Kyoto Univ. and UTC Joint Summer Training Course of Road Infrastructure Asset Management

Bridge Management (4) Probabilistic Deterioration Prediction

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Probabilistic Deterioration Prediction (1):
Markov Chain Model
Ex) Mr. A moves from area to area, Russia, Tokyo, New York, Hanoi, Melbourne, every month. Which city Mr. A will go depends on which city he stays now.

⇒ Markov Property

The probability distribution of future states of a process depends only upon the current state.
The state being in Russia is defined as 1, Tokyo; 2, New York; 3, Hanoi; 4, Melbourne; 5.

The probability from R to N

= Markov transition probability from state 1 to 3

= \( \pi_{13} \)

\[
\begin{bmatrix}
0.40 & 0.30 & 0.15 & 0.10 & 0.05 \\
0.10 & 0.50 & 0.10 & 0.20 & 0.10 \\
0.20 & 0.05 & 0.60 & 0.05 & 0.10 \\
0.05 & 0.05 & 0.30 & 0.40 & 0.20 \\
0.30 & 0.10 & 0.20 & 0.10 & 0.30 \\
\end{bmatrix}
\]

\[0 \leq \pi_{ij} \leq 1\]

\[\sum_{j=1}^{J} \pi_{ij} = 1\]
Application of Visual Inspection Data to MTPs

5 steps rating system for the results of visual inspection

1; new construction, 5; limit in service

Different Point from the previous example

⇒ Rating can not transit to better condition state.
Condition of bridges can not be recovered as long as no repair/rehabilitation carried out.

In the previous example, it is equivalent to setting up a restriction which Mr. A is not able to move from the south to the north.

\[
\Pi = \begin{pmatrix}
0.40 & 0.30 & 0.15 & 0.10 & 0.05 \\
0.50 & 0.10 & 0.20 & 0.10 \\
0.60 & 0.05 & 0.10 \\
0.40 & 0.20 \\
0.30 & 0.05 \\
\end{pmatrix}
\]

\[\pi_{ij} = 0 \ (i > j)\]
Significant Problem of Application

Existing Simple Method

No. of Samples (Visual Inspection Data)
- state 1 to 1; 50 samples
- 1 to 2; 30
- 1 to 3; 15
- 1 to 4; 4
- 1 to 5; 1

Markov transition probability (relative frequency)
- $\pi_{11} = 0.50$, $\pi_{12} = 0.30$, $\pi_{13} = 0.15$, $\pi_{14} = 0.04$, $\pi_{15} = 0.01$.

$$ \Pi = \begin{pmatrix} 0.50 & 0.30 & 0.15 & 0.04 & 0.01 \\ 0 & 0.60 & 0.30 & 0.05 & 0.05 \\ 0 & 0 & 0.70 & 0.20 & 0.10 \\ 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} $$

The existing method requires uniformity of the sampling interval.

Visual inspection intervals are not uniformity.

Neglect nonuniformity or extract only the data in same sampling intervals.
Concept of Proposed Method

Visual Inspection Interval: $2T$ years, Rating: $i$ to $j(i+1)$

Markov Transition Probability: $\pi_{ij}^{2T}$

How should we represent $\pi_{ij}^{2T}$ by $\pi_{ij}^T$ with inspection interval $T$ year?

Deterioration Path 1:

$h(0) = i \rightarrow h(T) = i \rightarrow h(2T) = j$

$\pi_{ii}^T \quad \pi_{ij}^T \quad \pi_{jj}^T$

Deterioration Path 2:

$h(0) = i \rightarrow h(T) = j \rightarrow h(2T) = j$

$\pi_{ij}^T \quad \pi_{jj}^T$

General Case

$\pi_{ij}^n T = \sum_{k_1=i}^{j} \pi_{ik_1}^{T} \sum_{k_2=k_1}^{j} \pi_{k_2k_1}^{T} \cdots \sum_{k_n-1=k_{n-2}}^{j} \pi_{k_nk_{n-2}}^{T} \pi_{k_{n-1}j}^{T}$

$$\pi_{ij}^{2T} = (\pi_{ij}^T \pi_{ij}^T + \pi_{ij}^T \pi_{jj}^T) = \sum_{k=i}^{j} \pi_{ik}^T \pi_{kj}^T$$
Estimation of MTP by Maximum-Likelihood method

Likelihood Function based on Simultaneous occurrence probability of Visual Inspection Results

\[ L = \prod_{n=1}^{N} \prod_{i=1}^{J} \prod_{j=1}^{J} \left( \pi_{ij}^{nT} \right)^{m_{ij}^n} \]

Log Likelihood Function

\[ \ln L = \sum_{n=1}^{N} \sum_{i=1}^{J} \sum_{j=1}^{J} m_{ij}^n \cdot \pi_{ij}^{nT} \]

In order to decide the unknown parameters which maximize the likelihood function, the log likelihood function is differentiate partially by each unknown parameter, the obtained nonlinear simultaneous equation is solved by numerical calculation

\[ \frac{\partial \ln L}{\partial \pi_{ij}^{T}} = 0 \]
Empirical Verification

Application for Actual Visual Inspection Data of RC Decks in NYC

7-Level Rating Standards (RC Decks)

<table>
<thead>
<tr>
<th>Ratings</th>
<th>Physical Meanings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deck is new or near new, almost no sign of deterioration</td>
</tr>
<tr>
<td>2</td>
<td>Between 1 &amp; 3</td>
</tr>
<tr>
<td>3</td>
<td>Only localized areas of leakage</td>
</tr>
<tr>
<td>4</td>
<td>Between 3 &amp; %</td>
</tr>
<tr>
<td>5</td>
<td>75% or more of the deck has leakage. Only localized spalled areas. Efflorescence</td>
</tr>
<tr>
<td></td>
<td>along the girder top flanges</td>
</tr>
<tr>
<td>6</td>
<td>Between 5 &amp; 7</td>
</tr>
<tr>
<td>7</td>
<td>Heavy spalling, Heavy efflorescence, Punch through has occurred or is likely</td>
</tr>
<tr>
<td></td>
<td>Deck saturated to point that concrete is rubble.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inspection Intervals (Years)</th>
<th>No. of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14,030</td>
</tr>
<tr>
<td>2</td>
<td>18,312</td>
</tr>
<tr>
<td>3</td>
<td>479</td>
</tr>
<tr>
<td>Total</td>
<td>32,821</td>
</tr>
</tbody>
</table>
Estimation Results of MTPs

<table>
<thead>
<tr>
<th>Rating</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.713</td>
<td>0.281</td>
<td>0.006</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.793</td>
<td>0.189</td>
<td>0.018</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0.852</td>
<td>0.142</td>
<td>0.006</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.893</td>
<td>0.101</td>
<td>0.006</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.917</td>
<td>0.063</td>
<td>0.020</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.919</td>
<td>0.081</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

- Employing all data including inspection interval 1 to 3 years.
- The decrease in the rating during a single interval is limited to 2 levels.
- When $i > j$, $\pi_{ij}=0$. $\pi_{jj}=1$ means absorbing condition.
- For every rating, the diagonal part (deterioration does not progress and the rating remains constant) shows the maximum of the MTPs.
- As deterioration progress, the speed of the deterioration becomes slower.
The expected lifetime of the rating to transit from $i$ to $i+1$:

$$E[RMD_i] = T \cdot \pi_{iJ}^T + \sum_{\ell=1}^{\infty} \sum_{m=i}^{J-1} (\ell \cdot T + T) \pi_{im}^T \pi_{mj}^T - \sum_{m=i+1}^{J-1} E[RMD_m]$$

The 1st + 2nd term: The expected No. of years between $i$ and $J-1$.

The 3rd term: the sum of the expected No. of years between $i+1$ to $J-1$. 

Diagram:

- Rating: $i$, $i+1$, $i+2$, $i+3$
- Time
- $E[RMD_i]$, $E[RMD_{i+1}]$, $E[RMD_{i+2}]$
The simplified method does not satisfy the time adjustment condition.

\[ \{\Pi^{(1)}\}^2 \neq \Pi^{(2)} \]

The interval of visual inspection is not determined randomly, but determined by considering physical properties of the RC decks.

The curve of the proposed method is between those obtained by the simple aggregation of the one-year and two-year inspection intervals.
Expected Path for Another Member

Primary Member

Secondary Member

Joint

- Proposed Method
- Simplified Method (Inspection Interval: 1 year)
- Simplified Method (Inspection Interval: 2 years)

Age [Years]  Rating

Proposed Method  Simplified Method

(Inspection Interval: 1 year)  (Inspection Interval: 2 years)
Calculation of Transition of The Rating Distribution

Definition of the state vector $X_t$:
Relative frequencies of each rating at a given time point $t$

$$X_t = [x_1(t) \ x_2(t) \ \cdots \ x_J(t)]$$

The No. of samples of rating $i$ at time point $t$
Total no. of samples

The state vector at time point $t+1$

$$X_{t+1} = X_t \Pi$$

The state vector at an arbitrary time point?

The state vector at time point $t+2$:
conducting recalculation after substituting $X_{t+1}$ with $X_t$

At arbitrary time point $t+a$:
repeating the above calculation the necessary no. of times $a$
a) All RC decks are the state of new construction.
Initial Vector; $x = [ 1 \ 0 \ 0 \ 0 \ 0 \ 0 ]$

- 15 years later, very few RC decks still keep rating 1.
- At around 42 years, 50% of them have reached the limit of use (rating 7).
- Under inappropriate management, in 20 years the ratio of the rating 7 will amount to 50%.

b) Actual visual inspection results of NYC in 1995
Initial Vector; $x = [ 0.001 \ 0.026 \ 0.092 \ 0.317 \ 0.382 \ 0.117 \ 0.0065 ]$
Probabilistic Deterioration Prediction (2): Random Proportional Weibull Hazard Deterioration Model
Statistical Deterioration Prediction by Hazard Model

- Failure Cumulative Distribution Function: $F(t)$

- Probability Density Function: $f(t)$

$$F(t) = \int_{0}^{t} f(u)\,du$$
- Survival Distribution Function: \( \tilde{F}(t) = 1 - F(t) \)

- Conditional Probability (the equipment survives until time \( t \), and moreover fails during the time interval period \( t, t+\Delta t \) )

\[
\lambda(t) \Delta t = \frac{f(t) \Delta t}{\tilde{F}(t)}
\]
Statistical Prediction by Hazard Model

Two-Type Deterioration Pattern

Time Dependent or not of Failure Probability

- **Poisson Type**
  - Exponential Hazard Function

- **Weibul Type**
  - Weibul Hazard Function
Weibul Deterioration Hazard Model

\[
\dot{\beta}(t) = \zeta m t^m A^1
\]

\[
f(t) = \zeta m t^m A^1 \exp(\ddot{\zeta} t^m)
\]

\[
F(t) = \exp(\ddot{\zeta} t^m)
\]
Disadvantage in the Existing Hazard Model

Deterministic Hazard Rate
- Same Deterioration Process under the Same Condition

How we can model the heterogeneity of Individual equipments?
Random Proportional Weibul Hazard Model

\[ i_{ij} (t_{ij}^k) = \expf \tilde{A}_{ij} \varsigma_i \left( t_{ij}^k \right)^m \tilde{A} 1 \]

\[ f_{ij} (t_{ij}^k) = \expf \tilde{A}_{ij} \varsigma_i \left( t_{ij}^k \right)^m \tilde{A} 1 \]

\[ \tilde{F}_{ij} (t_{ij}^k) = \expf \tilde{A}_{ij} \varsigma_i \left( t_{ij}^k \right)^m \tilde{A} 1 \]

Heterogeneity Parameter that is subject to a certain probability Distribution
Concept of Random Proportional Hazard Model

- **Base line Hazard Function:**
  \[ \dot{i}(t) = \varsigma t^m \]

- **Hazard Function of Equipment A:**
  \[ \dot{i}_A(t) = \varsigma m_A t^{m_A} \]

- **Hazard Function of Equipment B:**
  \[ \dot{i}_B(t) = \varsigma m_B t^{m_B} \]
Considerable Heterogeneity of Samples

- HDD
- Power Supply
- Data Processing Device

\[ \text{3 Types} \]

\[ \text{Installed in 9 Sub-System} \]

\[ \text{3 Usage: PC, Server, Others} \]

- Power Supply has Only one Usage
## Number of Samples

<table>
<thead>
<tr>
<th>Sub Sys. 1 PC</th>
<th>HDD</th>
<th>Power</th>
<th>Proc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>1</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>Sub Sys. 2 PC</td>
<td>9</td>
<td>96</td>
<td>10</td>
</tr>
<tr>
<td>Server</td>
<td>17</td>
<td>—</td>
<td>7</td>
</tr>
<tr>
<td>Others</td>
<td>1</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>Sub Sys. 3 PC</td>
<td>3</td>
<td>81</td>
<td>3</td>
</tr>
<tr>
<td>Server</td>
<td>23</td>
<td>—</td>
<td>15</td>
</tr>
<tr>
<td>Others</td>
<td>2</td>
<td>—</td>
<td>15</td>
</tr>
<tr>
<td>Sub Sys. 4 PC</td>
<td>12</td>
<td>27</td>
<td>5</td>
</tr>
<tr>
<td>Server</td>
<td>22</td>
<td>—</td>
<td>7</td>
</tr>
<tr>
<td>Others</td>
<td>16</td>
<td>—</td>
<td>16</td>
</tr>
<tr>
<td>Sub Sys. 5 PC</td>
<td>5</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>Server</td>
<td>15</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>Others</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Sub Sys. 6 PC</td>
<td>4</td>
<td>17</td>
<td>4</td>
</tr>
<tr>
<td>Server</td>
<td>8</td>
<td>—</td>
<td>6</td>
</tr>
<tr>
<td>Others</td>
<td>—</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>Sub Sys. 7 PC</td>
<td>2</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Server</td>
<td>9</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>Others</td>
<td>—</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>Sub Sys. 8 PC</td>
<td>32</td>
<td>51</td>
<td>23</td>
</tr>
<tr>
<td>Server</td>
<td>13</td>
<td>—</td>
<td>7</td>
</tr>
<tr>
<td>Others</td>
<td>—</td>
<td>—</td>
<td>16</td>
</tr>
<tr>
<td>Sub Sys. 9 PC</td>
<td>4</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Server</td>
<td>3</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>Others</td>
<td>—</td>
<td>—</td>
<td>5</td>
</tr>
</tbody>
</table>

Many kinds of Little samples
Available Information (Failure History)

**Failure History of All Equipments**
\[ \tilde{N} = (\hat{o}_1; \tilde{\theta}_1; \tilde{\delta}_M) \]

**Failure History of Equipment Type \( i \)**
\[ \hat{o}_i = (\hat{o}_{i1}; \tilde{\theta}_1; \hat{o}_{iN}) \]

**Failure History of Device \( j \) of Type \( i \)**
\[ \hat{o}_{ij} = (\hat{\epsilon}_{ij}^1; t_{ij}^1); \tilde{\theta}_1; (\hat{\epsilon}_{ij}^L; t_{ij}^L) \]
\[ i = 1; \tilde{\theta}_1; M; j = 1; \tilde{\theta}_1; N_i \]

\[ \hat{\epsilon}_{ij}^k : \text{Dummy Variable} \]
\[ \hat{\epsilon}_{ij}^j = 0 : \text{Failure} \]
\[ \hat{\epsilon}_{ij}^j = 1 : \text{Otherwise} \]

\[ t_{ij}^k : \text{Failure Time or Elapse Time} \]
Estimation of Hazard Model

\[ \tilde{i}_{ij}(t_k^{i_j}) = \frac{\zeta_{ij} m(t_k^{i_j})^m}{\tilde{\alpha}} \]

Standard Gamma Distribution

\[ \tilde{g}(\tilde{\pi}_{ij} : \tilde{\mu}) = \frac{\tilde{\mu}^\tilde{\pi}_{ij}}{\tilde{\alpha}^{\tilde{\pi}_{ij}} \tilde{\alpha}} \exp(\tilde{\alpha} \tilde{\mu}^{\pi_{ij}}) \]

Objectives: HDD, Power Supply, Data Processing Device

No. of Samples: Total 693

Available Data: Failure History (1998-2006.9)
2-Step Estimation Method

1. Estimation of $\zeta_i$, $m$, $\hat{u}$ by Maximum Likelihood Method

$$\ln L(\bar{y} ; i) = \prod_{i = 1}^{M} \prod_{j = 1}^{N_i} \ln L_{ij}(\delta_{ij} ; i)$$

$$= N \hat{u} \ln \hat{u} \prod_{i = 1}^{M} \prod_{j = 1}^{N_i} (s_{ij} + \hat{u}) \ln(\hat{u} + \zeta_i \hat{u}_{ij})$$

$$+ \prod_{i = 1}^{M} \prod_{j = 1}^{N_i} \ln(\hat{u} + k) + \prod_{i = 1}^{M} \prod_{j = 1}^{N_i} \prod_{k = 0}^{n} \ln \hat{u}_{ij} + \prod_{i = 1}^{M} \prod_{j = 1}^{N_i} \prod_{k = 0}^{n} \ln \hat{\zeta}_{ij} + \ln m + (m \bar{A} 1) \ln t_{ij}$$

2. Calculation of Heterogeneity Parameter $\hat{\zeta}_{ij}$

$$\hat{\zeta}_{ij} (\hat{\delta}_{ij}) = \frac{\prod_{i = 1}^{M} \prod_{j = 1}^{N_i} s_{ij} + \hat{u} \bar{A} 1}{\hat{u} + \zeta \hat{d}_{ij}}$$
Estimation Results

\[
\begin{array}{c}
i_{ij}(t_{ij}^k) = \gamma_0 \gamma_1 \gamma_2 \gamma_3 \phi m(t_{ij}^k) m \tilde{A} 1
\end{array}
\]

<table>
<thead>
<tr>
<th></th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>$\gamma_3$</th>
<th>$m$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Estimator</strong></td>
<td>1.251E-5</td>
<td>1.631E-6</td>
<td>5.293E-6</td>
<td>2.174</td>
<td>1.193</td>
</tr>
<tr>
<td><strong>t-value</strong></td>
<td>-5.104E6</td>
<td>-2.311E7</td>
<td>-9.182E6</td>
<td>49.031</td>
<td>2.182</td>
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<tr>
<td><strong>Log-Likelihood</strong></td>
<td></td>
<td></td>
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<td>-402.441</td>
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</tbody>
</table>
Calculation Results of Heterogeneity Parameters

<table>
<thead>
<tr>
<th>Sub Sys. 1 PC</th>
<th>HDD</th>
<th>Power</th>
<th>Proc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server</td>
<td>0.474</td>
<td>0.253</td>
<td>0.473</td>
</tr>
<tr>
<td>Others</td>
<td>0.462</td>
<td>---</td>
<td>0.462</td>
</tr>
<tr>
<td>Sub Sys. 2 PC</td>
<td>0.392</td>
<td>0.171</td>
<td>0.814</td>
</tr>
<tr>
<td>Server</td>
<td>1.76</td>
<td>---</td>
<td>0.405</td>
</tr>
<tr>
<td>Others</td>
<td>0.488</td>
<td>---</td>
<td>0.301</td>
</tr>
<tr>
<td>Sub Sys. 3 PC</td>
<td>0.454</td>
<td>0.114</td>
<td>0.454</td>
</tr>
<tr>
<td>Server</td>
<td>0.688</td>
<td>---</td>
<td>0.276</td>
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<tr>
<td>Others</td>
<td>0.430</td>
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<td>0.879</td>
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<td>Sub Sys. 4 PC</td>
<td>1.28</td>
<td>0.170</td>
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<tr>
<td>Server</td>
<td>0.780</td>
<td>---</td>
<td>0.756</td>
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<tr>
<td>Others</td>
<td>0.220</td>
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<td>0.837</td>
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</table>

<table>
<thead>
<tr>
<th>Sub Sys. 6 PC</th>
<th>HDD</th>
<th>Power</th>
<th>Proc.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.282</td>
<td>0.423</td>
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<td>Others</td>
<td>0.377</td>
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<td>0.849</td>
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</table>

<table>
<thead>
<tr>
<th>Sub Sys. 7 PC</th>
<th>HDD</th>
<th>Power</th>
<th>Proc.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.278</td>
<td>0.457</td>
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<tr>
<td>Others</td>
<td>1.21</td>
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<td>0.436</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Sub Sys. 8 PC</th>
<th>HDD</th>
<th>Power</th>
<th>Proc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server</td>
<td>3.92</td>
<td>1.15</td>
<td>0.557</td>
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<tr>
<td>Others</td>
<td>1.50</td>
<td>0.652</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub Sys. 9 PC</th>
<th>HDD</th>
<th>Power</th>
<th>Proc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server</td>
<td>0.883</td>
<td>0.707</td>
<td>0.583</td>
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<tr>
<td>Others</td>
<td>0.437</td>
<td>---</td>
<td>0.961</td>
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</tbody>
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Survival Curve of Each Type

Elapse Time (Month)

Survival Probability

HDD
電源部
本体

Survival Probability

0.5
Survival Curve Considering Heterogeneity (HDD)
Thank you for your attention.
Difference Between Civil and Information Systems

- 故障発生から直接的損失発生までタイムラグの短さ
- 複雑な階層構造
  下位の階層での故障が上位の機能を停止させる可能性
- 故障の横断的波及効果（情報伝達障害）
- 個別システムの高速な機能・性能の陳腐化
  2,3年周期の技術革新サイクル
- 豊富な代替案の存在
- 顧客サービス水準の高度化
異質性を考慮した生存曲線（電源部）
異質性を考慮した生存曲線（処理部本体）

生存確率

使用期間（ヶ月）

Average
Min（部局3サーバ）
Max（部局8サーバ）

生存確率
0.5
異質性を考慮した生存曲線（HDD）

用途別の期待生存確率

生存確率

使用期間（月）

生存確率

PC

サーバー

装置

用途別の期待生存確率