

Risk-Based Resource Allocation for Distribution System Maintenance

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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

Criterion	W	Score (0 - 1)	
		Pre-Maint	Post-Maint
Age	5	0.9	
Duty Cycle	18	0.95	
Environment	18	N/A	
Experience	5	0.9	
Clamps	3	1.0	
Bushings	3	1.0	
Tank	3	0.95	
Oil Dielectric	20	N/A	
Hydraulics	3	N/A	
Contacts	6	N/A	
Contact Box	4	N/A	
Solenoid	3	N/A	
Tank Liner	3	N/A	
Stringers	6	N/A	
Weighted Average		0.94459	



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:

$$\lambda(1/2) = \frac{\textit{Total no. recloser failures}}{(\textit{No. reclosers}) \times (\textit{No. years})}$$

- 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 one time

$$\lambda(0) = 0 \text{ failure} / 6.44 \text{ years} = 0.00000$$

$$\lambda(1) = 1 \text{ failure} / 6.44 \text{ years} = 0.15528$$

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

$$\lambda(0) = 0.0025$$

$$\lambda(1) = 0.060$$



System historical failure rates

Average failure rate:

23 of 341 reclosers failed:

$$\lambda(1/2) = \frac{23}{341 * 6.44} = 0.010473$$



***Use condition score to estimate
recloser failure rate:***

$$\lambda(x) = Ae^{B*x} + C$$

$$A = \frac{[\lambda(1/2) - \lambda(0)]^2}{\lambda(1) - 2\lambda(1/2) + \lambda(0)} \quad A = 0.0015321$$

$$B = 2 \ln\left(\frac{\lambda(1/2) + A - \lambda(0)}{A}\right) \quad B = 3.6514524$$

$$C = \lambda(0) - A \quad C = 0.0009679$$

$$\lambda(x) = 0.00153 e^{3.65x} + 0.00097$$



Example: Recloser Failure Rate Calculation

Using condition score:

$$\lambda \left(\frac{.99 - 0.944595}{.99 - .31} \right) = 0.002923$$

This failure rate is close to 0.0025, the best failure rate found on the system.

Criterion	W	Score (0 - 1)	
		Pre-Maint	Post-Maint
Age	5	0.9	
Duty Cycle	18	0.95	
Environment	18	N/A	
Experience	5	0.9	
Clamps	3	1.0	
Bushings	3	1.0	
Tank	3	0.95	
Oil Dielectric	20	N/A	
Hydraulics	3	N/A	
Contacts	6	N/A	
Contact Box	4	N/A	
Solenoid	3	N/A	
Tank Liner	3	N/A	
Stringers	6	N/A	
Weighted Average		0.94459	



Maintenance increases condition scores and allows inspection of all components.

Failure rate improves to

0.00201

from

0.00292

Criterion	W	Score (0 - 1)	
		Pre-Maint	Post-Maint
Age	5	0.9	0.95
Duty Cycle	18	0.95	0.98
Environment	18	N/A	N/A
Experience	5	0.9	0.9
Clamps	3	1.0	1.0
Bushings	3	1.0	1.0
Tank	3	0.95	0.98
Oil Dielectric	20	N/A	1.0
Hydraulics	3	N/A	0.98
Contacts	6	N/A	1.0
Contact Box	4	N/A	0.95
Solenoid	3	N/A	0.95
Tank Liner	3	N/A	0.98
Stringers	6	N/A	0.95
Weighted Average		0.945	0.976



Convert failure rate λ 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.

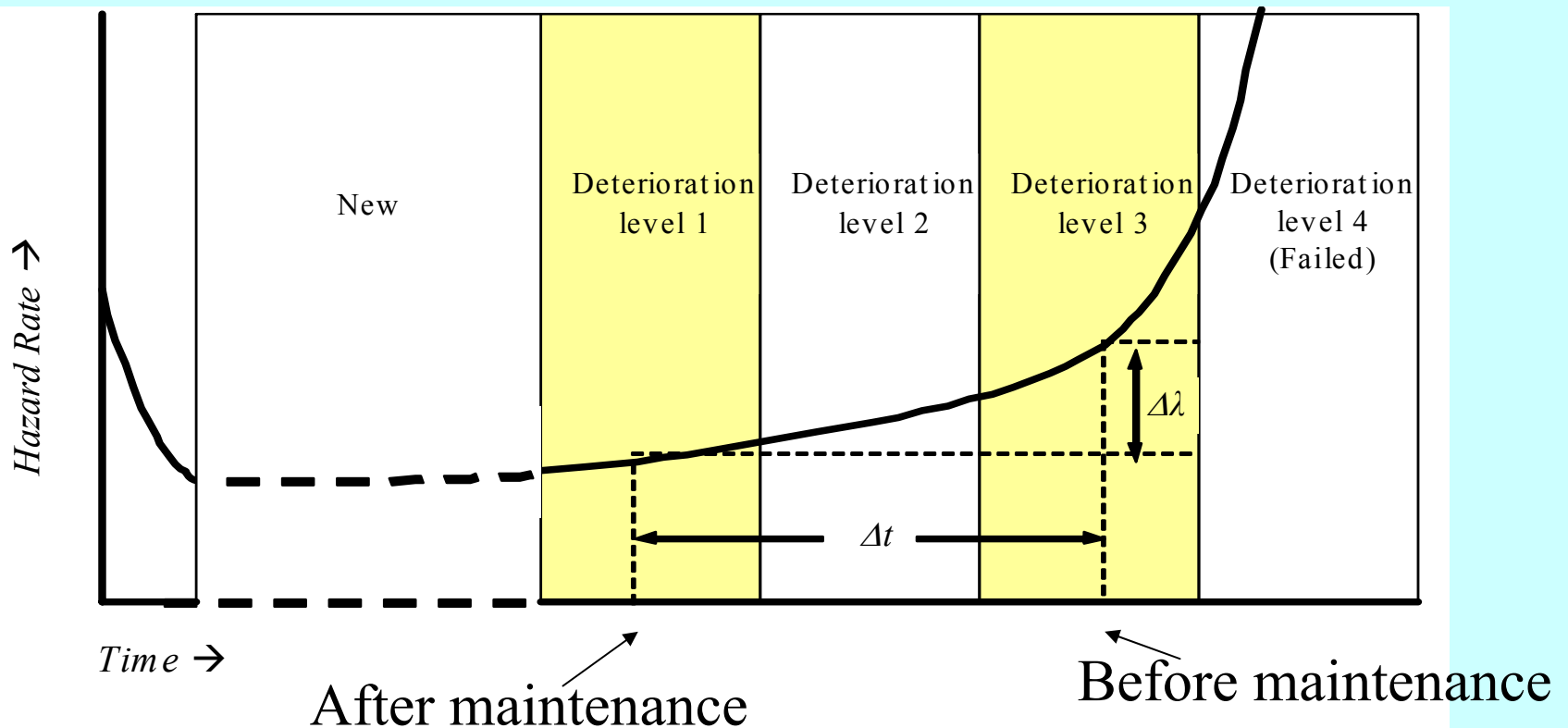
- Protection reliability (= reclose reliability) =

$$\sqrt{1 - \text{failure_probability}}$$

(input to reliability evaluation and optimizer)



Maintenance-Induced Hazard-Reduction



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 grnd-line strngth: drill
- 13,940 poles: min=1, max=79, $\mu=30$

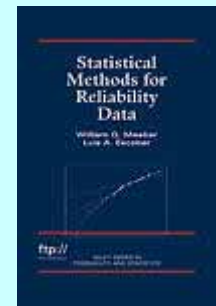


*Overall *Procedure for Wood Pole Condition (**Degradation) Assessment*

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

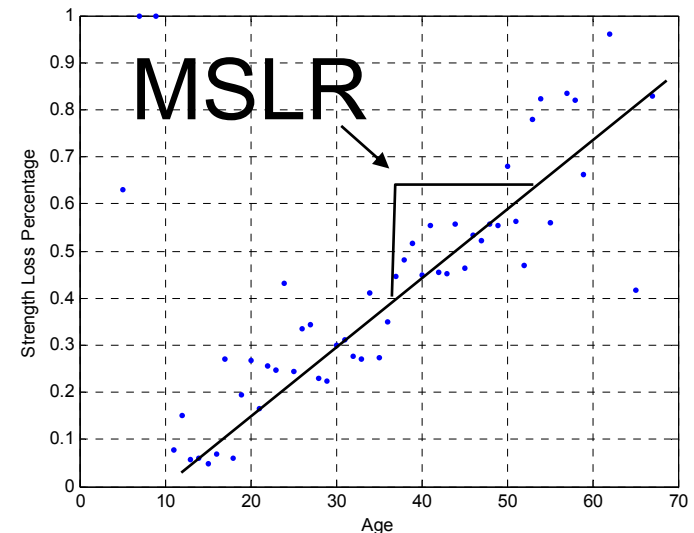
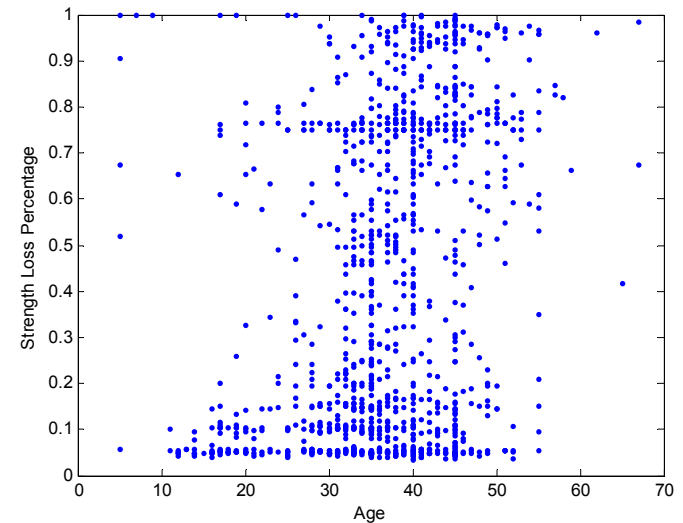
* Procedure described in PSerc report, & in Y. Li, S. Yeddapanudi et al, "Degradation Path Model for Wood Pole Asset Management," NAPS, 2005.

** W. Meeker, L. Escobar, "Statistical Methods for Reliability Data," Wiley, 1998, www.public.iastate.edu/~stat533

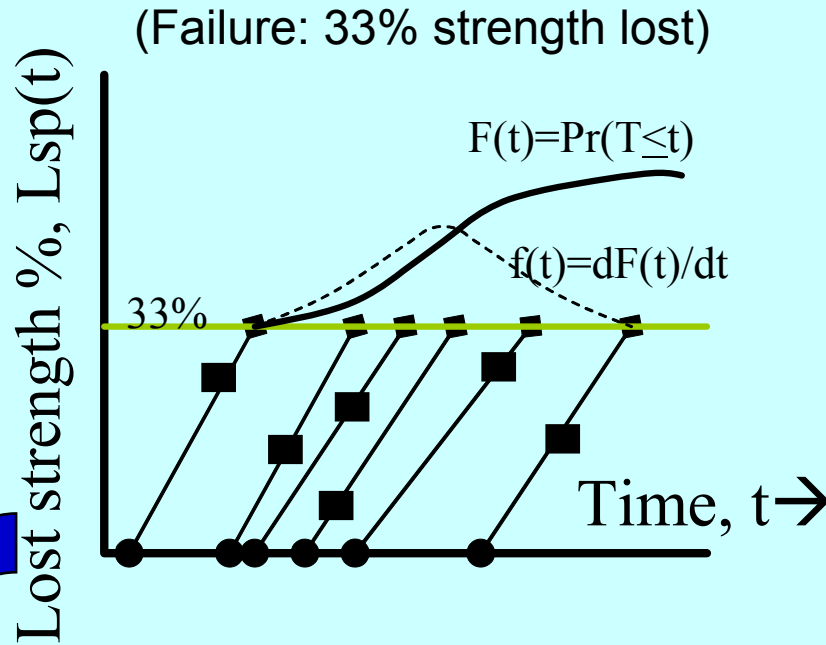


Steps 1, 2: Pole condition histories, MSLR

- 1163 decayed poles:
min=5,max=67, $\mu=37$
- For each pole i : Age, Res
strngth N/mm^2 , $Rsg_i(t)$
- Lost strength %:
 $Lsp_i(t)=1-Rsg_i(t)/\text{Initial Strngth}$
- Mean strength loss rate,
MSLR, determined from plot
- MSLR, $Rsg_i(t)$: estimate each
pole's penetration year



Step 3: Obtain component degradation paths
Step 4: perform lifetime analysis to get hazard



● PenetrationAge =

$$\text{PoleAge} - \frac{L_{sp}(\text{PoleAge})}{\text{MSLR}}$$

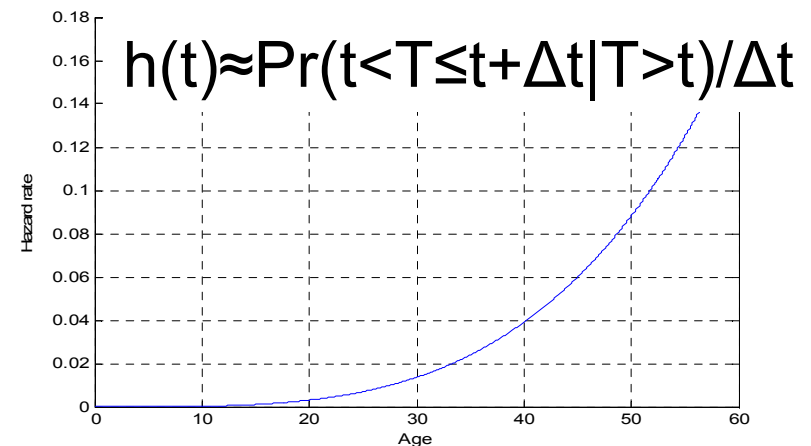
◆ FailureAge =

$$\text{PoleAge} + \frac{0.33 - L_{sp}(\text{PoleAge})}{\text{MSLR}}$$

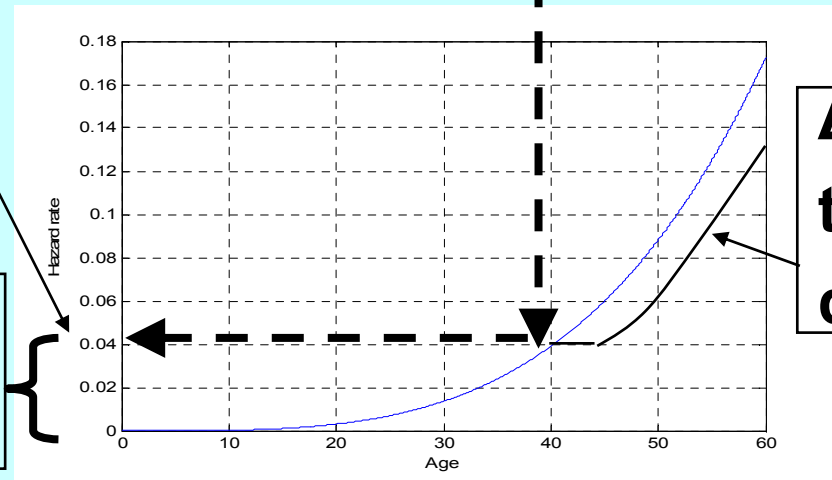
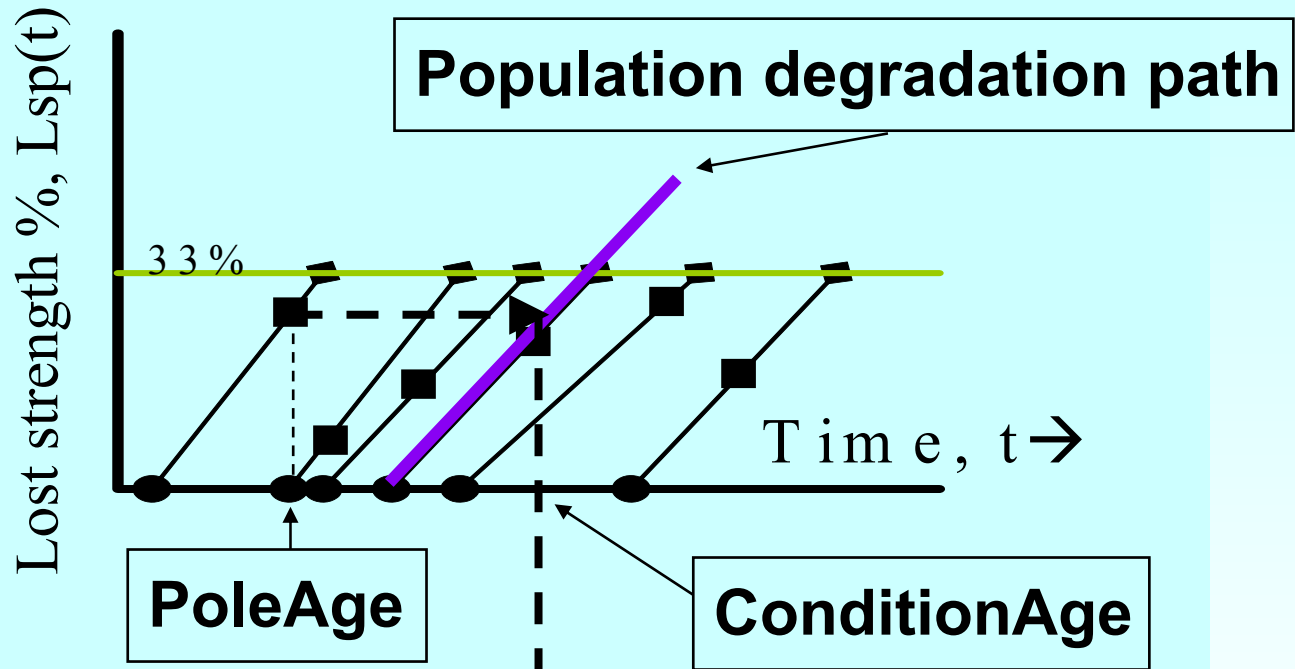
To compute hazard:
fit $F(t)$ to a Weibull

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

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



5. Map condition to hazard, estimate effect of maintenance



$\Delta\lambda$ from Pole treatment (stops decay for 5 yrs)

$\Delta\lambda$ from Pole Replacement

Some Typical Results

Pole	Age	$Lsp_i(age)$	Condition age	Failure rate (failures /year)
1	10	0	0	0
2	17	0.1025	14.5	0.001
3	39	0.0615	11.7	0.0004
4	42	0.2929	27.7	0.01



Some Typical Results

P o l e	A g e	Failure rate reduction (Failures/year)		Increase in Lifetime (year)	
		replace	treatment (per year)	replace	treatment
1	10	$2 \cdot 10^{-10}$	$2 \cdot 10^{-10}$	0.02	0.02
2	17	0.001	0.0003	14.5	5
3	39	0.0004	0.00015	11.7	5
4	42	0.01	0.0014	27.7	5



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 Δ SAIFI(k), Δ SAIDI(k), Δ EENS(k), Δ ECost(k) sens to $\Delta\lambda(k)$ for OH, UG line segments, & Δ PR(k) for reclosers.
- Sensitivities used to compute Δ SAIFI(k), Δ SAIDI(k), Δ EENS(k), Δ ECost(k) as function of maint effects on rel data
 - Woodpole maint reduces segment λ ; tree-trimming reduces λ of entire feeder.
 - Recloser maint reduces PR, assumed equal to RR.



Information Required for Predictive Reliability Evaluation Tool

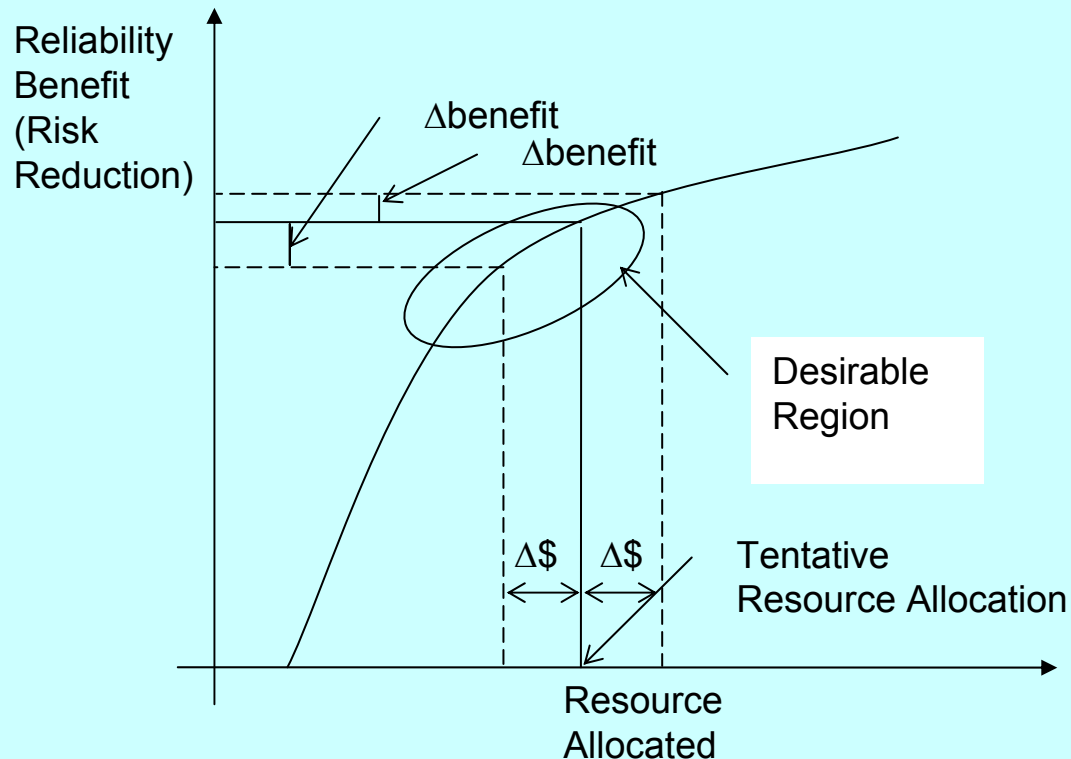
- System topology
- Customer and load data
- Reliability data, per the below table

	λ	MTTR	PR	RR	SR	MTTS
OH, UG line segments	√	√				
reclosers		√	√	√	√	√
fuses, breakers, sectionalizers		√	√		√	√
switches		√			√	√

All parameters defined, and the tool is described, in the PSerc report, and in a paper: S. Yeddanapudi, Y. Li, et al, "A Reliability Evaluation Tool for Risk-Based Evaluation of Allocation of Distribution System Maintenance Resources," to be submitted soon....

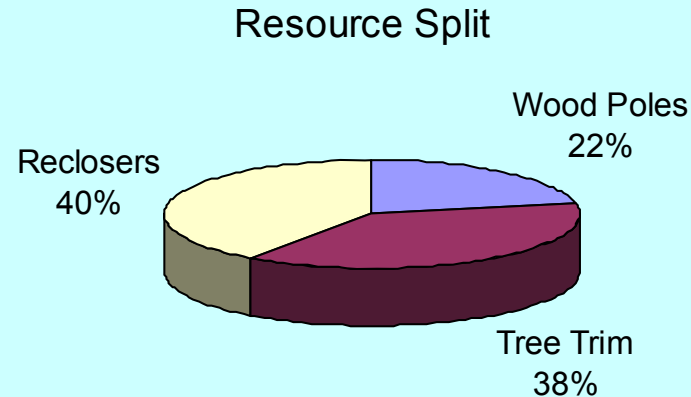
Asset Mgt: A resource allocation problem

- 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.

Task Selection

ID	Candidate Project	Selection
132	Recloser#25 Minor	<input checked="" type="checkbox"/>
133	Recloser#1 Major	<input type="checkbox"/>
134	Pole#2235 Treatment	<input checked="" type="checkbox"/>
135	Pole#3143 Replacement	<input type="checkbox"/>
136	Feeder#34 Tree Trim	<input checked="" type="checkbox"/>

Record: 6



Risk-Based Asset Management

1. Given $\Delta\lambda(k)$, $\Delta PR(k)$, compute corresponding $\Delta Risk(k)$ using predictive reliability evaluation tool.

$$\Delta Risk(k) = \overbrace{\alpha_1 \cdot \Delta SAIFI(k) + \alpha_2 \cdot \Delta SAIDI(k)}^{\text{Customer satisfaction}} + \overbrace{\alpha_3 \cdot \Delta ENS(k)}^{\text{Lost Revenue}} + \overbrace{\alpha_4 \cdot \Delta DevRisk(k)}^{\text{Cost of component failure}}$$

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

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

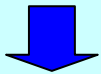
3. Perform 2-stage optimization as described in next two slides.....



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

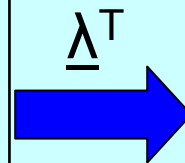
An integer program.

$$\begin{aligned} \max \quad & z = \sum_{k=1}^{N_p} \Delta Risk(k) \times Iselect(k) \\ \text{Subject to} \quad & \sum_{k=1}^{N_p} Iselect(k) \times Laborh(k) \leq TotLaborh(p) \\ & \sum_{k=1}^{N_p} Iselect(k) \times Cost(k) \leq Budget(p) \\ & Iselect(k) \in \{0,1\} \quad \forall k = 1,2,\dots,N_p \end{aligned}$$



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

$$\begin{aligned} \max \quad & z = \underline{r}x \\ \text{subject to} \quad & \underline{C}x \leq \underline{b} \\ & 0 \leq x_k \leq 1 \quad \forall k \end{aligned}$$



$$\begin{aligned} \max \quad & z = \underline{r}x - \underline{\lambda}^T (\underline{C}x - \underline{b}) \\ & = (\underline{r} - \underline{\lambda}^T \underline{C})x + \underline{\lambda}^T \underline{b} \\ \text{subject to} \quad & x_k \in \{0,1\} \quad \forall k \end{aligned}$$

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

VERY
FAST!

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

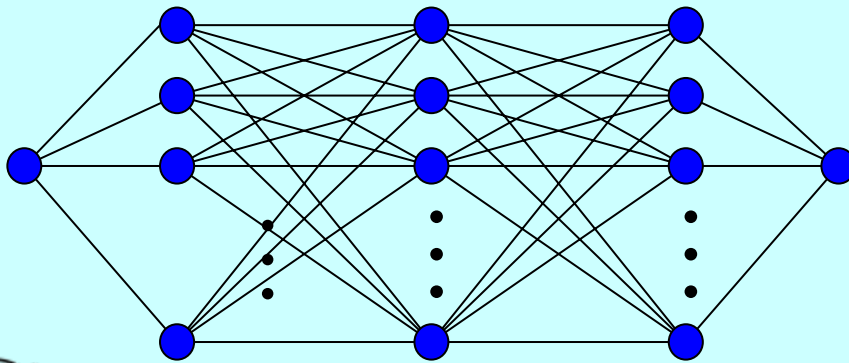
Previous problem results in a set of solutions for each program corresponding to different program budget levels.

Table I: Risk-reduction vs. budget

Budget (1000\$)	Risk-reduction form different category		
	Wood pole	Recloser	Tree-trim
0	0	0	0
1	4.2	3.75	2.25
...
9	19.8	13.5	14.4
10	20.7	13.5	15
...

Table II: Decision variable code table

Budget (1000\$)	Selected tasks from each category		
	Wood pole	Recloser	Tree-trim
0	000...000	000...000	000...000
1	010...100	101...001	100...010
...
9	100...110	110...101	010...101
10	110...011	111...100	110...110
...



Solved by DP

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

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

Contingency	Failure modes	Maintenance activity
Distribution line outage	Tree contact	Feeder-based tree trimming
	Pole fall	Pole treatment and replacement
Recloser malfunction	Mechanical failure and general aging	Minor maintenance (oil changing), major maintenance and replacement



Illustration

Project cost information

Category	Labor Pool	Task	Cost(\$)	Man hours
Pole	10 workers work 200 days per year and 8 hours per day	Pole treatment	200	8
		Pole replacement	3000	24
Recloser	2 workers work 80 days per year and 8 hours per day;	Minor maintenance	2500	40
		Major maintenance	5400	80
		Replacement	25000	40
Tree trimming	4 workers work 300 days per year and 8 hours per day	Feeder-based tree trimming	200/mile	7 per mile



Solution to Stage 1 Problem

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

Budget (1000\$)	Risk-reduction form different category		
	Wood pole	Recloser	Tree-trim
0	0	0	0
1	5128	0	0
2	8249	0	0
...
18	20886	330009	78017
...
68	38936	736718	238954
...



Risk-reduction vs. investment

Resource allocations beyond \$800k are probably not justifiable.

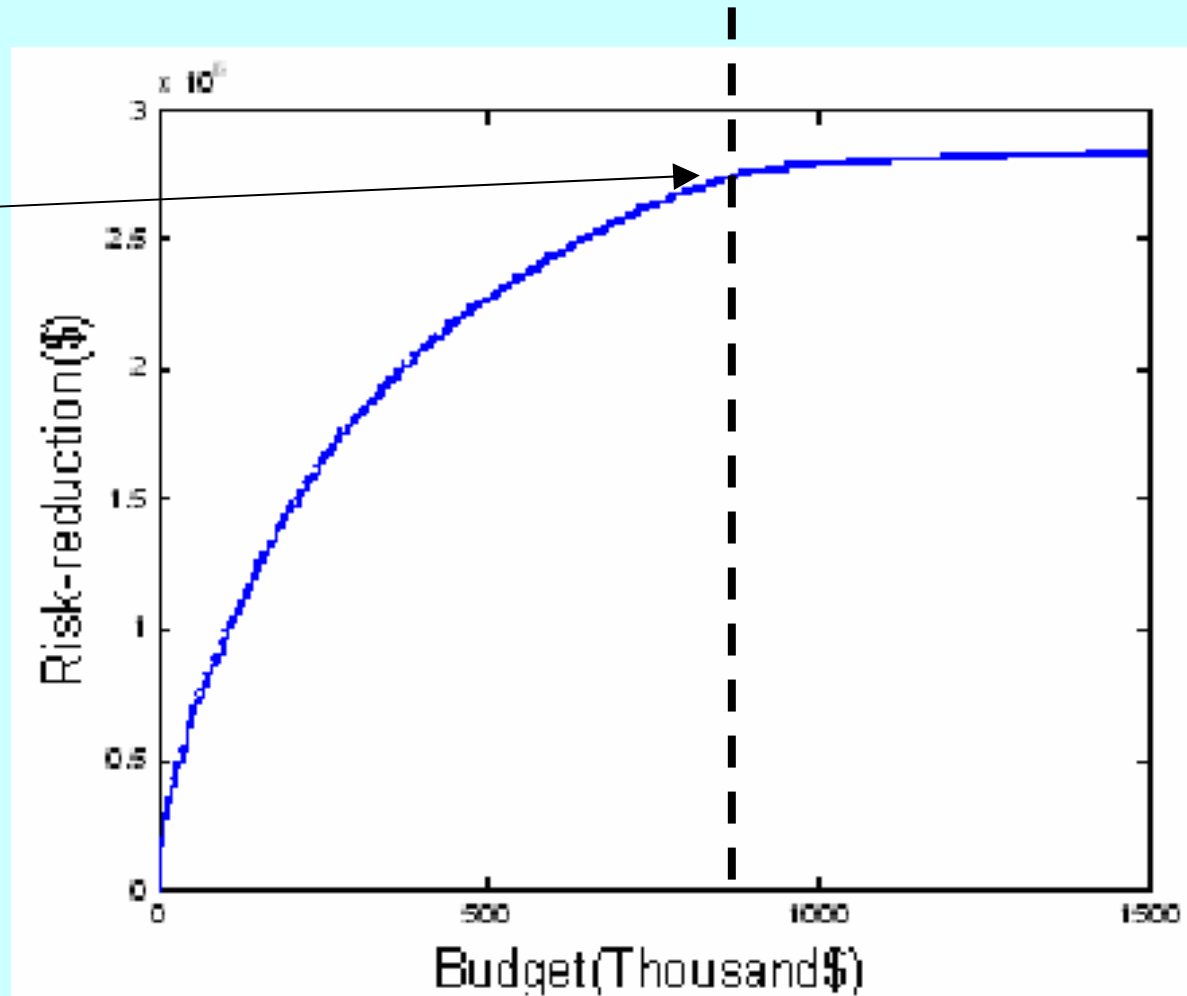


Fig. 5: The budget vs. risk reduction



Investment split

- 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.

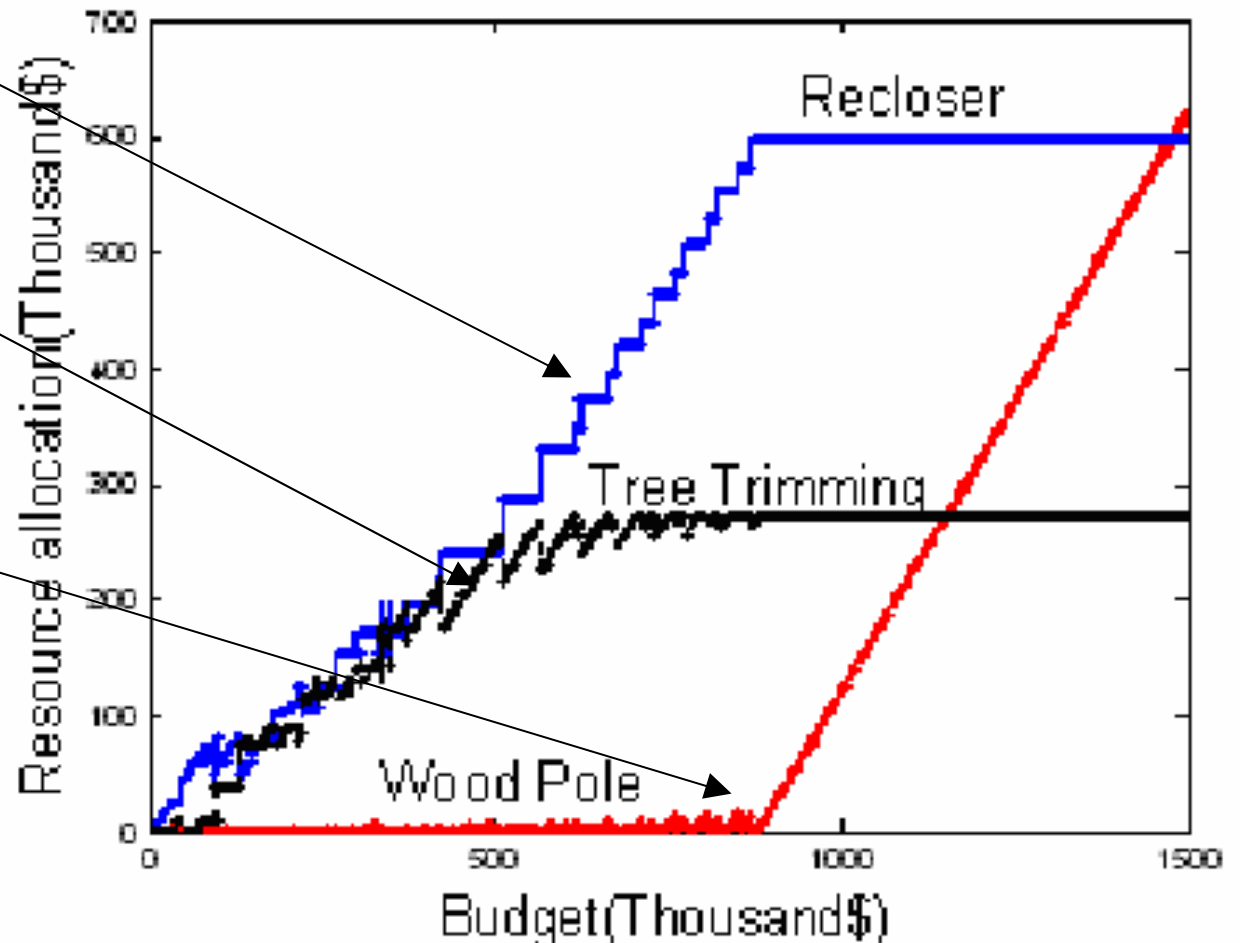
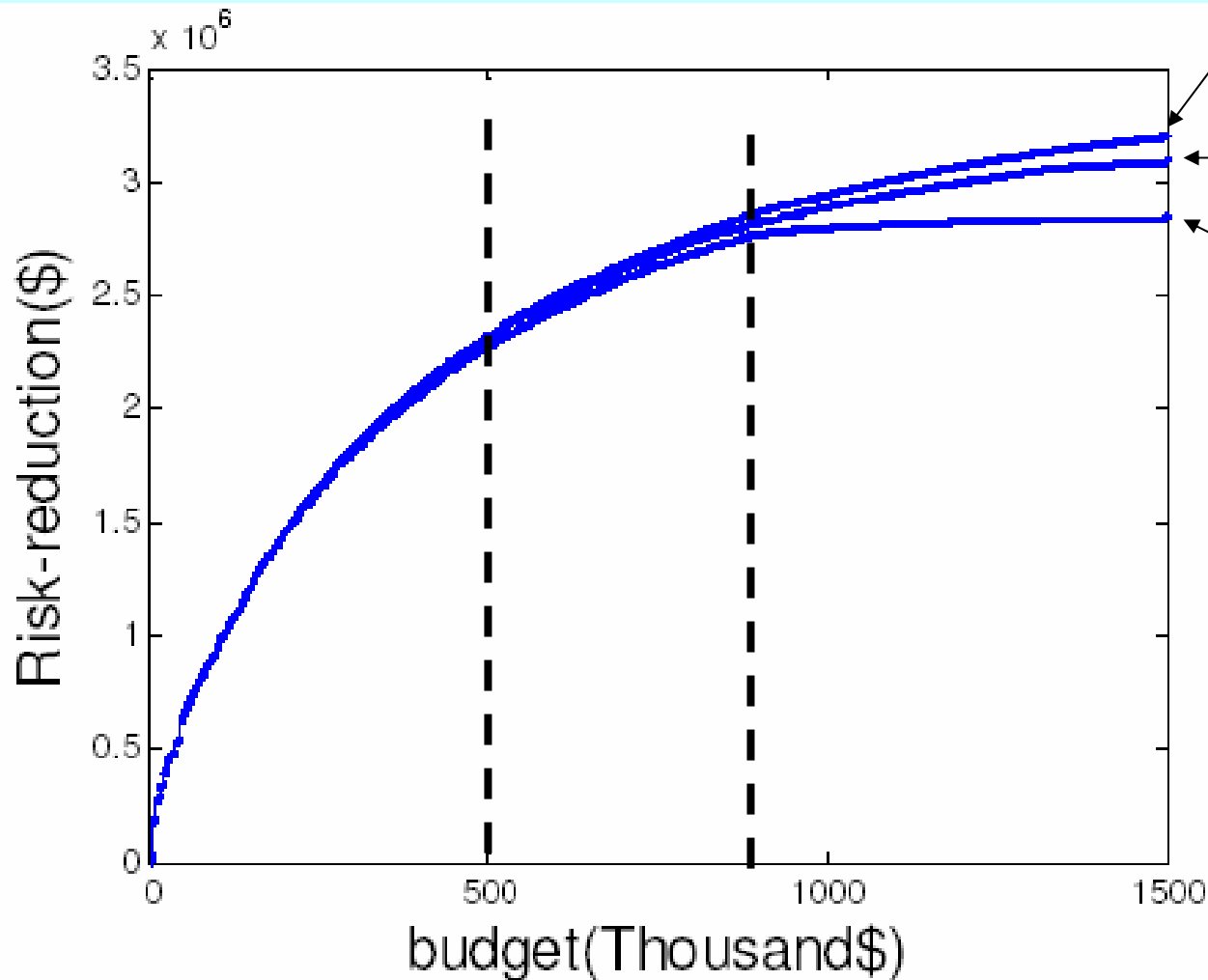


Fig.6: Budget splitting curve for different category task

Labor sensitivity



No labor constraint
1 additional recloser crew
Original labor constraint

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.

