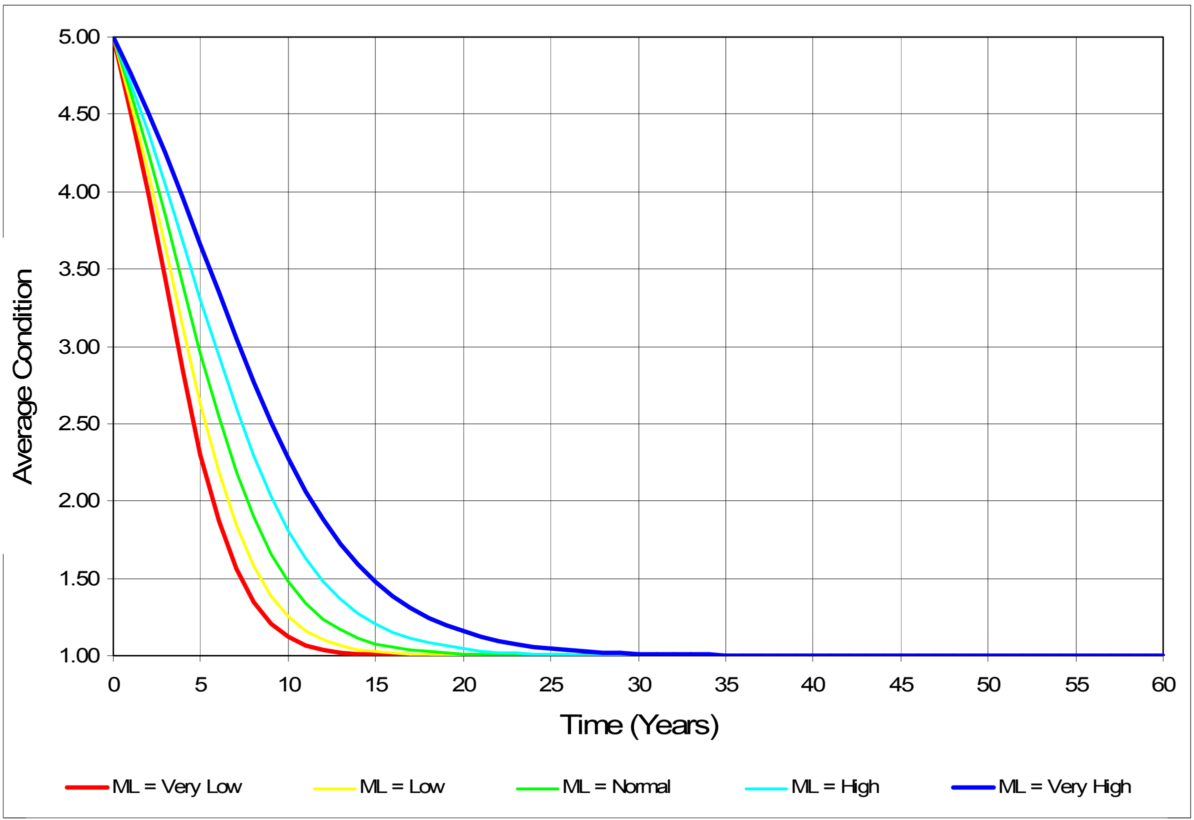


Figure 3-23: Performance over time curves for different levels of maintenance – 'base-line' model

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.

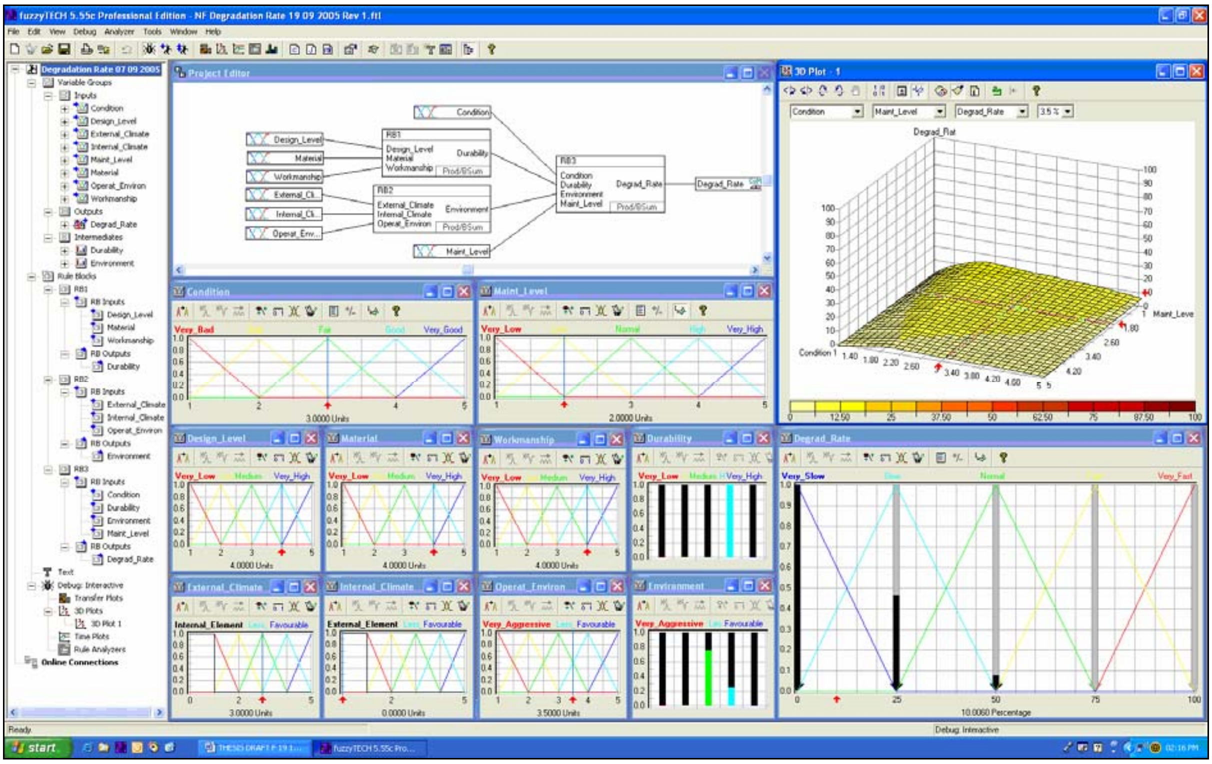


Figure 3-24: Screendump of revised fuzzyTECH model

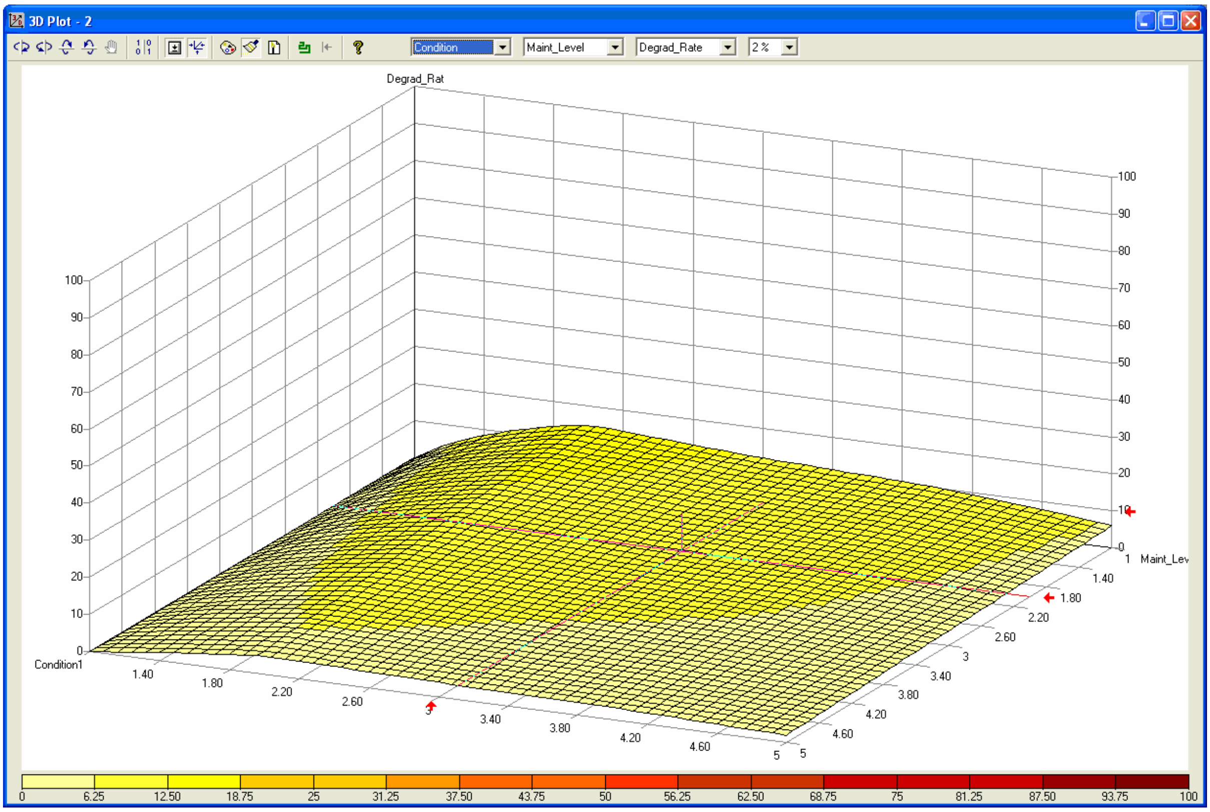


Figure 3-25: A 3-D Plot of the revised fuzzyTECH Model

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.

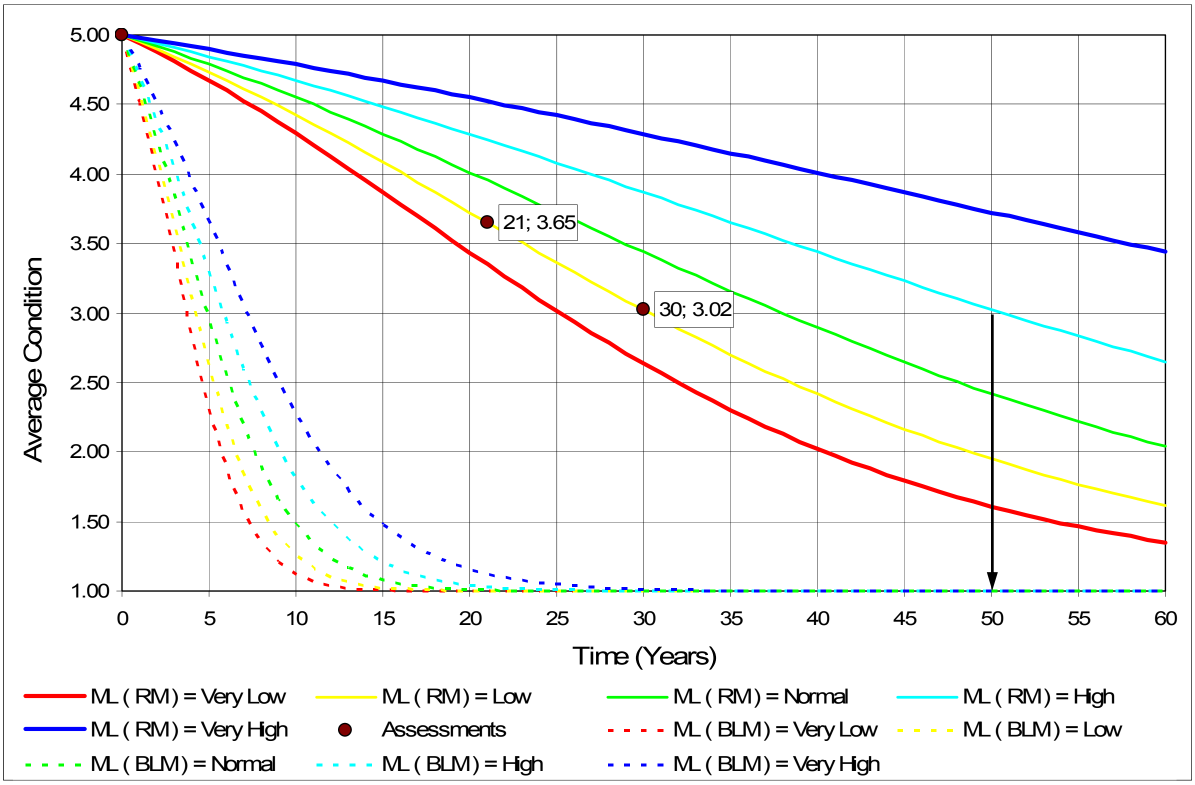


Figure 3-26: Performance over Time curves for different levels of maintenance – Revised Model (RM) vs 'Base-Line' Model (BLM)

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.

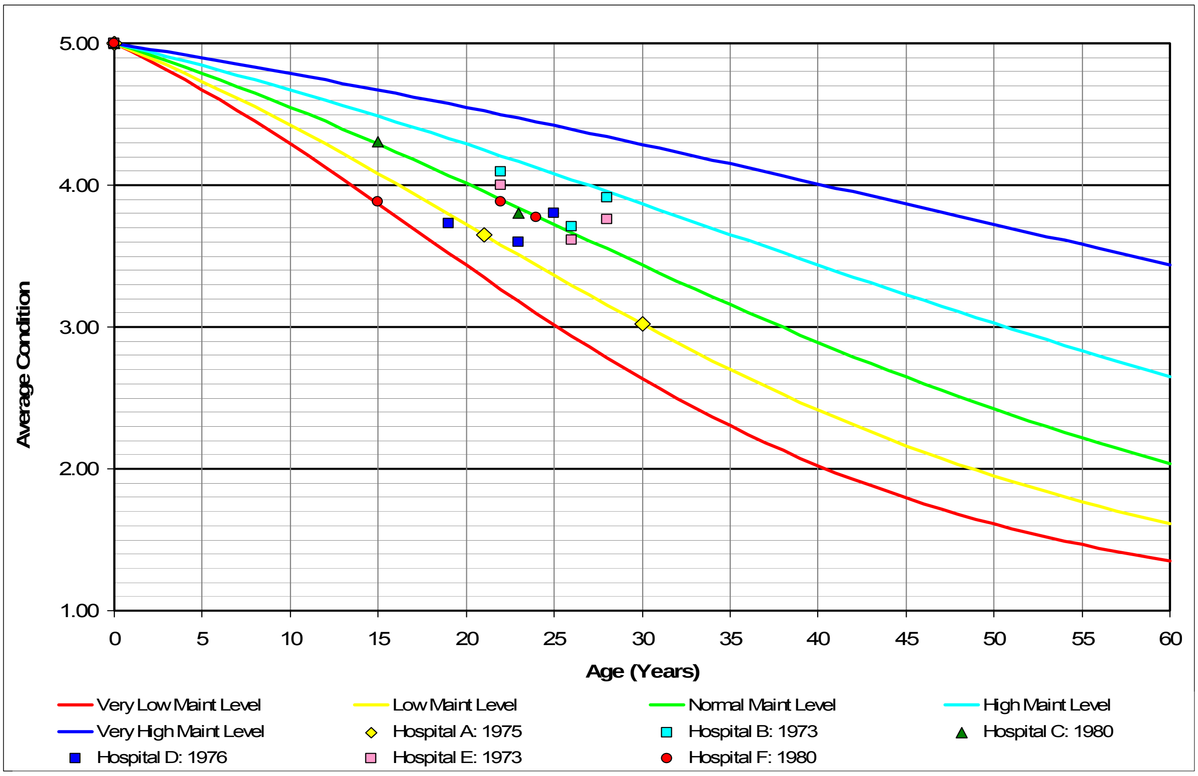


Figure 3-27: Performance over Time Curves for 'Slightly Aggressive' External Climate

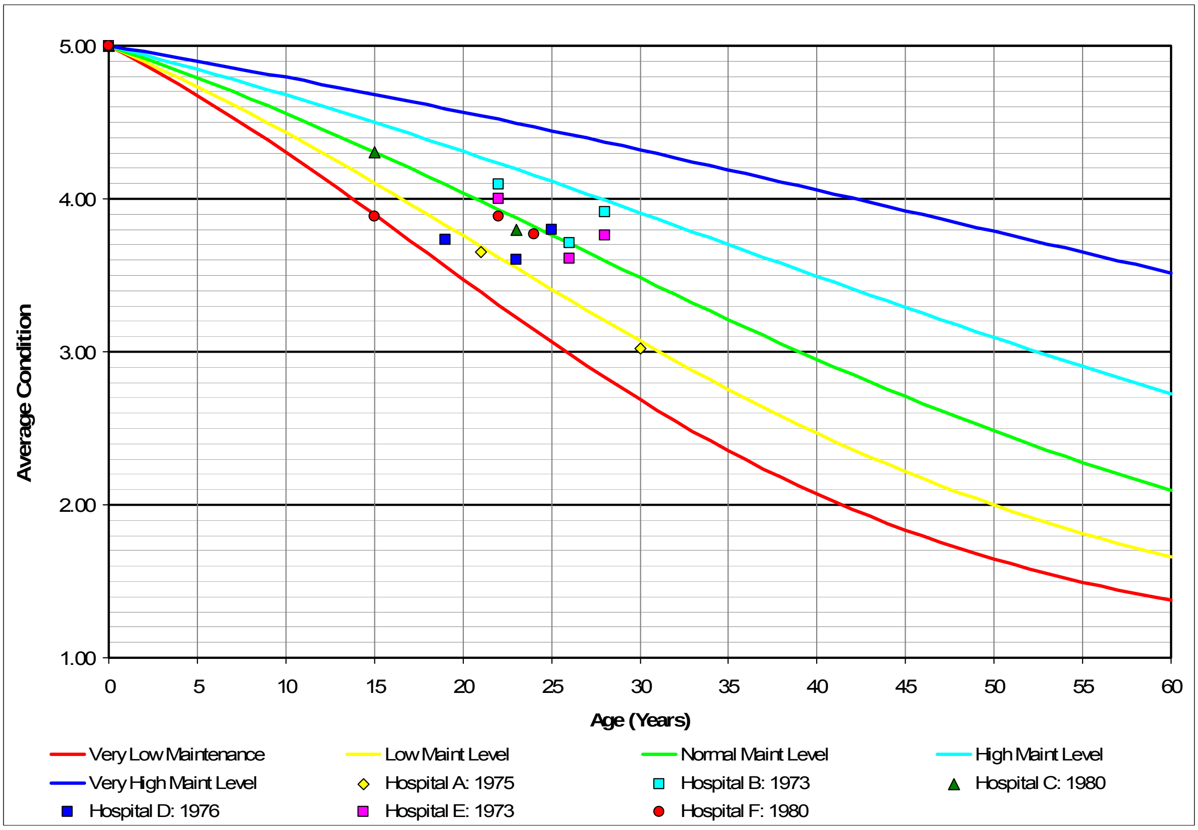


Figure 3-28: Performance over Time Curves for 'Less Favourable' External Climate

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.

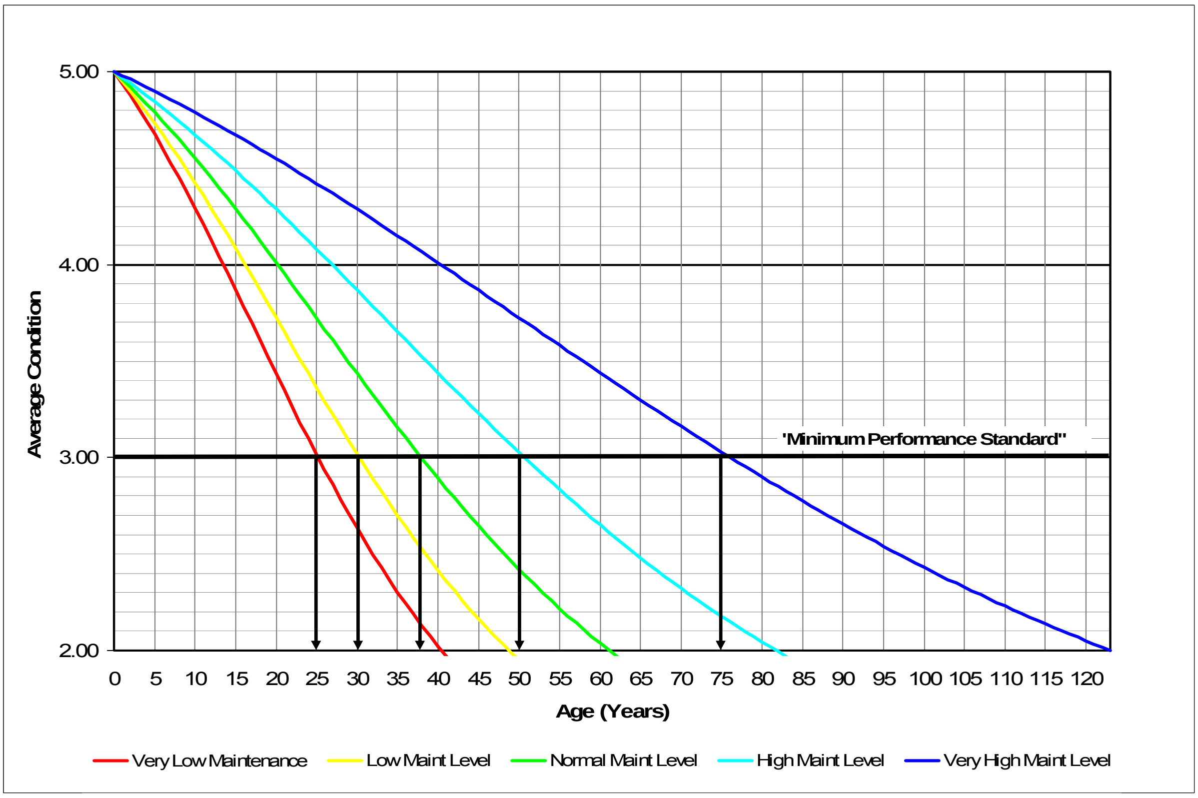


Figure 3-29: Service Life Prediction Graph for Academic Hospitals in South Africa in a 'Slightly Aggressive' External Climate

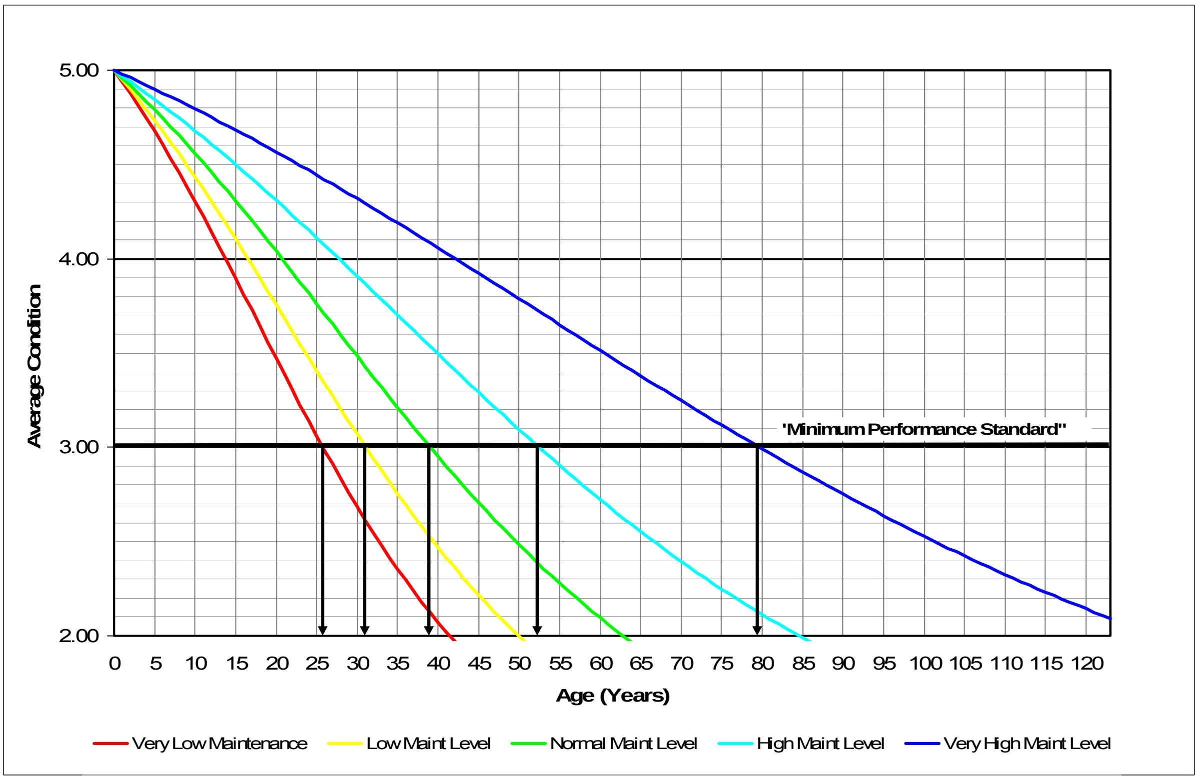


Figure 3-30: Service Life Prediction Graph for Academic Hospitals in South Africa in a 'Less Favourable' External Climate

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.

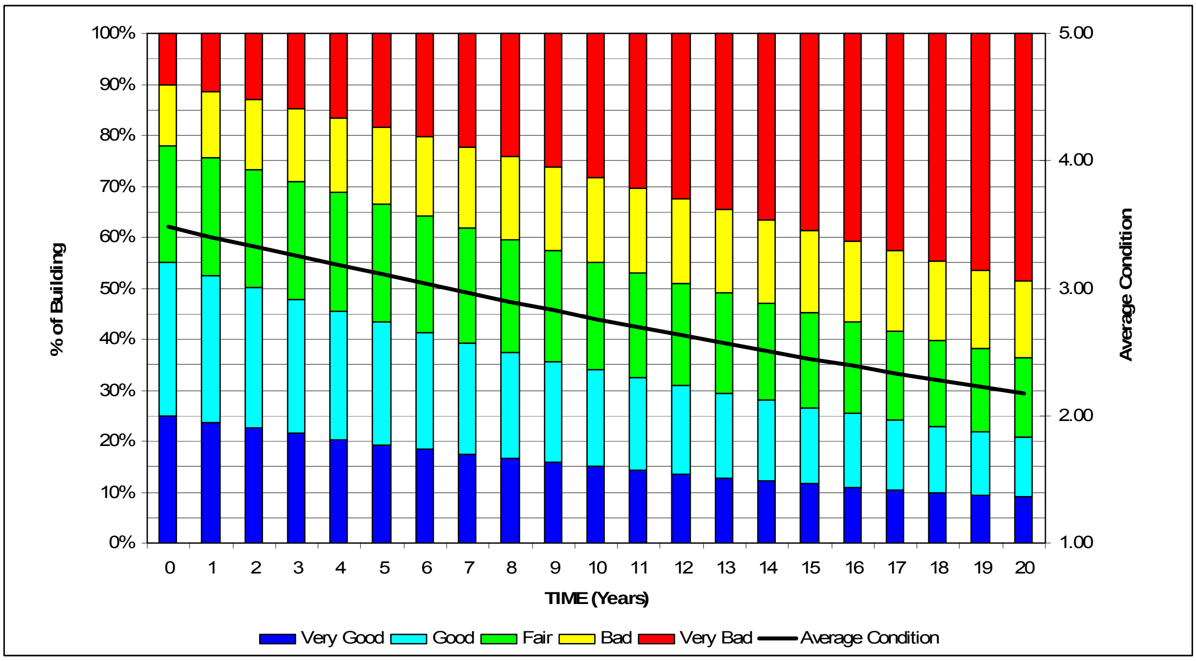


Figure 3-31: Anticipated change in condition profile and average condition over time

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.

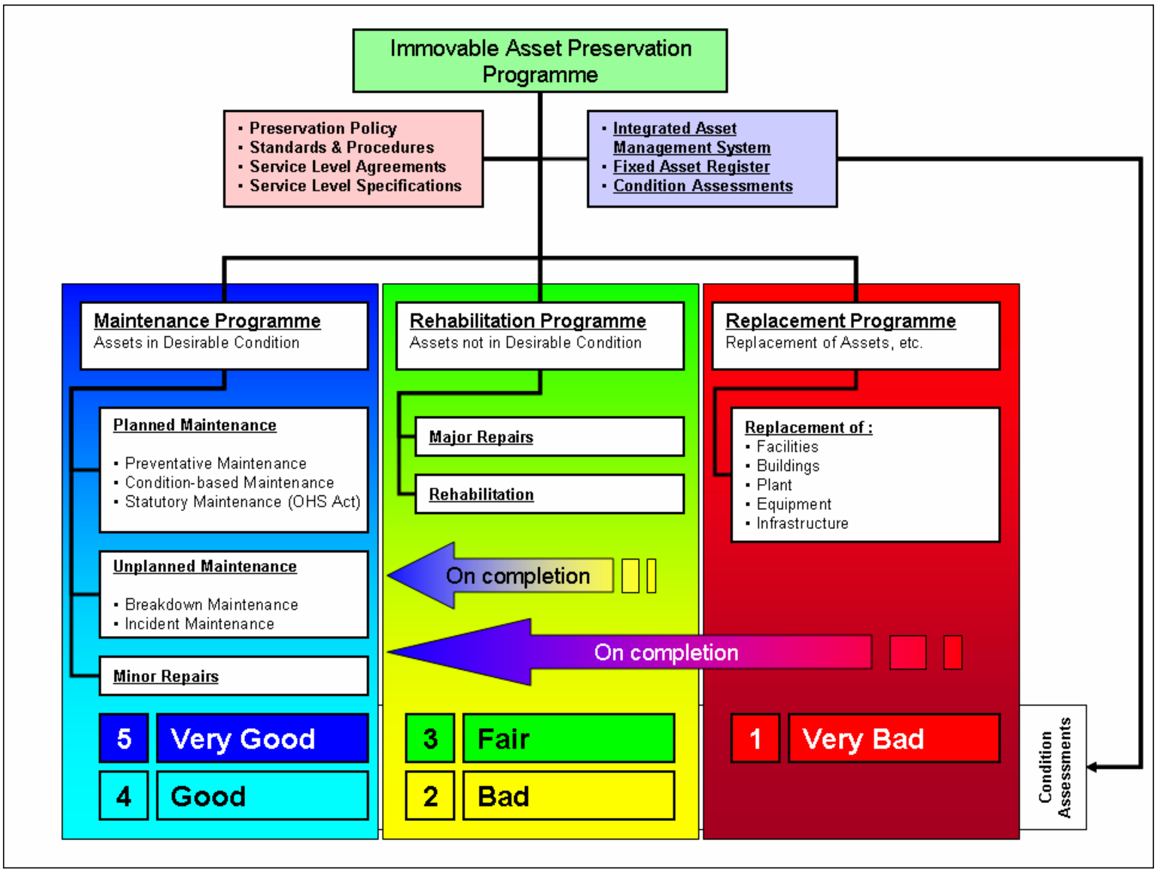


Figure 3-33: Preservation programme diagram

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

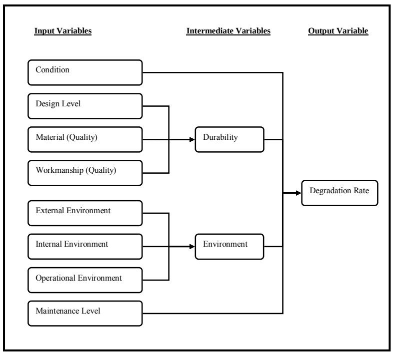
Table 3-22 below provides a graphic summary of the proposed methodology for ‘Service Life Prediction’ and strategic service life planning applications.

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



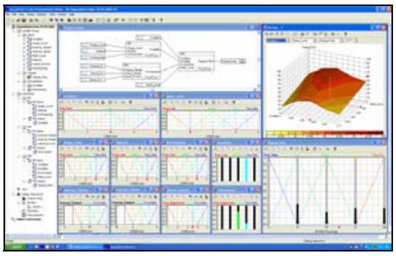
- Define Fuzzy structure
- Analyse degradation and durability factors for building or component under consideration

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



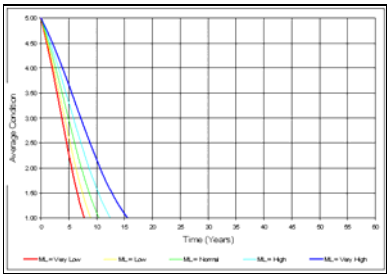
- Develop Fuzzy Sets for variables (factors) – input, intermediate and output
- Develop IF – THEN rules
- Feed into Neuro-fuzzy system
- Adjust ratings for each variable (factor) according to allocations made in Step 2

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%

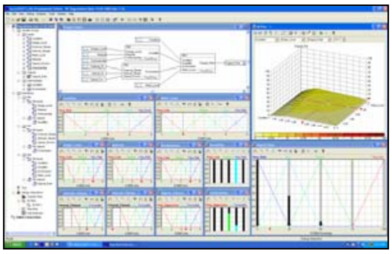
- Feed output from Neuro-fuzzy system into Markov Chain Transition Probability Matrix

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



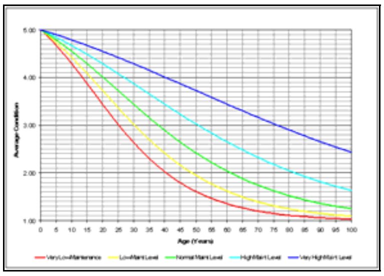
- Return to Neuro-fuzzy system and adjust ‘Degree of Support’ or weights of variables in Rule Blocks

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.
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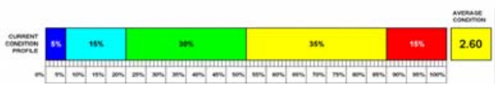
1	Very Bad	Replacement Required	The component or building has failed, is not operational or deteriorated to the extent that does not justify repairs, but should rather be replaced. The condition of the element actively contributes to the degradation of surrounding elements or creates a safety, health or life risk.

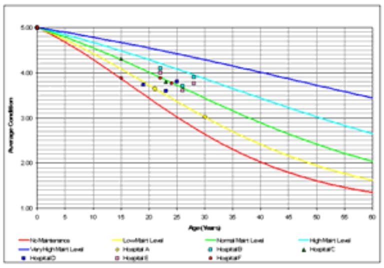
- Identify suitable pilot buildings or components
- Perform condition assessment of set of pilot buildings or components

11



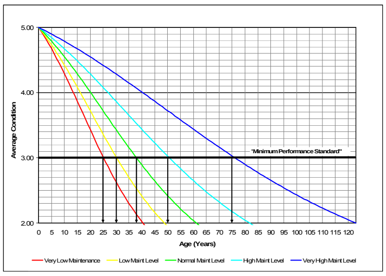
- Develop condition profiles of pilot buildings or components
- Calculate average conditions

12



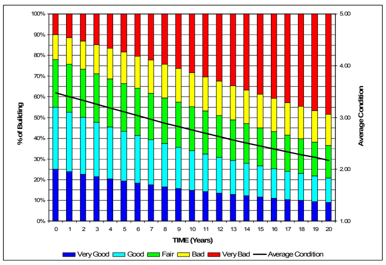
- Plot pilot building or component data on 'Performance over Time' graph from Step 9
- Compare plot with 'base-line' graphs
- If no or bad correlation between model and assessment data, return to Step 7 and repeat process
- If model correlates with assessment data → calibrated system

13



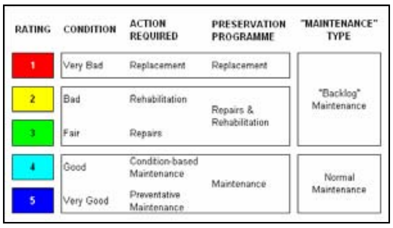
- Determine 'desirable' Service Level – (e.g. for hospital Average Condition > 3 on 5 point rating system)
- From calibrated 'Performance over Time' graph obtain predicted 'Service Life' for various levels of maintenance

14



- Run Markov Chain simulation with 'calibrated' Transition Probability Matrix
- Plot Anticipated Changes in Condition Profile and Average Condition from Markov simulation

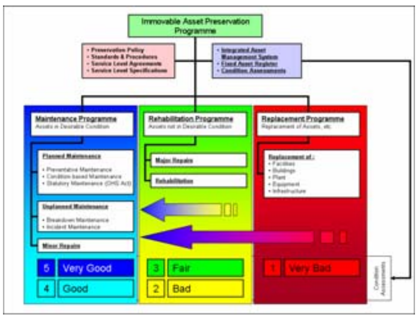
15



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		

- 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