Risk-Based Resource Allocation for Distribution System Maintenance

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Acknowledgement:
Bob Saint
NRECA
Maintenance Strategies

- Corrective
  - Run-to-fail

- Preventive
  - Time-based
  - Condition-based
  - Reliability-centered
  - Risk-based
Risk-based maintenance

- Condition is considered
- Also considered are:
  - Likelihood of failure
  - Consequences of failure
  - Cost of maintenance
- Seeks the “least cost” maintenance schedule
Risk-based maintenance

Within a limited maintenance budget, service the equipment that will minimize SAIDI, SAIFI, energy not served, cost of equipment failure, and contractual or regulatory penalties.
Risk-based maintenance depends on availability of historical data...

- Outage Management System
- Other records
- Accuracy of details is critical
  - What failed?
  - What caused the failure?
Outage History: Detailed information is needed

- Keep track of each component over time (they move around)
  - Service records
  - Failures
  - Failure causes
  - Repairs after failure

- Keep track of each location over time
  - Failures, causes, service
.. and condition data:

- Crew (and other) observations
  - sagging lines
  - rusted tanks
  - leaning poles
  - cracked insulators
  - leaking oil
  - tree trimming needs

- Recorders
Condition Monitoring
Other available data

- Electronic relay/recloser data
- Breaker/recloser operation counters
- Transformer insulation oil tests
- Voltage/power quality recorders
- Customer service complaints
- Marketing rep feedback
- Real-time monitoring
  - Transformer audible noise
  - Transformer oil condition
  - Conductor sag
  - Tree height
Data:

- A system of recording and communication is critical to making data available
- Details are important
- Availability of data is critical, but condition assessment programs must be designed to use whatever is available
Risk-Based Resource Allocation for Distribution System Maintenance

- Distribution component analysis: reclosers, wood poles, tree trimming
  - Condition assessment
  - Estimate failure rate from condition
  - Estimate failure rate improvement after maintenance

- System reliability analysis
  - Estimate risk reduction from maintenance
    » Reliability indices (e.g. SAIDI, SAIFI)
    » Energy not served
    » Cost of equipment failure
    » Regulatory/contractual penalties

- Optimize to perform resource allocation
### Recloser Condition Calculation

- This recloser was scored while in service (upper section only)
- Lower section must be scored with recloser out of service
- High score = good
- Low score = bad
- W = relative affect of criterion on failure rate

<table>
<thead>
<tr>
<th>Criterion</th>
<th>W</th>
<th>Score (0 - 1)</th>
<th>Pre-Maint</th>
<th>Post-Maint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>5</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>18</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>18</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experience</td>
<td>5</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clamps</td>
<td>3</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bushings</td>
<td>3</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank</td>
<td>3</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Dielectric</td>
<td>20</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulics</td>
<td>3</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contacts</td>
<td>6</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact Box</td>
<td>4</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solenoid</td>
<td>3</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank Liner</td>
<td>3</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stringers</td>
<td>6</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Weighted Average</strong></td>
<td></td>
<td><strong>0.94459</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Recloser Failure Rates

- Condition score places each recloser somewhere between the best and worst failure rates
  - Rates are preferably calculated from system historical data.
    System average recloser failure rate:
    \[
    \lambda(1/2) = \frac{\text{Total no. recloser failures}}{(\text{No. reclosers}) \times (\text{No. years})}
    \]
  - If system historical data are not available, then use published best, worst, and average failure rates:
    \[
    \lambda(0) = 0.0025 \quad \lambda(1/2) = 0.015 \quad \lambda(1) = 0.060
    \]

System historical failure rates

- Example: 6.44 years of data
- Each recloser failed either zero or once

\[ \lambda(0) = \frac{0 \text{ failure}}{6.44 \text{ years}} = 0.00000 \]
\[ \lambda(1) = \frac{1 \text{ failure}}{6.44 \text{ years}} = 0.15528 \]

- These values are too low and high to be realistic, because 6 years is not long enough, so use published values:

\[ \lambda(0) = 0.0025 \quad \lambda(1) = 0.060 \]
System historical failure rates

Average failure rate:
23 of 341 reclosers failed:

\[ \lambda (1/2) = \frac{23}{341 \times 6.44} = 0.010473 \]
Use condition score to estimate recloser failure rate:

\[
\lambda(x) = Ae^{Bx} + C
\]

\[
A = \frac{[\lambda(1/2) - \lambda(0)]^2}{\lambda(1) - 2\lambda(1/2) + \lambda(0)}
\]

\[
B = 2\ln\left(\frac{\lambda(1/2) + A - \lambda(0)}{A}\right)
\]

\[
C = \lambda(0) - A
\]

\[
\lambda(x) = 0.00153 e^{3.65x} + 0.00097
\]
Example:
Recloser Failure Rate Calculation

Using condition score:

\[
\lambda \left( \frac{0.99 - 0.944595}{0.99 - 0.31} \right) = 0.002923
\]

This failure rate is close to 0.0025, the best failure rate found on the system.
Maintenance increases condition scores and allows inspection of all components. Failure rate improves to 0.00201 from 0.00292.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>W</th>
<th>Score (0 - 1) Pre-Maint</th>
<th>Score (0 - 1) Post-Maint</th>
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<td>0.98</td>
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<td>N/A</td>
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<td>N/A</td>
<td>0.98</td>
</tr>
<tr>
<td>Stringers</td>
<td>6</td>
<td>N/A</td>
<td>0.95</td>
</tr>
<tr>
<td>Weighted Average</td>
<td></td>
<td>0.945</td>
<td>0.976</td>
</tr>
</tbody>
</table>
Convert failure rate $\lambda$ to protection reliability $PR$

- Failure probability $= \frac{\lambda \text{ (failures/yr)}}{\text{operations/yr}}$
  - Operations/yr are obtained from records for the recloser’s location (not the recloser itself) or are estimated if records are not available.

- Protection reliability (= reclose reliability) $= \sqrt{1 - \text{failure probability}}$
  
  (input to reliability evaluation and optimizer)
We consider benefit from failure rate reduction but neglect life-extension benefit: OK if maintenance is a renewal (tree-trim, pole/reclosure replacement).

We want to allocate resources through a decision on each component which accounts for total system benefit.
Example: Wood Pole Condition Assessment

- 90% wood pole failures occur at ground line
- Various ways to get ground-line strength: drill
- 13,940 poles: min=1, max=79, μ=30
**Overall Procedure for Wood Pole Condition (Degradation) Assessment**

1. Obtain condition history
2. Obtain mean strength loss rate: MSLR
3. Obtain component degradation paths and failure times for each pole
4. Perform lifetime analysis to obtain hazard
5. Map condition to failure rate & estimate effect of maintenance on failure rate


1163 decayed poles: min=5, max=67, μ=37
For each pole i: Age, Res strength N/mm², Rsgᵢ(t)
Lost strength %:
Lspᵢ(t)=1-Rsgᵢ(t)/Initial Strength
Mean strength loss rate, MSLR, determined from plot
MSLR, Rsgᵢ(t): estimate each pole’s penetration year
Step 3: Obtain component degradation paths
Step 4: perform lifetime analysis to get hazard

(Failure: 33% strength lost)

To compute hazard: fit $F(t)$ to a Weibull

$$F(t) = 1 - \exp[-(t/\eta)^{\beta}];$$

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

- Penetration Age = \frac{\text{Lsp(PoleAge)}}{\text{MSLR}}
- Failure Age = \frac{0.33 - \text{Lsp(PoleAge)}}{\text{MSLR}}

h(t) \approx \Pr(t < T \leq t+\Delta t | T > t)/\Delta t
5. Map condition to hazard, estimate effect of maintenance

Lost strength %, \( L_s(t) \)

Population degradation path

Failure Rate

Pole Age

Condition Age

\( \Delta \lambda \) from Pole Replacement

\( \Delta \lambda \) from Pole treatment (stops decay for 5 yrs)
## Some Typical Results

<table>
<thead>
<tr>
<th>Pole</th>
<th>Age</th>
<th>$Lsp_i(age)$</th>
<th>Condition age</th>
<th>Failure rate (failures/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>0.1025</td>
<td>14.5</td>
<td>0.001</td>
</tr>
<tr>
<td>3</td>
<td>39</td>
<td>0.0615</td>
<td>11.7</td>
<td>0.0004</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
<td>0.2929</td>
<td>27.7</td>
<td>0.01</td>
</tr>
</tbody>
</table>
## Some Typical Results

<table>
<thead>
<tr>
<th>Pole</th>
<th>Age</th>
<th>Failure rate reduction (Failures/year)</th>
<th>Increase in Lifetime (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>replace treatment (per year)</td>
<td>replace</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>$2 \times 10^{-10}$</td>
<td>$2 \times 10^{-10}$</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>0.001</td>
<td>0.0003</td>
</tr>
<tr>
<td>3</td>
<td>39</td>
<td>0.0004</td>
<td>0.00015</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
<td>0.01</td>
<td>0.0014</td>
</tr>
</tbody>
</table>
A Predictive Reliability Evaluation Tool

- Spread-sheet based enumerative reliability evaluation tool for distribution systems; validated using IEEE RBTS
- Computes SAIFI(k), SAIDI(k), EENS(k), ECost(k) as function of Reliability Data for OH, UG segments, reclosers, fuses, sectionalizers, breakers, switches.
- Faults are assumed to originate on OH or UG segments.
- Operational failure modes of protective & switching devices (failure to open for fault, failure to reclose after fault cleared) are modeled. For device failing to clear fault, backup protective device operates, interrupting a larger number of customers for longer duration of time.
- Computes $\Delta$SAIFI(k), $\Delta$SAIDI(k), $\Delta$EENS(k), $\Delta$ECost(k) sens to $\Delta\lambda(k)$ for OH, UG line segments, & $\Delta PR(k)$ for reclosers.
- Sensitivities used to compute $\Delta$SAIFI(k), $\Delta$SAIDI(k), $\Delta$EENS(k), $\Delta$ECost(k) as function of maint effects on rel data
  - Woodpole maint reduces segment $\lambda$; tree-trimming reduces $\lambda$ of entire feeder.
  - Recloser maint reduces PR, assumed equal to RR.
Information Required for Predictive Reliability Evaluation Tool

- System topology
- Customer and load data
- Reliability data, per the below table

<table>
<thead>
<tr>
<th></th>
<th>$\lambda$</th>
<th>MTTR</th>
<th>PR</th>
<th>RR</th>
<th>SR</th>
<th>MTTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH, UG line segments</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>reclosers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fuses, breakers, sectionalizers</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>switches</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Asset Mgt: A resource allocation problem

- Resource allocation problem A:
  ➔ How does the asset manager identify and justify the right total resource request?
Asset Mgt: A resource allocation problem

- Resource allocation problem B:
  ➔ How does the asset manager allocate the available resources among the different programs/categories?

- Resource allocation problem C:
  ➔ For each program, select the equipment to maintain.
1. Given $\Delta \lambda(k)$, $\Delta PR(k)$, compute corresponding $\Delta \text{Risk}(k)$ using predictive reliability evaluation tool.

$$\Delta \text{Risk}(k) = \alpha_1 \cdot \Delta \text{SAIFI}(k) + \alpha_2 \cdot \Delta \text{SAIDI}(k) + \alpha_3 \cdot \Delta \text{ENS}(k) + \alpha_4 \cdot \Delta \text{DevRisk}(k)$$

2. Associate a triplet with each maintenance candidate of component $k$:

$\{\Delta \text{Risk}(k), \text{Cost}(k), \text{Labor}(k)\}$

3. Perform 2-stage optimization as described in next two slides.....

Stage 1: For each program, select equipment to maintain for various program budgets

An integer program.

```
max \ z = \sum_{k=1}^{N_p} \Delta \text{Risk}(k) \times \text{Iselect}(k)

Subject to
\sum_{k=1}^{N_p} \text{Iselect}(k) \times \text{Laborh}(k) \leq \text{TotLaborh}(p)
\sum_{k=1}^{N_p} \text{Iselect}(k) \times \text{Cost}(k) \leq \text{Budget}(p)
\text{Iselect}(k) \in \{0,1\} \ \forall k = 1,2,\ldots N_p
```

Relax integer constraint; solve an LP to get dual variables.

```
max \ \ z = rx
subject to
C x \leq b
0 \leq x_k \leq 1 \ \forall k
```

Optimality criterion:
Select k if \( r_k - \hat{\lambda}^T C(k) > 0 \)

VERY FAST!
Stage 2: Allocate budget to programs and select tasks to get solution to Probs A, B, C

Previous problem results in a set of solutions for each program corresponding to different program budget levels.

Table I: Risk-reduction vs. budget

<table>
<thead>
<tr>
<th>Budget (1000$)</th>
<th>Wood pole</th>
<th>Recloser</th>
<th>Tree-trim</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>4.2</td>
<td>3.75</td>
<td>2.25</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>9</td>
<td>19.8</td>
<td>13.5</td>
<td>14.4</td>
</tr>
<tr>
<td>10</td>
<td>20.7</td>
<td>13.5</td>
<td>15</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Solved by DP

\[
\text{Max} : \sum_{i=1}^{p} \text{Cat } \Delta \text{Risk}(i, x_i)
\]

Subject to

\[
\sum_{i=1}^{p} x_i \leq \text{TotBudget}
\]

\(x_i\) Budget for category i
### Illustration

**Test System Information**

- A 66 feeder system (three counties)
  - 9504 overhead line segments
  - 84 reclosers

<table>
<thead>
<tr>
<th>Contingency</th>
<th>Failure modes</th>
<th>Maintenance activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution line outage</td>
<td>Tree contact</td>
<td>Feeder-based tree trimming</td>
</tr>
<tr>
<td></td>
<td>Pole fall</td>
<td>Pole treatment and replacement</td>
</tr>
<tr>
<td>Recloser malfunction</td>
<td>Mechanical failure and general aging</td>
<td>Minor maintenance (oil changing), major maintenance and replacement</td>
</tr>
</tbody>
</table>
## Project cost information

<table>
<thead>
<tr>
<th>Category</th>
<th>Labor Pool</th>
<th>Task</th>
<th>Cost($)</th>
<th>Man hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole</td>
<td>10 workers work 200 days per year and 8 hours per day</td>
<td>Pole treatment</td>
<td>200</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pole replacement</td>
<td>3000</td>
<td>24</td>
</tr>
<tr>
<td>Recloser</td>
<td>2 workers work 80 days per year and 8 hours per day;</td>
<td>Minor maintenance</td>
<td>2500</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Major maintenance</td>
<td>5400</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Replacement</td>
<td>25000</td>
<td>40</td>
</tr>
<tr>
<td>Tree trimming</td>
<td>4 workers work 300 days per year and 8 hours per day</td>
<td>Feeder-based tree trimming</td>
<td>200/mile</td>
<td>7 per mile</td>
</tr>
</tbody>
</table>
**Solution to Stage 1 Problem**

Table IV: Risk-reduction vs. budget of the test system

<table>
<thead>
<tr>
<th>Budget (1000$)</th>
<th>Risk-reduction form different category</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wood pole</td>
<td>Recloser</td>
<td>Tree-trim</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5128</td>
<td>0</td>
<td>0</td>
<td></td>
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<tr>
<td>2</td>
<td>8249</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>20886</td>
<td>330009</td>
<td>78017</td>
<td></td>
</tr>
<tr>
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<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
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<td>238954</td>
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<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>
Risk-reduction vs. investment

Resource allocations beyond $800k are probably not justifiable.

Fig. 5: The budget vs. risk reduction
• Recloser maintenance selection is discrete

• Tree-trimming maintenance continuously increases between recloser selections

• Wood pole maintenance should be done only for poles in very bad shape until needed tree-trimming and recloser maintenance is mostly done and budget still remains.

Fig. 6: Budget splitting curve for different category task
Labor sensitivity

Budgets above ~$800k should consider labor increase.

Budgets below ~$500k should consider labor reduction.

Fig. 7: Labor sensitivity
Concluding Statements

- Risk reduction is a quantifiable maint. objective.
- Should be data-driven, based on reliability theory.
- Maint. is a tractable resource allocation problem.
- Should use optimization procedures to solve it.