International Journal of Reliability and Applications
Vol. 5, No. 4, pp. 115-128, 2004

Optimal Maintenance Decisions for Power Supply Timber Poles

G. Chattopadhyay* and A. Rahman
School of Mechanical, Manufacturing and Medical engineering
Queensland University of Technology, Brisbane, Australia 4000

Abstract. Reliability of a power supply timber pole depends on complex combination of age, environmental factors involved in deterioration process and inspection and maintenance actions influencing reliability and safety. In this paper soil and human factors are identified, models have been developed and analyzed for optimal maintenance decisions related to electrical power supply timber poles.

Key Words : *Maintenance, Timber poles, Soil factors, Inground decay.*

1. INTRODUCTION

In today's increasingly competitive world, reliability of a system is extremely important. Reliability is the probability that a system or an item working under specified conditions will continue working up to a specified time period. Reliability of any product depends on the design, manufacturing process, inspection and quality control including human factors, environmental factors and maintenance actions during the period of service. Timber poles are widely used in the power supply industry because of high strength per unit weight; low cost and excellent durability. In Australian, more than 5.3 million timber poles with an investment of around AU$ 12 billion are in use (Rahman et al, 2003[1]). Reliability of timber poles is extremely important because any failure can cause a huge loss due to outage, damage of property and/or loss of lives. Factors such as age, durability of timber based on quality of wood, and inground decay due to soil factors influenced by moisture, clay contents, pH value, salinity, conductivity and chemical composition, climate and stress due to load from cross arm, cable, wind and ice have impact on pole life. Frequent inspection and maintenance can improve reliability of in service poles with an increased maintenance cost leading to reduced risk of in service pole failures. On the other hand, less frequent inspection and maintenance can reduce the maintenance cost. However, this decision can increase risks of in service pole failures. This paper is on modeling those factors for optimal maintenance decisions for power supply timber poles.

---

* Corresponding Author.
E-mail address: g.chattopadhyay@qut.edu.au

The outlines of this paper are as follows: In Section 2 factors affecting decay of timber poles are defined. Section 3 deals with development of models and analysis. Section 4 provides a numerical example for illustration. Final section contributes to summery and scope for future research.

2. FACTORS AFFECTING THE RELIABILITY OF TIMBER POLE

Factors affecting reliability of a system are shown in Figure 1.

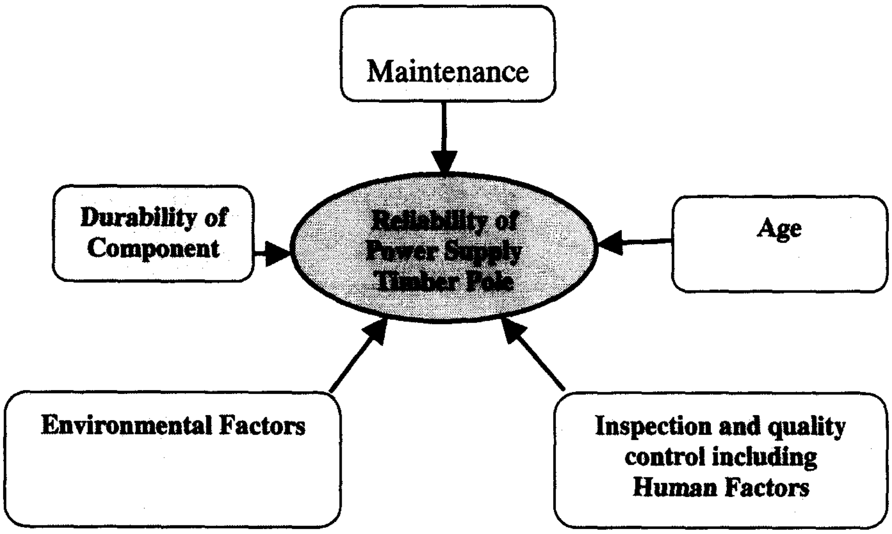

Figure 1. Reliability of complex infrastructure (Rahman, 2003)

Durability of timber poles is the capacity to perform a specified function, for a design life. This property is influenced by moisture content of timber and decay of timber materials in the presence of Oxygen and Moisture. Fiber saturation of timber occurs when moisture content is below 30% level. The compressive strength of pole is as much as 100% greater when the moisture content is reduced to 12% (Pearson et al, 1958). Durability is affected by metabolic activity and growth of aerobic microorganisms, such as bacteria and fungi if the moisture content in timber is more than 20%.

Environmental factors

Environmental factors such as soil composition, cyclic wetting and drying along with temperature cycles and overloading due to wind, cable and snow contribute to decay and in service failures of timber poles. Researchers have found that moisture and chemicals trapped inside the soil can cause algae, moss, and mould to grow and attack the inground section of timber poles. Raw data from industry also shows that decay of power supply timber poles is more in black clayey areas of Queensland compared to other areas

(Australian Clay Mineral Society, 1988; Wallace, 1988; Ward et al., 1991; Middleton et al, 1998).It is possible to identify risks of in service pole failures in any particular geographical area based on these factors. Foliente et al (2002) have classified Australian landscape into four in-ground-decay hazard zones such as A for lowest decay possibility, B, C for intermediate decay possibility and D for highest decay possibility. However no research has so far been carried out at individual pole level. In addition to moisture content, other soil factors such as the pH, salinity, conductivity and compactness of the soil are also considered in this paper for predicting their influence on inground decay. This is useful for inspection, repair and replacement decisions of in service timber poles.

Maintenance actions

Maintenance keeps an item or a system in useful working condition or restores it to a state in which it can perform its required function. Maintenance strategies used in industry are classified into three general types. These are: minimal repair, overhauling and replacements. A minimal repair does not make significant improvement and the condition after maintenance is "as bad as old" and is shown in curve 'b' of Figure 2. Since the components other than the failed parts of the system remains unchanged (Elsayed, 1996), Barlow et al 1960) the failure rate after maintenance does not change at all. In case of timber pole, minimal repairs are painting the component, insertion of pole saver rod into the decaying pole, application of bioguard bandage, chloropicrin and vapam treatment. Replacement enables the system to be "as good as new" and is shown in curve 'a' of Figure 2.

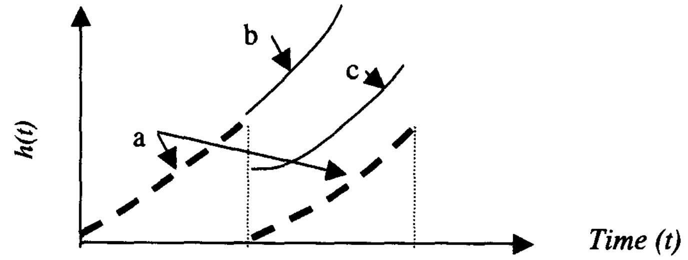

Figure 2. Hazard rate with effect of a. Replacement, b. Minimal repair, c. Overhauling (Chattopadhyay et al, 2002)

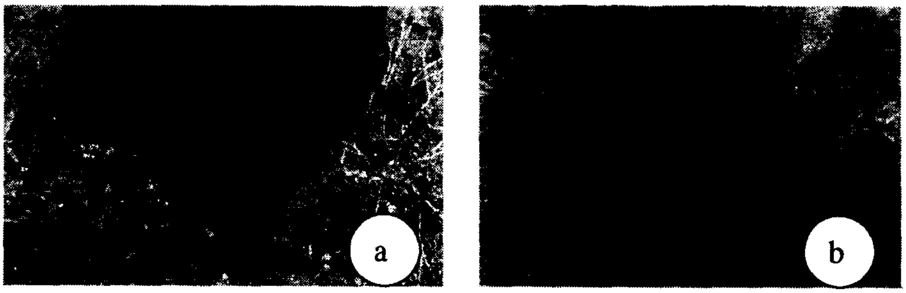

Figure 3. Minimal repair actions for timber pole - a. Bioguard bandage and b. Application of highly toxic Chloropicrin (Rahman, 2003)

Major repair, overhauling or upgrade as shown in curve 'c' of Figure 2, is a restorative action (Jardine, 1973) and the failure rate falls in between "as good as new" and "as bad as old" (Coetzee et al, 1997). Mechanical reinstatement and Quick Deuar pole reinstatement are used to extend the life of the pole an additional ten years of service life for a cost of 20 – 30 percent of the replacement by a new one.

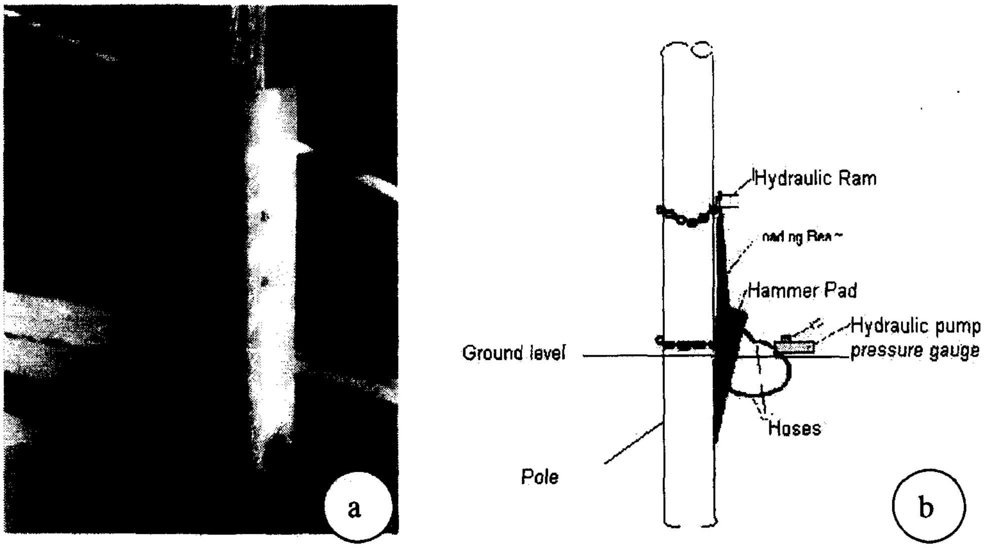

Figure 4. Overhauling or major repairing actions- a. Mechanical reinstatement b. Quick Deur Pole Reinstatement (Rahman, 2003)

Steel truss, fibre glass composite or steel encasements are used in mechanical reinstatement. For steel truss an open or close section truss is driven within 6 inches of the butt to provide solid foundation. 4 to 5 feet of the truss is extend above the ground level and banded to secure it to the pole. A c-shaped truss restores timber poles equivalent to new pole bending strength at the ground line (Bingel, 1995). The fibreglass "wrap" system restores poles to a reliable field service condition. Steel encasement provides an excellent strength performance, which consists of excavating around 3 feet deep, applying timber preservatives to the pole and then bolting a steel shell and the annulus is filled with acrylic modified mortar.

3. MODELLING MAINTENANCE COST

3.1 Assumptions

- Failure rate increases with time.
- Preventive maintenance (PM) restores life.
- The level of restoration is based on the quality of the maintenance and
- Cost of PM varies with level of restoration.

3.2 Notations

$h_{pm}(t)$	failure rate at time t, with maintenance.
$h(t)$	original hazard rate at time t when no maintenance is performed.
N	number of times maintenance is performed (including replacement).
x	fixed time interval of maintenance.
k	number of times maintenance is carried out.
τ	restoration out of maintenance action. $\tau = \alpha x$ where, α is the quality of the maintenance

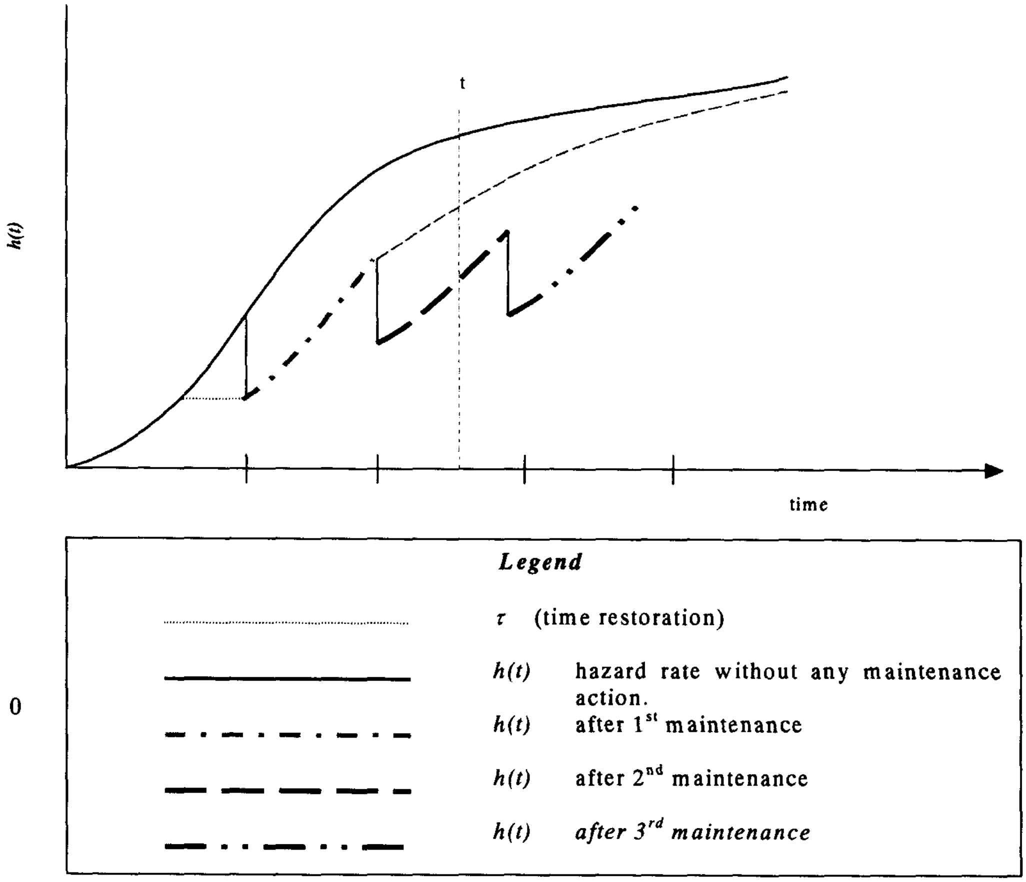

Figure 5. Maintenance model

From Figure 5, the hazard rate $h_{pm}(t) = h(t-k\tau)$.

3.3. Effectiveness of maintenance actions

Effectiveness of maintenance actions can be measured by its impact on the reliability or serviceability of a pole. If a maintenance action has a potential to extend service life from an expected service life of 30 years to 35 years, then the effectiveness of maintenance can be determined as follows:

$$\text{Effectiveness of maintenance} \quad \alpha = \frac{L_e - L_0}{L_e} = \frac{35-30}{35} = 0.15.$$

Where, L_e = Extended service life with preventive maintenance action
L_0 = Expected service life without preventive maintenance

Effectiveness of maintenance ranges from 0 to 1. $\alpha = 1$ signifies 'as good as new" and $\alpha = 0$, signifies 'as bad as old'. In real life this can vary from maintenance to maintenance and can be modeled using stochastic approach instead of deterministic approach explained here.

3.4. Expected cost per unit time

Expected Cost per unit time = (Expected Cost of minimal repair + Expected Cost of preventive maintenance + Cost of replacement)/Cycle time.

$$\begin{aligned} C(x, N) &= \frac{1}{Nx}[C_{mr}\left(\sum_{k=0}^{N}\int_{kx}^{(k+1)x} h_{pm}(t)dt\right) + (N-1)C_{pm} + C_{re}] \\ &= \frac{1}{Nx}\left[C_{mr}\left(\sum_{k=0}^{N}\int_{kx}^{(k+1)x} h(t-k\tau)dt\right) + (N-1)C_{pm} + C_{re}\right] \end{aligned} \qquad (1)$$

where

$C(x, N)$	is the expected cost rate per unit time
C_{mr}	is the unit cost for minimal repair
C_{pm}	is the cost of preventive maintenance
C_{re}	is the cost of replacement.

The failure rate of the Weibull distribution is given by

$$h(t) = \frac{\beta\, t^{\beta-1}}{\eta^{\beta}} .$$

Therefore, expected cost rate per unit time $C(x, N)$ *is* expressed as

$$C(x,N) = \frac{1}{Nx}\left[C_{mr}\left\{\sum_{k=0}^{N}\frac{\beta}{\eta^{\beta}}\int_{kx}^{(k+1)x}(t-k\tau)^{\beta-1}dt\right\} + (N-1)C_{pm} + C_{re}\right].$$

Finally, we have

$$C(x,N)=\frac{1}{Nx}\left[C_{mr}\left\{\sum_{k=0}^{N}\frac{x^{\beta}}{\eta^{\beta}}\left[(k-k\alpha+1)^{\beta}-(k-k\alpha)^{\beta}\right]\right\}+(N-1)C_{pm}+C_{re}\right]. \quad (2)$$

3.5. Human factors in inspection, quality control and maintenance

In real life, human factors play an important role in inspection, quality control and maintenance action where executive judgement is used in practice along with quantitative approach and various scientific testing techniques for repair and replacement decisions. The whole process consists of numerous steps. The overall reliability is dependent on reliability of the each step involved:

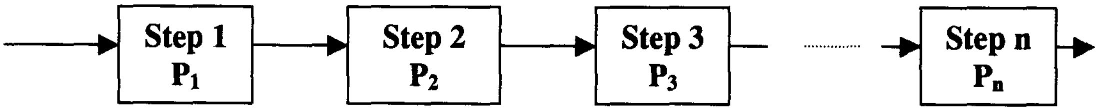

Figure 6. Inspection process

All the steps involved are assumed to be in series here. If the stages are independent of each other, the probability of successful decision-making can be termed as human reliability. The probability of human error is

$$P_{HE}=\frac{E_{en}}{E_{in}}$$

where

P_{HE} = the probability of human error
E_{en} = total number of known error of given type
E_{in} = total number of observations.

Therefore the reliability of the above process is

$$R_i = R_1 \times R_2 \ldots\ldots\ldots\ldots\ldots R_n .$$

Overall System Reliability, R is given by System Reliability × Inspection Reliability and the failure rate can be obtained by using overall system reliability.

For timber pole, we assume that the human reliability involves only in inspection. Let R_i represents the inspection reliability. Then the new failure rate $h_i(t)$ (assuming failures following Weibull distribution) can be given by

$$h_i(t) = \frac{1}{R_i}\frac{\beta}{\eta^{\beta}} t^{\beta-1} \,. \tag{3}$$

3.6. Modeling environmental factors

When environmental factors are taken into consideration, the failure rate of such component is become the product of a time dependent arbitrary or baseline line failure rate (when environmental and human factors were assumed to zero) and the functional formate of all the environmental parameters affecting the failure process. Failure rate function can be modelled considering environmental factors:

$$h^*(t) = \psi h_i(t) = \frac{\psi h(t)}{R_i(t)} \tag{4}$$

where

ψ = the environmental parameter

$h(t)$ = base line hazard rate

$h^*(t)$ = new hazard rate, taken into consideration of the environmental factors.

Failure times of repairable items are affected by

- Operating environment
- History (maintenance)
- Design (selection of material) and manufacturing.

It can be modeled using the covariates which influence the failure rate in a manner such that the observed failure rate is above or below the base line hazard rate depending on the human factor and maintenance quality (Kumar et al, 1993).

ψ might be time dependent and can be modelled as follows:

Exponential	$\psi(t;\theta) = e^{\theta}$
Logarithmic	$\psi(t;\theta) = \log\{1 + e^{\theta}\}$
Inverse linear	$\psi(t;\varepsilon) = \dfrac{1}{1+t\varepsilon}$
Linear	$\psi(t;\varepsilon) = 1 + t\varepsilon$

where, θ and ε are shape parameters based on the co-relationship with environmental conditions.

In modeling durability, Foliente et al (2002) suggests to introduce an in-ground degradation modification factor (k_d) that can be applied for a specified design service life. They have generated k_d for Australian timber poles, hard timber and soft timber with and without preservative treatment (Australian Standard 1604.1) and found that the hazard rate is inversely proportional to the degradation modification factor k_d. Therefore, hazard rate can be modelled as

$$h^{**}(t) = \frac{h^*(t)}{k_d} = \frac{\psi h(t)}{R_i k_d} . \tag{5}$$

3.7. Parameter estimation

Estimation of parameter is discussed in this section.

3.7.1 Estimation of base line parameters

Estimation of base line parameters β and η when effect of durability, environmental factors is kept zero:

Assuming the failure rate follows the Weibull distribution. The reliability function then can be presented as

$$R(t) = 1 - F(t) = e^{\left(\frac{t}{\eta}\right)^{\beta}}$$

and therefore

$$-\ln(1 - F(t)) = \left(\frac{t}{\eta}\right)^{\beta} .$$

Now taking log of both sides, we have

$$\log[-\ln(1 - F(t))] = \beta \log t - \beta \log \eta \; .$$

3.7.2 Estimation of parameters considering all factors

As the failure rate of the component changes with the durability, environmental and the human factors, the parameter needs to be re-estimated (Rahman et al, 2003[2])
Assuming the failure distribution follows the Weibull distribution, the failure rate can be given by

$$h^{**}(t) = \frac{\beta^*}{\eta^{*\beta^*}} t^{\beta^* - 1} . \tag{6}$$

4. NUMERICAL EXAMPLE

Let us assume the following numerical values:

Cost of minimal repair,	C_{mr}	= \$100
Cost of preventive maintenance,	C_m	= \$600
Cost of replacement,	C_{re}	= \$2500
Maintenance effectiveness,	α	= 0.8
Environmental parameter,	ε	= 0.1
Inspection reliability,	R_I	=0.9
Durability modification factor	k_d	=0.95.

Numerical example for estimating base line parameters:

In estimating the base line, we used and analyzed the failure data (censored) of timber poles from Electricity Supply Company located in different suburbs in Brisbane, Australia. Table 1 exhibits timber pole failure data in Brisbane, Australia.

Table 1. Timber pole failure data

Age	Failure dt
13	1
18	7
22	19
28	32
33	15
38	14
43	7
48	4
53	2
58	1
63	9
68	6

This tabulation is based on the assumption that failures occur continuously and a log(t) vs log[-ln(1-F(t))] was performed to estimate base line shape parameter β and characteristic life parameter η. That gives β = 3.55 and η = 37.8. By taking logarithm on both sides of the equation (6)

$$Log\left[h^*(t)\right] = Log\frac{\beta^*}{\eta^{*\beta^*}} + \left(\beta^* - 1\right)Log t.$$

Let us assume ψ_t be linear function of ε. The value of ε depends on the environmental variables and their quantitative influence in the deterioration process. Inspection reliability depends on the accuracy of instrument used in inspection, inspector's experience and judgment capabilities. $h^*(t)$ is given by

$$h^*(t) = \frac{\psi h(t)}{R_i k_d} = \frac{(1+\varepsilon t)}{R_i} \times \frac{\beta t^{\beta-1}}{\eta^{\beta}}$$

Table 2. Calculation of $log[h^*(t)]$ and $log\ (t)$

1	2	3	4	5	6	7	8	9
Age	Failure dt	f(t)	F(t)	R_i	ψ_τ	$h^*(t)$	$Log(t)$	$log[h^*(t)]$
13	1	0.0085	0.0085	0.9	2.3	0.0158	1.1139	-1.8019
18	7	0.0598	0.0684	0.9	2.8	0.0441	1.2553	-1.3560
22	19	0.1624	0.2308	0.9	3.2	0.0840	1.3424	-1.0757
28	32	0.2735	0.5043	0.9	3.8	0.1845	1.4472	-0.7340
33	15	0.1282	0.6325	0.9	4.3	0.3173	1.5185	-0.4985
38	14	0.1197	0.7521	0.9	4.8	0.5077	1.5798	-0.2944
43	7	0.0598	0.8120	0.9	5.3	0.7683	1.6335	-0.1145
48	4	0.0342	0.8462	0.9	5.8	1.1130	1.6812	0.0465
53	2	0.0171	0.8632	0.9	6.3	1.5564	1.7243	0.1921
58	1	0.0085	0.8718	0.9	6.8	2.1142	1.7634	0.3251
63	9	0.0769	0.9487	0.9	7.3	2.8024	1.7993	0.4475
68	6	0.0513	1.0000	0.9	7.8	3.6382	1.8325	0.5609

Regression analysis of columns 8 & 9 of the table 2 gives

$$Log[r^*(t)] = -5.456 + 3.26 Logt$$

where $\beta^* = 4.29$, and $\eta^* = 26.17$. By using MAPLE we get

- Cost rate per unit time, $C^*(N, x)$=\$ 69.53 per year
- Optimal interval between maintenance, x^*= 20 years
- Number of maintenance action, N^*= 3

Effectiveness of maintenance is often associated with cost associated with various options in repairs and replacements. Table 3 helps in decision making by simulating various "what if" scenarios.

Table 3. What if scenario for managerial decisions

C_{re} = \$2500, C_{pm}= \$600, C_{mr} = \$100, $\alpha = 0.8$

ε	0.1	0.2	0.3	0.4	0.5	0.6
β^*	4.29	4.4	4.447	4.47	4.49	4.5
η^*	26.17	23	21.9	20.78	19.8	19
N^*	3	3	3	4	4	4
x^* (Years)	20	20	20	15	15	15
$C^*(N, x^*)$ (\$)	69.53	75.53	79.60	83.00	85.30	88.75

C_{re} = \$2500, C_{pm}= \$300, C_{mr} = \$100, $\alpha = 0.3$.

ε	0.1	0.2	0.3	0.4	0.5	0.6
β^*	4.29	4.4	4.447	4.47	4.49	4.5
η^*	26.17	23	21.9	20.78	19.8	19
N^*	3	3	3	3	3	3
x^* (Years)	18.92	12.76	11.58	10.75	10.40	9.96
$C^*(N, x^*)$ (\$)	87.5	130.09	137.31	145.00	152.50	159.50

5. SUMMARY AND SCOPE FOR FUTURE WORK

The models on maintenance decisions so far concentrate only on operational parameters without considering durability of the timber poles, environmental and human factors. In this paper environmental and human factors are included to develop realistic models for maintenance decisions of timber poles. However, identification of environmental factors and estimation of parameters is a complex process. There is enough scope for future work on identifying significant environmental which covers soil factors for inground decay and human factors in inspection and repair/ replacement decisions that affect the reliability of a in service timber poles.

This research can be extended to develop models for inspection, repairs and replacements of timber poles. This includes:

- Development of reliability database based on inground decay
- Assessment of the residual life of timber poles.
- Cost effective condition monitoring of in-service poles and
- Cost effective decisions for prevention of inground decay and mitigation.

REFERENCES

Barlow, R. and Hunter, L.C, (1960). Optimum Preventive Maintenance Policies, *Operations Research*, **1 8**, 90 – 100.

Bingel, N.G. (1995). Cost Saving Benefits of Wood Structure Maintenance, ESMO – 95, 11-16.

Chattopadhyay, G., Rahman, A., Iyer R.M, Ho, D., Netra, G., (2002). Modeling Environmental factors in maintenance of high volume Infrastructure components, *3rd Asia-Pacific Conference on System Integrity and Maintenance and Exhibition, 25-27th September, Cairns Australia,* 66-71.

Coetzee, J.L., (1997). The Role of NHPP models in the Practical Analysis of Maintenance Failure Data, Reliability Engineering and System Safety, 56, 161-168.

Elsayed, A. E., (1996). *Reliability Engineering*, Addison Wesley Longman Inc, Reading, Massachusetts, U.S.A.

Foliente, G.C., Leicester, R.H., Wang, C., (2002). Durability Design for Wood Pole, *Forest Product Journal*, **52**.1, 10-19.

Jardine, A.K.S, (1973). *Maintenance Replacement and Reliability*, Topics in Operation Research Series, Pitman Publishing Corporation, N.Y., U.S.A.

Kumar, D., Klefsjo, B., (1993). Proportional Hazard Model: A Review, *Reliability Engineering & System Safety*, **44**, 177-188.

Pearson, R.G., Kloot, N.H. and Boyd, J.D., (1958). *Timber Design Handbook*, the Jacaranda Press.

Middleton, C. H. and Clem, R. (1998). Evaluation of Leucaena Germplasm on clay soils in central and southern inland Queensland, *International Workshop 1998, Hanoi, Aciar Proceedings, Australian Centre for International Agriculture Research*, Issue 86, 154-156.

Rahman, A., (2003). Modelling inground decay of wood pole for maintenance decisions, Master of Engineering Thesis, Queensland University of Technology, Brisbane, Australia.

Rahman, A. and Chattopadhyay, G.N., (2003^1). Identification and Analysis of Soil factors for Predicting Inground Decay of Timber Poles in Deciding Maintenance Policies, *Proceedings of the 16th International Congress and Exhibition on Condition Monitoring and Diagnostic Engineering Management, COMADEM 2003, Vaxjo, Sweden, 27-29 August 2003.*

Rahman, A. and Chattopadhyay, G.N., (2003^2). Estimation of Parameters for Distribution of Timber Pole Failure due to In-ground Decay, *Proceedings of the 5th Operations Research Conference on Operation Research in the 21st Century, the Australian Society of Operations Research, Sunshine coast, Australia, 9-10 May, 2003.*

Wallace, K.B. (1988). *Low cost roads on cracking soils; A review (with a Particular Reference to Queensland Conditions),* QUT, School of Civil Engineering, 199.

Ward, L.D., Norris, C.P., Thomas, E.C, (1991). Component interaction in zero-till planters for heavy clay soils of southern Queensland, *Soil and Tillage Research Journal,* Elsevier, **20**, 19-38.