4. RESULTS AND DISCUSSION

4.1. Introduction

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

4.2. Results

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

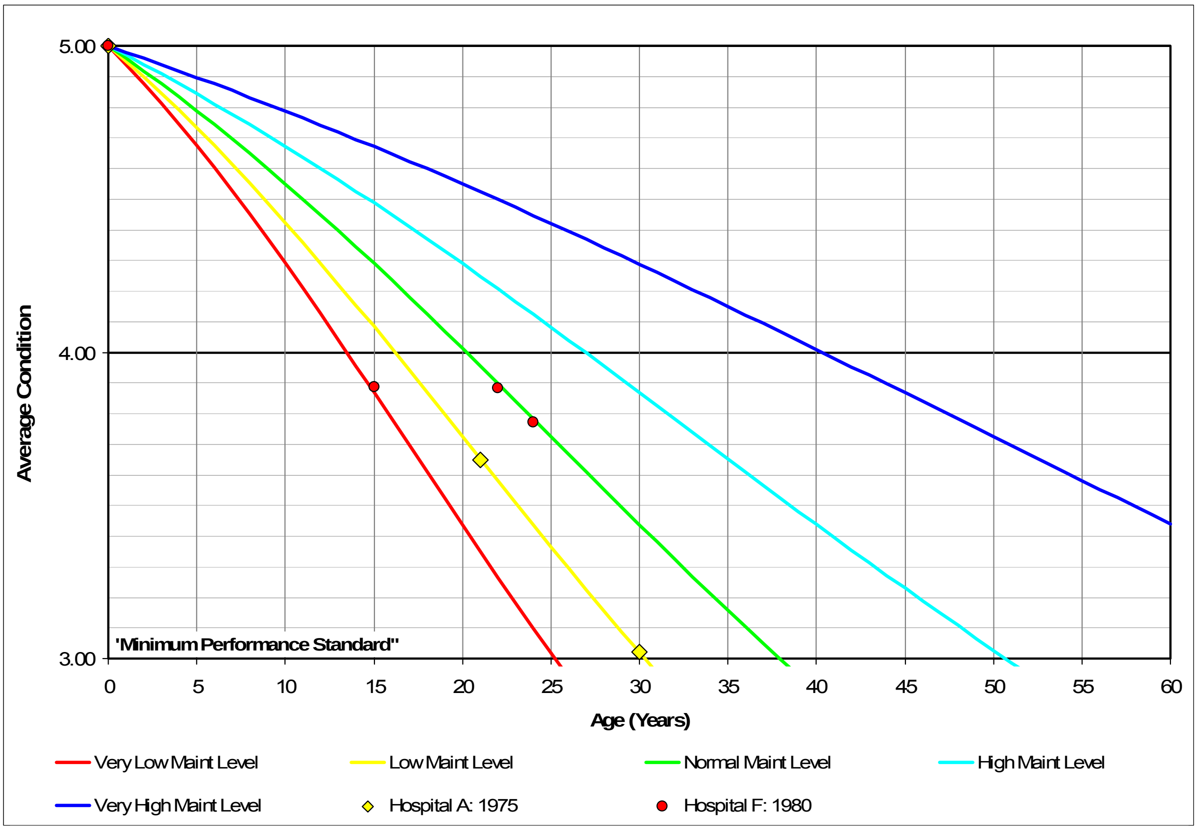


Figure 4-1: Service Life Prediction Graph for Hospitals A and F

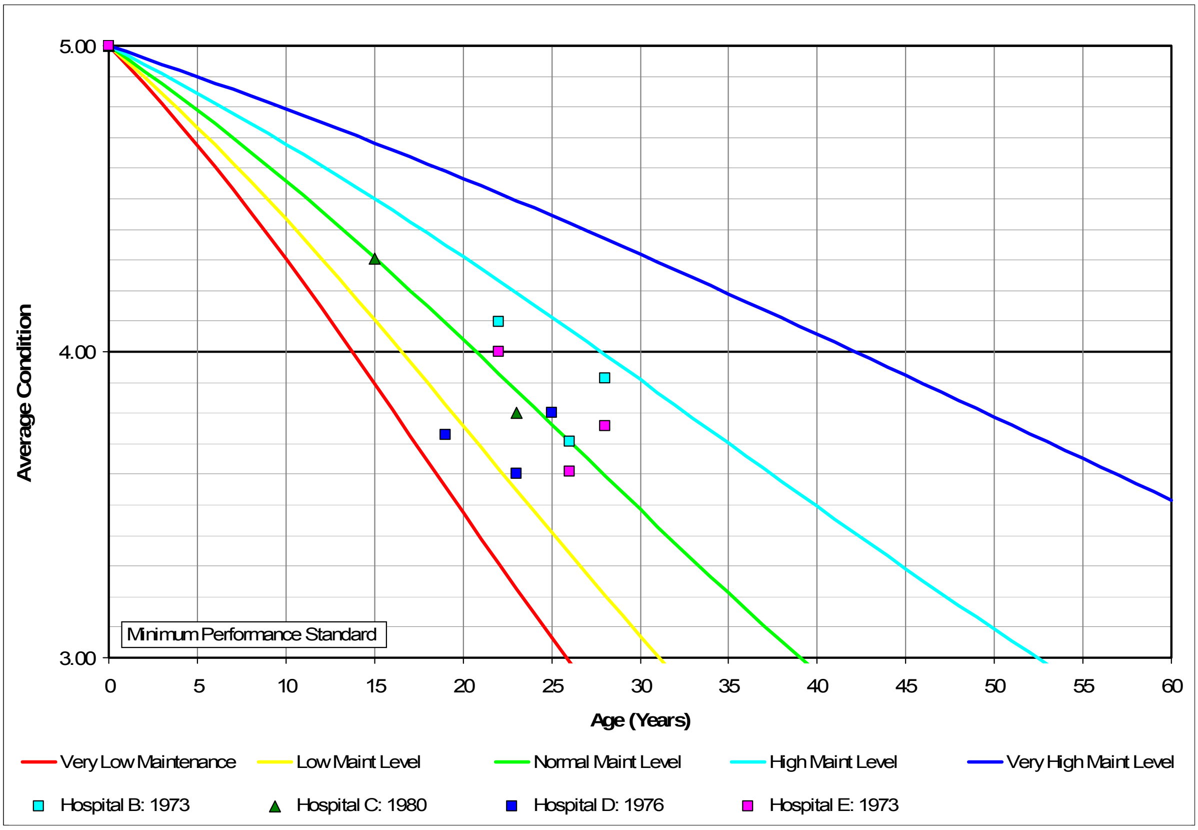


Figure 4-2: Service Life Prediction Graph for Hospitals B, C, D and E

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

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

Table 4-1: Predicted service life for hospitals

4.3. Discussion

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

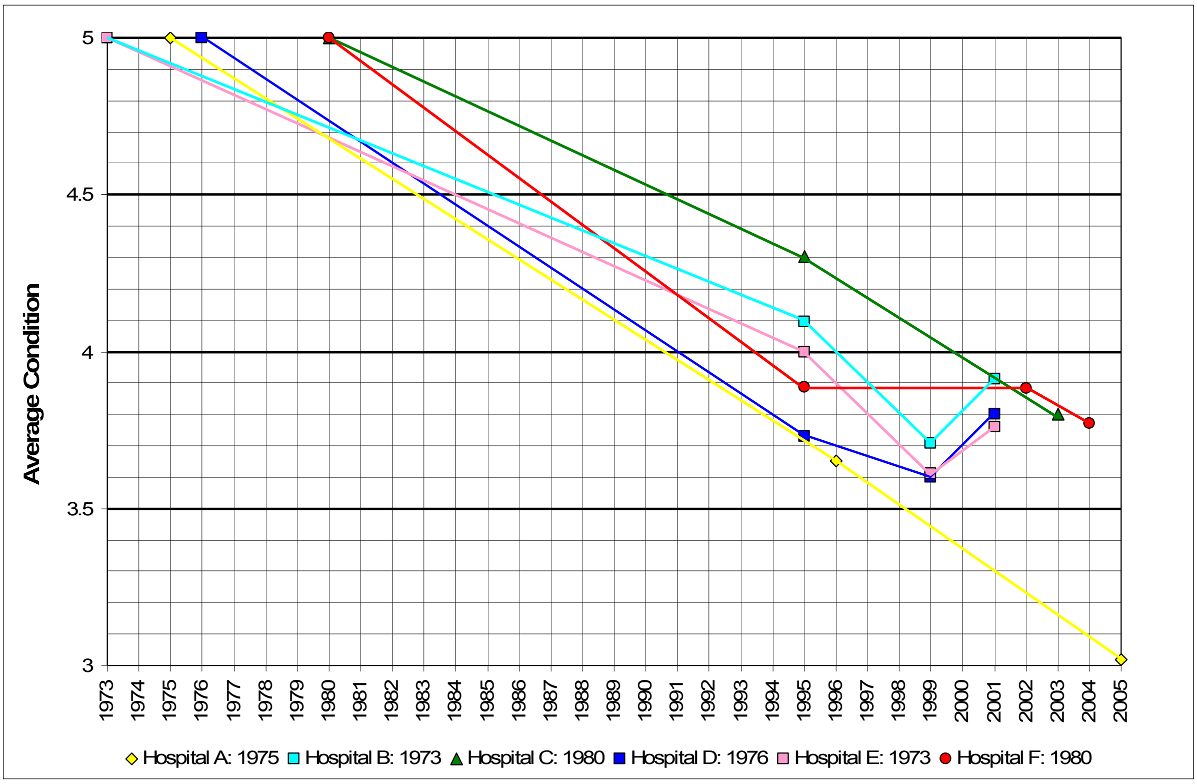


Figure 4-3: Performance of Pilot and Control Hospitals over Time (Calendar Years)

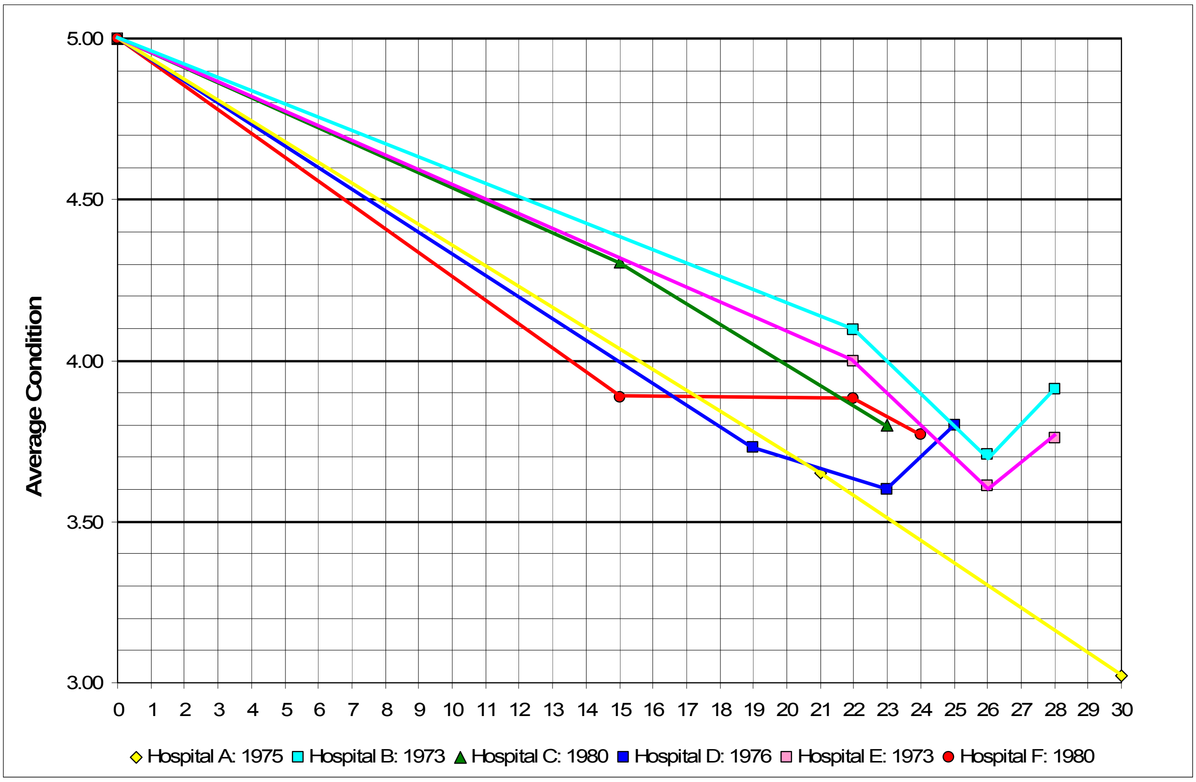


Figure 4-4: Performance of Pilot and Control Hospitals over Time (Age)

4.3.1. Hospitals

a.) Hospital A

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

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

b.) Hospitals B, D and E

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

c.) Hospital C

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

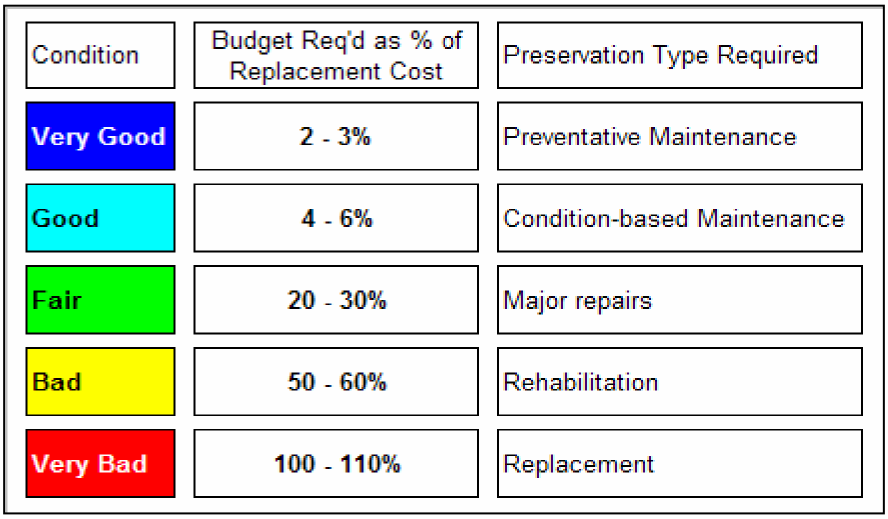
d.) Hospital F

In Figure 4-3 Hospital F, also in a ‘slightly aggressive’ external climate similar to the pilot site Hospital A, plots exactly on the curves without any adjustments to the revised model for the pilot site Hospital A. At age 15 years the average condition of Hospital F plots on the ‘Very Low’ maintenance level curve and then jumps to the ‘Normal’ maintenance level curve at ages 22 and 24 years. This can be attributed to a number of reasons. Records for the period prior to the 1995/6 NHFA is unfortunately hard to come by and it is assumed that the maintenance level was ‘Very Low’ during the period between completion of construction in 1980 and the NHFA in 1995 based on the general tendency to ‘neglect’ a new facility because it is new and does not require attention while other older facilities do require attention due to occupant/user complaints and demands. Therefore, it is quite possible, but very difficult to establish or confirm that the hospital’s maintenance was indeed on a ‘Very Low’ level. The sudden jump to a ‘Normal’ maintenance level seven years later is attributed to two major events. Firstly, the officials in that province paid attention to the results of the NHFA, reacted in a positive manner by doing regular condition assessments, and implementing a computer system, developed by the CSIR and used for the NHFA. The information collected during these annual assessments was used to update the database in the computer system and formed the basis for management decisions. The second event is the implementation of a hospital revitalisation programme resulting in upgrades and additions to the hospital. During the period 1995 and 2002, 15,400 m² or 18% of floor area, was added, which also had an impact on the average condition. What is however of interest is that the average condition for 2004 plots on the ‘Normal’ maintenance curve.

4.3.2. Maintenance level

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

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



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

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

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

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

4.3.3. Service life prediction

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

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

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

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

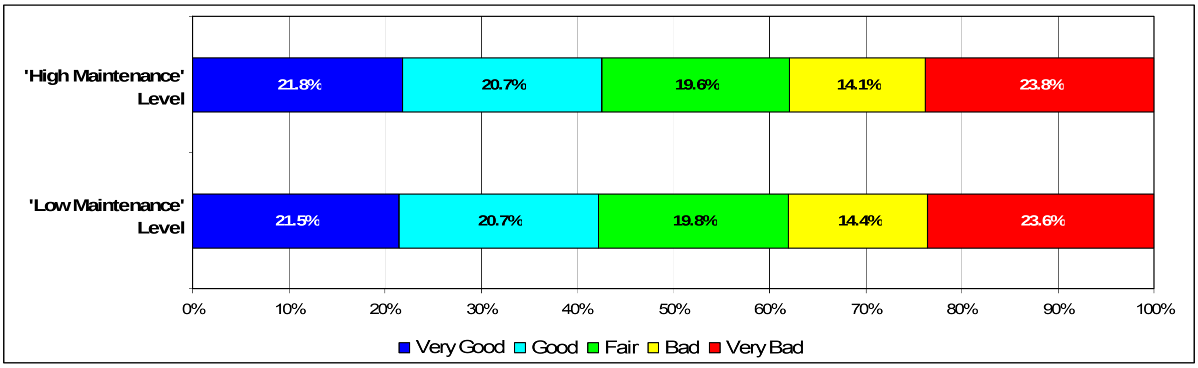


Figure 4-5: Anticipated condition profiles at end of service life (average condition 3)

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

4.3.4. Current Regime vs Proposed Model

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

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

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

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Introduction

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

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

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

5.2. Conclusions

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

5.2.1. Conclusion No. 1:

> Problem Statement No. 1:
>
> The 'state-of-the-art' Factor Method for service life prediction only calculates the estimated service life of a building or component, and cannot quantify changes in condition over time or determine the effect of maintenance level on service life.
>
> Hypothesis No. 1:
>
> The Markov Chain can be used to calculate the estimated service life of a building or component, quantify changes in condition over time and determine the effect of maintenance levels on service life.

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

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

5.2.2. Conclusion No. 2:

Problem Statement No. 2:

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

Hypothesis No. 2:

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

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

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

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

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

5.2.3. Conclusion No. 3:

Problem Statement No. 3:

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

Hypothesis No. 3:

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

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

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

5.2.4. Conclusion No. 4:

Problem Statement No. 4:

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

Hypothesis No. 4:

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

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

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

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

5.3. Contribution to Knowledge Base of Engineering Science and Practice

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

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

5.4. Recommendations

It is recommended that the following issues be investigated further:

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

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

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

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

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

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

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

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

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

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

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

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