A Reliability Based Approach for Management of Council Owned Buildings in Australia

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Abstract

With an aging stock of public buildings, development of innovative methods for management of risk of failure and optimizing of maintenance expenditure has become extremely important to Australian public work engineers. A major challenge in many sophisticated asset management systems is identifying the type and quantity of data required to establish a reliable predictive model for maintenance and renewal expenditure forecasts. With the high variability of condition data, a reliability based approach is more appropriate for predictive modeling. Another important observation made of traditional asset management systems is that the deterioration models are mainly a function of age. This has been observed to be unrealistic on many occasions.

The paper presents an innovative approach based on Markov process for deterioration modeling of buildings owned by local councils in Australia. The concept for the complete asset management model is presented with input data clearly identified. Using some preliminary data established from council records and consultation of experts, transition matrices for Markov process modelling have been established for major elements of council buildings. The complete process for deterioration prediction is demonstrated with a typical example.

Keywords: Markov process, Service life modeling, Infrastructure management, Risk management

1. Introduction

Management and sustainability of built infrastructure is an extremely important issue being addressed by many research organizations in the world. The research work funded by European communities lead the world in these areas as reported by Flourentzou et al [5], which are still continuing. There are several approaches reported in recent literature to address the issue.

These can be summarized as:

- Approximate methods where condition of different elements were rated A, B, C and D or 1, 2, 3, 4, 5 through condition inspections. Deterministic life cycle analysis is conducted assuming the time period of progression of deterioration to be fixed in one state (Hovde, [6]).

- Same as above with modifications for different exposure conditions and usage through fixed factors calibrated with data (ISO factorial approach Bamforth, [2], Tepley [13]).
- Reliability based methods using the discrete Markov chain for deterioration modelling.
- Reliability based methods using continuous Markov process (Maheswaran et al , [12]).
- Predicting life cycle of assets considering an integration of three drivers such as Market drivers, physical deterioration and functional obsolescence.

Out of the above, the most common approach used by the industry is a deterministic method based on condition data and fixed deterioration curves. However, these approximate methods lack the ability to account for uncertainties, which is essential to manage risk of maintaining assets to provide the required level of service delivery. Preliminary research at RMIT have indicated that to consider majority of the issues affecting management decision making for effective service delivery of councils a reliability-based approach incorporating some attributes of the ISO factorial approach and consideration of other drivers such as market and functional issues (Allehaux and Tessier, [1]) is essential. Use of Markov chain for deterioration modeling and decision-making is being explored at RMIT University in Australia to address this need.

Previous work on application of Markov process for deterioration modeling of structures have covered deterioration prediction of bridges due to chloride induced corrosion (Maheswaran et al, [11]), concrete structures (Lifecon, [11]) and separate elements of buildings (ISO1586, [9]). In no reported work, the application of Markov process has been attempted on a complex infrastructure systems comprising of a large number of elements. There have been some issues raised about the application of Markov process for predicting deterioration. The Markov curve has a shape which indicates flattening of the curve toward the end of the period whereas in real structures, opposite is observed. This is normally handled by predicting the last stage using a separate probability distribution (Lifecon, [10]).

2. Proposed methodology

2.1 Conceptual framework

In deterioration modelling the attributes of a model randomly change over time. A Markov chain is a probability model, which has a finite-state, for describing a certain type of stochastic process that moves in a sequence of phases through discrete points in time according to fixed probabilities. The process is stochastic because it changes over time in an uncertain manner. In this chain the future states are dependent only on the present state and independent from the any state before the present states. Markov chain consists of transition matrix and initial distribution. Transition matrix consist of a set of finite set of states S (1,1,3….n) and a propriety pi j to pass from state i to state j in one time step t. Time can be treated as either discrete (called Discrete-Time Markov Chain) or continuous (called Continuous-Time Markov Chain). In Markov chain the states are continuous and similarly the time could be either discrete (called Discrete-Time Markov Process) or continuous (called Continuous-Time Markov Process).

The first step for using Markov Chain modeling is evaluating the condition of building elements. This is to assess their physical, operational and maintenance conditions. For any building element a condition rating scheme constitutes of four ratings A, B, C and D where A represents new or nearly new element and do not required any maintenance action. D represents a condition which indicates that the element has to be replaced.

A	Excellent	The element is as new
B	Satisfactory	The element is sound, minor damage, minor maintenance required
C	Unsatisfactory	Major damage. Major maintenance required.
D	Failing	Serious damage. Element should be replaced

Although the deterioration processes evolve over continuous time, for simplicity, discrete time steps could represent these processes (such as the time of the building inspection). Hence in this paper Discrete Time Markov Chain will be considered as a model for predicting the life cycle for building element.

3.2 Discrete Time Markov Chain

Discrete Time Markov Chain is a finite-state stochastic process in which the defining random variables are observed at discrete points in time. This chain satisfies Markov property, which mean that given that the present state is known, the future probabilistic behaviour of the process depends only on the present state regardless of the past. If an element is in state "i", there is a fixed probability, Pij of it going into state j after the next time step. Pij is called a "transition probability". The matrix P whose ijth entry is Pij is called the transition matrix . Transition matrix consist of a set of finite set of state S (1,1,3….n) and a propriety pi j to pass from state i to state j in one time step t. In Markov chain pi j should satisfy two conditions

pij $\geq$ 0, and $\sum_{j} P_{ij} \leq 1$

This mean if an element is in state i, there is a (P_{ii}) probability that this element will stay in state i, and (1- P_{ii}) will move to next state j.

Present state at time t is i: $X_{t = i}$

Next state at time t + 1 is j: Xt+1 = j

Conditional Probability Statement of Markovian Property:

Pr{Xt+1 = j | X0 = k0, X1 = k1,…,Xt = i} = Pr{Xt+1 = j | Xt = i} ---------(1)

Discrete time means t ∈ T = {0, 1, 2, . . . }

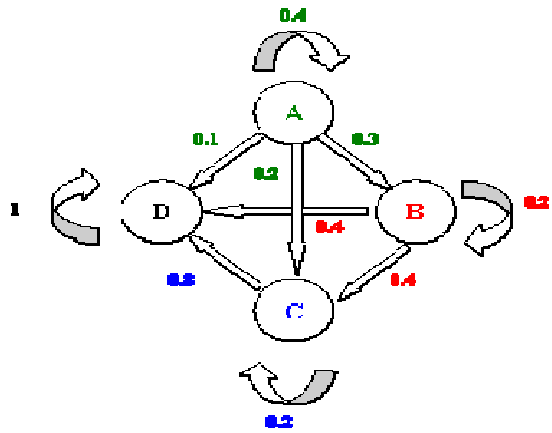

Figure 1: Transition from A to D

	State A	State B	State C	State D
State A	0.4	0.3	0.2	0.1
State B	0	0.2	0.4	0.4
State C	0	0	0.2	0.8
State D	0	0	0	1

Figure 2: Transition Matrix

Figures 1 and 2 show a typical transition matrix. The probability of an element being in a given state at a given point in time can then be depicted by the set of curves shown in figure 4.

An initial distribution ‘v’ is a single row matrix representing the number of elements in each state. In Markov chain after one time step the new distribution will be the result of multiplying initial distribution v by the transition matrix P

Distribution After 1 Step: vP

The distribution one step later, obtained by again multiplying by P, is given by (vP)P = vP^2.

Therefore distribution After 2 Steps = vP^2

Similarly, the distribution after n steps can be obtained by

vP^n

P2 is the two-step transition matrix for the system. Similarly, P3 is the three-step transition matrix, and Pn is the n-step transition matrix. This means that the ijth entry in Pn is the probability that the system will pass from state i to state j in n steps.

3.3 Prediction of the future cost

To predict the future cost for any element there are two kinds of costs: inspection cost, and element replacement cost or element repair cost, when the element makes a transition from one state to another.

Inspection cost is represented by the m-dimensional column vector

$$\mathbf{C}^{S} = \left(c_1^{S}, c_2^{S}, \ldots, c_m^{S}\right)^{T} \quad \text{---(2)}$$

Where each component is the cost associated with state i.

The cost of a transition is embodied in the m × m matrix

$$\mathbf{C}^{R} = \left(c_{ij}^{R}\right) \quad \text{-------------- ---(3)}$$

Where each component specifies the cost of going from state i to state j in a single step.

Expected cost of being in state i, (Jensen and Bard(2003)) is given by:

$$c_i = c_i^{S} + \sum_{j=1}^{m} c_{ij}^{R} p_{aij} \quad \text{---(4)}$$

Where, p_{aij} is the probability of maintenance action.

3.4 Absorbing states

An absorbing state is a state from which there is a zero probability of exiting. An absorbing state is a state j with $p_{jj} = 1$. In other words, without any maintenance action, element which reached condition D will stay in that condition forever. Calculating the expected number of steps to absorption (elements pass from different states to end up in state D) can help to obtain an overall view about the estimated life cycle for that element.

To calculate the absorbing states

Let $0, 1, \ldots, k$ be transient states and

$k + 1, \ldots, m - 1$ be absorbing states.

Let q_{ij} = probability of being absorbed in state j given that we start in transient state i.

Then for each j we have the following relationship

$$q_{ij} = p_{ij} + \sum p_{ir} q_{rj} , \quad i = 0, 1, \ldots, k$$

For fixed j (absorbing state) we have k + 1 linear equations in k + 1 unknowns, q_{rj} , i = 0, 1, , k.

3.5 Long term behaviour of the Markov Chain

If there are recurrent actions taken to repair or replace the element in any state it leads to a steady state probability, which help to set a stable maintenance plan and expenditure.

Calculation of steady state probability can be given by,

Let $\pi = (\pi_1, \pi_2, \ldots, \pi_m)$ is the m-dimensional row vector of steady-state probabilities for the state space S = {1,…,m}. To find steady-state probabilities, solve linear system:

$$\pi = \pi P , \quad S_{j=1,m}\, \pi_j = 1, \quad \pi_j \geq 0, \quad j = 1,\ldots,m$$

3.5 Building Weights

In linking the Markov model to a decision making process, the building weighting method suggested by Zhang [14] is appropriate. He has divided building network(N) into each individual building (b) then divided the building into its constituting system (s) which is dependent on its components(c). Finally he divided the component to elements (e). He suggested that the overall performance of a building network is eventually dependent on the performance of all the buildings elements. For each element there is a composite measure (w) of key factors (distress, structural capacity, safety……… (Hudson et al [8]) Then he multiplied these weights by assigning value for these factors (v). The result will provide conditions index for this element.

$$CI_t^{bsce} = \sum W * V \text{ -(5)}$$

According to Zhang (14) there are four allowable management actions that could be taken for each element in any estate (a1=replacement, a2=major repairing, a3= minor repairing, a4 no action). These can be incorporated by substitution in to the same expression.

3.6 Application

A major challenge in application of the proposed concepts is the quality and quantity of the data needed. A probability distribution is needed for all major data categories for elements of an infrastructure system. With the support of the Brimbank City Council in Victoria, data are currently being collected for this purpose.

3. Demonstration of the method

Process is demonstrated with a division of a building into five key components:

- Building Structure (30% of building weight)
- Building Exterior (15% of building weight)
- Building Interior (25% of building weight)
- Building Services (20% of building weight)
- Building Site (10% of building weight)

(The weighting system has been developed in consultation with Brimbank City Council).

Figure 5 shows probability curves for the building external finishes with time. The time step considered is 1 year with external walls finishes reaching the condition 'D" in 5 years. Transition matrix derived for the given probability curves are shown in figure 5.

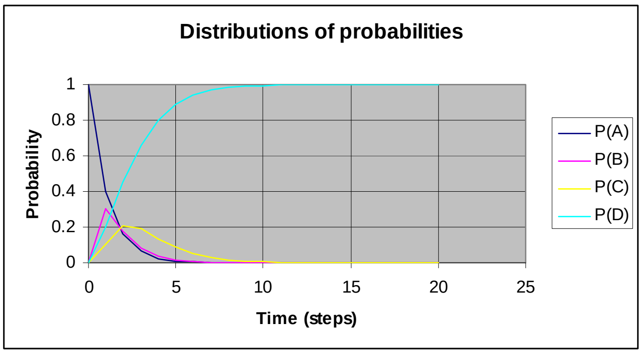

Figure 4: Cumulative Space

	State A	State B	State C	State D
State A	0.4	0.3	0.1	0.2
State B	0	0.2	0.4	0.4
State C	0	0	0.5	0.5
State D	0	0	0	1

Figure 5: Corresponding transition matrix

Once the transition matrix is developed for a given element type, the cost of maintenance can be calculated as a function of the deterioration curves.

The first step towards this is determining maintenance action matrix. Depending on the council asset management policy, different scenarios could be decided. In this paper a maintenance action has been assumed as per the following matrix

	State A	State B	State C	State D
State A	1	0	0	0
State B	0.7	0.3	0	0
State C	0.4	0.4	0.2	0
State D	0.5	0.3	0.2	0

Figure 6: Maintenance action Matrix

For example for elements in State C, 40% will be replaced to reach (State A), 40% will be repaired to State B, 20% will stay in State C

According to Zhang (14)

$sn=r*(M*P)^n$

Where

- sn – System performance
- M – maintenance policy matrix
- P – Transition matrix,
- r – Initial state vector.
- n – Time Step
- In external finish example (M*P):

	State A	State B	State C	State D
State A	0.4	0.3	0.1	0.2
State B	0.28	0.27	0.19	0.26
State C	0.16	0.2	0.3	0.34
State D	0.2	0.21	0.27	0.32

*Figure 7: (M*P)Matrix*

From this matrix future cost and status can be predicted as shown in figure 10 for ten time steps. Figure 8 shows the transient probability of the four conditions A, B, C, D against time step. In developing the figures, the cost is assumed to be in units with inspection cost assumed to be equal to one unit. Figure 9 shows the cost matrix for repair/maintenance.

Figure 8 also demonstrates reaching of steady state with a fixed maintenance regime. The asset manager can then identify the percentage of elements in each condition after reaching a steady state for a given maintenance regime. In this example, at the steady state, there will be 26.4% elements in condition A, 24.6% elements in condition B, 21.2% elements in condition C and , 27.8% of the elements in condition D. If this is not acceptable by the organisation, maintenance regime can be changed to reflect the strategic objectives of the asset manager.

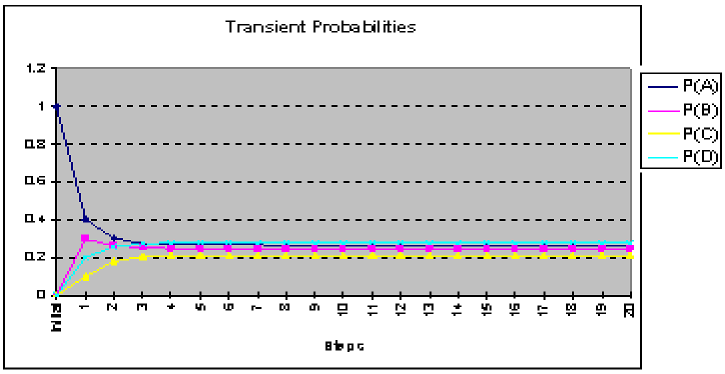

Figure 8: Future Prediction

	State A	State B	State C	State D
State A	1	0	0	0
State B	5	1	0	0
State C	7	4	1	0
State D	10	8	6	1

Figure 9: Repair/replace maintenance cost matrix

Time Step	State A	State B	State C	State D	Step Cost	Cum. Cost	NPW
Initial	1.000	0.000	0.000	0.000	2.400	2.400	2.400
1	0.400	0.300	0.100	0.200	5.507	7.907	7.406
2	0.300	0.263	0.181	0.256	5.783	13.690	12.185
3	0.274	0.251	0.203	0.272	5.852	19.542	16.582
4	0.267	0.248	0.209	0.276	5.871	25.413	20.592
5	0.265	0.247	0.211	0.277	5.876	31.289	24.241
6	0.264	0.247	0.212	0.278	5.877	37.166	27.558
7	0.264	0.246	0.212	0.278	5.878	43.043	30.574
8	0.264	0.246	0.212	0.278	5.878	48.921	33.316
9	0.264	0.246	0.212	0.278	5.878	54.799	35.809
10	0.264	0.246	0.212	0.278	5.878	60.677	38.075

Figure 10: Future prediction cost

To calculate the buildings weight all building elements should be inspected then overall building network weight formula could be applied. In this paper the effect of current physical condition of external wall finishes on the building weight will be calculated. Tables 1 and 2 present the assumed building element weighting for this example of external finishes.

Table 1: Weightings for Elements of Building Exterior

Building Exterior of the whole building weight	15.0%
External Walls	20.0%
Windows	13.0%
Doors	16.0%
Fire Escapes	16.0%
Roofs	16.0%
Steps/Ramps/Walkways	5.0%
Roofs	14.0%
Total Exterior weight	100.0%

Table 2: Weight factors for a given condition

State	Weight Factors
A	1
B	0.8
C	0.3
D	0.0

From the above tables, the discount weight for external walls finishes in state C can be calculated as = 0.3 * 20% * 15%= 0.9 %. However, according to figure 10, only 21.2% of elements will be in condition C. Therefore with the proposed maintenance action plan, we can say that the reduction of the building condition from 100%, due to deterioration of external finishes in condition C will only be 21.2% x 0.9% = 0.19%. The asset manager then can perform a similar evaluation for all the major components of the building to evaluate the reduction in building condition from 100%. This will allow him/her to establish a benchmark for the building condition.

4. Conclusions

The paper presented the concept of using Markov chain for deterioration modelling of buildings. Application of the methodology considering a fixed maintenance regime and an associated cost was presented. The methodology is quite powerful in establishing the relationship between an established maintenance regime and the future cost. This is then incorporated into the decision making through a building weighting method which can be used to enhance the outcomes of the Markov analysis process. Whilst the method requires a significant initial investment to establish :

- The deterioration matrix
- Maintenance regimes and associated costs
- Building weighting,

once the method is established, self calibration can be incorporated into the information system making the functioning of the system quite smooth. The concept is currently being implemented with a project funded by the CRC for Construction Innovation at RMIT University.

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